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Clay Alteration and Gold Deposition in the Genesis and Blue Star Deposits, Eureka County, Nevada

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Abstract

The Genesis and Blue Star sedimentary rock-hosted gold deposits occur within the 40-mile-long Carlin trend and are located in Eureka County, Nevada. The deposits are hosted within the Devonian calcareous Popovich Formation, the siliciclastic Rodeo Creek unit and the siliciclastic Vinini Formation. The host rocks have undergone contact metamorphism, decalcification, silicification, argillization, and supergene oxidation.

Detailed characterization of the alteration patterns, mineralogy, modes of occurrence, and associated geochemistry of clay minerals resulted in the following classifications: least altered rocks, found distal to the orebody, consisting of both metamorphosed and unmetamorphosed host rock that has not been completely decalcified; and altered rocks, found proximal to the orebody that have been decalcified. Altered rocks are classified further into the following groups based on clay mineral content: silicic, 1 to 10 percent clay; silicic-argillic, 10 to 35 percent clay; and argillic, 35 to 80 percent clay. Clay species identified are 1M illite, $2M_1$ illite, kaolinite, halloysite, and dioctahedral smectite.

An early hydrothermal event resulted in the precipitation of euhedral kaolinite and at least one generation of silica. This event occurred contemporaneously with decalcification which increased rock permeability and porosity. A second clay alteration event resulted in the precipitation of hydrothermal 1M illite which replaced hydrothermal kaolinite and is associated with gold deposition. Silver and silica deposition is also associated with this phase of hydrothermal alteration.

Hydrothermal alteration was followed by supergene alteration which resulted in the formation of supergene kaolinite, halloysite, and smectite as well as the oxidation of iron-bearing minerals. Supergene clays are concentrated along faults, dike margins, and within rocks containing carbonate. Gold mineralization is not associated with supergene clay minerals within the Genesis and Blue Star deposits.

Rocks classified as silicic-argillic in the Popovich Formation represent the most significant gold host. Silicic-argillic rocks commonly exhibit bedding-parallel alteration zones. This pattern of alteration indicates that stratigraphy as well as northwest-trending structures played a significant role in the migration of gold-bearing fluids. Based on K-Ar age determinations of hydrothermal 1M illite associated with gold, the main event of mineralization in the Genesis and Blue Star deposits occurred between 93 and 100 Ma, during mid-Cretaceous time.

Introduction

THE Genesis and Blue Star sedimentary rock-hosted gold deposits comprise part of the Carlin trend and are located 22 mi north of Carlin, Nevada (Fig. 1). Extensive clay alteration in these deposits allows for the examination of the association between gold and clay minerals. Toward this end, a characterization of the alteration patterns, mineralogy, modes of occurrence, and associated geochemistry of clay minerals was conducted. Additionally, the study of clay mineralogy made possible the approximation of the age of mineralization.

Associations of clay alteration and gold mineralization have previously been reported in sedimentary rock-hosted disseminated gold deposits in the Carlin trend. Hausen et al. (1987) noted the occurrences of gold covered with illitic clay. Bakken et al. (1989) found that clay minerals predominating in altered rocks were 1M and $2M_1$ illite, with variable amounts of kaolinite, and concluded that during ore-stage hydrothermal alteration 1M and $2M_1$ illite grew at the expense of feldspar and smectite. Arehart et al. (1989) reported alteration zoning in sedimentary host rocks in the Post deposit, 1.5 mi north of the Genesis deposit, consisting of an inner core of kaolinite, surrounded by a kaolinite-sericite zone. A distal chlorite-sericite zone is also present. Hofstra et al. (1991) reported the presence of detrital $2M_1$ illite in all zones in the Jerritt Canyon district, Nevada. They concluded that the preservation of detrital illite implies that hydrothermal fluids were moderately acid but not acidic enough to convert illite to kaolinite.

Within the Carlin deposit, Kuehn and Rose (1992) reported that distal, unaltered, siltstone containing calcite, dolomite, detrital illite, quartz, K feldspar, and pyrite was altered to decalcified, argillically altered, and silicified rocks containing detrital illite, hydrothermal sericite, quartz, and pyrite. Alteration proximal to fluid conduits consists of quartz, dickite-kaolinite, and pyrite.

Hausen et al. (1987) found that kaolinite percentages are notably higher in the Genesis pit than in other Carlin-type

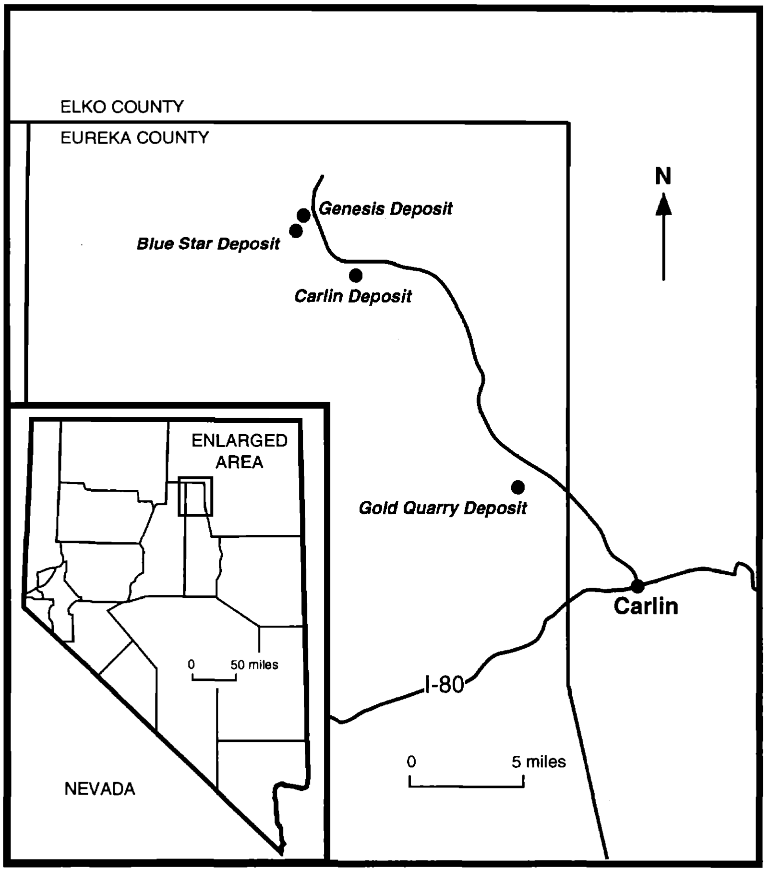

FIG. 1. Location of the Genesis and Blue Star deposits.

deposits. Kaolinite was observed with stringers of fine unoxidized pyrite and therefore was interpreted as hypogene in origin. Hausen et al. (1987) also identified two samples containing 1 to 4 μm gold, averaging 22.5 and 3.5 wt percent illite and kaolinite, respectively.

