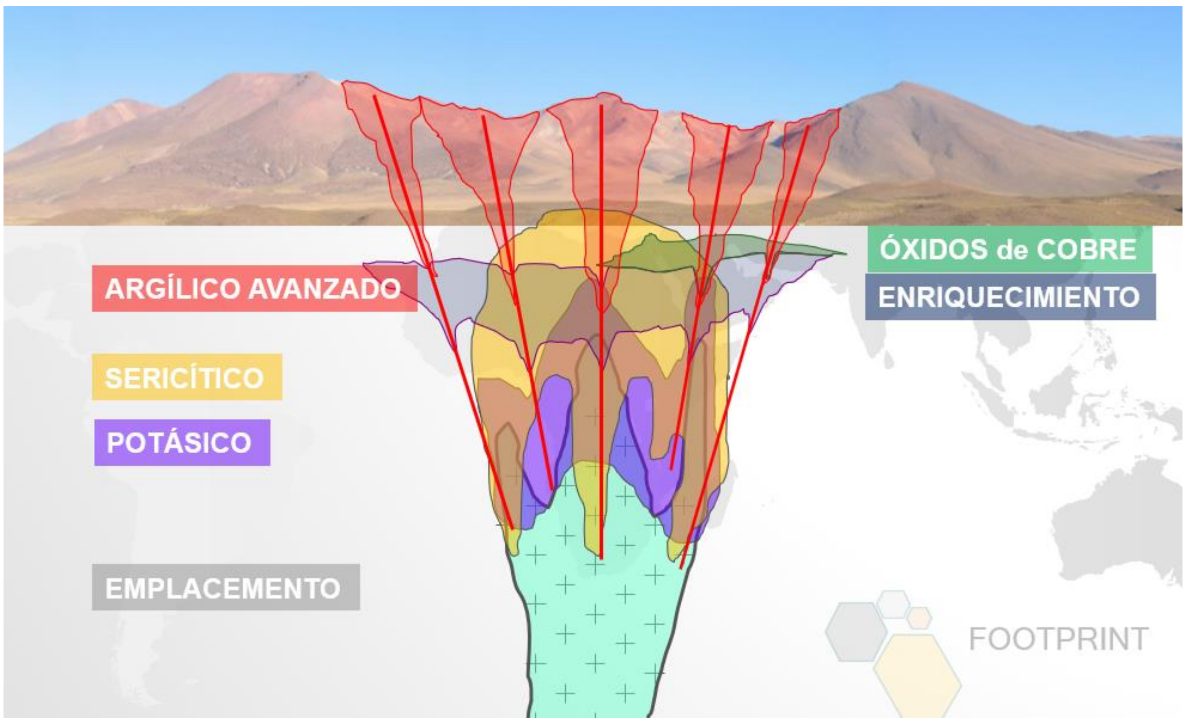
FOOTPRINT SPA

PORPHYRY Cu HYDROTHERMAL SYSTEMS -CHAPTER 1



JORGE ZAMORANO
FOOTPRINT SpA
www.footprintspa.cl

INTRODUCTION

Considering the previous post related to the introduction to the porphyry copper systems this publication corresponds to the first of three chapters focused on the study of these hydrothermal systems. The current chapter is centered on the pro-grade early evolution known by the name of potassic alteration or k-silicate alteration.

Prior to initiate this episode is necessary to be taken in account that some hydrothermal systems-related conceptual ideas widely known worldwide have been complemented by the author based on abundant observations collected from the fieldwork.

This publication just pretends to be a practice guide to the geologist-enthusiasts at porphyry-type systems. Thence, most mineral associations mentioned here correspond at main mineral paragenesis observed by the hand-lens and in some cases supported by thin section and Terraspec (ASD) studies.

CONCEPTUAL IDEAS

Generally a porphyry system corresponds a multi-pulse hydrothermal centre where coexist pulses related to potassic imprint (main intermineral-), another ones linked to the principal hydrolisis stage (late intermineral-), others were emplaced when the system it was shutting down (very late intermineral-) or openly them entered after the decease of the system (post mineral-). Notwithstanding, there are less complex multi-pulse systems where exist just one pulse by stage (main-, late-, very late- and post-porphyry), or simply either of them are absents.

The current chapter and the two upcoming publications will take in account a multi-pulse hydrothermal system.

POTASSIC FOOTPRINT

The potassic alteration begins developing since emplacement of the first pulse released from underlying magma chamber -6 to 10 km at depth (Sillitoe, 2010)-, and is accompanied by a portion of the hypercritical fluid. During rise this liquid-gas mix reaches its thermodynamic solvus and separates into a gas phase and a hypersaline liquid phase.

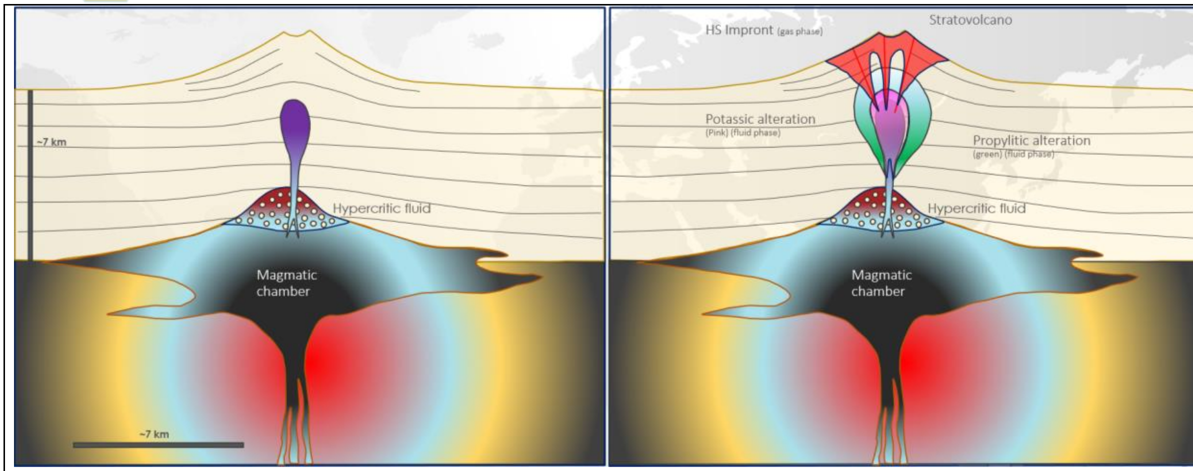


Figure 01. (Left) Emplacement of first pulse from the magmatic chamber. (Right) Space-relationship between potassic and propylitic alterations and high sulfidation imprint.

The hypersaline liquid phase interacts in the porphyry/wall-rock vicinity developing the potassic alteration and propylitic imprint outward (figure 1). While the gas phase, due to its composition, reaches shallower levels shaping the advanced argillic footprint (HSS).

