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The formation of auriferous quartz-sulfide veins in the Pataz region, northern Peru: A synthesis of geological, mineralogical, and geochemical data

D.W. Schreiber [1,2], **G.C. Amstutz** [1] **and L. Fontboté** [1,3]

[1] Mineralogisch-Petrographisches Institut der Universität, Im Neuenheimer Feld 236, W-6900 Heidelberg, FRG
[2] Present address: Institut für gewerbliche Wasserwirtschaft und Luftreinhaltung, Unter Buschweg 160, W-5000 Köln 50, FRG
[3] Present address: Département de Minéralogie, 13, Rue des Maraîchers, CH-1211 Genève 4, Switzerland

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Abstract. The Pataz region in the eastern part of the North Peruvian Department La Libertad hosts a number of important gold mining districts like La Lima, El Tingo, Pataz, Parcoy, and Buldibuyo. Economic gold mineralization occurs in quartz-sulfide veins at the margin of the calc-alkaline Pataz Batholith, that mainly consists of granites, granodiorites, and monzodiorites. The batholith is of Paleozoic age and cuts the Precambrian to Early Paleozoic low-grade metamorphic basement series. Its intrusion was controlled by a NNW-trending fault of regional importance. The gold-bearing veins are characterized by a two-stage sulfide mineralization. Bodies of massive pyrite and some arsenopyrite were formed in stage 1, and after subsequent fracturing they served as sites for deposition of gold, electrum, galena, sphalerite, and chalcopyrite. It is concluded that gold was transported as a $AuCl_2^-$-complex by oxidizing chloride solutions and deposited near older pyrite by micro-scale redox changes and a slight temperature decrease. Mineralogical, textural, geochemical, and microthermometric features are interpreted as a consequence of mineralization at considerable depth produced by a hydrothermal system linked with the emplacement of the Pataz Batholith.

The Pataz region in the Eastern Cordillera of Northern Peru constitutes one of the major gold-producing zones in the country. Among the few existing geological studies, De Lucio (1905), Tarnaviecki (1929), and Wilson and Reyes (1964) refer to the whole region, whereas Samaniego et al. (1977) and Argüelles and Vidal (1982) deal with certain mining districts. Results of detailed geologic and metallogenetic studies are reported by Lochmann (1985) and Schreiber (1988), Schreiber (1989a and b), and Schreiber et al. (1990a and b).

A series of auriferous quartz-sulfide veins hosted by calc-alkaline plutonic rocks account for most of the extracted gold. The scope of this paper is a synthesis of the essential geologic, geometric, paragenetic, and fluid characteristics in order to outline a general physicochemical model of the hydrothermal ore-forming processes.

Regional geology

The stratigraphic column of the Pataz region includes rocks from Precambrian to Cenozoic age. Basement series belonging to the Marañón-Complex (Wilson and Reyes 1964) are widespread and comprise Proterozoic phyllites, metavolcanic rocks, and Early Paleozoic slates (Fig. 1). Non-metamorphic sediments from Upper Paleozoic to Early Tertiary form a thin discordant cover mostly found in complicated graben structures. The zones of the Western Cordillera adjacent to the Marañón Valley, however, consist of thick Mesozoic sediments. East of the river Marañón the Lavasén Volcanics, mainly SiO_2-rich ignimbrites of a Late Tertiary age, build up the highest summits.

The Marañón Valley forms an important morphologic and tectonic lineament, separating the Western Cordillera from the Eastern Cordillera of the Andes. Schreiber (1989b) showed that longitudinal structures trending roughly NNW-SSE, approximately parallel to the actual continental margin, played a key role from the beginning of the Phanerozoic.

The Pataz Batholith, the most important plutonic body and host-rock of the auriferous veins, intruded along such a NNW-SSE-oriented fracture zone into the Proterozoic to Early Paleozoic basement rocks. Dioritic and monzodioritic precursors locally cropping out at the margins of the batholith were followed by increasingly acidic magmatic pulses with the maximum being of granodioritic to monzogranitic composition. According to detailed petrographic and geochemical studies (Schreiber 1989a) the Pataz Batholith is assigned to the I-type (Chappell and White 1974) and magnetite-type (Ishihara 1977). It constitutes a calc-alkaline magma suite with a wide range of SiO_2-contents. Probably it was generated in a post-orogenic tensional and fracture regime, and could be regarded as a "Caledonia I-type"

