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Vein Density, Orientation, Paragenesis and Wall Rock Alteration of the Ferrobamba Cu-Mo Porphyry Deposit, Apurimac Region, Peru

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1. Introduction

This study summarizes information on vein density, orientation, and paragenesis collected during detailed pre-mining outcrop mapping across the Ferrobamba porphyry Cu-Mo deposit located in the Apurimac Region of central Peru. Geology is described by Guillen et al. (2010). Vein-focused outcrop mapping was conducted at a scale of 1:5, with 123 stations mapped on a consistent 50cm by 50cm aluminum field grid at various orientations. Outcrops and veins were mapped using the Anaconda method. Information on vein mineralogy, alteration selvage, vein orientation and host-rock alteration was collected for 1290 individual observations. Gridded vein density shows discreet zones of high vein density (n > 0.7) within a broader north north-west corridor of moderate vein density (n = 0.5-0.6) spatially associated with the Jahuapaylla stock, previously believed to be unrelated to Cu-Mo mineralization. A significant change in dominant vein orientation occurs with the emplacement of the Jahuapaylla stock, and late monzodiorite dikes. Vein cross-cutting relationships indicate 15 vein types based on mineralogy. Vein paragenesis progresses from sugary quartz, quartz-albite, early biotite, sodic-calcic, calc-potassic, quartz-Kfeldspar, quartz-bearing biotite and open space veins without alteration halos, to late carbonate. Alteration of mafic and feldspar phenocrysts in the host rocks shows a broad zonation outward from the Jahuapaylla stock, from proximal potassic to argillic, sodic, and eventually distal propylitic. Outcropping alteration patterns suggests a deep level of exposure within the porphyry system.

2. Methods

Vein mapping was conducted at 123 stations across the Ferrobamba deposit. Planned mapping stations were not all accessible due to development activities. Each station was mapped on of a 50cm by 50cm grid at a scale of 1:5, as described by Haynes and Titley (1980). Locations were recorded with a Trimble R8 RTK DGPS. The mapping grid was consistently oriented north-south; however, the mapping plane was varied to capture all vein orientations and eliminate bias from 2D mapping. Outcrops were mapped using the Anaconda method (Einaudi, 1997; Brimhall et al. 2006), which involves recording vein mineralogy, vein selvage mineralogy, vein orientation, and host rock alteration of feldspar, mafic and groundmass sites graphically using various color codes. This information was recorded for 1290 individual observations from the mapping stations. Field maps were digitized using MapInfo Professional 12 and an area percent vein density and total vein length were calculated for each station (Figure 1). The cumulative length of all veins within the map grid were divided by the total sample area to yield total vein densities (n/cm; after Haynes and Titley, 1980). Data were imported into ArcGIS 10 for gridding using spline with lithological and alteration barriers. Alteration patterns were interpreted from observations collected during vein mapping and constrained to lithological boundaries. Vein paragenetic relationships were documented during re-logging of 4860m of historic drill core using methods described by Seedorf and Einaudi (2004).

3. Results

3.1. Vein Density

Vein density (n/cm) varies systematically with host rock and alteration intensity across the Ferrobamba deposit. The spatial distribution of vein types is complicated by multiple overprinting intrusive events. High vein densities (n > 0.6 cm-1) occur in discreet zones within a broader north north-west corridor of moderate vein densities generally limited to the spatial extent of the Jahuapaylla stock and associated dikes. Little to no veining can be traced into the limestones of the Ferrobamba Formation. Considerable quartz veining occurs within endoskarn and skarn zones within and around the Ccomerccacca and Jahuapaylla stocks. Zones of highest vein density (n >0.7 cm-1) occur in close proximity to the Jahuapaylla stock and monzodiorite dikes. A zone of intense stockwork veining with vein densities >0.8 cm-1 occur within the central portion of the Jahuapaylla stock.

3.2. Vein Orientations

Multiple overprinting vein assemblages occur within each intrusive unit. The dominant strike of veins are 140°-320° and 175°-355° related to the Ccomerccacca and Jahuapaylla stocks respectively. The oldest intrusive rock in the Ferrobamba complex, the Pioneros stock is cut by distinct sets of veins likely related to the nearby Ccomerccacca, Jahuapaylla and Taquiruta stocks. The Taquiruta stocks contain veins with orientations similar to veins of the Ccomerccacca stock, which cut both the Pioneros and Taquiruta stocks. Veins within both skarn and endoskarn closely resemble the dominant orientations of veins from both the Ccomerccacca and Jahuapaylla stocks as well as the late monzodiorite dikes. A significant change in dominant vein orientation occurs with the emplacement of the Jahuapaylla stock, with veining changing from 140°-320° to 175°-355°. A second change in dominant vein orientation occurs with the emplacement of the late monzodiorite dikes with veining parallel to the dominant strike of the dikes.