The dominant physicochemical conditions at porphyry/wall-rock environment exhibit temperatures between 800°C - 400°C (Roedder, 1984), with 40-60 wt percent of NaCl equivalent range (Hedenquist and Lowernstein, 1994), neutral pH or slightly alkaline and low-medium sulphur fugacity (fS_2) and moderate oxygen fugacity (fO_2).

ALTERATION-MINERALIZATION FEATURES

The emplacement of the pulse generates an "action zone" characterized by a ductile volume centered in the porphyry body and immediate wall-rock, caused mainly by the heat provided by the intrusion. The dimensions of this zone depend on, form of the host porphyry or dike complex, composition and volume of the porphyry, depth of the emplacement, wall-rock-type, etc.

According early alteration assemblages which are possible observe with hand-lens exist at least four remarkable sub-events whose "chronology" -from oldest and youngest- is as follow:

- Biotite-magnetite ± Cu-sulfides ± Au (pervasive, replacement, veinlets)
- Very fine- to fine-grained intergrowths of quartz and k-feldspar ± albite/Cu-sulfides ±Au (through channelways)
- K-feldspar and Irregular and discontinuous to regular A-quartz type veinlets/Cu-sulfides ±Au (stockwork, sheated and individual veins)
- Planar and continuous B-Quartz veining with irregular concentration of Moly.

BIOTITE-MAGNETITE ASSOCIATIONS

The temporality relationships set this kind of assemblages as first to be formed. Notwithstanding, is necessary to be account that there are at least three biotite-magnetite associations and possibly respond to different sources.

PERVASIVE BIOTITE-MAGNETITE

The association is characterized by fine-grained secondary biotite-magnetite ± silica generally formed in the andesitic wall-rock or its equivalent in sedimentary units. The intensity varies from moderate to highly penetrative and the rock result partly or totally obliterated. Generally the alteration displays blacky brown, brown to reddish brown colour depending of the K^{+}, Mg^{+} and Fe^{3+} cation concentrations (figure 02). The responsible of this alteration could be:

- Contact metamorphism related to precursor plutons previously emplaced and possibly are spatially, temporally and genetically related to the hydrothermal system.
- Recrystallization (Hornfels) produced by the emplacement of the porphyry itself.
- K-metasomatism related to porphyry pulse itself.
- Combination of two or three points outlined above.

Copper mineralization seems to be present just in the third case (k-metasomatism). Nevertheless, commonly this type imprint is poorly mineralized. The dimensions exhibited for this penetrative association are widely variable spanning from some tens of meters to several hundred of meters.

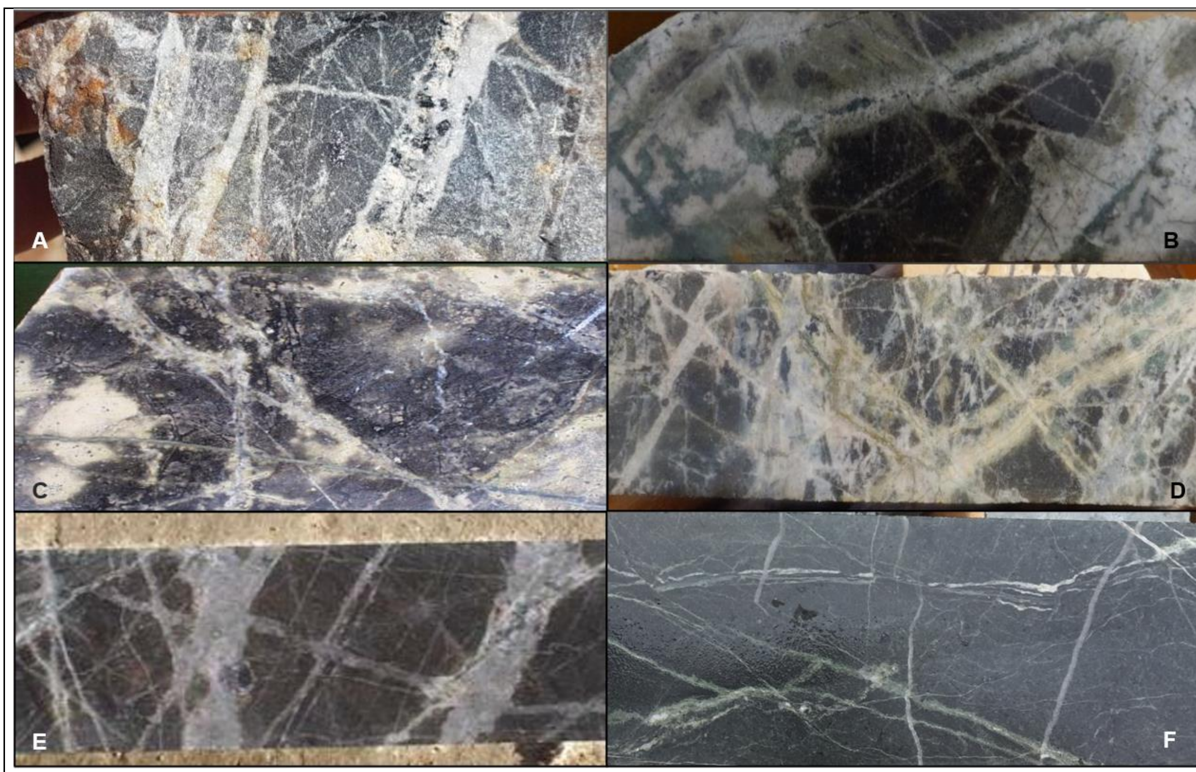


Figure 02. Very fine-grained secondary biotite-magnetite assemblages in wall-rock.

REPLACEMENT BIOTITE-MAGNETITE

This imprint corresponds to replacement that affects mostly to the ferromagnesian minerals (amphibole and/or biotite and/or pyroxene). These primary minerals are partially or totally destroyed and converted to a mosaic of small-grained biotite micas (figure 03). Sometimes the hypersaline fluid brings all the elements building its own secondary biotite, in this case not necessarily potassic metasomatism is needed.