Geologic Setting

The Genesis and Blue Star deposits are located at the northern edge of the Lynn window in the Roberts Mountain thrust and are hosted within lower plate Devonian sedimentary rocks (Fig. 2). The main ore host is the Middle Devonian Popovich Formation, which is the lowermost exposed unit and consists of 1,000 to 1,200 ft of gray to black, thin- to medium-bedded, silty to micritic limestone with interstratified calcareous siltstones and mudstones (Jordan, 1990). Locally, this unit is thermally metamorphosed to marble and diopside-rich calc-silicate hornfels. The Late Devonian Rodeo Creek unit overlies the Popovich Formation and is comprised of slightly calcareous siltstones, siliceous mudstones, and quartz sandstone (Jordan, 1990). The upper plate of the Ordovician Vinini Formation consists of siltstone, chert, and minor silty limestone. The Rodeo Creek unit and the Vinini Formation are identified as quartz-rich hornfels where they are metamorphosed (Kofoed, 1991). Paleozoic rocks are unconformably overlain by the Tertiary Carlin Formation which consists of medium- to thickly bedded, tan to gray tuff, tuffaceous siltstone, and fluvial sedimentary rocks (Jordan, 1990).

The Goldstrike granodiorite stock, located approximately 1 mi north of the Genesis and Blue Star deposits, has an apporximate age of 158 Ma (Arehart et al., 1993). The stock ranges from granodiorite to granite in composition and is comprised primarily of plagioclase, orthoclase, biotite, quartz, and hornblende (Arehart et al., 1993). Locally, equigranular and porphyritic dikes and sills, thought to be related to the Jurassic Goldstrike granodiorite stock, intrude the Devonian sedimentary rocks along northwest-trending structures (Jordan, 1990). Tertiary dikes and stocks are common on a regional scale but are not well exposed in the Blue Star deposit. Mesozoic intrusive activity was accompanied by, and contributed to, doming and folding of Paleozoic sedimentary rocks (Christensen et al., 1987).

Steeply dipping normal and strike-slip faults cut sedimentary rocks locally in three successive faulting events, trending northwest, northeast, and north-northwest, respectively (Finn, 1991). Mineralization is closely associated with the first event of northwest-trending faults and locally offset by the northeast-trending event. On a regional scale, mineralization appears to be focused at the intersection of northwest and northeast faults (Finn, 1991). The third event, trending north-northwest, offsets mineralization and is associated with Basin and Range normal faulting (Kofoed, 1991). The Genesis and Blue Star deposits are cut by two major faults, the northwest-trending Genesis fault and the northeast-trending K fault; the latter has been intruded by a dacite porphyry named the

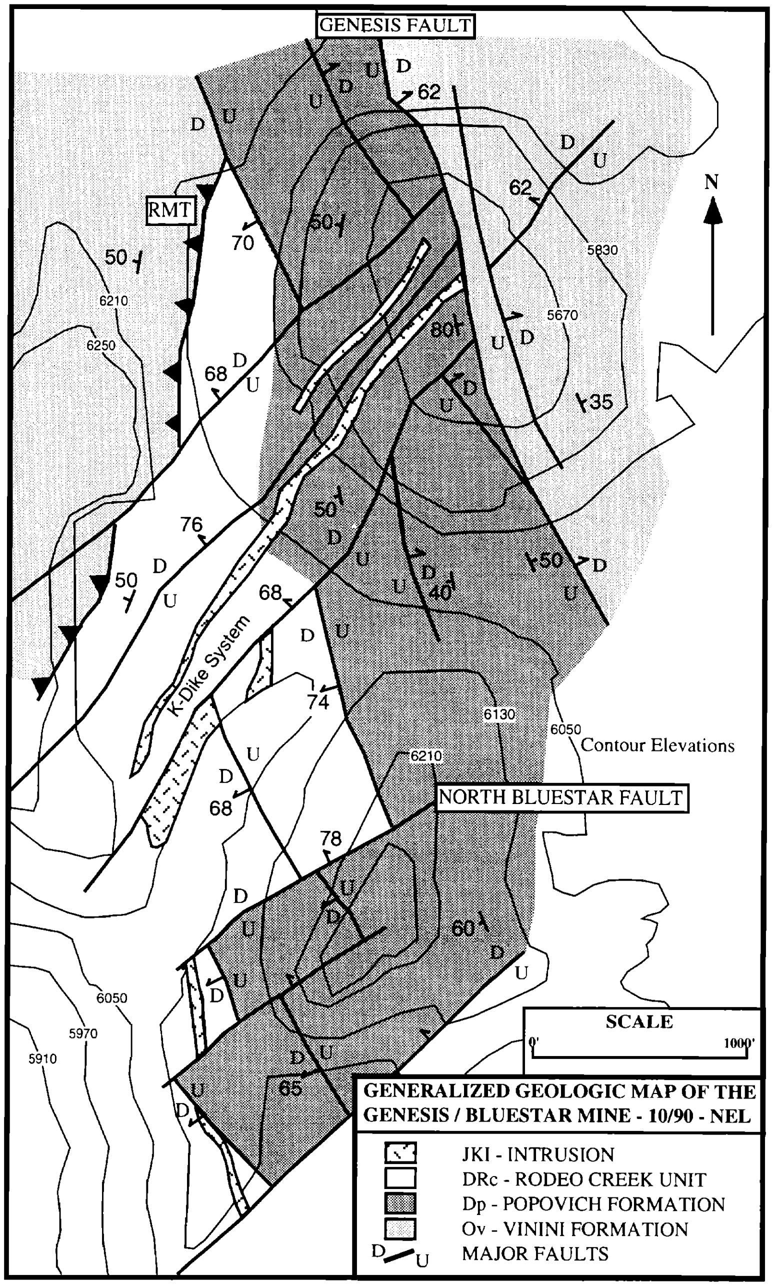

FIG. 2. Generalized geologic map of the Genesis and Blue Star mine area (modified from Finn, 1991).

K dike. The K dike is believed to be Tertiary (30–40 Ma) in age and is sparsely mineralized (Kofoed, 1991; K. Paul, pers. commun., 1996).

The rocks at Genesis and Blue Star have undergone thermal metamorphism, decalcification, silicification, argillization, and supergene oxidation. Metamorphism is related to the intrusion of the Goldstrike stock. Decalcification predates ore deposition but played a key role in ground preparation by increasing rock permeability. Silicification is ubiquitous; occurring in stages of vein or pervasive alteration. Clay alteration appears closely associated with gold deposition. Christensen et al. (1987) believe that, on a regional scale, gold deposition occurred at the time of, or just after, clay alteration. Late-stage supergene oxidation is superimposed on all earlier alteration and mineralization events.

Gold at Genesis and Blue Star occurs predominately as disseminated submicrometer-sized particles within lower plate rocks (Jordan, 1990). More specifically, gold occurs in two distinct zones, the main and the west zones. The main zone gold is hosted within decalcified, silty units of the Popovich Formation and the west zone gold is hosted predominately within the Rodeo Creek unit (Jordan, 1990).

The maximum age of gold mineralization is estimated to be 158 Ma as indicated by ore hosted by the Goldstrike stock

(Arehart, 1993). A minimum age of 5 Ma is indicated by mineralized clasts in the Pliocene Carlin Formation (Christensen et al., 1987).