3.3. Vein Paragensis

Vein paragenesis is outlined in table 1. Early veins show a progression from sugary quartz, to inter-grown quartz-albite veinlets (similar to 'A' type veins of Gustafson and Hunt, 1975) within the Pioneros and Taquiruta stocks. All early A-type veins cut the Pioneros-Taquiruta intrusive contact, indicating the veins formed after the emplacement of the Taquiruta stock. The Pioneros stock is not related to mineralization as previously reported (MZB of Guillen et al. 2010). Dark micaceous veinlets, wispy biotite and sulfide veinlets, and sodic-calcic actinolite - Na-feldspar veinlets are observed within the Ccomerccacca stock, and are also observed cutting and offsetting A-type veinlets within the Pioneros and Taquiruta stocks. Calc-potassic veins of quartz-k-feldspar-actinolite-apatite cut and offset sodic-calcic veins within the Ccomerccacca stock and are also observed within the Jahuapaylla stock. Calc-potassic veins are often overprinted by garnet and clinopyroxene skarn assemblages within the Ccomerccacca stock. Vein dikes of the Jahuapaylla stock cut and offset fresh and skarn altered calc-potassic veins within the Ccomerccacca stock. Transitional quartz-kfeldspar and quartz-bearing biotite veins cut and offset calc-potassic veins, extend into skarn zones, and are associated with strong bornite-chalcopyrite-molybdenite mineralisation at the margins of the Jahuapaylla stock, which was previously documented as unrelated to mineralization (MZH of Guillen et al. 2010). The quartz-bearing biotite veins show strong lateral variability in mineralogy dependent on host rock and precursor alteration. Open space crystalline and grey-banded veins lacking wall rock alteration (typical 'B' veins of Gustafson and Hunt, 1975) cut and offset quartz-bearing biotite veins and are associated with both the Jahuapaylla stock and the late monzodiorite dikes. Weak skarn alteration is associated with high density B vein zones.

3.4. Hydrothermal Alteration

Hydrothermal alteration of varying intensity occurs within all outcropping intrusive units. Distal alteration 2 kilometers from the central Jahuapaylla stock is manifest as weak chloritization of biotite within the Pioneros stock. Distal chloritization passes to a zone of weak propylitic alteration within 1.2km of the Jahuapaylla stock that includes epidotization of plagioclase. Within 800 meters of the Jahuapaylla stock, the propylitic assemblage includes weak sericitization and epidotization of feldspars and with weak chloritization of hornblende and biotite. A zone of sodic-calcic alteration flanks the southern margin of the Ferrobamba deposit. This sodic-calcic assemblage includes actinolite - chlorite - magnetite alteration of mafic phenocrysts and epidote-sericite/clay alteration of feldspars.

Secondary magnetite forms on the western and eastern margins of the strong sodic alteration zone. A zone of visually distinct argillic alteration, manifest as green clay alteration of feldspar phenocrysts, increases in intensity towards the margins of the Jahuapaylla stock. This zone overprints strong sodic-calcic alteration. No evidence of phyllic alteration was observed from surface mapping. Strong potassic alteration with k-feldspar replacement of plagioclase and secondary biotite replacement of hornblende occurs within the Jahuapaylla stock. The intensity of potassic alteration increases outwards from a strong quartz stockwork zone in the center of the stock, to a zone of strong potassic alteration around the margins of the stock where it overlaps with well-developed quartz-bearing biotite veins. A narrow zone of k-feldspar replacement of plagioclase occurs within a broader zone of secondary biotite alteration of the Ccomerccacca stock where it is in contact with the Jahuapaylla stock.

4. Discussion and Conclusions

Vein density within the Ferrobamba deposit is strongly controlled by proximity to the Jahuapaylla stock. Alteration zonation is clearly centered around the Jahuapaylla stock, grading outward from a central potassic zone dominated by the alteration assemblage of secondary biotite and lesser K-feldpsar, and strongly mineralized quartz-bearing biotite veins with lesser magnetite. The abundance of sodic alteration exposed at surface suggests a deep level of exposure for Ferrobamba. Vein paragenesis supports the observed alteration patterns and reltionships to causative intrusions. Cross-cutting vein relationships indicate the Pioneros Stock is not related to mineralisation, with the bulk of the skarn-forming alteration and mineralizing veins temporally and spatially related to the Jahuapaylla Stock. Unique calc-potassic vein assembages herald the onset of skarn formation, with a transition to dominantly potassic quartz-bearing biotite veins marking the introduction of high-grade chalcopyrite and bornite mineralization. Anaconda style mapping, and systematically developing vein paragenetic relationships, has lead to a new understanding of the Ferrobamba deposit with the methods directly applicable to both the Exploration and production environments.

