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Gold Deposition at Gold King, Silverton Caldera, Colorado

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Abstract: The Tertiary Silverton caldera collapsed asymmetrically to the southwest 27.5 m.y. ago. Resurgent volcanic activity is expressed by a quartz-monzonite stock at the southern caldera margin and the Red Mountain porphyry stock in the northwest of the caldera which were emplaced at 25 m.y. and 11 m.y. b.p., respectively. The apical Eureka graben formed between 27.5–22.5 m.y. ago and transects the Silverton caldera southwestward. In the northeast, it terminates at the 22.5 m.y. Lake City caldera margin. This graben, as well as caldera faults, provide dominant structural control for base and precious metal deposits.

The epithermal gold mineralization of the Gold King mine is proximal to the Red Mountain stock in the north central part of the caldera. Here, west-northwest striking faults related to the collapse of the caldera intersect northeast faults of the Eureka graben. Superimposed upon earlier base metal mineralization at 23 to 22.5 m.y. b.p., the 11 m.y. younger gold metallization was a distinct event at Gold King. Supergene enrichment of the hypogene precious metal assemblage resulted in a metal tenor of up to 3,016 g/t gold and 1,088 g/t silver. The deposit is hosted by quartz-latite tuffs, flows and flow breccias of the Burns Formation. Veins up to 5 m wide follow steeply southeast and northwest dipping structures of the Eureka graben. Subsidiary veins up to 2 m wide branch off the main lode and are termed "flat veins" because of their conformable strike but shallow dip of 45° to 50° toward the northwest.

Meteoric water-dominated hydrothermal solutions generated by the Red Mountain stock ascended through intensely fractured, ferruginous Proterozoic formations and overlying Oligocene caldera fill. These solutions were funnelled into the open fracture system causing vein emplacement and argillic, advanced argillic and phyllic alteration, as well as silicification and sericitization of the wall rock. Argillic alteration accompanies elevated gold grades and possibly ore carrying structures at Gold King. Gold was probably leached from Proterozoic basement greenstones and transported as bisulfide complexes. Decay of these complexes and subsequent gold deposition resulted from oxygenation at near neutral pH, triggered by mixing with fresh meteoric water and/or boiling of the hydrothermal solution close to the paleo-surface.

Fluid inclusion data indicate deposition temperatures of 280° $\pm$ 10° C for the vein filling quartz-, electrum (95/5 weight% Au/Ag), hessite-, petzite-, sylvanite-, krennerite-, altnite-, tetrahedrite-, bismuthinite-, $\pm$ pyrite, $\pm$ chalcopyrite, $\pm$ sphalerite, assemblage.

The Paleozoic and Mesozoic rock cover had been mainly eroded when volcanism began, exposing the Proterozoic basement. The gold bearing solutions show predominant meteoric character. It is, therefore, likely that the underlying basement consisting of Proterozoic olivine and tholeiitic basalt, ferruginous sediments and iron formation was the source for the gold metallization.

Introduction

This paper discusses the possible source, transport and deposition of gold in the northern portion of the Silverton caldera, San Juan Mountains, Colorado. Structural, lithologic and geochemical factors for the control of ore are considered in an attempt to explain the genesis and distribution of the Gold King lode. Epithermal, bonanza-type precious metal deposits, like those of the Gold King mine, are coveted because of their economic value, and have been the subject of detailed exploration and research during the past two decades.

Silverton were predominantly derived from meteoric water, and at the Sunnyside mine, became progressively meteoric with time (CASADEVALL et al., 1974). The adjacent Sunnyside deposit was initially mined for base metals only. When mine workings proceeded southwest toward the Gold King mine in the 1970's, increasing gold values were recovered. The Gold King lode was first mined in 1886. Until 1917, 665,500 tons of ore averaging 14.65 g/t gold, 74.32 g/t silver, 0.71% lead and 0.52% copper were produced. No significant ore production was recorded past 1917. At present, the average estimated ore grade at Gold King is 10.9 g/t gold and 90 g/t silver, for an ore reserve of 1,459.000 tons.