The forming of this secondary biotite is directly related at emplacement of the porphyry and the development of its potassic alteration. Copper mineralization is spatially and genetically associated to this sub-event and copper sulfides content generally appear intergrowth between the small crystals of secondary biotite

From the copper content standpoint is hardly determinable due to this paragenesis appears overprinted by other early sub-events and the copper contribution seeing partly altered.

$$\underset{\text{(biotite)}}{KFe_3AlSi_3O_{10}(OH)_2} = \underset{\text{(secondary biotite)}}{0.6KFe_3AlSi_3O_{10}(OH)_2} + 2Fe^{2+} + 0.4H_2O + 0.6O_2 + \underset{\text{(orthoclase)}}{KAlSi_3O_8}$$

$$\underset{\text{(hornblende)}}{CaFe_5Al_2Si_7O_{22}(OH)_2} + 2K^+ + Fe^{2+} + 2H_2O = \underset{\text{(secondary biotite)}}{Fe_3AlSi_3O_{10}(OH)_2} + SiO_2 + 2Ca^{2+} + 2H^+$$

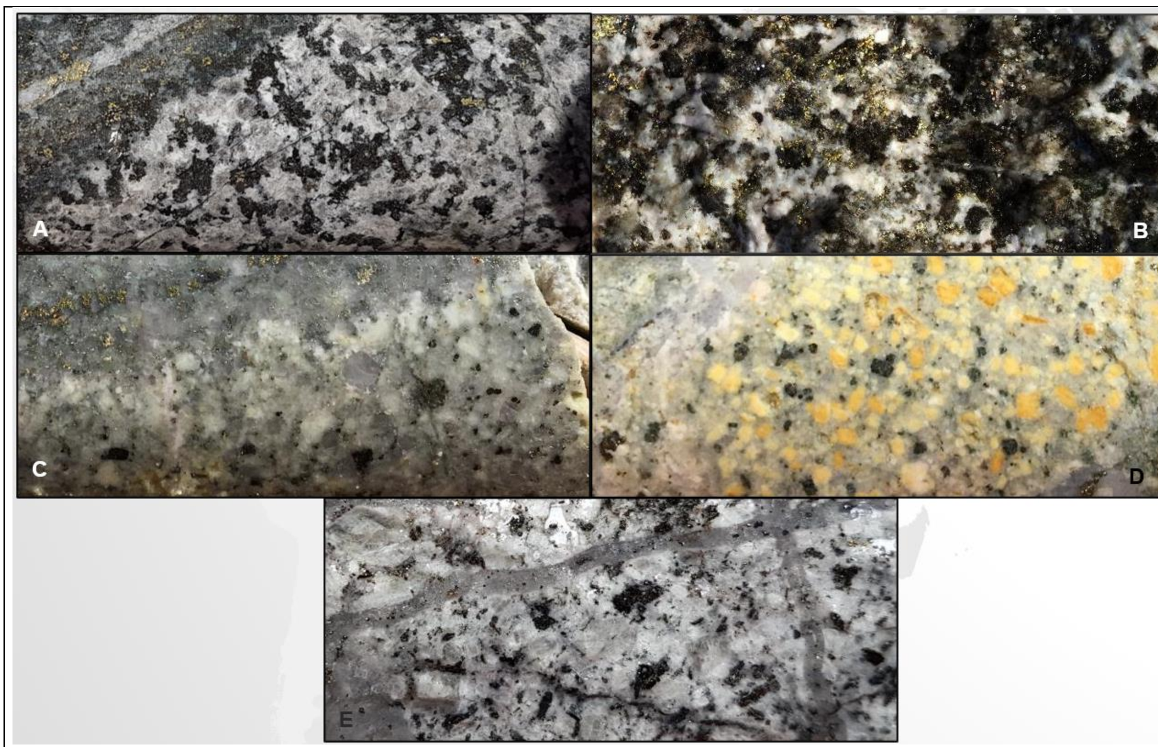


Figure 03. Fine-grained secondary biotite mosaics recrystalized over ferromagnesian phenocrystals.

EARLY BIOTITE VEINING

This kind of veining is developed during the potassic metasomatism, rather ferric, ferrous and potassic metasomatism, which finally leads to the formation of secondary biotite-magnetite assemblage in veining-type array (figure 04). These veins are formed in environment ductile restricted mainly to the porphyry and immediate wall-rock. Copper mineralization (Bornite and/or Chalcopyrite) is commonly disseminated in the halo and minor stringers. However, the stockwork-type arrays are scarcely developed avoiding a significant copper contribution to the system.

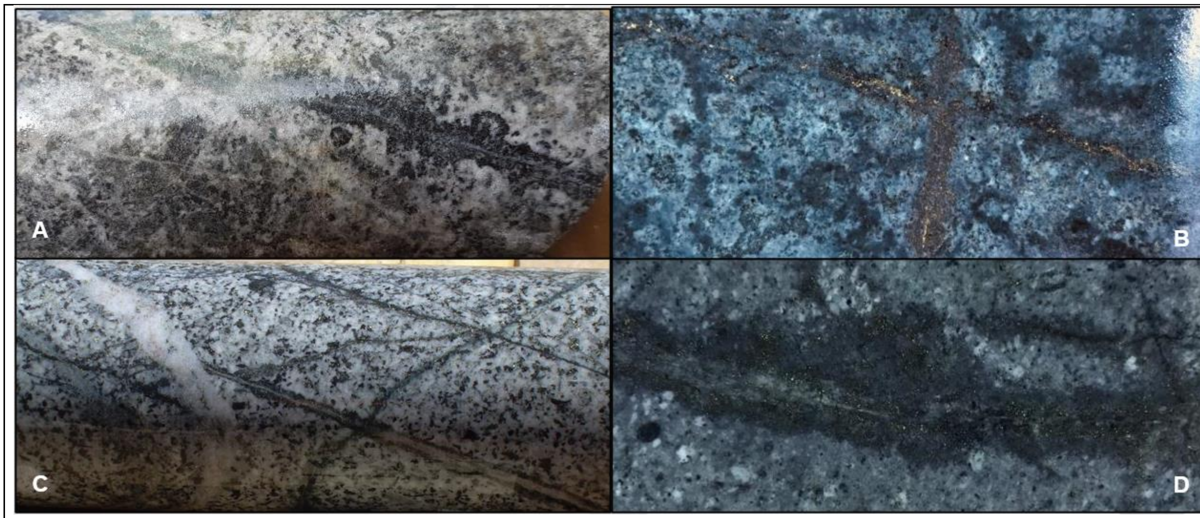


Figure 04. EB veining host irregular disseminated chalcopyrite concentrations.

QUARTZ-K-FELDSPAR INTERGROWTH

This subevent of potassic imprint mainly comprises a pinkish white to pink microcrystalline- to fine-quartz-k-feldspar intergrowth and minor concentrations of albite whose formation is driven and developed through channelways. The dimensions of these channelways varies from millimeters up to several hundreds of meters of this microcrystalline mass. Mostly the original constituents are partly or completely transformed to quartz-feldspar displaying in some cases a fine-graphic texture between quartz and k-feldspar. In thin sections the intergrowths look like micro-veins, micro-breccias or graphic intergrowths.

This assemblage is possible to observe it accompanying to any early porphyry pulses (with potassic imprint), in the figure 05 (F and G) porphyry fragments with A-quartz veining and borders partially assimilated seem float in a fine-grained quartz-k-feldspar matrix, even them exhibit flow banding textures.