Methods of Research

Approximately 6,000 ft of mine bench was mapped at a scale of 1:600 in the Genesis and Blue Star mines to determine the distribution and degree of clay-altered and silicified zones as well as the spatial relationships of alteration type to structures. For background control, samples were taken in unmineralized areas at nine localities outside the mine area. Three diamond drill holes, totaling approximately 2,550 ft in length, were also sampled. Individual samples did not cross bedding units or mix alteration types. A total of 200 samples was collected.

X-ray diffraction analyses were conducted at the U.S. Geological Survey Clay Petrology Laboratory in Denver, Colorado. Rock samples were prepared for XRD analysis by crushing to 1- to 4-mm-size particles. The particles were then dispersed using sodium hexametaphosphate in deionized water and ultrasonically disaggregated. Samples were washed in a high-speed centrifuge to eliminate flocculation. The <1.0-μm fraction was concentrated by centrifugation. Oriented slides were made with the <1.0-μm fraction for 200 samples using the Millipore ® filter transfer method. Random mounts were made with the <1.0-μm fraction onto a frosted glass slide for 35 samples using the back-loaded method outlined by Moore and Reynolds (1989). Air-dried and ethylene glycol-saturated, oriented slides were analyzed with a Picker X-ray diffractometer at 34 kV and 18 mA, using a scintillation detector and an Ni-filtered CuKα radiation. Data were collected at 20 steps per degree with 1 s per step. The diffractometer was controlled with an HP 9825A computer. Random mounts were analyzed using a Philips APD 3600 X-ray diffractometer at 45 kV and 30 mA, using a graphite monochromator CuKα radiation, and theta compensating slits. Data were collected at 50 steps per degree with 2 or 3 s per step. This diffractometer was controlled with a Data General Nova 4 computer.

The relative wt percent of each clay mineral was calculated from the intensity of its diffraction peaks using the method outlined by Moore and Reynolds (1989). The diffraction peaks used to calculate relative wt percents were kaolinite, 002; illite, 002; and smectite, 003, for glycolated samples. The mineral intensity factors used were as follows: 2.19 for kaolinite, 0.51 for illite, and 0.81 for smectite (Moore and Reynolds, 1989).

Scanning electron microscope (SEM) analyses of clay phases were conducted at the Colorado School of Mines in Golden, Colorado. Twenty-five samples were studied with a model ISI 100B scanning electron microscope at 30 kV and 100 mA, using a tungsten filament. Elemental analyses were conducted with a Kevex energy dispersive X-ray fluorescence analyzer. One-hundred and fifty polished thin sections were studied under transmitted and reflected light to determine mineralogical relationships. Textural relationships as well as mineral paragenesis were investigated in detail.

Geochemical analyses were carried out by Bondar-Clegg, Inc. (Sparks, Nevada). Samples were pulverized to a -150 mesh and at least two splits were made for quality control purposes. Silver was determined using an aqua regia digestion and atomic absorption spectrometry (AAS). Arsenic was analyzed using instrumental neutron activation analysis. Gold was determined using AAS. Those samples containing more than 10,000 ppb gold were reanalyzed using a one ton fire assay with an AAS finish. Background values for each element were provided by Newmont Exploration Ltd. (Paul, pers. commun., 1992). For data analysis, samples below detection limits were assigned half the lower detection value.

Alteration

The Genesis and Blue Star deposits are known for their pervasive and intense clay alteration. Therefore, it is difficult to identify the formation or protolith from which samples are taken. Sample collection and identification was constrained by map relationships. Those samples identified as belonging to the Popovich Formation had a calcareous protolith. Samples identified as belonging to the Rodeo Creek and Vinini units, collectively referred to as siliciclastic rocks, had a siliciclastic protolith and lacked significant carbonate material. Further, XRD analyses showed no relic calc-silicate minerals within siliciclastic rocks.

In order to compare and contrast mineralogy in rocks that have undergone numerous alteration events, the following categories have been distinguished: least altered rocks, found distal to the orebody, consisting of metamorphosed and unmetamorphosed rocks, which have not been completely decalcified; and altered rocks, found proximal to the orebody, which have been decalcified. Altered rocks are further classified into the following groups based on field and petrographic estimation of clay mineral content: silicic, 1 to 10 percent clay; silicic-argillic, 10 to 35 percent clay; and argillic, 35 to 80 percent clay. These relationships are outlined in the following classification descriptions as well as in Table 1.

Least altered Popovich Formation

The least altered Popovich Formation consists of limestone, marble, and calc-silicate hornfels rocks containing few to no clay minerals. Within samples containing minor amounts of clay minerals, kaolinite is observed replacing carbonate (Fig. 3). Kaolinite precipitation is also associated with the precipitation of quartz. The least altered Popovich Formation is predominately found distal to the orebody, containing <0.001 oz/t gold.

Altered Popovich Formation

The silicic Popovich Formation consists of decalcified and intensely silicified rock, where silicified masses are commonly podlike in shape and bounded by faults. Silicic rock also occurs in bedding-parallel zones which are locally adjacent to layers of silicic-argillic alteration. Silicic-argillic alteration within the Popovich Formation refers to decalcified, moderately silicified rock, comprised of 10 to 35 percent clay minerals. However, the intervening rock has not been extensively argillically altered since primary bedding features are clearly discernible. Silicic-argillic alteration occurs as pervasive zones extending over a wide area, within distinct units, and less commonly along faults and dike margins. Argillic alteration refers to rock that is white to a pale gray-green, friable, with local occurrences of buff, limonitic oxidation. Clay is pervasive throughout the rock and bedding is only locally discernible.

TABLE 1. Alteration Classifications Used to Describe Rocks in the Genesis and Blue Star Mines

Unaltered	Least altered	Silicic	Silicic-argillic	Argillic
Popovich Formation				
Limestone, marble, calc-silicate hornfels	Calcite present, minor clay minerals	Decalcified, intensely silicified, 1–10% clay minerals	Decalcified, moderately silicified, 10–35% clay minerals	Decalcified, 35–80% clay minerals, oxidized and friable
		Bedding-parallel alteration as well as pod-shaped zones bounded by faults	Pervasive as well as bedding-parallel alteration	Adjacent to faults and dikes, overprints silicic-argillic alteration
Siliciclastic rocks				
Siltstone, siliceous mudstones, quartz sandstone, hornfels	Minor calcite present, detrital illite parallel to bedding	Decalcified, intensely silicified, 1–10% clay minerals	Decalcified, silicified, 10–35% clay minerals	Decalcified, silicified, 35–80% clay minerals
		Silicification is pervasive, clay along bedding planes	Clay minerals are concentrated along bedding planes and fractures	Abundant clay along bedding planes and fractures, overprints silicic and silicic-argillic zones

Zones of argillic alteration are most commonly observed adjacent to faults and dike margins and grade outward, 0.5 to 2 m, into zones of silicic-argillic alteration.

Least altered siliciclastic rocks

The least altered siliciclastic rocks consist of fine-grained, slightly calcareous, siltstone comprised dominantly of quartz and illite. Illite occurs parallel to bedding. Locally, siliciclastic rock is metamorphosed to hornfels. Clay-rich partings, 1 to 5 mm, as well as euhedral, 2 to 4 mm, diagenetic pyrite occur along bedding planes. Least altered siliciclastic rocks contain <0.001 oz/t gold and are found distal to the ore zone.