Regional Geology

The San Juan volcanic field is a 2.2 km thick accumulation of Oligocene pyroclastic rocks and lava flows that rest upon Precambrian basement and Paleozoic and Mesozoic rock formation (Figure 1). Proterozoic basement crops out to the north of the volcanic field and constitutes the Gunnison greenstone belt, which contains small greenstone-hosted gold deposits (HORLACHER, 1988). The southern extension of the belt is covered by volcanic formations of the San Juan volcanic field. Two windows of these Proterozoic basement rocks are located just north and east of the Silverton caldera. To the north, quartzites and pelitic schists of the Uncompahgre Formation are exposed at Ouray. To the east, the yet undated granite of Cataract Gulch mineralogically resembles the 1.35 b.y. Trimble granite of the Proterozoic Needle Mountains, located just south of the Silverton caldera (LARSON and TAYLOR, 1986). In addition, olivine and tholeiitic basalts of "great but unknown thickness", ferruginous sediments and minor iron formation constitute the Proterozoic Irving Formation in the Needle Mountains.

The Proterozoic basement and overlying Paleozoic and Mesozoic rocks were uplifted before explosive volcanism began at the Silverton volcanic center about 28 m.y. ago (STEVEN and LIPMAN, 1976). The Silverton caldera collapsed assymmetrically to the southwest at 27.5 m.y.b.p. (STEVEN and LIPMAN, 1976). During this event, bounding ring faults and west-northwest-trending collapse faults formed. Following this, the Eureka graben subsided from 27.5 to 22.5 m.y. (STEVEN and LIPMAN, 1976). This took place in response to doming, centered between the Silverton and the 22.5 m.y. old Lake City cauldrons. The graben is an important controlling structure for later mineralization. Its bounding faults and subsidiary fractures became important ore carriers during the following base metal and even younger precious metal mineralization. The base metal stage was preceded and accompanied by a district wide propylitic alteration, whereas the younger precious metal mineralization is linked to local solfataric alteration of argillic and acid-sulfate type.

Two subsequent intrusions are possible heat sources for these mineralizing events. The quartz-monzonite stock at the southern margin of the Silverton caldera is 25 m.y. old (LIPMAN et al., 1976) and the Red Mountain stock yields a potassium-argon age of 11 m.y.

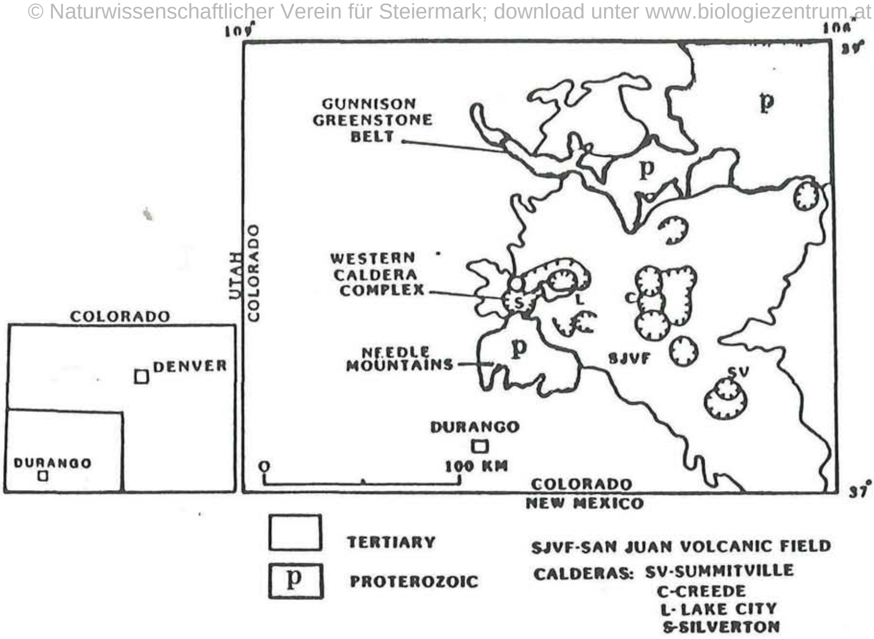

Figure 1: The Tertiary San Juan volcanic field is superimposed upon the Proterozoic Gunnison greenstone belt. The western caldera complex hosts the Gold King mine within the Silverton caldera (S).