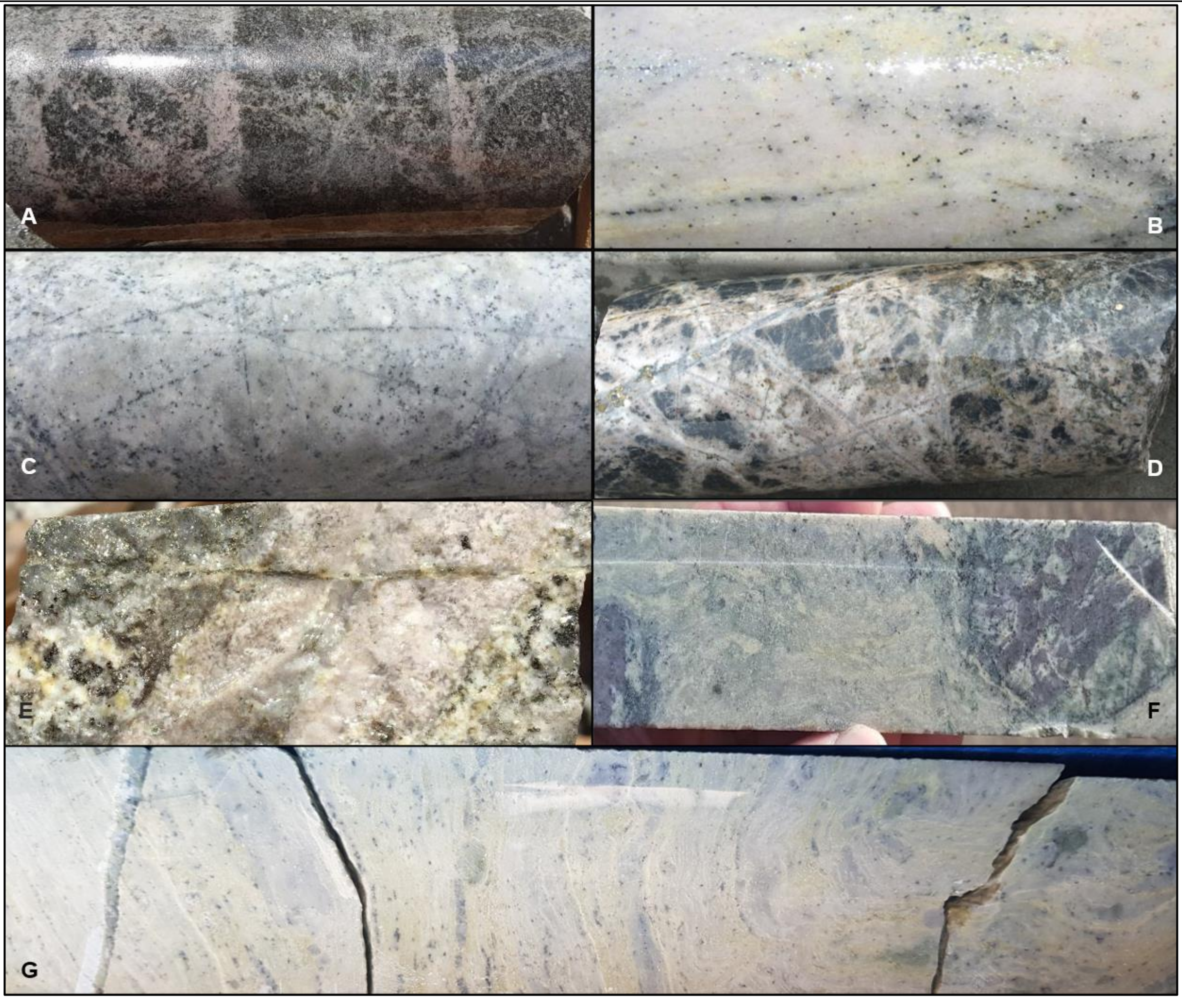


Figure 05. A) Very fine-grained quartz-k-feldspar cutting strong secondary biotite in andesite; B) intense potassic-quartz alteration obliterates completely original texture of porphyry; C) very strong silica-k-feldspar assemblage over dacite volcanic rock; D) Andesite unit affected by three early sub-events: 1) relict of pervasive magnetite-secondary biotite (dark colour); 2) fine-grained k-feldspar-quartz intergrowth introduced via channelways within a essentially ductile environment (white and pink colours); 3) All subevent outlined above are superimposed by A-type veinlets array; E) Fine-grained Intergrowth of quartz-k-feldspar in channelway through main intermineral diorite porphyry; E) Fragments of diorite porphyry with A-quartz veining floating in silica-k-feldspar dense mass over printed by strong sericite alteration. Note flow banding in the mass endorsing highly dense fluid; F) Remarkable flow banding texture in quartz-k-feldspar microcrystalline aggregate overprinted by sericite-illite assemblage.

Usually abundant disseminated copper mineralization accompanies these intergrowths with concentrations of bornite and chalcopyrite and lesser extent covellite and chalcocite. In the mines of Chuquicamata (Siña et al., 2006) and Rosario-Collahuasi (Zamorano, 2003) and the advanced projects of Los Sulfatos (Zamorano, 2011), West Wall (Zamorano, 2008) and El Encierro (Zamorano, 2016) significance volumes with high grade of copper have been reported.

In general quartz-k-feldspar imprint cut biotite-magnetite associations and commonly is developed within the vicinity of early porphyry pulses and immediate wall-rock. Notwithstanding, quartz-k-feldspar paragenesis have been observed beyond the limits of the ductile and ductile-fragile zones although in minor concentrations.

K-FELDSPAR and A-QUARTZ VEINING

This sub event is characterized by the formation of microcrystalline K feldspar, as a consequence of an intense potassic metasomatism. Since this process occurs mostly under ductile deformation conditions, it is therefore grown and distributed through a network of channelways. The result can then be interpreted as a "stockwork" formed by channels in a multidirectional array (figure 06, F).

K feldspar formation can be described by the following reactions:

$$NaAlSi_3O_8 + K^+ = KAlSi_3O_8 + Na^+ \quad \text{(albite- K-feldspar)}$$

$$CaAlSi_3O_8 + K^+ = KAlSi_3O_8 + Ca^+ \quad \text{(anortite – K-feldspar)}$$

While the K-feldspar formation is still ongoing, small crystals of translucent gray quartz, can also begin to grow through the channelways forming veins. These veins are characterized by quartz-crystal mosaic, polygonal base, irregular borders, without central suture. Due to formation periods of the quartz-veinlet and k-feldspar-channelways are not exactly simultaneous is common observing quartz veins in absent of k-feldspar

Quartz veins occur as stockwork-, sheeted veins-type arrays, or simply isolated veins. Regarding the copper contribution, this event is generally is associated to significant copper sulfide contents, characterized by bornite and chalcopyrite occurring mostly as dissemination in both quartz veinlets and K-feldspar channelways.