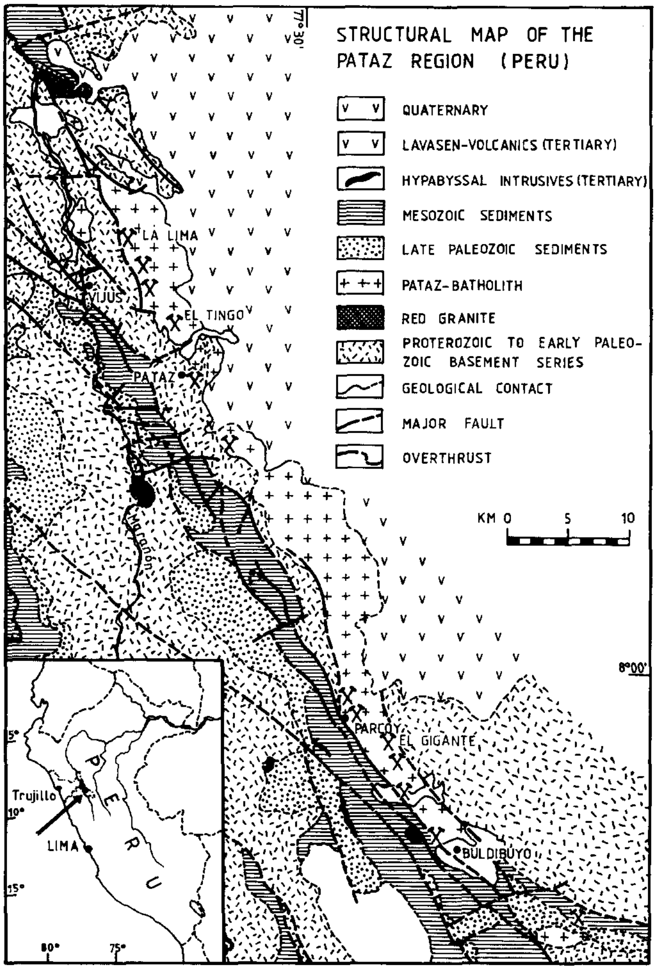

Fig. 1. Geological map of the Pataz Region, Northern Peru (from Schreiber 1989a, including data from Wilson and Reyes 1964; Wilson et al. 1967; Lochmann 1985

(Pitcher 1983) or "post-collision granite" (Pearce et al. 1984). Recently radiometric dating by the ^{40}Ar/^{39}Ar method yielded ages of 321 ± 1 Ma for biotite and 305 ± 8 Ma for hornblende separates (Lochmann et al., in prep.); consequently the emplacement of the Pataz Batholith is assigned to the Middle Carboniferous.

Auriferous quartz-sulfide veins

Auriferous quartz-sulfide veins occur all along the Pataz Batholith, especially in the vicinity of its western contact with basement series. The important mining districts La Lima, El Tingo, Pataz, Parcoy, and Buldibuyo show a NNW-SSE-alignment like most structural features in the region (Fig. 1). The veins are generally hosted by the plutonic rocks and in a few cases continue in the adjacent basement rocks. They are not found, however, beyond the northernmost outcrops of the Pataz Batholith although the fracture zone that controlled the emplacement of the pluton extends some tens of kilometers more to the north. This geometric feature and additional evidence from fluid inclusions support a genetic link of vein formation with post-magmatic hydrothermal processes.

The auriferous quartz veins have a thickness of some decimeters to 1 or 2 meters. Generally they are some hundreds of meters long, in rare cases up to 2 km, and their vertical extension is nearly in the same range. Locally, two or more parallel vein structures are found. The veins mainly strike approximately N-S and dip 40–50° to the east. These directions form a sharp angle with the western contact of the Pataz Batholith and can sometimes be related to a compressional tectonic pattern that led to various reactivations before, during, and after mineralization. Additionally, a vertical uplift component seems to have taken place. The extreme topography of the Pataz region causes vein exposure between 2700 m and 4200 m above sea level in the south, and as low as 1700 m in the north. Gold mineralization is not restricted to a certain level. In individual vein structures, however, it is concentrated in a few economic orebodies with 10 g/t Au and more that are situated within lean or barren zones.