Geologic Setting of the Gold King Mine

The Gold King deposit is located in the northern part of the Silverton caldera (Figure 2), and is proximal to the Red Mountain porphyry, the youngest stock of the Silverton volcanic center. At Gold King, northeast faults of the Eureka graben intersect older, west-northwest striking fractures related to the caldera collapse. The deposit is hosted in rocks of the Burns Formation, which is part of the caldera fill and outflow. The caldera fill, a sequence of three volcanic units, becomes less silicic towards the top. The lowermost Eureka member, a lithic rhyolitic ashflow tuff, is covered by relatively homogenous and ridged quartz-latite flows, flow breccias and tuffs of the Burns Formation, which responded to post-depositional tectonic strain with a more or less consistent fracture system. This resulted in the formation of sufficient open-space sites for later hydrothermal mineralization. Above the Burns Formation, a transition zone of quartz-latitic to andesitic tuffites marks the change to the overlying andesitic pyroclastites of the Henson Formation. The chemical, sedimentary and pyroclastic character of the Henson andesite is manifest by a sequence of laterally and vertically inhomogeneous, interleaved volcanic breccias and layers of lapillite and tuffite. Hence, only an irregular fracture system developed in these youngest volcanic rocks above the Burns Formation.

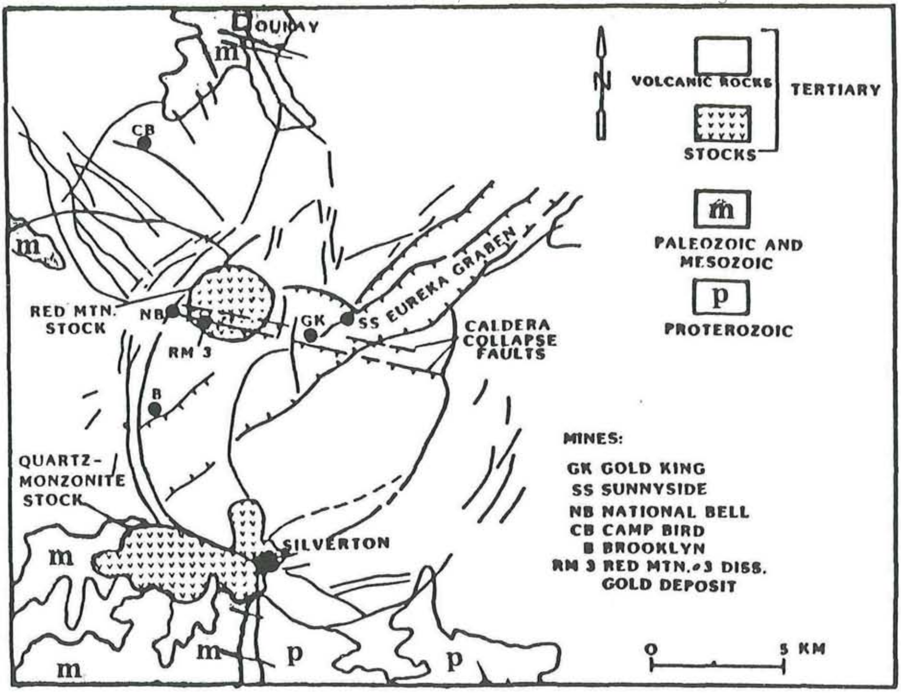

Figure 2: Location of the Gold King mine in the north central part of the Silverton caldera, proximal to the Red Mountain porphyry stock.

The Gold King Lode

The Gold King and Davis lodes consist of two sub-parallel veins merging downward from the upper most #1 to the lowermost #7 level (Figure 3). The strong, northeast trending veins are presently known over a total length of 1.1 km. Their maximum width is 5 m., but in parts, they are represented by fault gauge only. The pinching and swelling is characteristic of epithermal veins.

Until 1917, ore was mainly broken from the dominant Gold King-Davis veins. Subsidiary flat veins branch off the main lode and yield significant, yet unmined ore reserves.

The positions of high grade gold shoots are controlled by their specific elevations, as well as their locations, with respect to the lithologic Burns/Henson boundary (Figure 3). Generally, high grade gold ore is found within the central and upper portion of the Burns formation only. Although the Henson formation hosts jasperoidal veins and veinlets, it does not yield any significant mineralization above the Gold King lode. The transition zone thus marks the boundary between ore-hosting rock below and barren country rock above.

