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GEOLOGICAL SURVEY

Chlorine-rich biotites from the Blackbird mining district, Lemhi County, Idaho--evidence for a saline hydrothermal brine

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ABSTRACT

Mafic volcaniclastic rocks rich in biotite that are spatially associated with Co-Cu ores at Blackbird contain high chlorine concentrations. Chlorine concentrations as high as 1.87 wt. percent have been determined by microprobe analysis of iron-rich biotite. Rocks contain up to 1.01 wt. percent Cl and 0.10 wt. percent F. Halogen concentrations are proportional to the abundance of biotite and muscovite in the rocks because most Cl resides in biotite and most F is in muscovite. Fluid inclusions of uncertain age, but possibly of pre-metamorphic hydrothermal origin, also indicate very saline fluids by the presence of daughter salt minerals. Scapolite, restricted to strata of appropriate composition, also appears to be an indicator of saline fluids.

The high chlorine concentrations in rocks and in biotite are unusual for greenschist-facies regionally metamorphosed rocks. Highest chlorine concentrations are recorded in biotite within 3 km of the Blackbird mine, but anomalous concentrations are also present in biotite-rich rocks as far as 13 km from the mine. The limit of the halogen anomaly has not been determined. Fluids with salinities more than 10 times that of sea water circulated through the Yellowjacket and added potassium, chlorine, and other elements in a large volume of rocks, probably during diagenesis and possibly aided by overpressures associated with submarine slumping. Speculatively, the saline brines could have been pore fluids resembling oil field brines, or could have been submarine geothermal brines as at the Red Sea. The saline fluids would have facilitated transport of iron, cobalt, and other base metals to the ore deposits.

INTRODUCTION

Mafic volcaniclastic rocks characterized by more than 50 percent black biotite, distinctive host rocks for cobalt-copper deposits of the Blackbird mining district, about 30 mi west of Salmon, Idaho (fig. 1), contained a highly saline, chlorine-rich pore fluid that may have played an important role in ore formation. Three types of evidence that supports this inference includes: (1) super-saline fluid inclusions that contain numerous salt daughter minerals; (2) high chlorine concentrations in biotite, and to a lesser extent in muscovite; and (3) high chlorine concentrations in metasedimentary rocks. Stream-sediment samples from the Blackbird area also contain high chlorine concentrations (H.V. Alminas, oral commun., 1988). The highest chlorine values are observed in samples within 3 km of the Blackbird mine, but moderately high values are found 13 km distant and the full extent of the chlorine anomaly has not been determined. The chlorine is associated with widespread potassium metasomatism that is thought to have been produced by heated pore fluids expelled from underlying fine-grained sediments (Nash and Hahn, 1986) or a volcanic-related submarine geothermal system.

Highest chlorine values are in biotite-rich rocks because biotite is the principal residence of Cl. Biotite-rich rocks are prominent in the immediate area of the Blackbird mine; they are economically important because the cobalt-copper deposits occur in, or within a few meters of, strata comprised of 50 to 100 percent biotite (Nash and Hahn, 1986). These strata have been termed "mafic volcaniclastic rocks"; they are interpreted to be sedimented mixtures of basaltic and siliciclastic detritus (Hahn and Hughes, 1984; Nash and Hahn, 1986). Some of the mafic rocks described here also contain garnet or chloritoid, and all are richer in Fe-Mg-K than most strata in the Yellowjacket Formation in the region (Nash and Hahn, 1986). The mafic

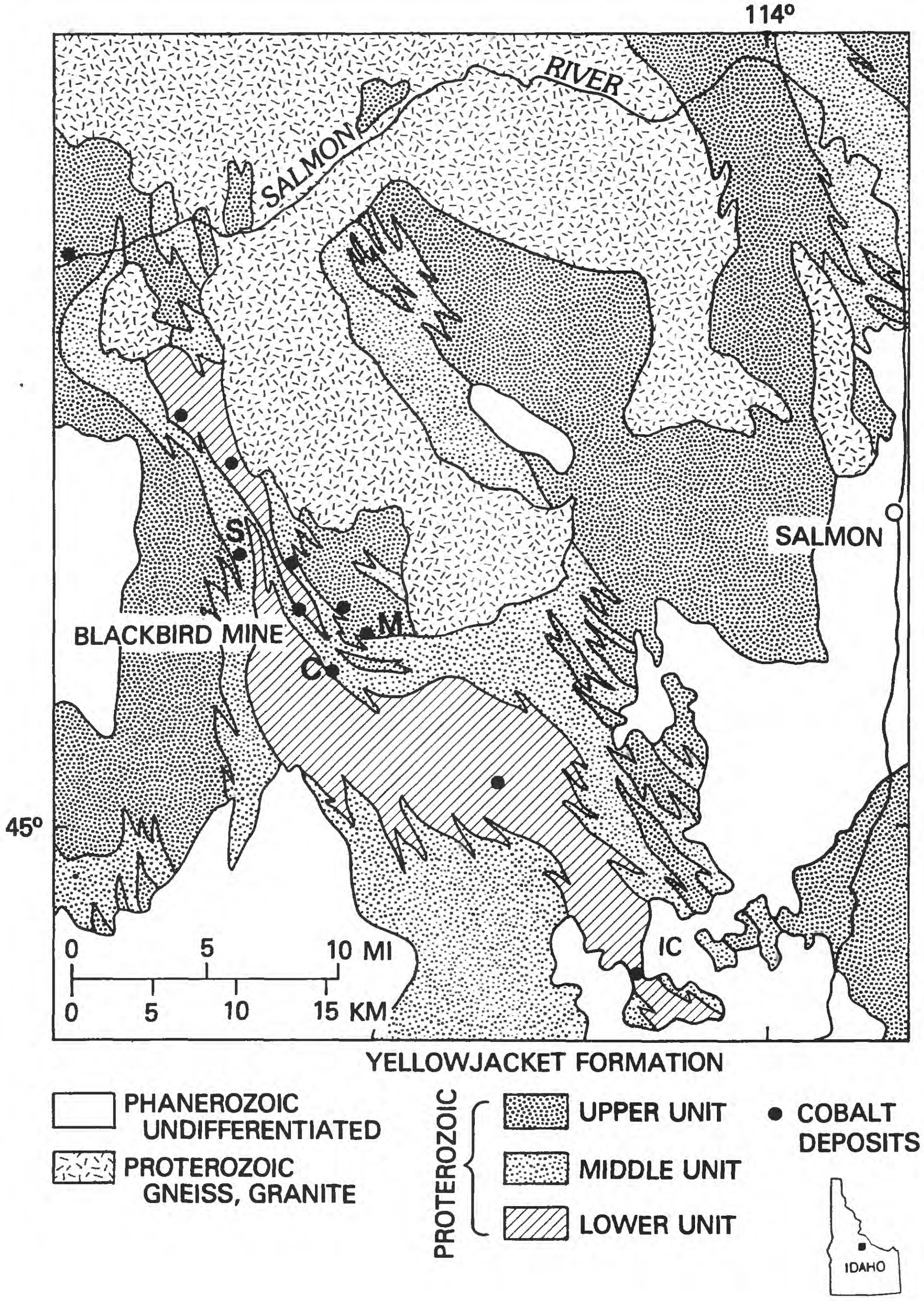

Figure 1. Location and generalized geology of the Idaho Cobalt Belt, Lemhi County, Idaho. Cobalt deposits: C, Conicu; IC, Iron Creek; M, Merle; S, Sunshine.

character of the biotite-rich strata is a distinctive feature of sub-basins in the Yellowjacket basin, and chlorine-rich biotite may be diagnostic of the volcano-sedimentary environment in which the ore deposits formed.

The origin of the saline brine is not known. Discussions that follow raise new questions about the sources of fluids and metals at Blackbird that can not be answered here. Geochemistry of the Blackbird ores and altered hostrocks, discussed previously (Nash and Hahn, 1986; Nash and others, 1987), is complex and suggests to the author the likelihood of multiple hydrothermal stages and multiple sources for various constituents. Although a mafic volcanic source is favored for key ore metals (Co, Cu, Au) because of the intimate spatial association of ores and mafic strata and dikes, a different source for other constituents (K, Cl, B?) such as in underlying fine-grained sediments and their pore fluids would not be incompatible with known ore geology. Mafic volcanism could have driven a synsedimentary geothermal system. The discussions that follow are a preliminary considerations of geochemical aspects of the postulated saline brine; analogies are mentioned only for their geochemical implications (gross composition, temperature, pressure) and not their tectonic setting or sources of metals or fluids.

Acknowledgements

This and other geochemical studies of the Blackbird mine area were made possible by the cooperation of Noranda Exploration, Inc. I thank Elaine Brandt for making the halogen analyses, and Ed DuBray, Karl Evans, and Steve Ludington for helpful reviews and discussions.