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Figure 1. Example of field map, mapping grid and digitized veins from within the Ferrobamba deposit

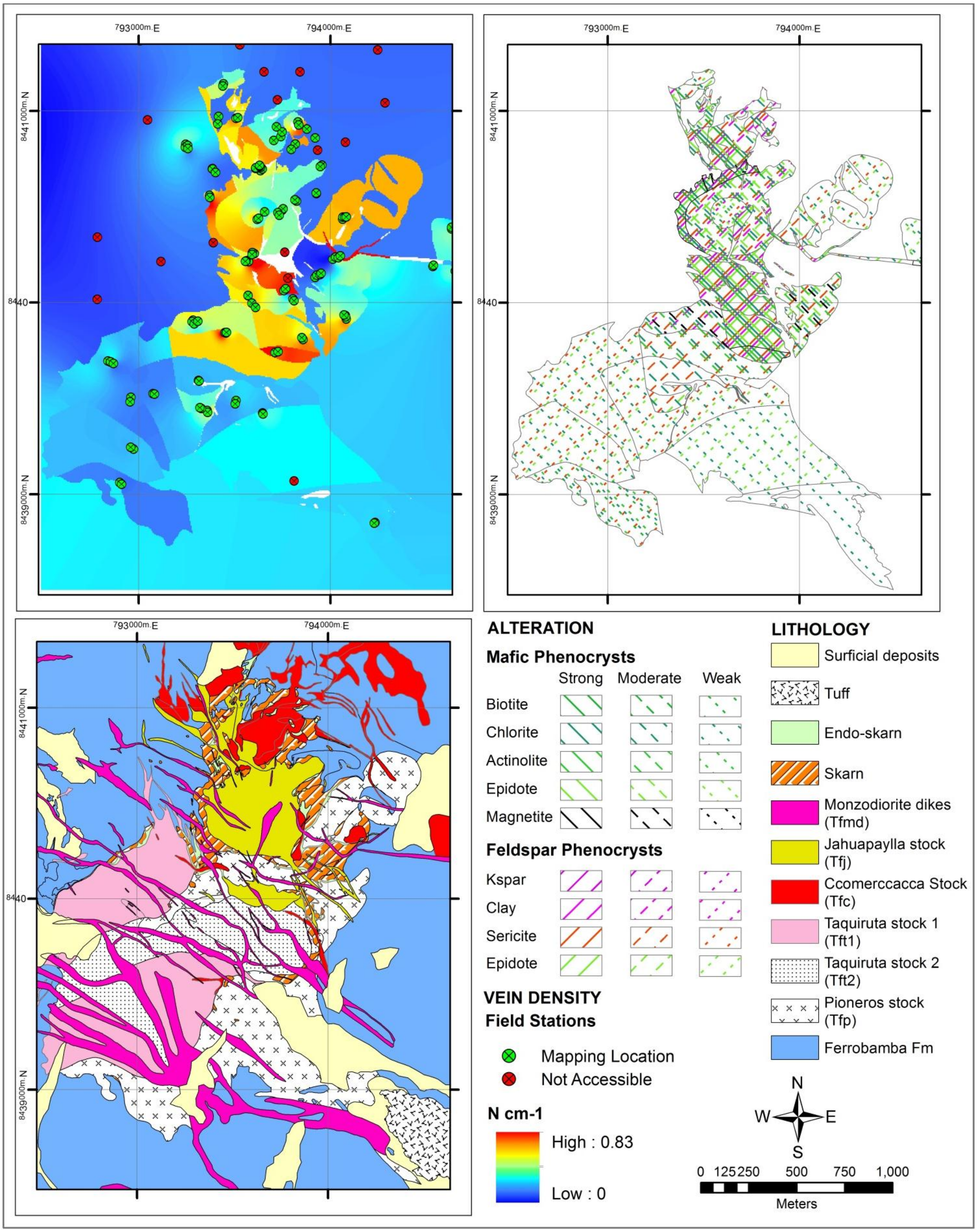

Figure 2. Vein density (cm-1), station locations, alteration and geology of the Ferrobamba deposit. Veining shows discreet zones of high vein density (n > 0.7) within a broader corridor of moderate vein density (n = 0.5-0.6) associated with the Jahuapaylla stock. Alteration mapped according to the Anaconda method shows a broad zonation from distal propylitic, to sodic, to argillic, to potassic centered on the Ccomerccacca and Jahuapaylla stocks. Lithology shows the Cretaceous Ferrobamba limestone wall-rock intruded by the Eocene Ferrobamba complex listed from oldest (Pioneros Stock) to youngest (Monzodiorite dikes)