Altered siliciclastic rocks

Within the siliciclastic Rodeo Creek unit and Vinini Formation, silicic rocks are decalcified, black to brown, fine-grained siltstone or hornfels, and are generally oxidized. Recrystallized silica is commonly present. Locally, silicified masses occur as podlike zones near faults. Within silicic-argillic siliciclastic rocks, clay minerals are not pervasive, but they are concentrated along bedding planes and fractures, 0.25 to 2 cm. Argillic siliciclastic rocks consist of gray to black, fine-grained siltstone or hornfels with greater than 35 percent clay minerals. Zones of argillic siliciclastic rocks are found adjacent to faults and dikes grading outward, up to 0.5 m, into silicic-argillic and silicic rock. Primary bedding features are visible within all altered siliciclastic rocks.

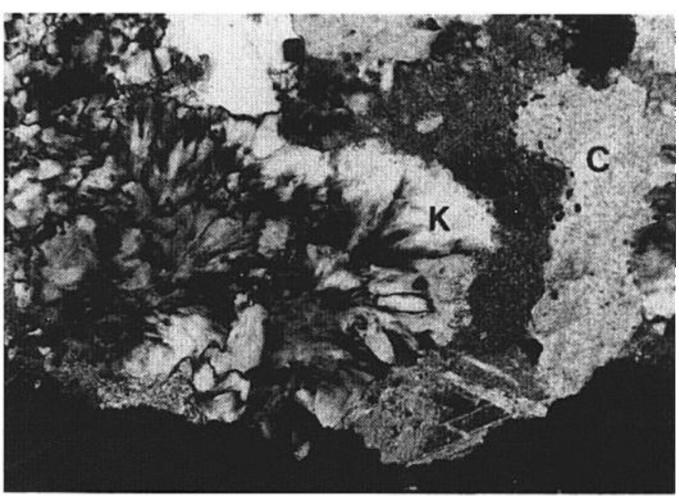

FIG. 3. Photomicrograph of partially altered Popovich Formation containing carbonate (C) being replaced by kaolinite (K). Gold content = 0.0001 oz/t; clay content = 84 percent kaolinite, 16 percent smectite. Field of view = 1 mm; sample 289.

Mineralogy and Distribution of Clays

Thirty-five randomly oriented slides were analyzed to identify clay mineral polytypes. Clay species identified are 1M and $2M_1$ illite, kaolinite, halloysite, and dioctahedral smectite; no dickite was observed. The sample population consisted of 12 samples of altered Popovich Formation, 13 samples of altered siliciclastic rocks, seven samples of altered intrusive rock, and three fault gouge samples. Of primary interest, all 25 samples of altered host rock contained 1M illite; $2M_1$ illite was identified in five samples of altered siliciclastic rocks and in only one sample of altered Popovich Formation. Kaolinite was found in all samples with the exclusion of the gouge samples which were comprised of halloysite and smectite. Halloysite was also identified within one sample of argillic siliciclastic rocks and one sample of altered intrusive rock. Smectite was also identified within three samples of altered intrusive rocks.

A comparison of the relative percent change of clay species was also made between sample populations. Within the Popovich Formation there is a significant increase in the amount of illite and kaolinite and a decrease in smectite in altered rocks compared to least altered rocks. Only a slight increase in the amount of illite and kaolinite is observed in altered siliciclastic rocks compared to least altered siliciclastic rocks. Smectite occurrence decreases significantly within altered siliciclastic rocks. Altered intrusive rocks show a development of illite and an increase in kaolinite-halloysite compared to unaltered intrusive rocks; smectite occurs within both rock

TABLE 2. Relative Clay Abundance within Each Sampling Group

	Least altered	Silicic	Silicic-argillic	Argillic
Popovich Formation	Smectite dominant, kaolinite minor, illite minor	1M illite present, kaolinite present, smectite absent	1M illite dominant, kaolinite present, smectite absent	Kaolinite dominant, 1M illite present, smectite present
Siliciclastic rocks	Illite dominant, kaolinite present, smectite present	1M illite present, kaolinite present, smectite absent	1M illite present, $2M_1$ illite present, kaolinite present, smectite absent	1M illite present, $2M_1$ illite present, kaolinite present, smectite absent
	Unaltered	Altered		
Intrusive rocks	Smectite dominant, kaolinite present, illite absent	Kaolinite dominant, halloysite present, smectite present, illite present		
	Gouge			
Faults and fractures	Kaolinite dominant, smectite dominant, halloysite present, illite minor			

types. All three clay species occur within structural zones, where kaolinite-halloysite and smectite are the dominant species. Table 2 illustrates further the dominant clay species identified within each alteration classification as well as those for intrusive rocks and gouge samples collected from structural zones.

Alteration Mineralogy and Association with Gold

Within the Genesis and Blue Star deposits, gold is hosted predominately within silicic-argillic rocks within the Popovich Fomation. Altered siliciclastic rocks represent a significantly less important host. Gold is rarely detected above 0.001 oz/t in least altered rocks, intrusive rocks, and fault gouge. The presence of gold was not identified within photomicrographs but detected by geochemical analysis.

Altered Popovich rocks that contain <0.001 oz/t gold consist dominantly of fine-grained quartz and kaolinite. Detrital quartz and feldspar clasts are replaced by kaolinite and cryptocrystalline quartz. The association of quartz overgrowths and euhedral kaolinite is also observed (Fig. 4). Altered Popovich Formation containing >0.001 oz/t gold consists dominantly of a fine-grained quartz, ± kaolinite, which is locally replaced by pods of illite or crosscut by veins of illite and quartz. Figure 5 shows an illite-quartz vein crosscutting altered Popovich Formation which contains 0.56 oz/t gold. SEM photographs revealed that prismatic illite formed directly at the expense of kaolinite (Fig. 6A and B). Kaolinite plates with resorbed edges are present. Illite is also observed within argillic Popovich Formation, encapsulated by quartz overgrowths, suggesting coprecipitation of quartz and illite. A relationship between Au and pyrite could not be established since little to no pyrite is observed in the altered Popovich Formation host rocks.

Altered siliciclastic rocks containing <0.001 oz/t gold consist dominantly of recrystallized quartz, ± kaolinite, with local preservation of detrital illite. Where present in the matrix, kaolinite occurs in euhedral books. Siliciclastic rocks containing >0.001 oz/t gold consist of a recrystallized quartz, ± kaolinite, ± detrital illite matrix and are locally cut by silica and/or illite veins. Pyrite is observed within silicic-argillic and argillic siliciclastic rocks along bedding planes as subhedral, 1- to 2-mm, crystals. Concentrations of illite also occur along bedding planes and fractures. This occurrence of illite differs from that observed in the Popovich Formation and is possibly due to differences in the porosity and brittle nature of the two rock types following decalcification. Siliciclastic rocks are less porous and more brittle than the Popovich Formation and clays will precipitate in areas of higher permeability such as fractures and bedding planes.