GEOLOGIC SETTING

Cobalt-copper deposits of the Blackbird district occur in clastic rocks of the Middle Proterozoic Yellowjacket Formation that probably formed in a rift basin (Hughes, 1983). The deposits are stratabound within distinctive fine-grained clastic and volcaniclastic rocks that comprise only a small part of the Yellowjacket Formation (Hughes, 1983; Nash and Hahn, 1986). The mine area underwent at least one period of metamorphism and deformation in the Precambrian, and rocks of the region were thrust eastward during Paleozoic(?) and Cretaceous orogenies, then cut by Cenozoic normal faults. Regional greenschist metamorphism occurred prior to contact metamorphism associated with 1,370 Ma granitic plutons (Evans and Zartman, 1981).

The Yellowjacket Formation in east-central Idaho is the oldest sedimentary unit in a Proterozoic section that is at least 15,000 m thick. Regionally, and in the mine area, three lithostratigraphic units are distinguished (Hughes, 1983; Connor and others, 1985) (fig. 1). The lower unit, more than 3,000 m thick, is predominantly grey-green argillite and siltite with lesser amounts of fine-grained quartzite and impure carbonate. Sedimentary features suggest deposition in a deep marine basin by turbidity currents as basin-plain and distal turbidite deposits. The upper part of the lower unit contains some coarser clastic rocks (fine-grained quartzite).

The middle unit, about 1,200 m thick, hosts the largest Co-Cu deposits of the Idaho Cobalt Belt (Hughes, 1983; fig. 1). The middle or B unit of Hughes (1983) is a complex of coarsening upward cycles of argillite, siltite, and fine-grained quartzite, and contains distinctive interbeds of biotite-rich rock. Zircon from mafic beds in the middle unit yielded apparent U-Pb ages of about 1,670-1,700 Ma (Hahn and Hughes, 1984); these ages should be considered maximum ages because of possible inherited radiogenic lead (K.V. Evans, written commun., 1986). Sedimentary structures are abundant in this unit and include graded beds, silt-sand couplets, flute casts, load structures, slumped beds, and sand dikelets. These clastic sediments were probably deposited in a submarine fan complex.

Layered biotite-rich rocks are common in the middle unit (fig. 2). Individual mafic beds are 1 to 20 cm thick and tend to occur in packages about 2 to 10 m thick comprised of mafic volcaniclastic strata and interbedded siltite and quartzite. Along-strike continuity of these beds is not well known because of poor outcrop, but most mafic packages can be correlated between drillholes 100 m apart. The layered mafic packages are 10 to 200 m thick and are useful for district-scale mapping (fig. 2). Mafic beds tend to be massive or faintly laminated and generally are not foliated. Depending upon metamorphic grade they are comprised chiefly of biotite or biotite-garnet ±chloritoid. Beds up to 10 cm thick of granular quartz or fine tourmaline are interbedded with the mafic rocks; the lack of clastic textures indicate these are chemical sediments, or "exhalite". Biotite-rich argillites resemble mafic rocks but have finer metamorphic biotite, more clastic quartz grains and layers, and graded bedding.

The upper unit of the Yellowjacket in the mine area is more than 1,000 m thick and is mostly thick bedded quartzite with planar laminations. Interbeds of fine clastic rocks and mafic strata are rare. Cross-beds and ripples are the most common sedimentary structures. Sedimentation probably occurred in a mid-fan or shallow marine shelf, although some hummocky beds probably reflect shallow-water wave action.

Metamorphosed mafic dikes and sills of several types intrude the Yellowjacket Formation. Although these rocks rarely crop out, they are common in float, drillcore, and mine workings where they are 1 to 30 m thick. Most dikes are dark green to black and are weakly porphyritic. Metamorphic minerals are biotite, zoisite, plagioclase, siderite, and minor quartz. Some dikes are grey with equal amounts of metamorphic plagioclase and mafic silicate minerals. A few diatremes, intersected in drillholes, contain fragments of ultramafic rock, gabbro, and carbonate rock composed of coarse-grained calcite; the carbonate fragments may represent carbonatite because no clean limestone is known in the basement. Mafic volcaniclastic rocks of the middle unit are most abundant in areas having mafic dikes and are chemically similar to the mafic dikes.

Proterozoic granitic rocks intrude the Yellowjacket about 3 km north and east of the Blackbird mine (fig. 1). The granitic rocks generally have large K-feldspar phenocrysts and some have gneissic fabric. Samples from various phases of the large body yield discordant Rb/Sr model ages of about 1,500 Ma (Armstrong, 1975) and zircons yield a more reliable U-Th-Pb age of 1,370 Ma (Evans and Zartman, 1981). Metamorphic grade increases toward the intrusive body, reaching a maximum grade of hornblende-cordierite-sillimanite in the contact zone.

Tertiary volcanic rocks of the Challis volcanic field cap some ridges about 5 km from the mine. Tertiary mafic and felsic dikes fill some fault zones and intrude the Yellowjacket in the mine.

The dominant structural features of the area are north to northwest-striking faults and shear zones. One of the largest of these, the White Ledge, appears to have substantial strike-slip movement and marks the western limit of mafic strata in the mine area (fig. 2). The garnet isograd is offset by some of the north-trending faults. Folds of many types and scales are present. Folds are most evident near the Merle and Idaho zones (fig. 2); beds are locally overturned in the Idaho zone. Some tight folds are near north-

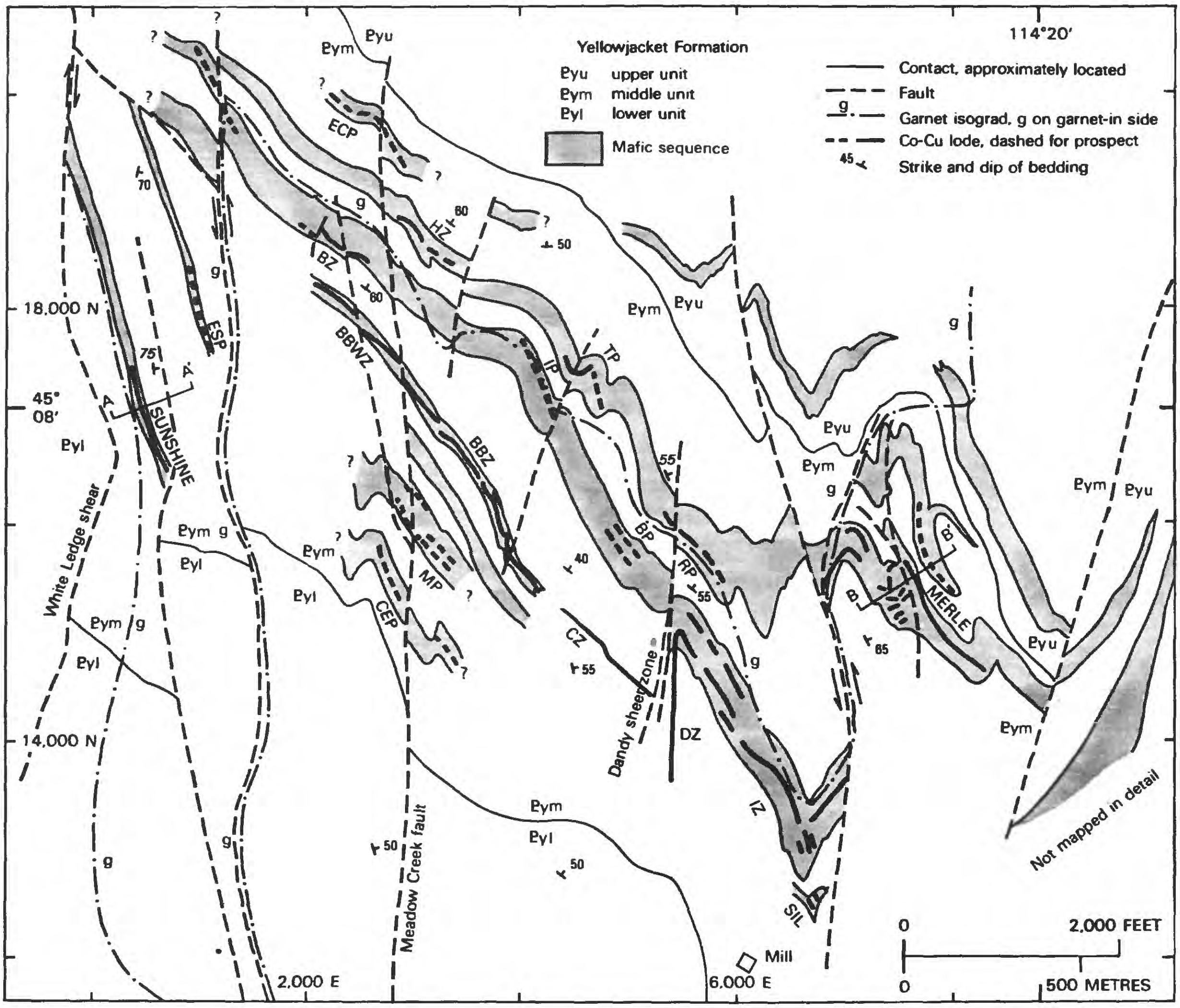

Figure 2. Generalized geology of the Blackbird mine area showing the location of Co-Cu deposits and prospects (generalized from unpublished mapping by Noranda Exploration, Inc., 1982). The Blackbird underground mine developed ore from a series of deposits spanning about 2.3 km from the Idaho Zone to the Blacktail zone. Abbreviations: BZ, Blacktail zone; BBZ, Brown Bear zone; BBWZ, Brown Bear west zone; BP, Buckeye prospect; CZ, Chicago zone; CP, Chelan prospect; CEP, Catherine-Ella prospect; DZ, Dandy zone; ECP, East Chelan prospect; ESP, East Sunshine prospect; HZ, Horseshoe zone; IZ, Idaho zone; IP, Iowa prospect; MP, Mushroom prospect; RP, Ridgetop prospect; SIL, South Idaho lode; TP, Toronto prospect

trending shears and seem to be produced by drag. Other folds are associated with areas of soft-sediment deformation and are interpreted as slump folds.