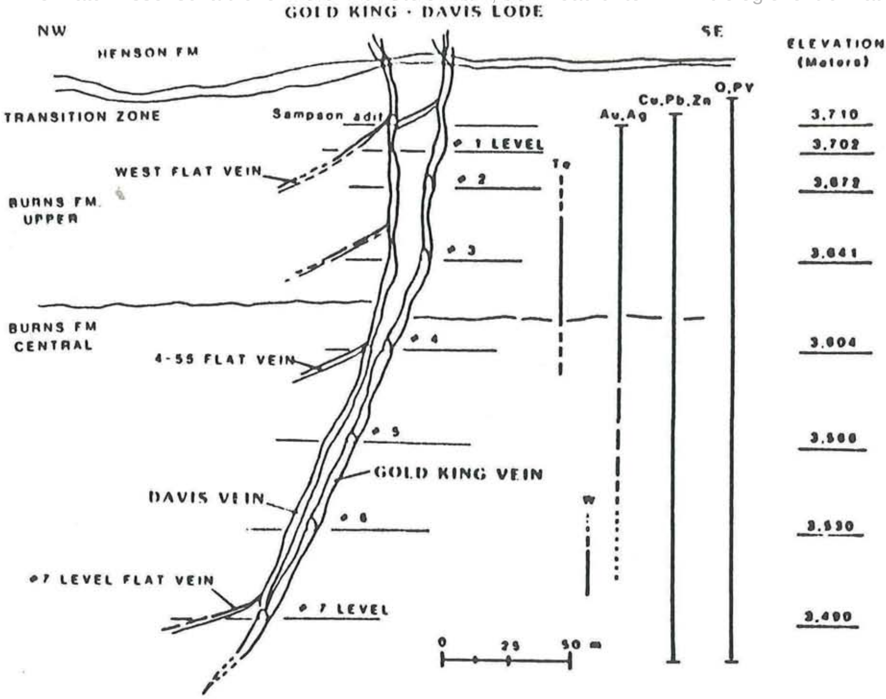

Figure 3: Schematic cross section of the Gold King-Davis lodes with subsidiary flat veins. The vertical distribution of precious metals, base metals and quartz/pyrite gangue is indicated to the right of the vein couple.

Alteration

Alteration suites at Gold King are summarized in Figure 4. An earliest, pervasive propylitic alteration of epidote, chlorite, calcite, ± pyrite, ± magnetite is recognized throughout the host rock. This alteration preceded and accompanied the early district-wide base metal mineralization at 22.5 m.y. (LIPMAN et al., 1976).

Along faults, and surrounding the veins, argillic alteration haloes indicate possible gold mineralization. This alteration was contemporaneous with gold metallization and an argillic (kaolinite) alteration can be distinguished from an acid-sulfate (alunite) type at Gold King (Figure 4). Progressing towards a vein phyllic (quartz-sericite-pyrite) alteration sets in and finally merges with silicification at the vein wall.

Sericite alteration appeared with two different hydrothermal events. Based upon potassium-argon ages from sericites, two major hydrothermal events occurred within the Silverton caldera. The first sericite alteration took place at 21 m.y. and, therefore, post-dates the district-wide propylitic alteration at 22.5 m.y. (LIPMAN et al., 1976). The second, 13 m.y. old sericitization pre-dates the argillic alteration of the Red Mountain district at 11 m.y. Thus, both events of sericite alteration appear to be separate from the early propylitic and later argillic alteration.

The latest alteration at Gold King was supergene in character and takes the form of opalitic stain upon massive quartz and pyrite in the lower part of the Gold King and Davis veins. This alteration oxydized the deposit and caused significant enrichment of the gold lode.

	ALTERATION	WALL ROCK	MINERALS	ELEMENTS	AGE (m.y.)
hypogene	PROPYLITIC	↓	epidote, chlorite/montmorillonite, calcite, pyrite, magnetite, quartz	FE,MO,MN, CA,CL,SI	≥22.5
	ARGILLIC		kaolinite-sericite	AL, SI,K,NA, FE,CL,CA	
	ACID-SULFATE		alunite		≤11
	PHYLLIC (QSP)		quartz, sericite, pyrite	SI,K,FE,S,AL	
	SERICITIZATION	↓	quartz, sericite	SI,K,AL	21 13
		— VEIN WALL —			
supergene	OPALITIC STAIN		silica gel	SI	RECENT

Figure 4: Summary of alteration suites at Gold King.