The orebodies are characterized by a rather simple and repeated two-stage paragenesis with quartz and a few common sulfides (Fig. 2 and 3). The cross-cutting relations of the ore minerals show a very uniform paragenetic timing all over the Pataz region, though the amounts and ratios of sulfides as well as alteration minerals differ considerably from vein to vein. The oldest vein mineral is sub- to euhedral, rather coarse-grained quartz; later it was accompanied by pyrite and in many cases arsenopyrite. After this *first stage* the structures were probably sealed for a certain time but subsequently a brecciation (due to tectonic reactivation) created open spaces and allowed the deposition of galena, sphalerite, some chalcopyrite, and gold in the *second stage* (Fig. 2 and 3). Carbonates are absent during stage I and II; locally they are found as small younger fissure fillings. The ore textures are generally irregular: massive quartz and pyrite, banded pyrite and arsenopyrite are common as well as fracturation, fissure filling, small-scale replacement, and pseudobanding by mineral-growth starting on movement planes.

Microscopically the stage II minerals, especially Ag-poor gold and galena, are often found within tiny fissures and cracks cutting the originally coarse-grained, but fractured pyrite (Fig. 2). Often these minerals, especially sphalerite with common inclusions of chalcopyrite, galena, and occasionally electrum, have partly replaced pyrite. Both, fine gold with 4 to 14 wt% Ag and electrum (24 to 40 wt% Ag) occur as infillings of small veinlets with sizes ranging from a few microns to hundreds of microns in the older pyrite, which sometimes shows a certain recrystallization following the Au-precipitation. According to the intergrowth features the marked bimodality of Au/Ag ratios is not due to different deposition times but to locally varying precipitation conditions (Schreiber 1989a). It must be emphasized that the minerals of stage II are always linked with pyrite of stage I. Gold is scarcely present together with quartz and very rarely associated with arsenopyrite. Even when sphalerite or galena form a cement of brecciated quartz crystals, massive pyrite can be found at short distance (within a few decimeters or meters). At a vein scale the same feature is observed: the pyrite-rich bodies control the economic ore zones which were the favourable sites of gold deposition in stage II.