Three types of Co-Cu deposits are recognized in the Idaho Cobalt Belt (fig. 1). (1) The most important of these are Co-Cu-As-rich deposits of Blackbird mine type. These contain approximately equal amounts of cobalt and copper minerals, generally cobaltite (CoAsS) and chalcopyrite, with variable amounts of gold and pyrite. The deposits have tabular form and are closely associated with mafic sequences (fig. 2). (2) Cobaltiferous-pyrite deposits, with variable chalcopyrite content, occur at Iron Creek about 28 km southeast of the Blackbird mine (fig. 1). These deposits contain abundant very fine to coarse-grained pyrite. Bedded magnetite occurs below the Co-pyrite zones. (3) Cobaltite-bearing, tourmaline-cemented breccias are common in the lower unit of the Yellowjacket Formation for many kilometers south and east of the Blackbird mine. Only a few contain more than 0.1 percent Co.

METHODS

Most samples for this study came from drill core in and near Cu-Co deposits, and a smaller number were collected from road cuts and outcrops outside of ore zones. Most samples were studied in thin or polished thin sections, and 372 samples were submitted for major and minor element chemical analyses. The analytical methods and most of the geochemical results were described by Nash and others (1988). New results for chlorine and fluorine (table 1) were determined by Elaine Brandt using specific ion electrode methods (Jackson and others, 1988). Localities of analyzed samples are shown on figures 3A and 3B.

Selected minerals in polished thin sections were analyzed on an ARL model SEMQ microprobe using six wavelength dispersive spectrometers. Most of the analyses included 12 elements (Si, Al, Fe, Mg, Mn, Ca, Na, K, Ti, Ba, Cl, and F), using minerals such as amphibole and feldspar of well established and uniform composition as standards. The standards for Cl and F were synthetic halite and fluor-phlogopite, respectively, and the calibrations were checked by analysis of several mica and amphibole standards, including a biotite with 1.11 weight percent Cl (Lee, 1958). Although these analytical runs were not optimized for Cl and F, which produce lower count rates than major and heavier elements, replicate analyses indicate results have an accuracy of about +/- 10 percent. Backgrounds were determined by off-peak measurements on the analyzed grains. Analyses reported in table 1 are the average of three spot analyses (20 second counting period); data were reduced by online software utilizing "MAGIC IV".

RESULTS

The first indication of high chlorine concentration in rocks of the area was fluid inclusions that contain halite (NaCl) and as many as six other daughter minerals (Nash and Hahn, 1986). Second was the discovery of high Cl concentrations in biotite during microprobe analysis of mafic silicates. Subsequently, Cl and F were determined for 40 metasedimentary rocks (table 1) and found to be unusually high. Earlier chemical analyses of ores and wallrocks (Nash and others, 1988) did not include halogen analyses because anomalous concentrations were not expected in these metasedimentary rocks.

EXPLANATION OF FIGURES 3A AND 3B

	Lower Proterozoic
Ꝑg	Porphyrictic granite
bi	Biotite-bearing phyllite and quartzite
bi-gar-ctd	Biotite-garnet-chloritoid granofels and schist
───	Contact, approximately located
━━━	Fault or Shear Zone , approximately located
●534	Sample locality

FIG. 3 Locations of analyzed samples from surface exposures. Topography and geology shown on A and B are modified from Vhay (1948)

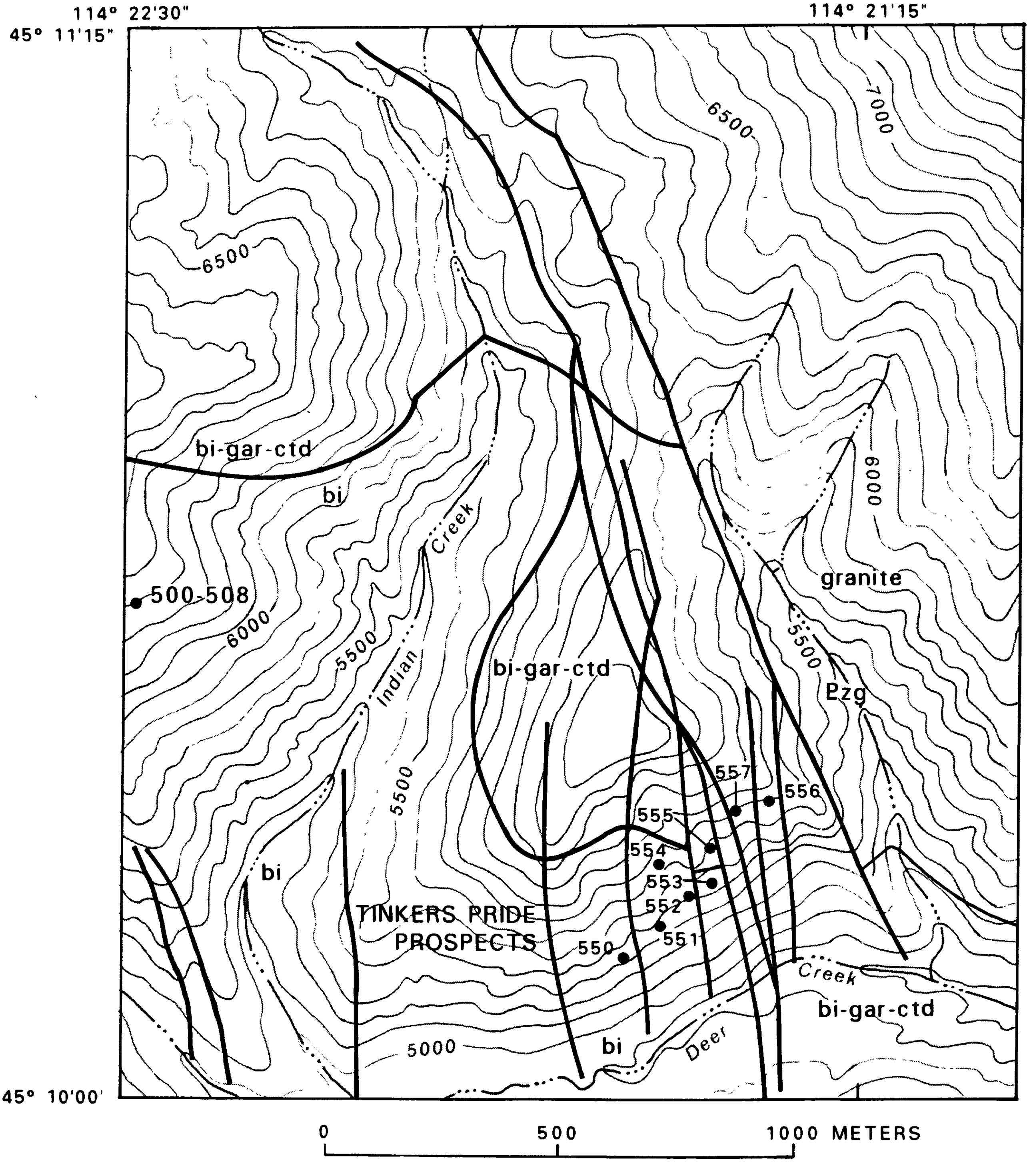

FIG. 3A Locations of analyzed samples in area of Tinkers Pride prospect, 6 km north of Blackbird Mine.