As in altered Popovich rocks, illite is encapsulated by quartz overgrowths within siliciclastic rocks containing high gold grades (Fig. 7). As a result, in both the Popovich Formation and siliciclastic rocks, some unkown fraction of the illite was included in the greater than μm-size fraction of the sample

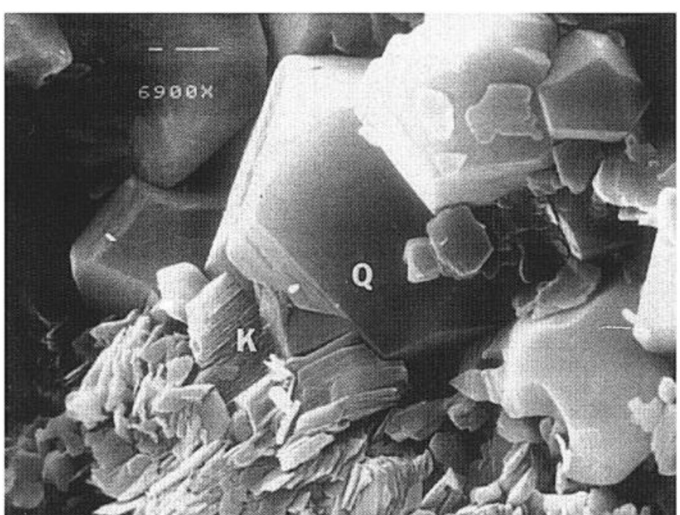

FIG. 4. SEM photograph of euhedral kaolinite (K) and quartz overgrowths (Q) observed in a sample of calc-silicate hornfels. Gold content = 0.0002 oz/t, clay content = 100 percent kaolinite. Field of view = 16.3 mm, sample 259.

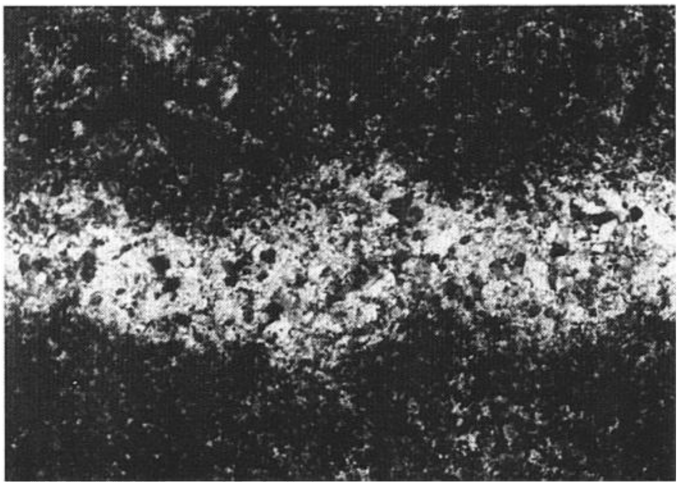

FIG. 5. Photomicrograph of Popovich Formation consisting of a quartz, ± kaolinite, ± Fe oxide matrix, crosscut by an illite and silica vein. Gold content = 0.56 oz/t. Field of view = 4 mm, sample of Gen C-1 core.

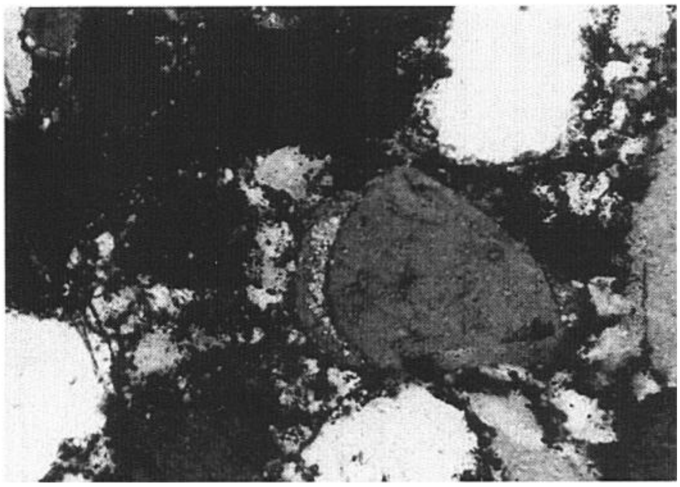

FIG. 7. Photomicrograph of silicic siliciclastic rock containing illite (center of photo) encapsulated by quartz overgrowths. Gold content = 0.044 oz/t. Field of view = 1 mm. Sample 145.

and not detected by X-ray diffraction. Within the same sample, kaolinite is observed within pore spaces and is interpreted to be supergene in origin (Fig. 8).

Geochemistry

Geochemical analyses were conducted for the following elements: Au, Ag, As, Cu, Zn, Sb, Hg, Pb, Mo, and Tl. Although the host rocks were enriched in all elements, only Ag yielded a direct relationship to gold. The relationship between Au and Ag is much more apparent within altered Popovich Formation rocks than within altered siliciclastic rocks (Fig. 9). Au and Ag revealed significant relationships to clay minerals; other elements showed no correlation.

Figures 10 and 11 show relationships between Au and Ag and the relative weight percent of illite and kaolinite. A direct relationship exists between increases in gold and silver content and an increase in illite abundance as well as an inverse relationship between kaolinite and gold and silver content. These relationships are most obvious within the Popovich Formation (Fig. 10) and less pronounced in siliciclastic rocks (Fig. 11) for two reasons. First, siliciclastic rocks are less permeable and do not permit extensive introduction of clay minerals or Au and Ag. Second, detrital illite exists within siliciclastic rocks which do not contain gold. Some scatter in the Au to clay correlations is also attributed to encapsulation of hydrothermal illite by quartz within samples containing gold as well as the presence of supergene kaolinite in gold-bearing samples. Regardless of the scattering effects, the petrographic, XRD, and assay relationships imply coprecipitation of Au and 1M illite contemporaneous with kaolinite destruction.

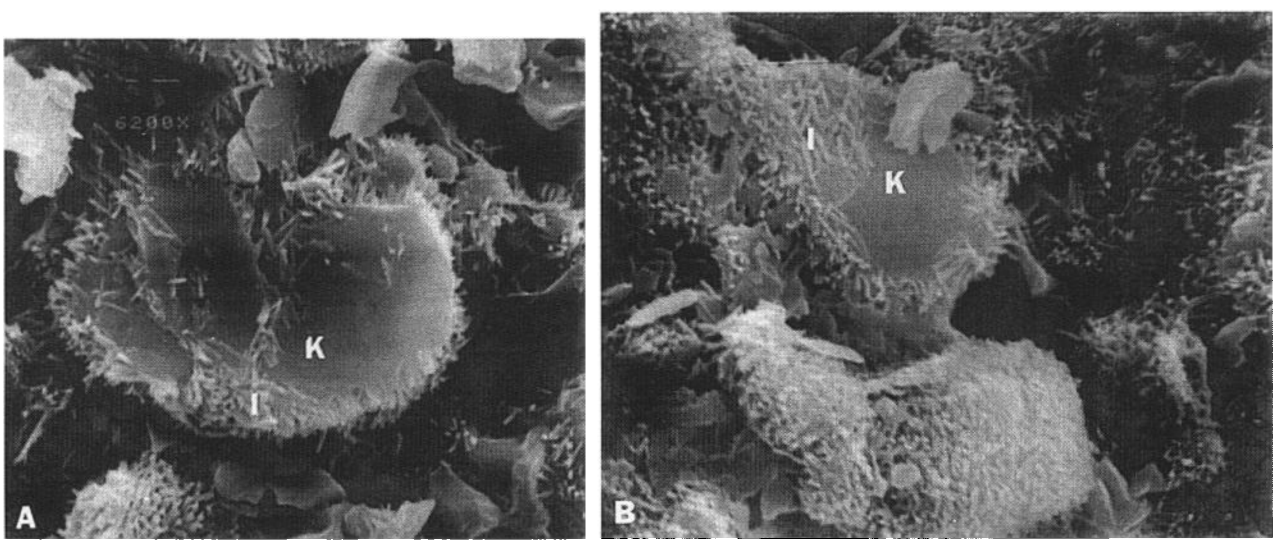

FIG. 6. A. SEM photograph of prismatic illite (I) forming at the expense of kaolinite (K). Field of view = 25 mm. B. SEM photograph of prismatic illite (I) replacing kaolinite (K). Field of view = 10.8 mm. Gold content = 0.589 oz/t; clay content = 98 percent illite, 2 percent kaolinite. Sample 1.