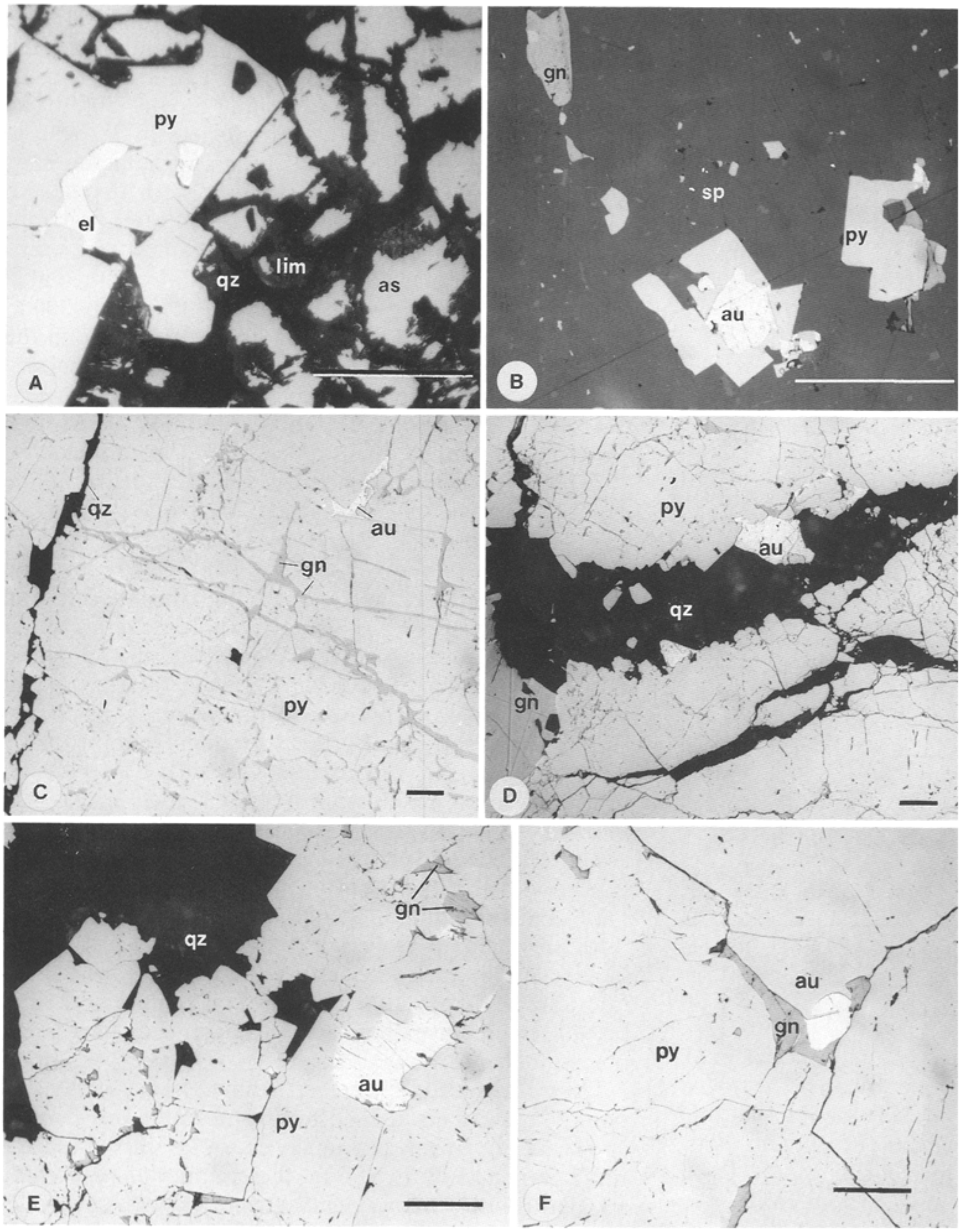

Fig. 2. Microphotographs (*A–F*) of polished sections from ore samples of auriferous quartz-sulfide veins showing the important paragenetic features and cross-cutting relations; the *bar* corresponds to 0.1 mm. *A* – inclusions of electrum in pyrite oblique arsenopyrite with limonitic rims; *B* – gold in or near small relictic pyrite crystals that "survived" replacement by sphalerite; *C* – gold, galena, and quartz in fissures cutting older pyrite; *D* – quartz, galena and gold (stage II) filling a small fracture in pyrite (stage I); *E* – fractured pyrite with different fissure systems filled with quartz or with galena and gold; *F* – galena and gold in fractured pyrite

Hydrothermal alteration, often very intensive, is restricted to a zone within some decimeters (occasionally exceeding 1 or 2 meters) from the walls. The original minerals of the former diorites, granodiorites, and monzogranites are completely decomposed to an association of quartz, sericite, chlorite ± pyrite ± arsenopyrite, epidote, clay minerals, leucoxene, etc. In the northern districts of the Pataz Region sericitic alteration appears to be more common than chloritization, whereas chloritic alteration predominates in the southern districts.

Enrichment by oxidation and formation of quartz-limonite ores with sometimes visible gold can be either a relative one, originated by dissolution of the sulfides, or it may reflect a certain mobility of gold under these conditions.

The average Au/Ag ratio of the Pataz-Au-ores is ≥ 1 but extremely variable. The district of Parcoy is characterized by very fine gold with massive pyrite and a very low content of base-metal sulfides that are present only as scarce microscopic inclusions and infillings of veinlets in pyrite. Electrum is found in those districts that are richer in base-metals (e.g. Buldibuyo, Pataz, and La Lima). It should be pointed out that gold, though contemporaneous with Ag, Cu, Pb, and Zn, does not correlate quantitatively with these metals. The missing correlation can be accounted for either different deposition conditions or, more likely, by some regional compositional differences of the mineralizing solutions during the second stage. On the other hand, the silver-content of gold/electrum as well as that of the whole ore shows a certain correlation with the amount of base-metal sulfides present.