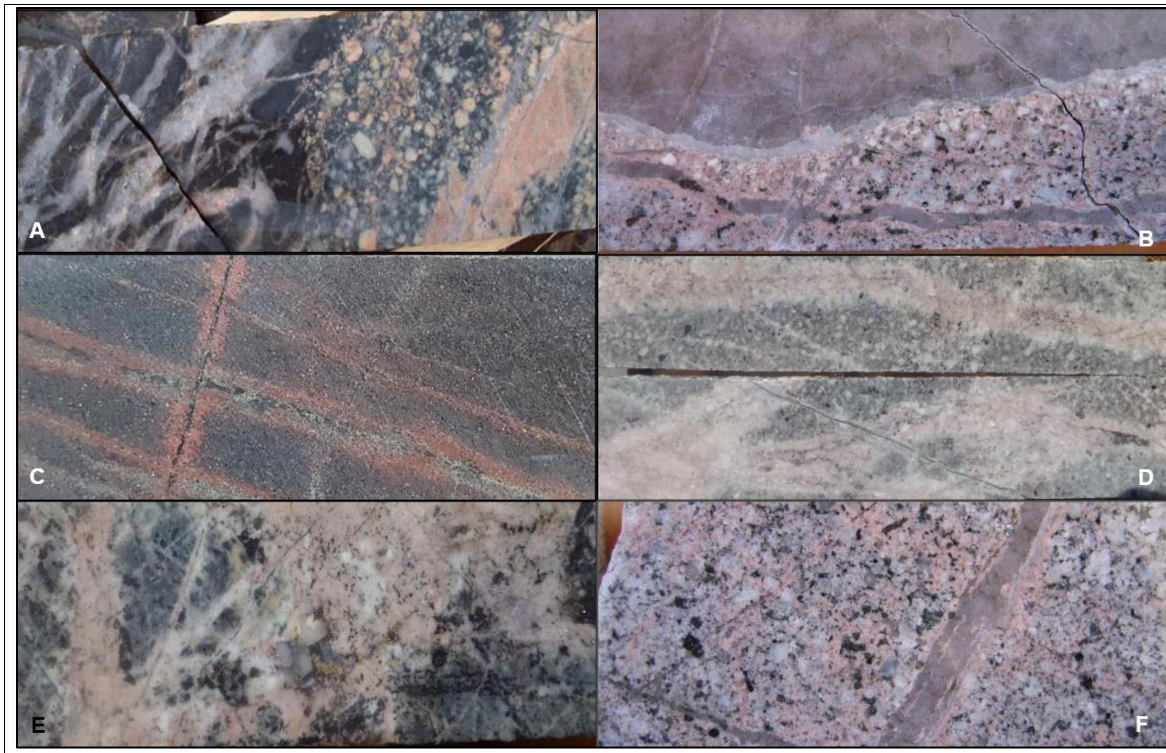


Figure 06. A) Reddish-pink k-feldspar channelway partially cut by gray A-quartz vein; B) Pink-k-feldspar channelways in multidirectional array used by a couple irregular-shaped A-quartz veins; C) rectilinear reddish-k-feldspar veins formed in sedimentary wall-rock; D) K-feldspar channelways in quartz-monzodiorite porphyry; E) K-feldspar-albite irregular channelway in andesite wall-rock; F) k-feldspar polidirectional channelways partially used by two A-quartz veins

In porphyry/host rock vicinity the veinlets show irregular shapes and sinuous patterns (figures 7, 8). However, as we moved away from this environment the veins become straighter and more regular (figure 06, C), reflecting the transition to a more ductile-brittle to brittle deformation. The volume covered by the veins encompasses both the porphyry and the host rock, with dimensions between hundreds of meters up to two kilometers in the best of cases.