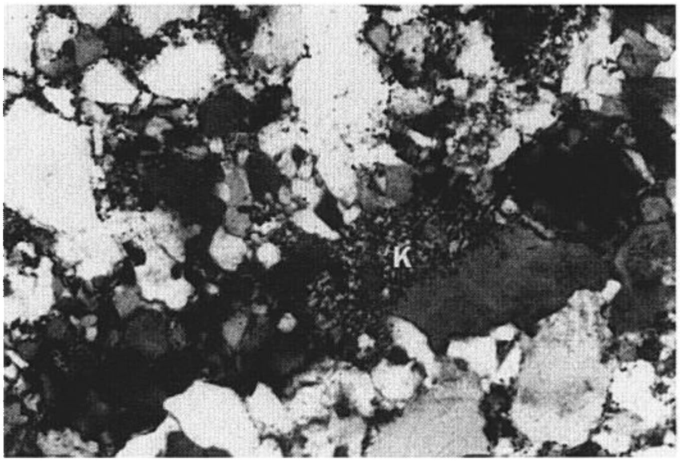

FIG. 8. Photomicrograph of supergene kaolinite (center of photo) within pore spaces between quartz grains. Gold content = 0.044 oz/t. Field of view = 2 mm. Sample 145.

Radiometric Age Dating

Ages of gold mineralization along the Carlin trend have been constrained to the time period between Late Jurassic to Early Cretaceous and the Pliocene. This range of mineralization was established based on mineralization within the Goldstrike stock emplaced about 158 Ma and clasts of mineralized Roberts Mountains Formation within the Pliocene Carlin Formation (Christensen et al., 1987; Arehart et al., 1993).

A number of additional studies have reported ages within this range. Bakken and Einaudi (1986) suggested a pre-late Tertiary age for gold deposition. They reported that north-northeast-trending Basin and Range faults were often barren and postdate gold mineralization within the Carlin deposit. Hofstra et al. (1991) also stated that deposits in the Jerritt Canyon district are younger than the most recent folding event; mineralization is suggested to be Cretaceous to Eocene in age but older than Basin and Range faulting.

Arehart et al. (1993) suggested a mid-Cretaceous age for gold deposition at the Post-Betze deposit. Utilizing K-Ar, $^{40}Ar/^{39}Ar$, and fission track techniques, fine-grained hydrothermal sericite from mineralized host rocks yielded ages near 117 Ma. Other studies suggest a late Tertiary age for gold mineralization based on structural evidence. For example, Radtke (1985) proposed that Basin and Range faults served as structural conduits for hydrothermal fluids.

The association of illite with gold established within the Genesis and Blue Star deposits allows for the geochronological study of the mineralizing event utilizing K-Ar techniques. Three samples of Popovich Formation were dated by conventional K-Ar methods at Geochron Laboratories in Cambridge, Massachusetts. The samples, two silicic-argillic and one argillic, were selected based on their high gold and illite contents as well as their lack of other K-bearing minerals. The samples were located approximately 500 ft apart. The clay in each sample was 100 percent hydrothermal 1M illite. At least 0.7 g of the <1-μm-size fraction was submitted for analysis. Both K and Ar concentrations were determined in duplicate. The average age for precipitation of hydrothermal 1M illite is 96.5 Ma. The results are summarized in Table 3.

K-Ar dating of hydrothermal illite is controversial due to the fact that argon can be lost from the clay mineral structure and consequently yield a younger than actual date. However, studies conducted by McDougall and Harrison (1988) indicate that temperatures must be greater than 250°C for a significant time interval for illite to lose much radiogenic argon. Numerous other authors suggest a temperature less than 250°C for gold deposition along the Carlin trend (Ratdke, 1985; Kuehn and Rose, 1987; Kuehn, 1989; Arehart, 1993). Therefore, the authors believe there has been no notable argon loss from the illite crystals analyzed in this study. Further, it is highly unlikely that such consistent ages would be obtained from samples collected 500 ft from one another, if they had lost or gained appreciable argon (E.C. Simmons, pers. commun., 1996).

Discussion

The following alteration events have been identified within the Genesis and Blue Star deposits: contact thermal metamorphism, decalcification, silicification, argillic alteration, and supergene oxidation. Metamorphism and supergene oxidation did not play a significant role in the formation of clay minerals associated with gold.

Decalcification played a crucial role in ground preparation

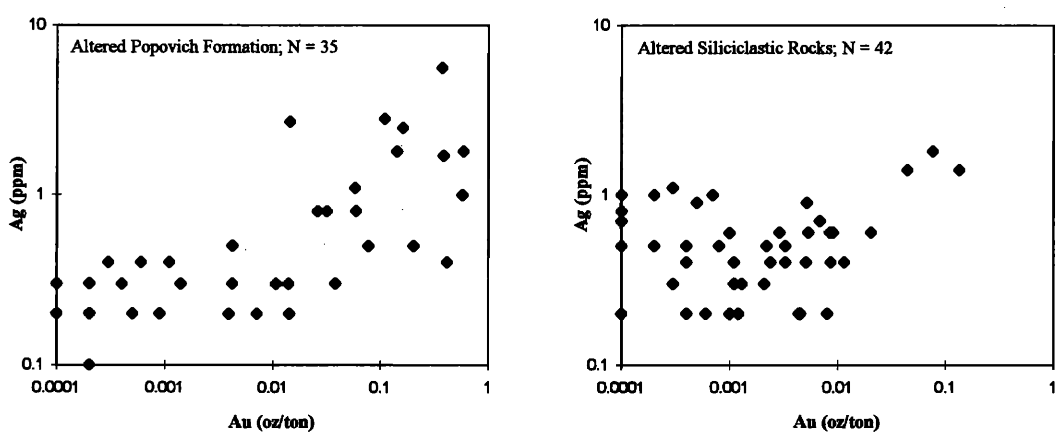

FIG. 9. Relationships between Au and Ag within altered Popovich Formation rocks and altered siliciclastic rocks.