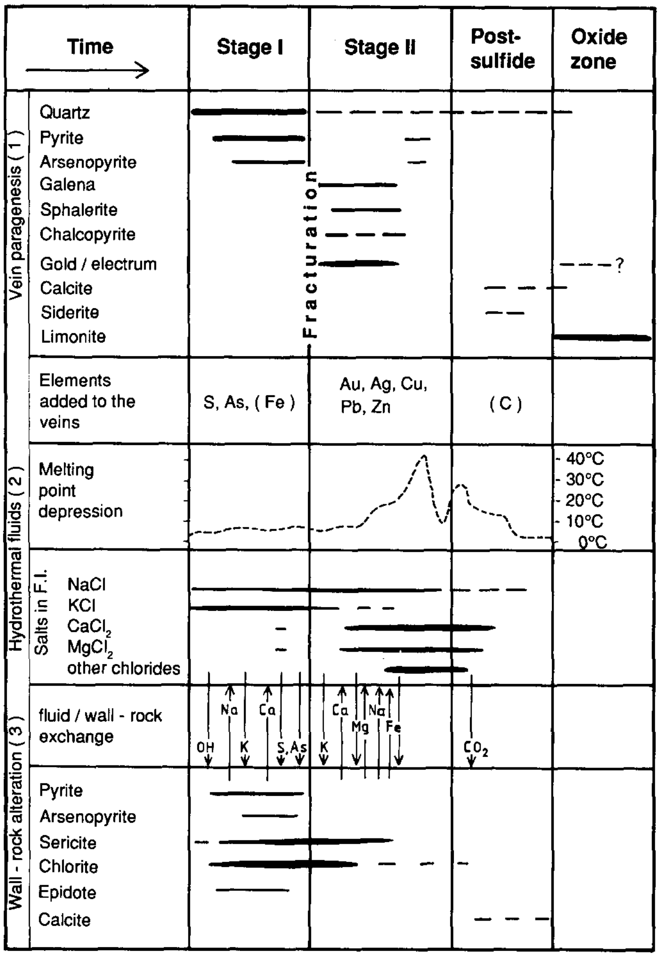

Fig. 3. Synthesis of paragenetic, fluid inclusion, and wall-rock alteration characteristics of the auriferous quartz-sulfide veins hosted by the Pataz Batholith. This representation summarizes in a chronological way observations and conclusions concerning (*1*) the vein minerals, (*2*) respective hydrothermal fluids, and (*3*) hydrothermally altered wall-rocks. Probable interactions between (*1*), (*2*), and (*3*) are indicated. The section "elements added to the veins" shows microscopic and geochemical data of the vein mineralization. Microthermometric measurements of fluid inclusions are reflected schematically by "melting point depression" and "salts in fluid inclusions". The section "fluid/wall-rock exchange" is based on geochemical mass balances between hydrothermally altered and equivalent non-altered rocks supported by microthermometric and petrographic observations. Gold-enrichment in the oxide zone results essentially from dissolution of the surrounding sulfide minerals. Gold-mobility under supergene conditions seems possible, but there is no evidence for this process

Timing of hydrothermal development

On the basis of the above described characteristics, a general model for the hydrothermal evolution of the auriferous veins in the Pataz Region is presented, including the results of microthermometric studies and mass balance data of wall-rock reactions described in more detail by Schreiber (1989a).

A synthesis of macro- and microscopic observations together with fluid inclusion and geochemical data is presented in Fig. 3. Stage I with quartz, pyrite, and arsenopyrite is characterized by aqueous KCl-NaCl-solutions that must have brought sulfur and arsenic and can be explained as residual waters set free by magma consolidation at deeper levels. Stage II is characterized by increasing salinity and significant amounts of $CaCl_2$ and other chlorides, reflecting intensive wall-rock interaction. K is fixed in the walls forming sericite, while Na and Ca move into the solution. The deposition of Au, Ag, Cu, Pb, and Zn is strongly controlled by the presence of fractured pyrite (Fig. 4) which is partly replaced. This feature can be explained by transport in an almost sulfur-free chloridic solution at high oxygen fugacity that, in contact with pyrite, responded by deposition of both gold and sulfides. An adequate complex for this hypothesis constitutes $AuCl_2^-$, known to be of decreasing solubility when the oxygen fugacity diminishes or when the pH increases (Seward 1984; Shenberger and Barnes 1989).