Elevated gold values appear with argillically altered wall rock at Gold King, whereas alunite alteration accompanies very low gold values.

Mineralization

Four phases of hypogene vein filling formed the Gold King deposit (Figure 5). Quartz and pyrite first filled large portions of the available open fault-fracture system. Preferentially, in the lower part of the deposit, massive pyrite is the vein filling gangue mineral together with "bull" quartz.

The second phase is base metal-sulfide bearing. Chalcopyrite, galena and sphalerite are its main constituents, accompanied by pyrite and quartz. This phase is district-wide and probably was linked to the 22.5 m.y. collapse of the Lake City caldera.

Superimposed upon phase 2, precious metallization was introduced as a relatively late, single phase. This event is probably linked to the acid-sulfate alteration of the Red Mountain stock at 11 m.y.b.p. Still available open spaces in vein centers were filled with free gold and a telluride assemblage of hessite, petzite, sylvanite, krennerite and altaite. Tetrahedrite-Tennantite and bismuthinite, as well as pyrite, some chalcopyrite and possibly minor sphalerite, also accompany this assemblage. Free gold appears as electrum with a relatively high purity, averaging 95% gold and 5% silver at Gold King. Primary fluid inclusions in associated milky quartz indicate temperatures of 270° to 290° for this phase.

The fourth and last phase of hypogene mineralization at Gold King precipitated quartz and fluorite only. This phase probably represents the cooling period of phase 3.

Following hypogene mineralization, supergene alteration oxydized and enriched the precious metal assemblage. Free gold is found along joints within the 4-55-flat vein. Oxydational enrichment of the deposit led to extremely high precious metal grades of up to 3,016 g/t and 1,088 g/t silver. The supergene alteration also led to the formation of bornite and covellite.

	MINERALIZATION		ELEMENTS	AGE (m.y.)	ALTERATION
hypogene	PHASE 1	quartz, pyrite	SI,FE,S	>22.5	PROPYLITIC PHYLLIC
	2	chalcopyrite, galena, sphalerite, quartz, pyrite	CU,PB,ZN, S,AG,SI, (low FE)		
	3	electrum, tellurides, tetrahedrite/tennantite, bismuthinite	AU,AG,TE,BI, SB,AS,S,BI,CU	≤11-10	ARGILLIC
	4	fluorite, quartz, huebnerite	F,MN,SI,W	<10	
supergene	5	electrum, (tellurides), covellite, bornite	AU,AG, (TE),CU,BI		OPALITIC STAIN

Figure 5: Summary of five phases of mineralization at Gold King.

Geochemical Aspects

At Gold King, ore is associated with kaolinite and possibly sericite alteration. These minerals form from hydrothermal solution within the pH-ranges of 5.8 to 4 and 5.8 to 6.5 respectively. Gold was probably transported in hydrothermal solutions as bisulfide complexes of $Au(HS)_2$ (ROMBERGER, 1986). Changes from low log a_{O_2} to higher $^{2}\log a_{O_2}$ cause the decay of the complex by oxygenation. This can be triggered by mixing with fresh meteoric water and/or boiling.

The following reaction demonstrates the breakdown of a gold-bisulfide complex by oxygenation:

$$\underset{(aq)}{Au(HS)_2^-} + \underset{(aq/g)}{2\,O_2} \rightarrow \underset{(n)}{Au^0} + \underset{(aq)}{SO_4^{2-}} + \underset{(aq)}{2\,H^+} \rightarrow \underset{(aq)}{H_2SO_4}$$

In this reaction, gold is reduced from Au^+ to Au^0. Once the complex is broken up, gold becomes insoluble and precipitates from hydrothermal solution. Continued release of hydrogen cations and sulfate anions results in the generation of the strong acid H_2SO_4 and decreased pH with a gold solubility possibly four orders of magnitude lower than that of the initial solution. Hydrogen ions released during reactions with wall rock will lower the pH, also causing or re-enforcing gold precipitation. Decreased pH causes significant precipitation of silica from hydrothermal solution as well. Thus, silicification and the growth of quartz veins with euhedral quartz crystals follows alunite alteration.