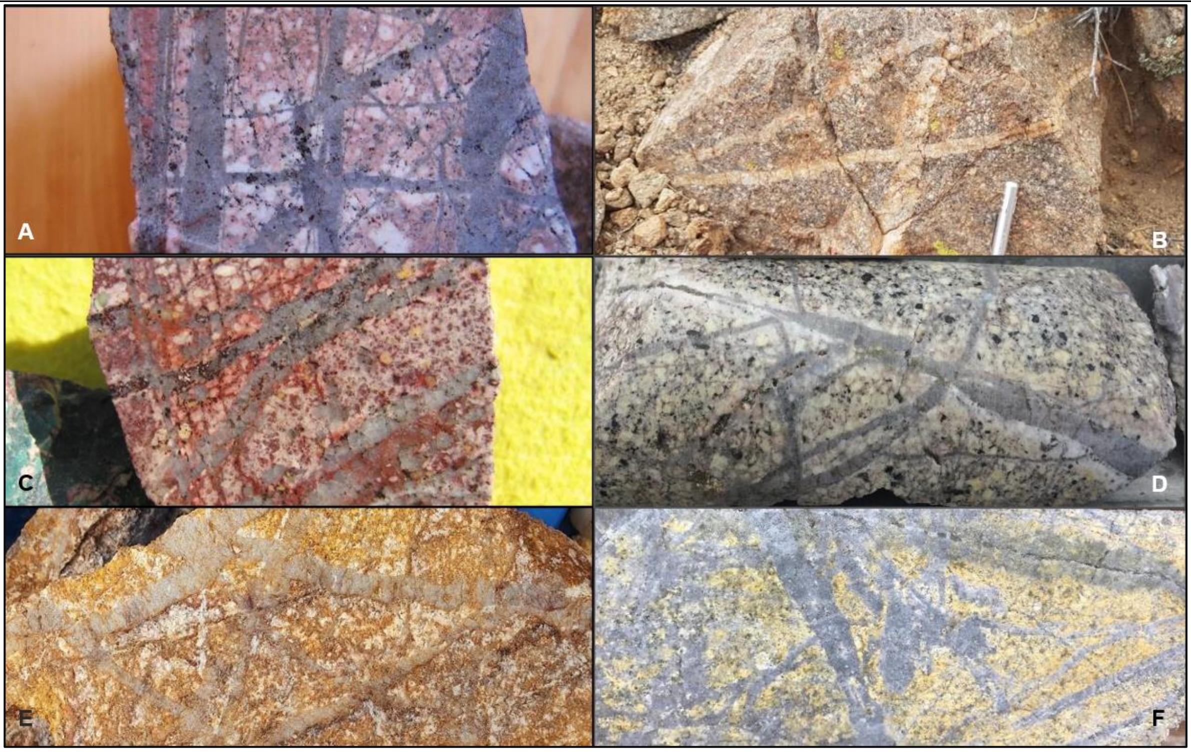


Figure 07). A-quartz veinlets partially sinuous

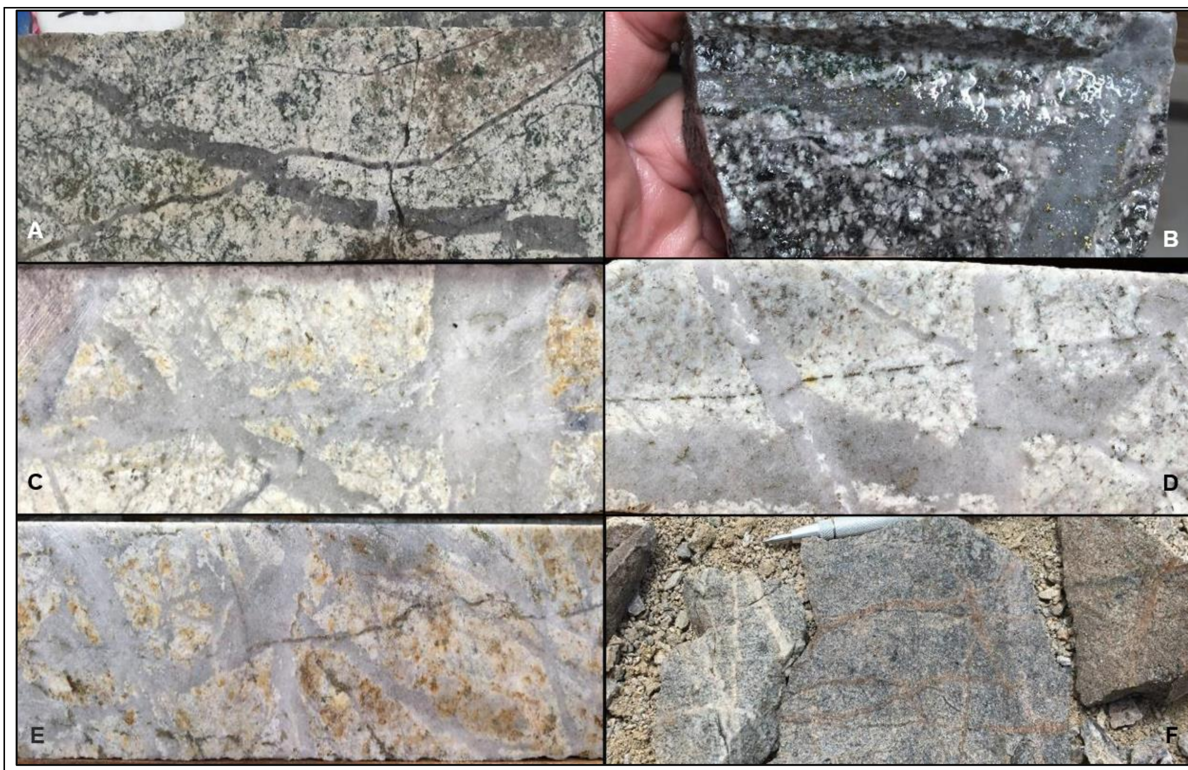


Figure 08). Curved, offset, partly teared, sinuous A-quartz type-veinlets formed in a notorious ductile environment.

In case of emplacement of additional porphyry pulses to the system the most noticeable changes can be observed in the following aspects:

- Formation of intrusive breccias
- Increase on volume of k-metasomatism
- Increase on intensity of k-metasomatism
- Several quartz-veinlet generations
- Re-biotitization

Undoubtedly the emplacement of potassic alteration-related additional pulses brings benefits from the volume, intensity and copper content points of view.

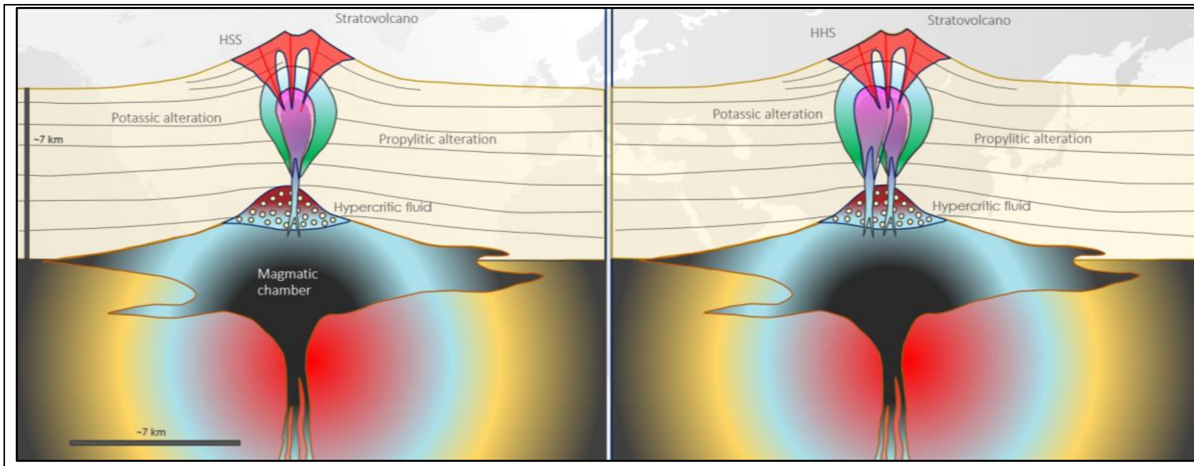


Figure 09). Potassic and propylitic imprints developed by the emplacement of one porphyry pulse (left) and two porphyry pulses (right).

INTRUSIVE BRECCIAS

These breccias are formed by the violent intrusion of any of the early pulses. These processes include intrusion, degasification, sealing of conduits and subsequent brecciation.

Normally these structures are classified as intrusion breccias, although they can also be detailly described based on their matrix and cement dominant content:

- **Intrusive breccia** in the case the matrix is dominantly intrusive (figure 10, A, E and F)
- **Intrusive breccia of biotite** in the case the matrix is mostly biotite (figure 10, B, C and D). -other matrix components: K feldspar, silica, albite, magnetite, tourmaline, chlorite, etc.-

When breccias formed by means of emplacement of main intermineral porphyries develop considerable vertical extensions -beyond potassic boundary (at least 500 m)-, then a vertical zonation can be observed including alteration minerals, iron oxide minerals and sulfides content. A clear example is the study carried out by Frikken et al (2005) in the Brecha Sur-Sur area (CODELCO ANDINA). The alteration/mineralization patterns are profoundly influenced by the liquid and gas phases between 4100 to 2750 masl (figure 11). The first one phase controls the process in the potassic domain characterized by biotite-anhydrite under 3100m downward, whereas the gas phase is dominantly present from 3100m up to current surface (4100 mals) and is characterized by tourmaline occurrences and a strong overprinting of sericite-silica. Between 3000 m and 3100 masl a transition zone is developed (tourmaline-biotite), here both liquid and gas phases operate indistinctly.

The iron oxide occurrence also exhibits a vertical zonation, magnetite (Fe_3O_4) is dominant over specularite (Fe_2O_3) under 3150masl their concentrations are similar between 3150 up to 3600m, and above 3600m the specularite increases considerably its concentration in comparison to magnetite.