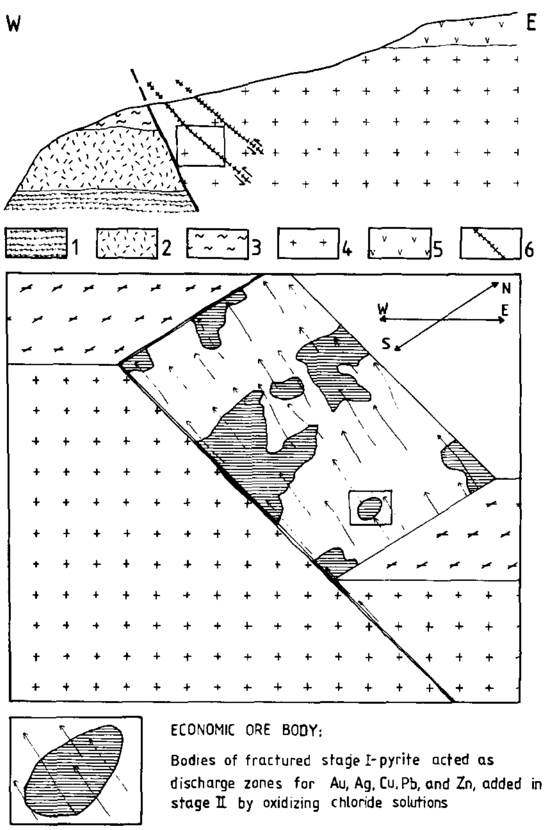

Fig. 4. Illustration of the suggested mineralization processes especially during the "gold-stage", and respective geometric relations. *1* – phyllites; *2* – metavolcanic rocks; *3* – slates (1, 2, and 3 = basement series); *4* – Pataz Batholith; *5* – Lavasén Volcanics; *6* – auriferous veins. The pyritic bodies acted as a chemical barrier for the almost sulfur-free chloride solutions of stage II that carried Au, Ag, Cu, Pb, and Zn. Deposition is thought to be due to the interaction of these fluids with pyrite resulting in a liberation of S and subsequent precipitation of Cu-, Pb-, and Zn-sulfides, and in a drop of oxygen fugacity that would decrease the solubility of the considered $AuCl_2^-$-complex

At the end of the second stage a certain recrystallization of pyrite is observed that sometimes changes the form of secondary fissure fillings with gold, galena, etc. Postsulfidic fluid inclusions have low homogenization temperatures and either high or low salt contents, perhaps partly displaying the beginnings of meteoric influence.

For the main elements and a number of trace elements real gains and losses caused by hydrothermal alteration of the wall-rocks were calculated. Ti, Al, P, Zr, Nb, Y and Th were immobile in most, but not all, cases. The walls are generally enriched in K, Rb, and OH^- and depleted in Na, Ca, Ba, and Sr. Different tendencies are characteristic for Si, Fe, Mg, Mn, Pb, Zn, and Cu reflecting temporal and subordinate spatial variations. Though fluid inclusion studies consistently revealed chloride solutions without significant CO_2, chemical changes with respect to S-, As-, base-metal- and precious metal-contents especially between stage I and stage II must be considered.

The range of homogenization temperatures for stage I and II from 150 to 330 °C is rather wide and may be interpreted to be more likely due to pressure changes than to variations of the formation temperature (Schreiber et al. 1990). Gold deposition must have happened at temperatures above 300 °C according to the highest observed homogenization points, but probably not very much higher. Pressure estimations yield a maximum of 1.7 kb corresponding to approximately 7 km of rock-pile if lithostatic conditions are assumed. A formation depth of various kilometers is consistent with the big vertical extension of the mineralization as well as of the hosting batholith, the upper limit or roof of which is not observable in the whole region.

Conclusions

The auriferous quartz-sulfide veins in the Pataz region formed under conditions of medium to great depth. Typical features include: a variable Au-Ag-ratio with averages ≥ 1, bimodal fineness, repeated tectonic movements resulting in pressure changes, and a narrow but intensive wall-rock alteration. The veins are geometrically linked with the Pataz Batholith and must be related with postmagmatic hydrothermal processes. The originally KCl-NaCl-rich fluids are interpreted as magmatogenic. The absence of carbonates and CO_2 during the sulfide stages reflects significant differences as compared to gold deposits formed under metamorphic conditions (Kerrich and Fyfe 1981; Roedder 1984) and to the otherwise similar group of "medium depth deposits" reported to be of great importance in the USSR (Borodaevskaya and Rozhkov 1974). The generation of hydrothermal fluids and the mineralization of the veins appear to be much more closely related to the hosting Pataz Batholith than in many other vein gold deposits in or around intrusive bodies. Nevertheless gold must not necessarily be of magmatic origin: it could have also been leached out of country rocks as discussed previously (Schreiber 1989 a + b).

Gold was introduced to the veins with stage II solutions accompanied by varying amounts of Ag, Cu, Pb, and Zn. The control exercised by fractured pyrite on the deposition of these metals is thought to be linked with the following process. Transport of gold, silver, and basemetals in chloride solutions under oxidizing conditions and deposition in contact with pyrite that provided sulfur. In this concept gold-precipitation is due to a drop in the oxygen fugacity and, in addition, to temperature decrease. Galena, sphalerite, and chalcopyrite were formed contemporaneously consuming the sulfur of the destabilized pyrite. The proposed mineralization mechanism is illustrated in Fig. 4. The pyritic bodies that had formed at structurally favourable sites in stage I acted as a physicochemical barrier for the later gold-bearing fluids.

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