Discussion

Magmatic doming caused uplift and subsequent erosion of Paleozoic and Mesozoic formations at the Silverton volcanic center. When volcanism began, probably a minor portion, if any, of the Paleozoic and Mesozoic rock cover remained at the apex of the dome. North of Ouray, some Paleozoic and Mesozoic rocks are preserved and host minor ore deposits of late Mesozoic age (LUEDKE and BURBANK, 1981). But only one relatively small block of Paleozoic Leadville-Ouray limestone and one block of Hermosa/Molas formation are present in the relatively undisturbed area of Ironton Park, northwest of the caldera (LUEDKE and BURBANK, 1964).

Because of its lithologic composition of thick tholeiitic and olivine basalts, ferruginous sediments and iron-formation, the Proterozoic basement is a favorable gold source.

Tholeiites and iron-rich chemical sediments of Archean age have been shown to be gold enriched (MEYER and SAAGER, 1985). In addition, the great gold potential of Archean greenstone belts was pointed out by HUTCHINSON (1984). Therefore, the similar Proterozoic rocks of the Irving Formation to the south of the caldera, and the Gunnison greenstone belt to the north, represent likely sources for the gold, which probably was remobilized by the later Tertiary magmatism and related hydrothermal activity. Whatever the gold source, physico-chemical conditions combined to form a high grade, epithermal vein deposit. Hosted by relatively brittle Tertiary caldera fill above intensely fractured basement rocks, the Gold King lode is close to the young Red Mountain porphyry stock. This stock probably supplied the heat source for meteoric water-dominated hydrothermal solutions. These solutions probably leached gold from Proterozoic basement rock and carried it as bisulfide complexes.

A combination of TILLING, GOTTFRIED and ROE's (1973) view emphasizing geologic setting and duration of hydrothermal systems over source rock enrichment to form an ore body, with HUTCHINSON's (1987) interpretation of hydrothermal leaching processes within basement rocks and with subsequent gold precipitation in overlying, less consolidated caldera fill, provides an acceptable explanation for the geologic setting and origin of the Gold King deposit. During repeated magmatic and tectonic activity, the caldera roof was intensely fractured. Thus, a relatively large surface of Proterozoic basement rock was exposed to hydrothermal leaching and, therefore, a relatively short time period may have been sufficient for the formation of the Gold King veins. Chemically, acid sulfate (alunite) alteration follows the breakdown of bisulfide complexes and argillic (kaolinite) alteration. At decreasing pH, gold solubility rapidly decreases as well. This also is true for silica, which results in silica-flooding. Thus, the following alteration sequence is suggested for deposits like the Gold King. Argillic alteration with gold precipitation was followed by acid sulfate alteration, accompanied by only minor gold, and this was followed in turn by silicification.

Conclusions

The location and character of the rich Gold King lode is controlled by structural and lithologic properties of the host rock and by physico-chemical characteristics and changes of the metal-carrying hydrothermal solutions. The nearby Red Mountain porphyry stock served as the heat source for meteoric water-dominated solutions. These solutions probably leached gold from Proterozoic basement rock and carried it as bisulfide complexes. The flow path of hydrothermal solutions was outward from the Red Mountain stock along west-northwest fractures of the Silverton caldera.

At the intersection of these fractures with faults of the Eureka graben fresh meteoric water mixed with these hydrothermal solutions which may also have begun to boil due to upward decrease in confining pressure. This caused oxygenation and the breakdown of soluble gold-bisulfide complexes, re-precipitated gold, and caused argillic alteration followed by acid-sulfate alteration and silicification of the wall rock. Kaolinite and alunite represent the types of argillic and acid-sulfate alteration at Gold King, respectively. The argillic type accompanied the main (third) phase of gold-introducing mineralization. The acid-sulfate type followed this phase and was generated by strongly acidified solutions that resulted from oxygenation and possibly boiling that caused prior gold precipitation. Consequently, the best gold values accompany argillic alteration, whereas veins in rocks with acid-sulfate alteration carry only low gold values. Alteration types are, therefore, useful exploration guides.

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