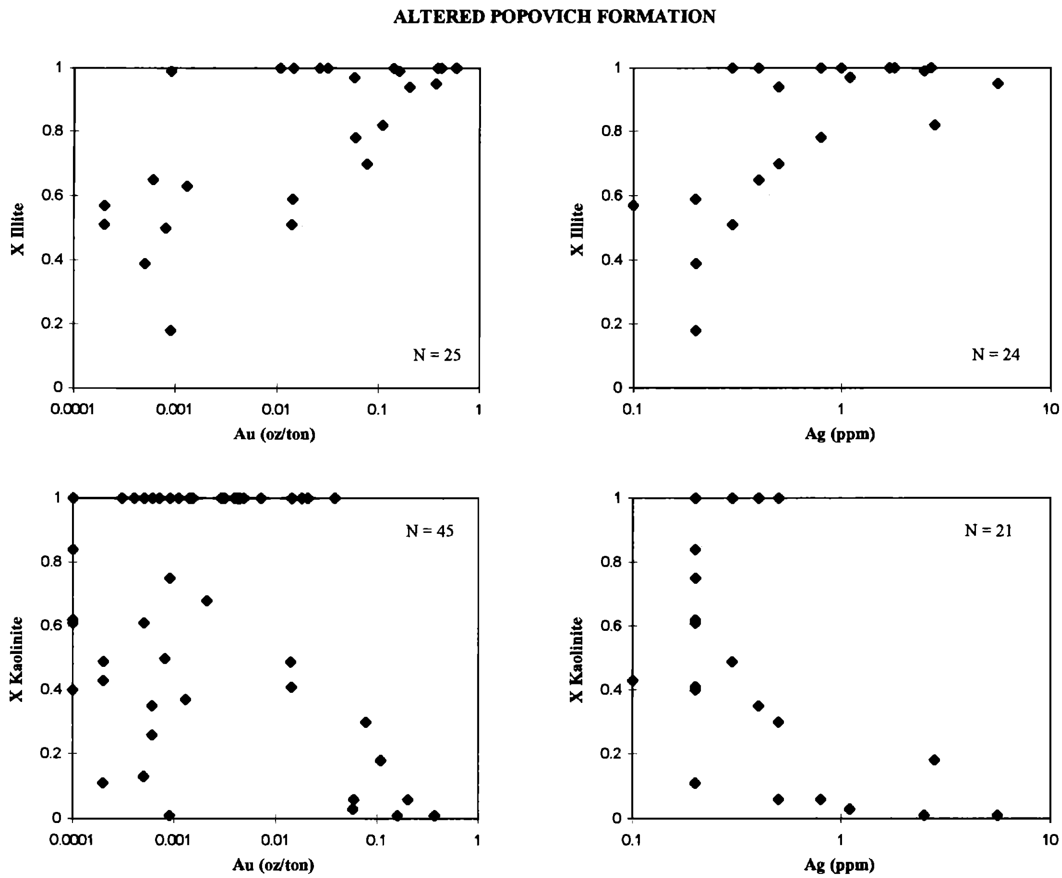

FIG. 10. Relationships between Au and clay species within altered Popovich rocks. X illite = wt percent illite/wt percent all clays, X kaolinite = wt percent kaolinite/wt percent all clays.

by increasing porosity and permeability within sedimentary rocks (Ratdke, 1985). The calcareous Popovich Formation acquired greater permeability and porosity than the quartz-rich siliciclastic rocks. Harvey (1991) points out that magnesium metasomatism associated with the Goldstrike intrusion resulted in the development of abundant calc-silicate hornfels within the Popovich Formation. Harvey (1991) suggests that this event of weak magnesium metasomatism also played an important role in making the Popovich Formation preferentially receptive to gold-bearing fluids.

Differences in mineralogy, porosity, and permeability explain why clay minerals within the Popovich Formation are abundant and disseminated throughout the rock, whereas within siliciclastic rocks clay minerals are concentrated along fractures and bedding planes. These differences also explain why gold is most prevalent within the Popovich Formation host rocks.

At least three silicification events have been identified within the Genesis and Blue Star mines. SEM analyses confirm the presence of titanium within both euhedral kaolinite and quartz, replacing carbonate and indicating that at least one silicification event occurred during hydrothermal kaolinite precipitation. Veins of illite and quartz are found crosscutting matrices of kaolinite and quartz, indicating a second event of silica precipitation associated with hydrothermal illite precipitation. Moderated silica precipitation occurs within distinct bedding units, suggesting that silica-bearing fluids migrated along stratigraphic units. Silicic rocks also occur in highly oxidized, podshaped masses, bounded by faults. These pods generally contain <0.001 oz/t gold and commonly crosscut bedded zones of mineralized silicic-argillic rocks. This suggests that a generation of silica was introduced along structures and postdates the gold mineralizing event.

Clay alteration is dominant in rocks categorized as silicic-argillic and argillic. Silicic-argillic alteration occurs as pervasive zones extending over a wide area and within distinct units. Within silicic-argillic rocks, illite is observed replacing kaolinite. Argillic alteration is concentrated around faults and dike margins and commonly overprints bedding-parallel zones of silicic-argillic alteration. These relationships are indicative of at least three different episodes of clay formation.

Illite, kaolinite, and smectite are the principal clay species identified in the Genesis and Blue Star deposits. Illite and kaolinite contents increase within hydrothermally altered host rocks when compared to least altered rocks. Smectite decreases in altered host rocks as compared to least altered calcareous rocks. Clay mineral occurrences within least altered and altered rocks indicate that at least one generation of both kaolinite and illite are associated with hydrothermal alteration and that smectite was not stable under these hydrothermal conditions.