The sulfides content shows a vertical as well as horizontal zoning being chalcopyrite widely present in the deeper levels while in shallow zones plenty chalcopyrite and pyrite are common. Some similar occurs in the horizontal plane: in the central area of the breccia body chalcopyrite is del dominant sulfide passing gradually to chalcopyrite-pyrite association outward.

Notice in some cases the wall-rock xenoliths in the marginal parts of some porphyries may be sufficiently abundant to form intrusions breccias (Sillitoe, 2010), and not necessarily responds to violent intrusions.

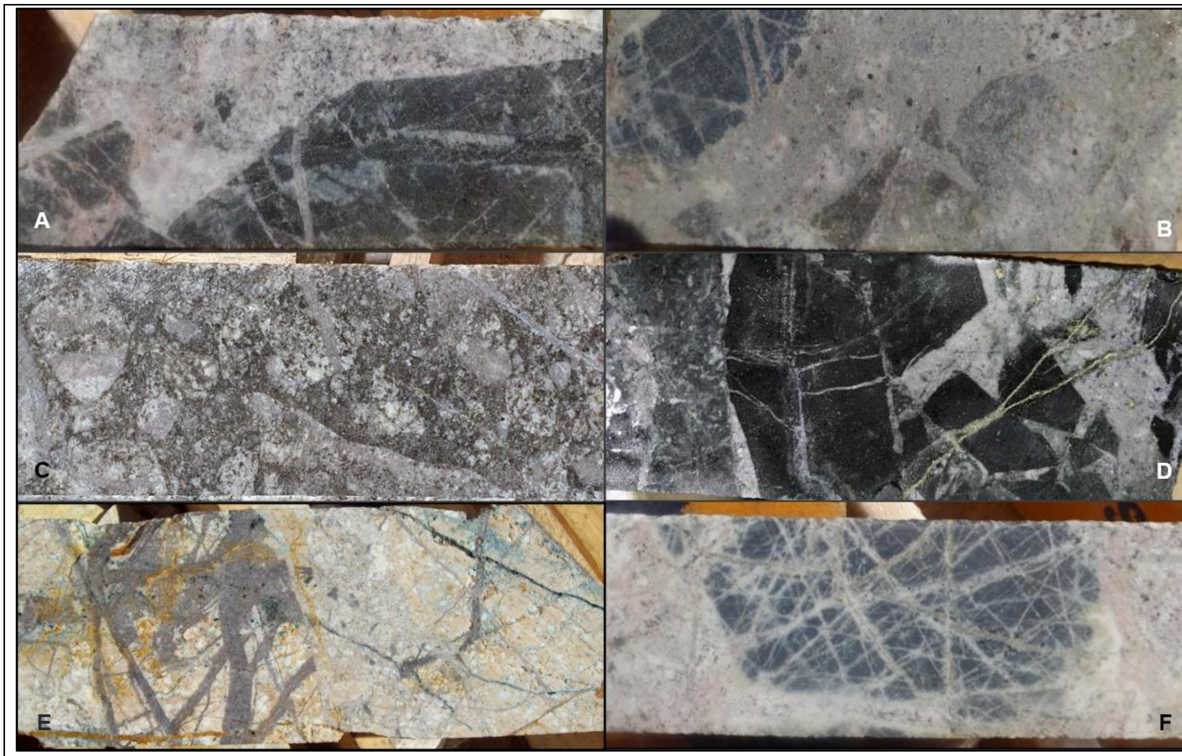


Figure 10. A) Andesite fragments with intense secondary biotite and A-quartz veins floating quartz-monzonite porphyry with potassic alteration; B) Andesite and quartz-monzonite porphyry fragments with potassic alteration include fine-grained quartz-feldspar intergrowth; C) Biotite breccia characterized by porphyries and andesite fragments potassically altered; D) Strongly altered andesite fragments included very fine-grained quartz-k-feldspar intergrowth; E) Porphyry fragments with A-quartz veinlets supported by quartz-monzonite porphyry potassically altered; F) Andesite fragment with K-feldspar veinlets "stockwork" included quartz-monzdiorite porphyry with potassic alteration.

.

B-TYPE VEINING

As the system begins to cool down, porphyry/host rock vicinity passes from a ductile to a ductile-brittle and then brittle deformation conditions. Consequently, the A-type veins are followed by the B-type veins (Gustafson y Hunt, 1975), which typically have molybdenite contents. In general, copper sulfides concentration tends to decrease in this stage, but copper and iron sulfides are still quite common.

This kind of veins are characterized by planar and continuous shapes, with a central suture. They are formed by grey quartz, with variable amounts of K feldspar, minor anhydrite and instertitial biotite. The external part of the quartz-veins could content subtle “halos” with k feldspar.

The formation of this kind of veins is related to brittle deformation conditions. As a result, they show a central suture, indicating that the process was subjected by lower temperatures, with rock fracturing and filling of open spaces.

In terms of extension, this sub event is normally constrained to the potassic zone. More extended zones are possible but not frequent.

This episode is the most important from the moly content point of view (subproduct).

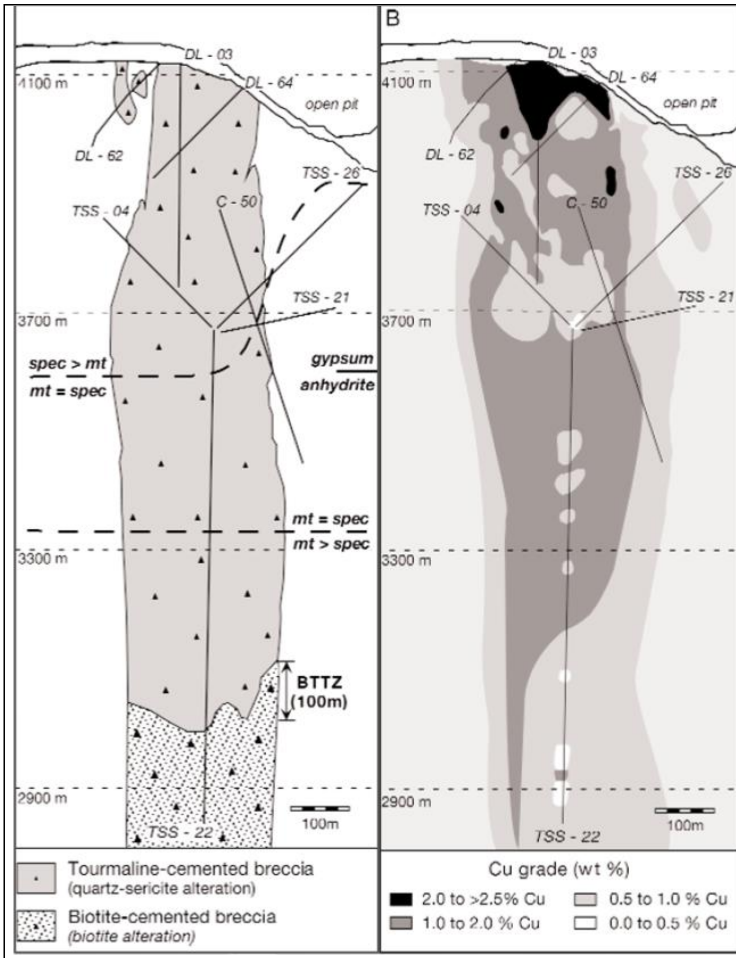


Figure 11. (From Frikken, 2005). East-West cross section through Sur Sur tourmaline breccia. Filled triangles correspond to biotite-cemented breccia; unfilled triangles represent tourmaline-cemented breccia. (BTTZ = biotite-tourmaline transition zone; mt = magnetite; spec = specularite; TSS, C and DL are drillholes