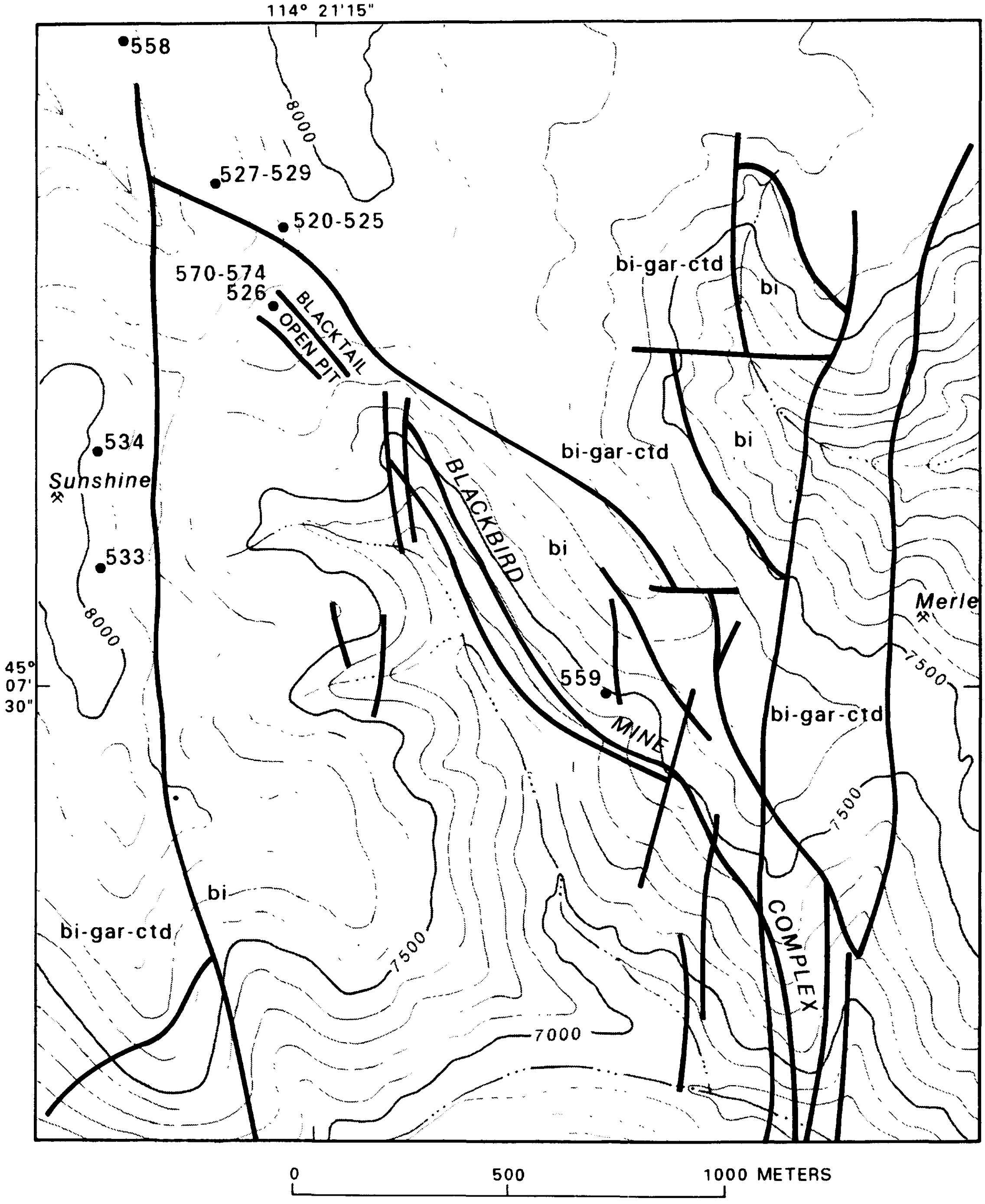

FIG. 3B. Locations of analyzed samples in Blackbird mine area

Chemical Analyses

Anomalous halogen concentrations are evident in chemical analyses of 40 rock samples (table 1); Cl concentrations range from 0.01 to 1.01 weight percent, and F ranges from less than 0.01 to 0.10 weight percent. The mineralogy of the samples is outlined in Appendix 1. Qualitatively, samples NIC510 and NIC574 are richest in biotite, whereas samples NIC504S and NIC527C have highest amounts of detrital quartz. Values for SiO_2 in excess of about 50 wt. percent (table 1) indicate clastic quartz is a component in the metasediment, and the abundance of micas is roughly proportional to whole rocks K_2O concentrations, although some of the samples with highest K_2O contain potassium feldspar. Iron and Mg are contained chiefly in biotite, garnet, and chloritoid (Appendix I). Chlorine concentrations (table 1) are roughly proportional to the amount of mica in these samples. These rocks contain no fluorite, thus F must reside in micas, especially muscovite.

The abundance of Cl in metamorphic rocks is not well known; most reported values are in the range of 50 to 400 ppm (Fuge, 1978). Hence, nearly all the results in this study (table 1) are unusual, and values greater than 0.2 percent (2000 ppm) may be exceptionally high. The abundance of F in metamorphic rocks also has been little studied; reported values are chiefly in the range of 80 to 450 ppm (Koritnig, 1978). Most of the F values (table 1) thus are in the normal range, but values greater than about 0.06 may be weakly anomalous.

Microprobe Analyses

The electron microprobe is effective for the chemical analysis of metamorphic (or other) minerals because the micron-sized electron beam can be focused within individual grains to yield analytical results that are not subject to the complications and ambiguities of occluded trace mineral grains that can be present in classical chemical analysis of minerals separated from rocks (for example, Guidotti, 1984). Consistent microprobe analyses show very clearly that Cl and F are present within the lattice of micas. Results shown in table 2 include information on Fe and Mg as a guide to the character of the biotite. As for any microprobe analysis, it is not possible to directly determine oxidation state of iron, thus total Fe is reported as FeO, and no determination of water or hydroxyl is possible by this technique. The values shown are the average of three or four individual analyses of spots within an area of about $100\mu m^2$, and do not include results for spots that deviated by more than about 20 percent. Representative complete analyses and structural formulas are given in table 3.

Most of the biotite grains are iron-rich with an Fe/Mg atomic ratio of 2.6 to 5.8 and could be termed "annite" (Deer and others, 1962a). Chlorine ranges from 0.29 to 1.84 wt. percent, and F ranges from 0.07 to 0.61 wt. percent. On an atomic basis, the Cl/F ratio exceeds 1.8 except for the grains with lower Fe (intermediate Fe/Mg). Computed structural formulas, as in table 3, show that Cl occupies 0.08 to 0.50 of the four possible hydroxyl positions in biotite. Many of the biotites have 10-12 percent of hydroxyl positions filled by Cl, which is uncommonly high--much more than in biotites from porphyry copper deposits (Munoz, 1984) that are noted for their high Cl contents and formation from very saline hydrothermal ore fluids. Chlorine is uniformly distributed in the analyzed biotite grains, but drops to very low values where biotite has been altered to chlorite. Also, the grain-to-grain variation in Cl within a thin section is small. The accommodation or enrichment of Cl in Fe-rich biotite is consistent with the principle of "Cl-Mg-avoidance" in biotites (Munoz, 1984).

Coarse porphyroblasts of colorless muscovite, prominent in many mafic layers, were analyzed by microprobe (Nash, unpub. data, 1988). The muscovites contain relatively higher amounts of F than do coexisting biotite, and Cl is much lower than in the biotite. The muscovites contain less than 0.05 wt. percent Cl and 0.05 to 0.31 wt. percent F. The enrichment in F in muscovite relative to biotite is normal for these micas (Munoz, 1984). Muscovite contains very little of the Cl in the Yellowjacket rocks, but probably contains most of the F. Analyses of muscovite are not as useful as those for biotite to characterize the distribution of Cl in the Yellowjacket Formation.

Microprobe analyses of garnet and chloritoid show they contain essentially no F or Cl (<0.02 wt. percent). Apatite could carry as much as about 3.7 wt. percent Cl (Deer and others, 1962b), but has not been analyzed. Because there is generally less than 0.2 wt. percent P_2O_5 in these rocks (Nash and others, 1988), equivalent to less than about 0.4 percent apatite, not much of the total chlorine in these rocks could be carried in apatite.

Fluid Inclusions

Fluid inclusions are prominent in hydrothermal quartz that cements sulfide-bearing ores of the Blackbird district. Pyrite and chalcopyrite accompany the quartz. The fluid inclusions are easily studied at 1,000 magnifications, but few are large enough to run on a heating stage. The inclusions are consistently liquid-rich, and most have at least one daughter mineral. The vapor bubble is relatively large, about 25 volume percent, and suggests trapping at temperatures of 300° C or more, but filling temperature estimates are not reliable for high salinity inclusions of small size. Most of the inclusions contain a cubic daughter mineral with moderate relief that is believed to be halite; some contain a second cubic mineral with lower relief and rounded edges as observed for sylvite (KCl) in highly saline fluid inclusions of porphyry copper systems. As many as four other daughter minerals accompany the halite and sylvite(?). No liquid CO_2 was observed, but would have been difficult to detect optically in these small inclusions. Some of the polyphase inclusions were run on a heating stage. The halite daughter minerals dissolved on slow heating to 250-350° C. The liquid phase expanded on heating and filled the inclusions at temperatures of 275-375° C. Not all of the daughter minerals dissolved at those temperatures; this is a characteristic of some daughter minerals from other localities that are suspected to be sulfates. The inclusions did not decrepitate during heating, but decrepitation would be expected if the inclusions were CO_2-rich. A large pressure correction could be required for these filling temperatures.

The age of the fluid inclusions is not known. They are most abundant in quartz that cements disruption structures, but some halite-bearing inclusions have been observed in metamorphic bull quartz. The quartz cement is thought to be synsedimentary in age, filling soft-sediment breccias (Nash and Hahn, 1986), but there is no proof that the fluid inclusions are primary. All saline fluid inclusions could be secondary and thus of any later age.