Paragenesis	Vein Morphology			Vein Fill				Vein Halo		
	Vein Type	Structure	Crystal habbit	Width	Gangue	Sulfides	Sulfide Intensity	Width	Gangue	Sulfides
1	A1 sugary qtz veins	Irregular walls	Saccaroidal	0.5-3cm	Qtz	none		none	none	none
2	A2 Qtz-Albite intergrown	Irregular walls, discontinuous qtz center	Crystalline - euhedral	0.2-2cm	Qtz-Albite +/- Epidote	Cpy	Weak	0.1-0.2cm	+/- Albite	none
3	A3 Qtz-Albite halo	Irregular walls, discontinuous qtz center	Crystalline - euhedral	0.1-0.5cm	Qtz +/- Biotite-Chlorite > Albite	Cpy	Weak	0.2-0.8cm	Albite	none
4	EDM	Irregular, diffuse	fine euhedral	0.5-1cm	Biotite-chlorite-Kspar	Cpy	Moderate	0.2-0.5cm	Kspar	Cpy
5	Biotite-sulfide veinlets	wispy seams	fine massive	0.1-0.2cm	Biotite-chlorite +/- sericite	Cpy>Mo	Strong	none	none	Cpy
6	Sodic-calcic 1	Irregular walls, discontinuous	Fibrous-radiating	0.1-0.3cm	Actinolite +/- chlorite	Py>>Cpy	Weak	0.5-1cm	Chlorite-Sericite	Py
7	Sodic-calcic 2	Irregular walls, discontinuous	Fibrous-radiating	0.1-1cm	Actinolite +/- Qtz-Albite-chlorite-epidote	Cpy	Weak	0.2-0.8cm	Albite +/- Magnetite	none
8	Calcic-Potassic 1	Irregular walls, Discontinuous	fine saccaroidal	0.1-1.0cm	Qtz-Kspar-Actinolite-Biotite	Cpy-Bn>Mo	Moderate	0.2-2.0cm	Kspar	Cpy-Bn>Mo
9	Calcic-Potassic 2	Irregular diffuse	euhedral	0.2-2.0cm	Kspar-Actinolite-Apatite +/- Qtz	Cpy-Bn>Mo	Moderate	0.2-2.0cm	Kspar-Actinolite-Apatite +/- Qtz	Cpy-Bn>Mo
10	Qtz-Kspar	Irregular walled often with centerline	Sugary saccaroidal	0.2-2.0cm	Qtz-Kspar +/- Magnetite-Biotite	Cpy-Bn	Trace	0.1-0.2cm	Kspar	none
11	Qtz-bearing veins with Biotite	Irregular to straight walls. Veins & Fine hairline stockwork	fine saccaroidal to crystalline	0.1-2.0cm	Qtz-Biotite-Green Sericite +/- Kspar-calcite-magnetite-Actinolite	Cpy-Bn>Mo	Intense	0.2-2cm	Kspar-green sericite +/- qtz-biotite-magnetite-actinolite	Cpy-Bn>Mo
12	B	Irregular walls	Crystalline and vuggy to massive milky	0.2-4cm	Qtz +/- Kspar	Cpy-Mo-Bn	Strong-Intense	none	none	none
13	Grey-banded	Straight-walled, banded	fine saccaroidal to milky massive	0.5-1cm	Qtz	Mo>Cpy-Bn	Weak-moderate	none	none	none
14	Banded Ca-Se-Qtz	Irregular walled, banded, rare centerline	crystalline euhedral	0.5-3cm	Banded green sericite-euhedral comb qtz-pink/white calcite	Cpy-Pb-Zn-Ag	Weak-moderate	0.1-1.0cm	Green sericite	Py
15	Carbonate	Straight-walled	Fine crystalline	0.2-3cm	Calcite-Siderite +/- chlorite	none		none	none	none

Table 1. Vein paragenesis of the Ferrobamba deposit outlining morphology, vein fill and halo mineralogy. Porphyry vein nomenclature based on Gustafson and Hunt (1975).