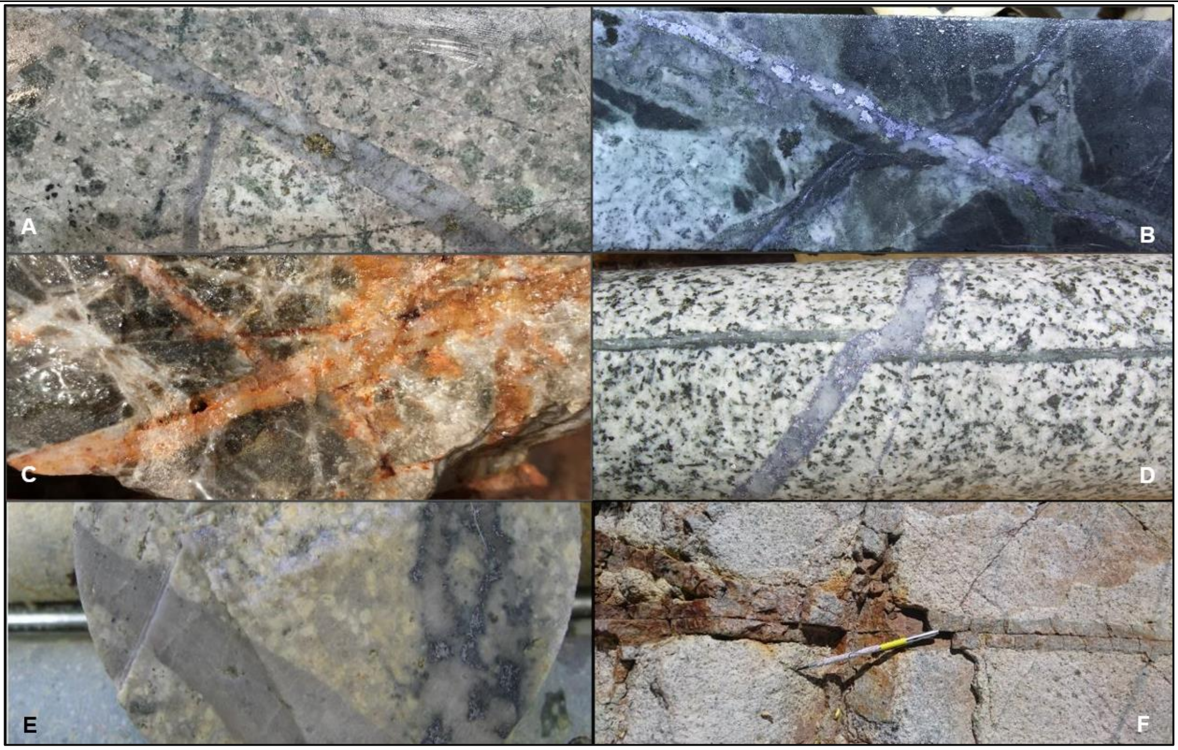


Figure 12. Molybdenite and ferrimolybdite host in B-type veinlets.

PORPYLITIC ALTERATION

Propylitic alteration corresponds to chlorite-epidote-magnetite-calcite-albite-Illite-montmorrillonite/pyrite association and, which is situated beyond of k-silicate alteration. These paragenesis partly is formed from the most cations exchanged during the potassic alteration (Ca, Na, Mg, Fe). These cations are transported out of the potassic boundaries where thermodynamic conditions allow the crystallization of paragenesis outlined above. Additionally, there is a contribution of the gas phase (CO2, H2O ± S) which, join to the cations, produces significant change in chemical composition that finally generates the assemblage at issue (Seedorf et al., 2005).

Habitually, the propylitic halo exhibits a zonation vertically as well as horizontally characterized by an inner part with an association of chlorite-magnetite±albite±illite/pyrite further out an chlorite-epidote-magnetite±illite /pyrite assemblage which pass gradually to epidote-calcite±chlorite/±pyrite externalmost part.

All associations are formed in exclusively host rock.

The dominant thermodynamic conditions for this assemblage correspond to temperatures variable between 150°C-300°C, pH neutral to slight alkaline

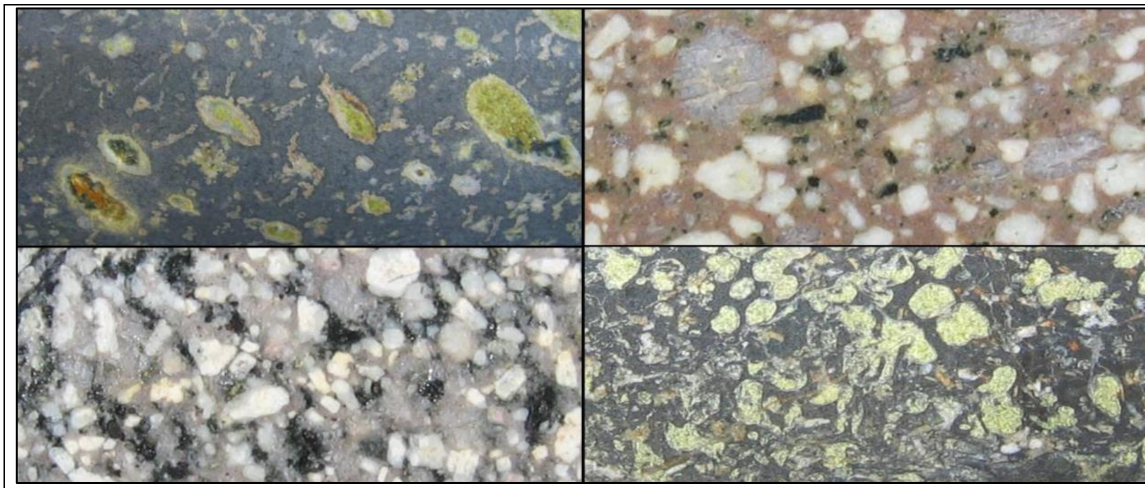


Figure 13. Chlorite-epidote/pyrite, chorite-magnetite/pyrite associations.