Fluid inclusions in metamorphic rocks and metamorphic veins have a wide range in composition (Crawford, 1981; Touret, 1981). Their most characteristic feature is high CO_2 content, generally indicated by a third fluid phase of liquid CO_2. Salinities reported for metamorphic rocks are variable but generally much lower than indicated by the halite and other daughter minerals in the Blackbird samples. Inclusions described by Trommsdorff and Skippen

(1986) and by Mercolli (1982) have salinities similar to those in the Blackbird samples; however, the Alpine fluid assemblage includes CO_2-rich fluid inclusions that coexisted with the saline type and reflect unmixing of the CO_2 vapor. There is no evidence in our preliminary studies of Blackbird inclusions for the distinctive high CO_2 compositions of other metamorphic terranes.

DISCUSSION AND INTERPRETATION

Literature Review

Scant data is available for halogens in metamorphic rocks and minerals because the role of chlorine and fluorine in metamorphic systems is little studied. Most of the existing data concerns occurrences of high Cl rocks or minerals in high grade metamorphic environments (granulites, charnockites, and skarns) and does not provide geologic evidence for the source of Cl, although a plutonic or evaporite source often is implied. The subject of Cl in metamorphic micas was included in a thorough review by Guidotti (1984), who did not make any generalizations because there was so little data. Leelanandam (1970) described a Fe-Ti-rich biotite with 1.96 wt. percent Cl and 1.71 wt. percent F from a pegmatite cutting charnockite. A similar occurrence of biotite in charockite contains 2.07 wt. percent Cl and 2.60 wt. percent F, the highest Cl recorded for a biotite (Kamineni and others, 1982). Dallmeyer (1974) made a detailed microprobe study of biotites from pelitic gneisses but did not include F and Cl in the microprobe analyses; wet chemical analyses revealed 0.66 to 1.19 wt. percent Cl and 0.61 to 1.19 wt. percent F. Lee (1958) described a Fe-rich biotite with 1.11 wt. percent Cl and 0.23 wt. percent F from a biotite-garnet-schist; this locality is on Deer Creek, about 6 km north of the Blackbird mine. Lee's sample locality is near my sample localities NIC550 to NIC558, as will be discussed later. Biotites coexisting with scapolite in metamorphosed iron formation contain 0.08 to 0.49 wt. percent Cl (Ekstrom, 1972).

Biotite developed in deeper parts of the Salton Sea Geothermal Field (SSGF) at 325-360° C contains 0.15 wt. percent Cl or less and 0.16 to 0.57 wt. percent F (McDowell and Elders, 1980). The SSGF has been the subject of numerous detailed studies and is the archetype of a geothermal system with nonboiling, highly saline fluids (Helgeson, 1968). Chlorine concentration in the brine is about 150,000 ppm (15 wt. percent). The SSGF is a possible actualistic analog for the Blackbird biotite, although two important differences are the much lower Fe in SSGF biotite and the single stage of metamorphism at SSGF.

Amphiboles commonly contain up to 2 wt. percent Cl, and some (generally K-rich hastingsite) contain 3 to 4 wt. percent Cl (Suwa and others, 1987). These Cl-rich amphiboles tend to form in amphibolites and charnockites, similar to some Cl-rich biotites. Formation of these Cl-rich amphiboles, as well as Cl-rich scapolite, may provide useful analogs for the formation of Cl-rich biotites. Ekstrom (1972) provides a useful analysis of chlorine activity in the formation of scapolite (Cl-marialite) coexisting with biotite that contains about 0.5 wt. percent Cl. Amphiboles containing up to 4.0 wt. percent Cl form during metamorphism of oceanic basalts (Vanko, 1986). Fluid inclusions suggest that the fluids were about 50 wt. percent NaCl and 400-500° C. The highly saline environment proposed by Vanko (1986) for the oceanic hydrothermal system is an attractive analog for the Blackbird system.

Chlorine in Yellowjacket Metamorphic Rocks

Whole rock analyses (table 1) and microprobe analyses of biotite (table 2) indicate anomalous amounts of Cl in nearly all analyzed samples. The highest Cl value for a rock is 1.01 wt. percent for a mafic volcaniclastic rock at the Haynes-Stellite cobalt deposit; the sample contains about 50 percent biotite, 20 percent muscovite, and 30 percent detrital quartz. The lowest values, 0.01 and 0.03 wt. percent, are for samples that contain mostly quartz and about 20 percent biotite. Spatially, four groups of samples can be considered. (1) Samples distant from the Blackbird mine (6 to 14 km) contain up to 0.60 wt. percent Cl and average about 0.3 wt. percent. (2) Samples with garnet or chloritoid in areas of higher metamorphic grade (the series NIC520 to NIC534, table 1) contain less Cl (about 0.15 wt. percent) than biotite-only rocks. (3) Mafic dikes that have been highly metasomatized to massive rocks with 80 percent or more biotite (note high K2O contents; samples NIC510, 526, 554) contain high amounts of Cl, about 0.4 wt. percent. However, less modified dikes such as NIC559 that retain igneous feldspars and contain abundant epidote as well as biotite contain much less Cl (0.12 wt. percent). This alteration suggests that Cl accompanied the pervasive potassic metasomatism that affected the Yellowjacket rocks (Nash and Hahn, 1986). (4) Ore-bearing samples are not included in table 1, but microprobe analyses of biotite from those zones (table 2) reveal them to be rich in Cl. Biotite-rich rocks that host ore are presumed to be enriched in Cl, possibly similar to sample NIC574 with 1.01 wt. percent Cl.

Scapolite is present in layered mafic rocks distant from the Blackbird mine and is permissive evidence for saline conditions. Scapolite, or micas judged to replace scapolite, is present in samples NIC508, 551, 552, 557, 570, 571, and 574 (table 1). Scapolite formation may be related to high Cl activity (Ellis, 1978). Another factor in the formation of scapolite in the Yellowjacket Formation must be the availability of Ca and Na; the depletion of these elements in the Blackbird mine area (Nash and others, 1988) may explain the absence of scapolite in those rocks. Scapolite is particularly abundant in the altered carbonate strata of Moyer Creek (sample NIC575); these impure carbonate strata are a minor part of the lower unit of the Yellowjacket Formation (J. Connor, oral commun., 1987). Scapolite in the Yellowjacket Formation is restricted to beds of appropriate composition (ie, it is stratabound), similar to worldwide occurrences in regional metamorphic terranes (Shaw, 1960; Serdyuchenko, 1975). The stratabound occurrences often are associated with meta-evaporites that contain halite or anhydrite, which are not known in the Yellowjacket. Formation of scapolite by Na-Cl-rich fluids derived from enclosing sedimentary rocks (Shaw, 1960; Serdyuchenko, 1975; Ramsay and Davidson, 1970) seems appropriate for occurrences in the Yellowjacket, although evaporite strata for a source of Cl may not be required.

The description of a Cl-rich biotite by Lee (1958) was a landmark for biotite geochemistry, but some revisions are required for Lee's description of the sample locality and geologic setting. The locality can be estimated through the use of the detailed map of Vhay (1948) and the statement (Lee, 1958, p. 107) that "Granite has intruded the biotite schist within 500 yards of the shear zone both to the north and to the east..." This places Lee's sample in the vicinity of the Tinker's Pride cobalt prospects. My samples NIC550 to NIC558 were collected in this area. The "acidic dikes" mentioned by Lee are Tertiary in age and related to the Challis volcanics. They seem to produce negligible alteration of wallrocks and did not play a significant role in metamorphism. Lee was unsure "whether the rock is a metamorphosed dike or a rock developed in place out of sheared material." I agree with Lee that "metasomatism has certainly played a role in its formation." However, the inference that the Proterozoic granite was the source of the metasomatic fluids is probably wrong. Biotite-rich layered rocks and altered mafic dikes, and layers rich in tourmaline are common in the Tinker's pride area, extending from the granite to at least 2 km to the west. The strata, rich in Fe-Mg-K-B as well as Co-Cu-As-S, are mineralogically and geochemically identical to the much more abundant mafic volcaniclastic strata in the Blackbird mine area 6 km to the south. They probably have been offset from the Blackbird strata by a north-trending shear zone (Nash and Hahn, 1986). The origin of these mafic strata is complex and much debated (Nash and Hahn, 1986), but their stratiform nature is compelling evidence that much of their bulk composition was established at the time of sedimentation. Stratiform tourmaline, abundant in both the mine area and in the Tinker's Pride area, is interpreted to have formed as a sea-floor exhalative sediment (Nash and others, 1987). The Cl-rich biotite describe by Lee (1958) is very rich in Fe. It coexists with about 30 percent garnet, thus closely resembles my samples NIC552 and 555 that must come from within 100 m of Lee's locality. Lee's Cl-rich biotite is similar to the other Cl-rich biotites from the Yellowjacket Formation described here.