Both 1M and $2M_1$ illite are identified within the Genesis

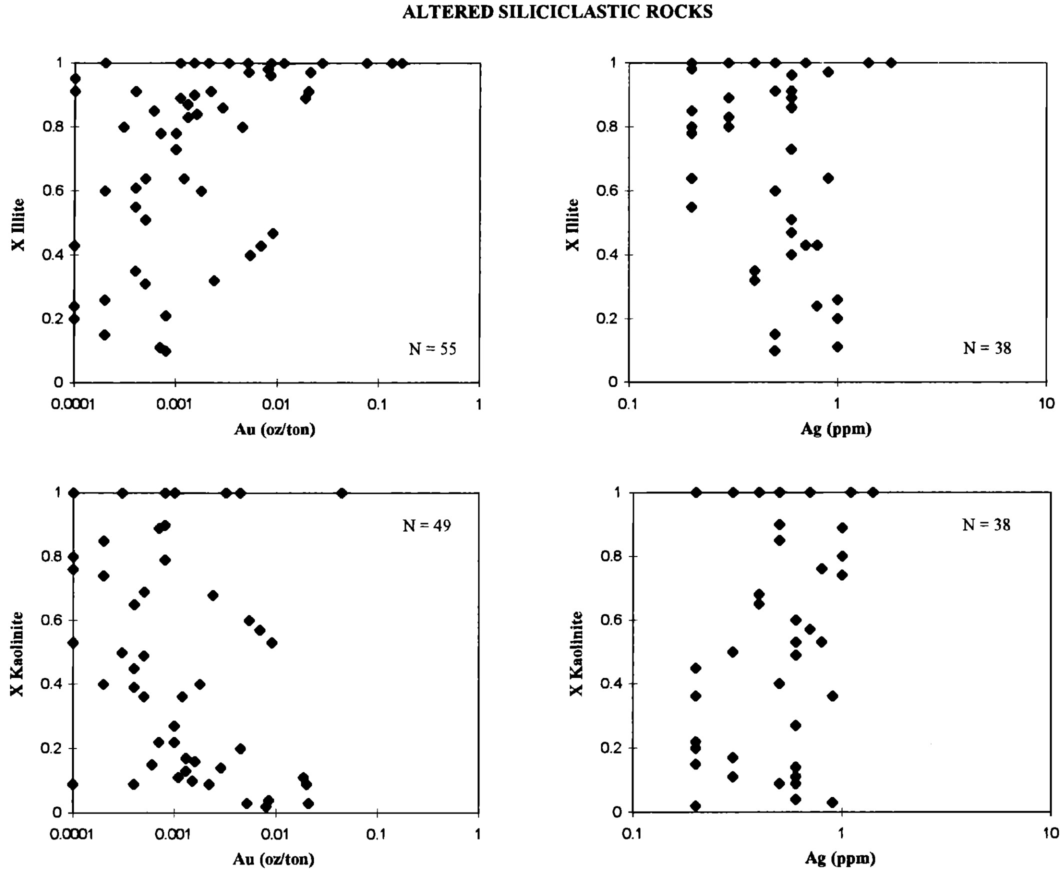

FIG. 11. Relationships between Au and clay species within altered siliciclastic rocks. X illite = wt percent illite/wt percent all clays, X kaolinite = wt percent kaolinite/wt percent all clays.

and Blue Star deposits. The $2M_1$ illite occurs almost exclusively within siliciclastic rocks; 1M illite occurs in both the Popovich Formation and the siliciclastic rocks. Least altered siliciclastic rocks contain a significant amount of detrital muscovite and illite. Bailey (1984) reports that the dominant natural muscovite polytype is $2M_1$ and the dominant natural illite polytype is 1M. The occurrence of $2M_1$ illite within siliciclastic rocks, its absence within the Popovich Formation, and the association of 1M illite with gold specifically within the Popovich Formation suggests that $2M_1$ illite represents a detrital component, whereas the 1M illite polytype represents a hydrothermal alteration product.

Kaolinite and halloysite polytypes exist in altered Genesis and Blue Star deposit host rocks. Eroshschev-Shak et al.

TABLE 3. K-Ar Data for Three Hydrothermal 1M Illite Samples from Popovich Formation Host Rocks

Sample no., alteration	Au (oz/t)	$^{40}Ar_{rad}/^{40}Ar_{total}$	$^{40}Ar_{rad}$ (ppm)	^{40}K (ppm)	$^{40}Ar_{rad}/^{40}K$	Age (Ma)
1, silicic-argillic	0.589	0.493	0.02302	4.047	0.005690	95.4 ± 2.4
27, silicic-argillic	0.383	0.731	0.04706	8.098	0.005811	97.3 ± 2.4
192, argillic	0.416	0.685	0.04163	7.216	0.005769	96.7 ± 2.4

Constants: $^{40}K/K = 1.193 \times 10^{-4}$ g/g, $k_\beta = 4.962 \times 10^{-10}$/yr, $(k_e - k_e') = 0.581 \times 10^{-10}$/yr

(1991) demonstrate that halloysite favors a lower temperature (<60°–75°C) and a higher pH environment, whereas kaolinite forms in a wide range of temperatures and predominates in more acidic conditions. It has already been noted that halloysite was identified only within intrusive rock, gouge, and altered rocks classified as argillic. Eroshschev-Shak et al. (1991) also report that kaolinite ordering increases with increasing temperature. Within altered samples containing 0.001 oz/t Au, kaolinite, replacing carbonate, is extremely well formed, possibly reflecting a greater degree of internal order. The identification of these two polytypes, associated with different formation conditions, indicates that there were at least two kaolinite-precipitating events, one hydrothermal and one supergene. This could explain the noted abundance of kaolinite within the Genesis and Blue Star deposits.

Smectite clays are dioctahedral, suggesting the dominance of either aluminum or ferric iron within the octahedral sheet. Although a specific formula was not determined, the association of smectite with calcium-bearing minerals suggests that the interlayer cation is calcium. Smectite is believed to form at temperatures lower than 150°C from near-neutral oxidizing fluids. Ellis (1970) found that within hot spring and epithermal environments, smectite does not exist above 150°C. Eslinger et al. (1979) believe that the influx of reduced hydrothermal fluids promotes the destruction of smectite, and the reduction of structural ferric iron to ferrous iron within montmorillonite contributes to the conversion of montmorillonite to illite. Smectite is found within least altered host rock, intrusive rocks, and fault gouge and is interpreted to be supergene in origin.

Between 93 and 100 Ma, hydrothermal gold-bearing fluids migrated along northwest-trending structures and distinct stratigraphic units. This resulted in the precipitation of abundant gold and 1M illite and the destruction of kaolinite. However, minor local mineralization of the Tertiary, northeast-trending K dike cannot be attributed to this event. Therefore, a less than 40 Ma hydrothermal event must be responsible for remobilizing gold into the K dike. Further, some kaolinite enrichment observed within intrusive and argillic host rocks may also be attributed to a less than 40 Ma hydrothermal event and not solely to supergene alteration. Additional work in the Genesis and Blue Star deposits is needed to determine the actual age and nature of gold remobilization.

Conclusions

Decalcification resulted in the replacement of calcite by euhedral hydrothermal kaolinite. The altered Popovich Formation containing <0.001 oz/t gold consists dominantly of recrystallized quartz and euhedral kaolinite. Illite replaces euhedral kaolinite within rocks containing >0.001 oz/t gold. Illite is present in patchy replacement zones or in crosscutting veins and is often encapsulated by quartz overgrowths. Illite crystals are also observed on the edges of kaolinite plates. Further, within rocks that contain gold and illite, kaolinite plates have resorbed edges. Based on these relationships, it is suggested that a single hydrothermal event resulted in the precipitation of gold, 1M illite, silver, and silica contemporaneously with kaolinite destruction.

Rocks classified as silicic-argillic Popovich Formation represent the most significant gold host. Silicic-argillic rocks commonly exhibit bedding-parallel alteration zones. This pattern of alteration indicates that stratigraphy as well as northwest-trending structures played a significant role in the migration of gold-bearing fluids.

Hydrothermal alteration was followed by supergene alteration which resulted in the formation of supergene kaolinite, halloysite, and smectite, as well as the oxidation of iron-bearing minerals. The formation of supergene clay minerals is concentrated along faults, dike margins, and within fractures. Gold mineralization is not associated with supergene clay minerals within the Genesis and Blue Star deposits.

Based on the direct relationship established between hydrothermal 1M illite and gold occurrence, the main event of gold deposition in the Genesis and Blue Star mines is believed to have taken place between 93 and 100 Ma, during mid-Cretaceous time. This is consistent with a Cretaceous age for the Welches' Canyon stock located 18.5 km south of the Genesis and Blue Star deposits (Arehart et al., 1993). This event of intrusive activity may be responsible for the generation of local hydrothermal activity and the formation of the Genesis and Blue Star deposits.

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