In summary, the geologic associations suggest that the Cl-rich biotites formed by metasomatism of pre-existing dikes and strata with appropriate major element composition, most notably high iron content. The association of potassic metasomatism, and presumably Cl, with soft-sediment disruption structures in the Blackbird mine area (Nash and Hahn, 1986) and the pervasive metasomatic infiltration suggests that the K-Cl-rich fluid was present early in the history of the rocks. No fracture controls such as veins are evident, and no alteration selvages are seen.

The Cl concentrations observed in rocks, biotite, and fluid inclusions are unusual for ore deposits and metamorphic systems and provide a record of fluids that were extremely rich in chlorine. At this time only qualitative estimates seem possible because details of processes that incorporated Cl into rocks, minerals, and fluid inclusions are poorly known. The presence of substantially higher Cl concentrations in rock and biotite analyses than in normal greenschist facies rocks suggests equilibration with a fluid phase with more Cl than seawater. Fluid inclusions often yield a direct measure of fluid compositions, but the inclusions in the Blackbird samples are complex and the compositions may have changed by leakage or necking down; the very saline polyphase inclusions with salinities in excess of 40 wt. percent are probably best considered to be maximum estimates. One possible calibration for Blackbird is the Salton Sea system with about 15 wt. percent Cl that yields a biotite with about 0.1 wt. percent Cl[2] (McDowell and Elders, 1980). The Blackbird area biotites contain about 4 to 18 times as much Cl, suggestive of much higher Cl in the associated fluid.

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[2] The Cl values were considered unreliably high by McDowell and Elders because of Cl in the epoxy mounting material; note also that the much higher Mg in the biotite from SSGF would tend to exclude Cl by "Cl-Mg avoidance" (Munoz, 1984).

Models and Mechanisms

Several mechanisms of Cl enrichment seem possible for the geologic setting of the Yellowjacket basin and Blackbird ore system. Geologic and geochemical evidence (Nash and Hahn, 1986; Nash and others, 1987) suggests three likely settings for Cl enrichment: (1) On the seafloor, at the sediment-water interface. Stratiform layers of unusual composition, containing tourmaline, cherty silica, gold, cobalt, and iron, are interpreted to be chemical sediments or hydrothermal exhalites (Nash and others, 1987) that reflect unusual fluids that also might have been rich in Cl. (2) During shallow burial, at times of submarine slumping and soft-sediment deformation (Nash and Hahn, 1986; Nash, 1989) when partly lithified sediment was disrupted and cemented by silica, ankerite, micas, and sulfides. The timing of the disruptions, association with a thick section of underlying fine-grained clastic rocks, and the geochemical signature (K-Si-B) suggest the action of over-pressured pore fluids. (3) During one or more stages of metamorphism. The rocks studied are products of one or all of these environments and associated processes, so it is likely that the Cl in them was affected by those processes.

There are at least two Modern analogs of the seafloor environment of brine formation. One is possibly the Red Sea stratified brines that attain salinities of about 26 wt. percent and 50 to 60° C (Degans and Ross, 1969; White, 1981). Chlorine is enriched about 9.5 times, K is about 6 times, and metals such as Pb and Zn are 1,400 to 27,000 times the composition of seawater. Another possible analog is the Southern Juan de Fuca Ridge (SJFR) where hydrothermal brines discharging from vents have salinities up to twice the seawater value and temperatures >300° C (Von Damn and Bischoff, 1987). The physical and chemical properties of these submarine brines and their high metal content have been thoroughly analyzed and discussed as likely analogs of ancient submarine ore deposits (Cathles, 1983; White, 1981; Lydon, 1983). Significantly, potassium, chlorine and metal contents increase together with the temperature of these brines.

Subsurface brines known to develope in oil fields or in the Salton Sea geothermal field are pertinent analogs to pore fluids that moved through the Yellowjacket during consolidation and diagenesis (Hughes, 1983; Nash and Hahn, 1986; Nash, 1989). The thick section of fine clastic sediments is one that typically would have had high initial content of pore fluid, and that fluid is characteristically released during compaction, submarine sliding, or tectonically induced periods of dewatering (reviewed by Nash, 1989; Sibson and others, 1975). Alteration that produced enrichment in K, Si, and B (Nash and Hahn, 1986) might also have included Cl. The enrichment of sedimentary pore fluids in K and Cl (and many other elements) has been studied in detail in oil fields and shown to occur during diagenesis at temperatures of about 100 to 130° C and depths of <12,000 feet (Hanor, 1979; Lydon, 1983). Membrane filtration or reverse chemical osmosis is widely advocated as the mechanism for enrichment of salinity in the pore fluids to values in excess of 20 wt. percent. This process is deemed especially effective for basins with overpressures generated by rapid deposition of fine clastics and for basins lacking evaporites as a likely source of chlorine (Graf, 1982)--circumstances that fit the Yellowjacket. A pore fluid with the general composition of an oil field brine or of the Salton Sea brine (Helgeson, 1968) would be consistent with compositions inferred from rocks and minerals at Blackbird. Faulting and overpressuring during compaction are advocated as mechanisms for episodic dewatering of basin brines and movement toward the surface or discharge on the seafloor (Badham, 1981; Lydon, 1983; Sawkins, 1984). This is called the "stratal aquifer model" (Lydon, 1988) after the requisite stratification of sands and muds in the section. The Yellowjacket stratigraphy fits this model, as does the tectonic setting (unstable, rifted, epicratonic basin), and geochemistry.

Development of a Cl-rich fluid during metamorphism is a possibility, but there is scant literature on this topic because petrologists have generally ignored chlorine. The progressive dehydration that is typical of progressive metamorphism or polymetamorphism might logically produce a residual fluid with increased Cl but the details of where the Cl would reside have not been established. The behavior of interlayer water and hydroxyl in clays during progressive diagenesis or very low grade metamorphism is known (eg., Lydon, 1983), but Cl-OH exchange in metamorphic minerals such as chlorite has not been investigated. If the principles of Cl-OH exchange for biotite (Munoz, 1984) hold for chlorite, perhaps chlorite could accommodate Cl during progressive metamorphism. A new model for chlorine enrichment by loss of low density CO_2 and H_2O in metamorphism (Trommsdorff and Skippen, 1986) explains the formation of very saline fluid inclusions and halite in some high grade metamorphic rocks. Loss of CO_2 from carbonate-bearing rocks is a key part of the process. The Trommsdorff-Skippen model does not seem appropriate for Blackbird because carbonate rocks are a minor part of the Yellowjacket section, and there is no evidence for a CO_2-rich fluid as would be interpreted from visible liquid CO_2 or decrepitation of inclusions on heating.

The biotite discussed here may have formed in an unconventional type of metamorphism at shallow depth. The original bulk composition of the mafic volcaniclastic strata and dikes would have been ideal for creating Fe-biotite when reacted with a K-Cl-rich fluid. By analogy with modern seafloor geothermal systems (Cathles, 1983; Pottoff and Barnes, 1983; Goldfarb and others, 1983) or the Salton Sea geothermal system (McDowell and Elders, 1980), temperatures of 300-350° C would have been possible during shallow burial. The Fe-rich composition of the biotite would have been ideal for incorporation of high concentrations of Cl (Munoz, 1984).

Role of Saline Brine in Ore Formation

The highly saline brines postulated to have been present early in the history of the Yellowjacket basin near the Blackbird mine would have been a potent solvent for many of the metals in the ore deposits--especially Fe and Co (Crerar and others, 1985; Lydon, 1983). Cu can be transported by Cl-complexes, but also forms stable sulfide complexes. A minor puzzle is the known low concentrations of Pg-Zn-Ag at Blackbird, metals that would logically be transported by the saline brine (Lydon, 1983). At this point the role of saline brines in the formation of Blackbird ore deposits is circumstantial and permissive, chiefly based on inferences from spatial distribution of the halogen anomaly, modern geothermal analogues, and laboratory experiments. Alternatively, the brine may not have had a direct role in ore formation (ie, did not transport ore metals) but could be symptomatic of the hydrothermal-volcanic-sedimentary sub-basin of ore formation and thus be a useful exploration guide.

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Appendix 1. Description of analyzed samples

NIC500: Weakly layered mafic rock. Coarse intergrown biotite (35%), amphibole, (35%) carbonate (25%) with minor quartz

NIC501: Weakly layered mafic rock. Chiefly quartzite with layers rich in biotite or muscovite; overall 20% biotite and 10% muscovite.

NIC504S: White quartzite at contact with mafic rock. Quartz (70%) with feldspar (10), biotite (10), and amphibole (10).

NIC504T: Dark mafic rock at contact with quartzite. Amphibole (40) intergrown with biotite (30), clastic quartz (20), and feldspar (5); abundant apatite (2).

NIC505: Dark weakly layered mafic rock. Intergrown non-oriented green biotite and green amphibole, interstitial quartz and feldspar, abundant apatite; overall amphibole 45, biotite 35, quartz 15, feldspar <5, apatite 2.

NIC506: Dark masive mafic rock. Chiefly bronze biotite (90) with interstitial felspar (10), trace quartz.

NIC507: Mafic rock, float on strike with outcrop NIC500. Interbedded quartzite and mafic layers. Abundant fine tourmaline with quartzite layers. Overall, quartz (40), biotite (25), muscovite (15), feldspar (10), and tourmaline (10).

NIC508: Dark weakly layered biotite rock. Coarse tabular dark brown biotite with intergrown carbonate, interstitial quartz and dusty feldspar, altered porphyroblasts of scapolite(?); overall biotite 70, quartz 10, feldspar 5, carbonate 10, scapolite(?) 5.

NIC510: Massive dark mafic rock, Blacktail pit. Massively intergrown, unoriented biotite (85) and interstitial quartz (15); leached cavities from former carbonate(?). Probably a mafic dike.

NIC511: Weakly layered mafic rock. Green biotite (65) with lesser muscovite (5) with interlayers of recrystallized silt size quartz (30).

NIC512: Weakly laminated biotite-quartz rock. Interbedded siltite with equal amounts mica and quartz and argillite that is chiefly fine micas; micas are chiefly fine biotite (40) and muscovite (15).

NIC514: Weakly laminated biotite-chloritoid rock from Blacktail pit. Layers of chiefly quartz (50 overall) and chloritoid (25) with biotite (25); chloritoid is coarse poikilitic porphyroblasts with minor alteration to muscovite.

NIC520: Layered medium gray chloritoid-biotite rock, ridge east of Blacktail pit. Prominent coarse chloritoid (30) in layered matrix of fine quartz (40), biotite (20), and muscovite (10).

NIC521: Layered medium gray garnet-biotite rock. Prominent garnet porphyroblasts (20+) with scattered coarse chloritoid (originally 20) largely altered to muscovite; matrix is quartz (30) and biotite (20) with up to 5 percent tourmaline.

NIC522: Layered mica-chloritoid rock, chloritoid to 1 cm. Very coarse chloritoid is highly poikilitic with >50% quartz inclusions; matrix is quartz and biotite; overall quartz (60), biotite (15), and scattered garnet (5).

NIC523: Layered dark mafic rock with layers rich in chloritoid and in garnet. Layers not easy to see in section; variable amounts of coarse chloritoid and garnet in matrix of quartz and biotite, with retrograde (?) muscovite (5); overall quartz 40, biotite 25, chloritoid 20, garnet 10.

NIC524: Layered dark mafic rock with chloritoid. Prominent coarse chloritoid, relatively well-formed and twinned, with scattered garnet in matrix of quartz and biotite; overall quartz 40, biotite 25, chloritoid 20, garnet 10, muscovite 5.

NIC525: Weakly layered dark mafic rock with garnet. Coarse garnet porphyroblasts (25) with chloritoid highly altered to muscovite in quartz-biotite matrix; overall garnet 25, biotite 20, chloritoid 15, muscovite 5, and quartz 30.

NIC526: Massive biotite rock in Blacktail pit, probably a dike. Intergrown unoriented tabular biotite (80) with interstitial quartz (15) and minor feldspar (5).

NIC527A: Layered dark mafic rock with 1 cm layers rich in chloritoid or garnet; A is layer rich in garnet. Coarse garnet has abundant quartz inclusions, poorly formed, matrix is fine quartz and brown biotite; overall garnet 40, quartz 30, biotite 20, chloritoid 10.

NIC527C: Portion of 527 rich in chloritoid. Coarse chloritoid with abundant quartz inclusions, chloritoid abuts some garnet; overall chloritoid 30, garnet 10, quartz 40, biotite 20.

NIC528: Layered dark chloritoid-biotite rock. Coarse poikilitic chloritoid with abundant quartz inclusions, scattered garnet, matrix chiefly quartz and white micas; overall chloritoid 30, muscovite 25, quartz 25, biotite 15, garnet 5.

NIC529: Layered mica-chloritoid rock. Layers of quartzite with muscovite>biotite and minor chloritoid vs. dark layers with micas >quartz and biotite>muscovite; chloritoid chiefly in mica-rich layers; overall quartz 50, biotite 20, muscovite 15, chloritoid 15.

NIC531: Layered and foliated garnet (60)-biotite(30) schist.

NIC533: Weakly layered and foliated garnet-biotite rock. Coarse garnet porphyroblasts (50) in relatively coarse quartz (20)-biotite (30) matrix; zircons in biotite.

NIC534: Layered dark garnet-biotite granofels.

NIC550: Layered and foliated biotite rock; Tinkers Pride area. Layers defined by quartz with tourmaline vs. biotite; overall quartz 40, biotite 40, muscovite 5, tourmaline 10, K-feldspar 5.

NIC551: Dark biotite rock with white spots (scapolite?). Layers defined by quartz vs. micas; scattered porphyroblasts (20) altered to tan clay, might be cordierite(?); overall quartz 40, biotite 20, clay 20, muscovite 15, feldspar 5.

NIC552: Dark weakly layered biotite rock with scattered garnet. Weak layers of quartz vs. micas, scattered garnet and tan porphyroblasts of possible scapolite (with clay); overall quartz 40, biotite 20, garnet 20, muscovite 10, feldspar 10.

NIC553: Massive biotite rock, possibly a dike. Intergrown tabular crystals biotite with unusual red-brown color and abundant carbonate between biotite crystals; overall biotite 60, quartz 10, carbonate 20, feldspar 10.

NIC554: Massive biotite rock. Abundant biotite intergrown with dusty k-feldspar, no orientation suggests this is a dike; overall biotite 60, feldspar 30, quartz 10.

NIC555: Weakly foliated garnet-biotite rock. Prominent clean, euhedral garnet in matrix of chiefly micas; overall biotite 45, muscovite 20, garnet 25, quartz 10.

NIC556: Silvery gray massive biotite rock. Layers defined by quartz vs. micas, with scattered small garnets; micas unusually elongate; overall quartz 60, biotite 20, muscovite 20, garnet <5.

NIC557: Weakly layered biotite-garnet rock. Biotitic quartzite with kink folds and scattered small garnet and a few porphyroblasts of probable scapolite; overall quartz 40, biotite 25, garnet 10, muscovite 15, scapolite(?) 10.

NIC558: Layered garnet-biotite rock with about 30% garnet.

NIC559: Massive coarse grained mafic dike. Intergrown coarse grains of feldspar, epidote, amphibole, and biotite with iron oxides; overall feldspar 25, amphibole 35, biotite 30, epidote 10+.

NIC570: Fine grained biotite rock with white spots; Deep Creek road. Intergrown weakly layered fine quartz and biotite with fine muscovite and feldspar, scattered porphyroblasts of probable scapolite; overall quartz 30, biotite 30, muscovite 20, feldspar 10, scapolite 10.

NIC571: Layered gray and white biotite-scapolite rock. Layers defined by quartz-feldspar vs biotite-muscovite with scattered porphyroblasts of poorly formed phase (scapolite?); overall quartz 30, biotite 30, muscovite 20, feldspar 10, scapolite(?) 10.

NIC574: Weakly layered biotite rock, Haynes Stellite adit. Weakly layered quartz and fine biotite with coarse porphyroblasts of white mica; overall biotite 50, quartz 30, muscovite 20.

NIC575: Pale gray layered calc-silicate rock, Moyer Creek. Intergrown fine quartz, amphibole, scapolite rock; overall carbonate 30, amphibole 20, scapolite 30, feldspar 10, quartz 10.

Samples for microprobe analysis

H02-613: Horseshoe lode, disrupted ore zone; quartz cement 40, green biotite 50, ores 10.

M11B-246: Merle B lode, ore layer, layered biotite rock; green biotite 70, muscovite porphyroblasts 25, cobaltite 5.

M12A-111: Merle zone, footwall of A layer, layered biotite rock; green biotite 85, quartz 10, ores 5.

M13A-314: Merle B lode, ore layer; green biotite and muscovite matrix in disruption zone and a 5mm thick layer of green biotite.

M14B-275: Merle zone, hangingwall of B lode, layered biotite rock; fine and medium grained green biotite (70), swaths of coarse muscovite (20) and quartz (10).

M7B-439: Merle B ore layer, layered biotite rock; green biotite 40, muscovite 20, retrograde sericite 20, ores 10.

NIC506: described above.

NIC520: described above.

NIC574: described above.

S16A-624: Sunshine zone, hangingwall of ore layer; coarse granofels; brown and green biotite 40, chloritoid 25, garnet 10, muscovite 10, quartz <5.

S7B:299: Sunshine zone, footwall of ore layer; granofels; coarse chloritoid 50, brown biotite 30, muscovite (mostly retrograde) 20.

S8A-474: Sunshine zone, hangingwall of ore layer, layered granofels; 1 cm layer has quartz 50, chloritoid 20, brown biotite 20, garnet 10; other 2 cm layer has quartz 20, chloritoid 30, garnet 30, brown biotite 20.

S9A-279: Sunshine zone, footwall of ore layer; layered granofels; 2 cm layer of biotitic quartzite, 1 cm layer of chloritoid 30, brown biotite 40, and garnet 30.

Table 1. Partial chemical analyses of rocks, Blackbird District

[Total iron reported as FeO; the high iron content of samples NIC531 and NIC558 caused interference in X-ray fluorescence analysis, values for these samples (e.g. (34.0)) are from induction coupled plasma spectrometry; n.d., no data.

Sample	Cl %	F %	SiO_2 %	FeO %	MgO %	K_2O %
NIC500	0.14	0.06	39.6	11.5	13.4	4.55
NIC501	0.01	0.02	68.0	3.70	1.46	4.74
NIC504S	0.03	<0.01	68.3	2.04	1.48	0.77
NIC504T	0.09	0.07	48.8	8.42	10.1	1.72
NIC505	0.12	0.08	45.1	10.3	10.9	2.62
NIC506	0.26	0.09	41.7	15.0	10.8	8.40
NIC507	0.31	0.04	61.8	10.1	1.96	8.79
NIC508	0.19	0.04	42.4	14.0	6.87	4.62
NIC510	0.33	0.07	42.9	23.0	5.33	8.05
NIC511	0.63	0.04	61.2	17.4	1.57	5.47
NIC512	0.47	0.04	61.4	13.0	1.21	6.80
NIC514	0.16	0.02	64.3	14.4	1.17	2.55
NIC520	0.08	<0.01	59.2	13.2	0.89	2.43
NIC521	0.23	0.02	59.9	17.9	1.48	3.75
NIC522	0.10	<0.01	72.3	10.8	0.95	1.87
NIC523	0.17	0.04	48.0	20.7	1.26	4.07
NIC524	0.11	0.02	64.2	23.8	1.41	3.48
NIC525	0.08	<0.01	60.4	19.4	1.32	2.25
NIC526	0.52	0.04	42.9	20.9	6.17	7.50
NIC527A	0.20	0.02	56.6	19.8	1.22	2.19
NIC527C	0.14	0.02	76.8	9.98	1.03	1.51
NIC528	0.05	0.01	65.5	10.5	1.07	3.08
NIC529	0.13	0.01	64.8	11.5	0.93	3.36
NIC531	0.07	<0.01	n.d	(30.6)	(1.5)	(1.1)
NIC533	0.11	0.01	51.4	24.9	1.74	1.94
NIC534	0.24	0.02	62.2	16.3	1.22	3.06
NIC550	0.35	0.07	64.0	13.8	2.03	5.40
NIC551	0.21	0.02	69.5	6.50	1.14	4.82
NIC552	0.18	0.02	58.2	18.6	1.85	2.99
NIC553	0.24	0.10	43.6	15.7	4.22	5.30
NIC554	0.29	0.04	49.4	14.0	2.15	5.14
NIC555	0.23	0.03	43.3	19.8	1.84	6.52
NIC556	0.22	0.02	71.9	7.63	0.89	4.44
NIC557	0.44	0.02	57.1	15.3	1.26	6.19
NIC558	0.21	0.06	n.d.	(27.0)	(4.3)	(1.3)
NIC559	0.12	0.02	48.5	11.0	7.74	2.15
NIC570	0.13	0.01	63.0	5.72	1.51	5.83
NIC571	0.31	0.03	59.3	7.14	2.01	3.32
NIC574	1.01	0.08	55.4	17.6	2.37	7.33
NIC575	0.60	0.02	54.4	2.92	1.85	3.35

Table 2. Partial results of microprobe analyses of biotite, Yellowjacket Formation, Blackbird District

[Analyses shown are averages of 3 or 4 spot analyses on an individual grain or nearby grains; last characters in sample number (B, B2) designate subareas of the polished thin section for the analysis; %, element reported in weight percent; ratios are atomic ratios]

Sample	FeO %[1]	MgO %	Cl %	F %	Fe/Mg atomic	Cl/F atomic
H02-613B	31.1	3.0	1.08	0.31	5.75	1.86
H02-613B2	31.7	3.1	1.12	0.16	5.68	3.74
M11B246A	30.5	4.5	1.33	0.40	3.76	1.78
M11B246B	31.0	4.5	1.36	0.21	3.82	3.46
M11B246C	30.1	4.6	1.34	0.13	3.63	5.51
M12A-111A	30.1	3.6	1.19	0.23	4.64	2.76
M12A-111B	28.9	3.4	1.13	0.17	4.72	3.55
M13A-314A1	25.7	5.3	1.29	0.19	2.69	3.63
M13A-314A2	26.2	5.3	1.33	0.23	2.74	3.09
M13A-314B1	25.6	5.0	1.19	0.16	2.84	3.98
M13A-314B2	25.5	4.9	1.23	0.18	2.89	3.65
M14B-275A	26.0	3.7	1.13	0.61	3.90	0.99
M14B-275B	30.5	3.8	1.16	0.28	4.45	2.21
M14B-355A	27.5	4.2	1.27	0.11	3.63	6.17
M14B-355B	28.0	4.3	1.21	0.18	3.61	3.59
M7B-439A1	27.6	5.7	1.29	0.36	2.69	1.91
M7B-439A2	27.7	5.6	1.28	0.16	2.74	4.28
M7B-439B	27.9	5.7	1.26	0.36	2.71	1.87
NIC-506A	15.6	12.3	0.31	0.33	0.70	0.50
NIC-506B	17.7	12.2	0.34	0.21	0.80	0.86
NIC-506B2	16.2	12.5	0.34	0.37	0.72	0.49
NIC-506C	17.6	12.1	0.28	0.17	0.80	0.88
NIC-506C2	16.3	12.4	0.29	0.24	0.73	0.64
NIC-520B	28.1	9.0	0.92	0.07	1.73	7.03
NIC-574A	30.3	4.0	1.84	0.27	4.20	3.64
NIC-574B	30.7	4.1	1.83	0.26	4.16	3.76
S16A-624B	26.9	5.3	0.72	0.13	2.82	2.96
S16A-624C	28.1	4.8	0.81	0.20	3.25	2.16
S7B-299A	25.9	5.0	0.62	0.18	2.87	1.84
S7B-299B	25.5	5.4	0.63	0.19	2.62	1.77
S8A-474A	26.7	4.0	0.57	0.21	3.70	1.45
S8A-474B	26.9	3.9	0.51	0.16	3.83	1.70
S9A-279A	28.6	3.6	0.77	0.13	4.41	3.17
S9A-279B	28.7	3.6	0.76	0.22	4.42	1.84

[1] Total iron reported as FeO.

Table 3. Representative Microprobe Analyses and Formulas of muscovite and biotite

[Analyses shown are single spot analyses of adjacent mica grains in one polished section; total iron reported as FeO, water not determined; structural positions computed on the basis of 22 oxygen atoms, one of several possible ways to compute structure.]

	MUSCOVITE			BIOTITE		
	NIC574.1	NIC574.2	NIC574.3	NIC574.1	NIC574.2	NIC574.3
SiO_2 %	47.38	48.14	47.62	33.29	32.10	32.10
Al_2O_3 %	34.74	35.24	35.49	16.81	17.01	17.11
FeO %	2.90	2.28	2.35	30.71	30.56	30.87
MgO %	1.09	1.03	1.02	3.96	4.16	4.11
CaO %	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O %	0.17	0.21	0.17	0.02	0.03	0.04
K_2O %	10.19	10.22	10.02	9.19	9.28	9.35
TiO_2 %	0.10	0.00	0.03	0.65	0.69	0.69
MnO %	0.00	0.01	0.01	0.01	0.04	0.02
BaO %	0.12	0.16	0.22	0.00	0.13	0.13
F %	0.25	0.18	0.19	0.27	0.45	0.13
Cl %	0.02	0.04	0.01	1.87	1.80	1.82
	96.96	97.51	97.13	96.78	96.25	96.37
-O=F %	0.11	0.08	0.08	0.11	0.19	0.05
-O=Cl %	0.00	0.01	0.00	0.42	0.41	0.41
TOTAL %	96.85	97.43	97.05	96.24	95.65	95.90
POSITIONS BASED ON 22(O)						
Si	6.21	6.25	6.21	5.35	5.20	5.20
Aliv	1.79	1.75	1.79	2.65	2.80	2.80
Alvi	3.55	3.64	3.65	0.59	0.51	0.44
Fe++	0.31	0.24	0.26	4.12	4.13	4.20
Mg	0.20	0.18	0.18	0.93	0.99	0.99
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.07	0.07	0.07
K	1.69	1.68	1.67	1.87	1.91	1.92
Na	0.04	0.04	0.04	0.00	0.01	0.02
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.01	0.01	0.00	0.01	0.01
F	0.10	0.08	0.08	0.13	0.22	0.05
Cl	0.00	0.00	0.00	0.49	0.48	0.48
CATION VI TOTALS	4.06	4.06	4.09	5.71	5.70	5.70
Mg/Fe^{++}	0.67	0.80	0.77	0.23	0.24	0.23
$Mg/Mg+Fe^{++}$	0.40	0.44	0.43	0.18	0.19	0.19