Greisenisation and Permeability Changes in Granitic Intrusions Related to Sn-W Deposits: Case of Panasqueira

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Abstract. The W-Sn veins of Panasqueira are connected with a massive quartz-muscovite greisen cupola. This greisen results from interactions between granitic rock and acid Sn-W hydrothermal fluid, which causes the destruction of feldspars of the Panasqueira granite. Greisenisation can constitute an important factor of control on fluid flow, and its role on metal transport remains to be established. Mineral reactions of greisenisation involve a decrease of the rock volume and thus an increase porosity (~6%). Consequently permeability increases significantly (10^{-20} to 10^{-17} m²) enhancing fluid flow in the greisen cupola and promoting further hydrothermal alteration and transport of metals. Finally a part of the mineralization is trapped in this porosity, with precipitation of cassiterite and sulfides. Therefore, Sn-W fluids are able to generate their own pathways in initial impermeable granite via greisenisation reactions.

1 Introduction

Permeability is a critical parameter in processes of hydrothermal fluid flow and metals transport in magmatic-hydrothermal systems. Nowadays, fluid flow controlled by deformation and fracture permeability may be the most studied aspect of hydrothermal circulation in granitic intrusions. Greisenisation is a common type of hydrothermal alteration in apical parts of granitic intrusion related to Sn-W mineralization (Scherba 1970, Pirajno 1992). This metasomatic process can constitute another important controlling factor in hydrothermal fluid flow. Indeed, several authors have highlighted the impact of hydrothermal reactions on fluid flow via porosity and permeability changes (Yardley 1986, Ingebritsen and Appold 2012). Gain and loss of elements induced by mineral replacement reactions occurring during greisenisation can modify significantly the volume and the density of the rock (Stemprok et al. 2005, Halter 1996), and consequently affects fluid pathways by porosity and permeability changes. This time-dependant feature of the permeability is called hereafter 'dynamic permeability'.

This in turn can directly affect the continuation of hydrothermal circulation via potential feed-back between greisenisation and fluid circulation. However effects of greisenisation on the dynamic permeability that ultimately leads to fluid circulation and metals transport in granitic intrusion remains an important research topic. In order to investigate effects of greisenisation reactions, petrological study and experimental determinations of porosity and permeability have been combined for different granite alteration levels and various petrographic types from Panasqueira.

2 Geological setting of Panasqueira

The W-Sn-(Cu) Panasqueira deposit is located in the Central Iberian zone of Portugal (Fig. 1). This region is essentially composed of a flyshoïd series of schist and greywacke (Schist-Greywacke complex) folded and metamorphosed to lower greenschist grade during the Variscan orogeny. In the Panasqueira district, these schists are converted to spotted schist during the thermal metamorphism induced by the emplacement of the non-outcropping Panasqueira granite. The Sn-W mineralization occurs as dense network of sub-horizontal quartz-wolframite-cassiterite-sulfides veins concentrated in the vicinity of a hidden greisen cupola (Thadeu 1951, Kelly and Rye 1979) (Fig. 1). This greisen cupola represents the upper apex of the buried Panasqueira granite. Greisenisation of the granite results from interactions between granitic rocks and acid hydrothermal fluids which transport the Sn-W mineralization.

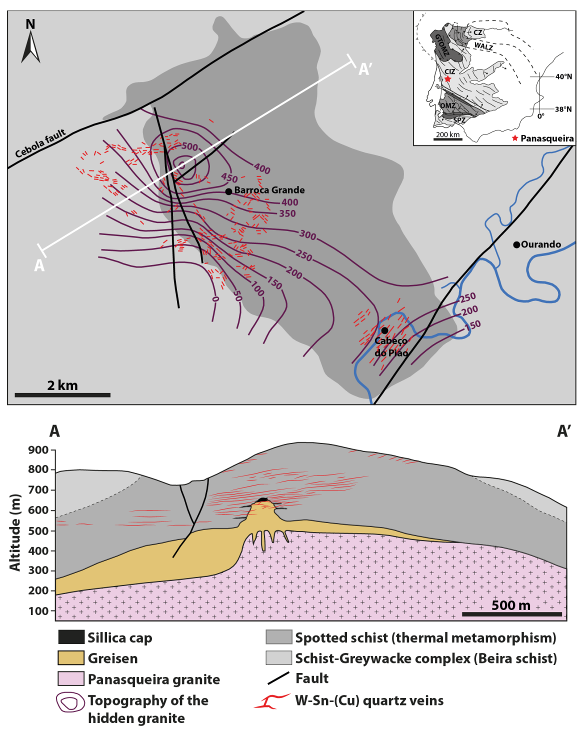

Figure 1. Location and cross-section of the Panasqueira deposit illustrating relationship between W-Sn veins and greisen.

3 Greisenisation and volume change

3.1 Alterations reactions

At Panasqueira, drill holes allow to follow the progressive transformation of the initial porphyric two micas granite in quartz-muscovite greisen from the deeper part to the apical part of the granitic body (Fig. 2). To determine mineralogical reactions involved by greisenisation, samples used in this study were selected in different levels of alteration between unaltered granite and the endmember muscovite-quartz greisen. Petrographic observations show that greisenisation caused destabilization and the total destruction of feldspars (Fig. 2b and 2d) and biotite (Fig. 2c) to produce the quartz muscovite assemblage (Fig. 2a) characteristic of the greisen. On the base of these observations we can define alteration reactions which occurred during greisenisation (Table 1).

3.2 Volumetric effects of greisenisation

The volume changes induced by alteration reactions defined previously can be calculated from molar volume data of each mineral phase and their stoichiometric coefficients. The molar volume change percentage (ΔV) is defined as the percent difference between the respective products of the stoichiometric coefficients and molar volumes of reactants and products:

$$\Delta V\ (\%) = 100.(\Sigma x^{p}_{i}.V_{i} - \Sigma x^{r}_{i}.V_{i})/(\Sigma x^{r}_{i}.V)$$

With x^{p}_{i} and x^{r}_{i} which are respectively stoichiometric coefficients of product and reactant minerals and V_i the molar volumes of associated mineral. Hydrothermal fluid and its dissolved species are absent before and after alteration processes, so only solid phases are taken in consideration. Calculations of molar volume changes were made based on the thermodynamic database of SUPCRT92 (Johnson et al. 1992) for 1 kbar and 450°C. Results of volume changes induced by each alteration reactions are summarized in the following table.

Table 1 Alteration reactions and molar volume changes induced by greisenisation.

Greisenisation reactions	ΔV (%)
3 K-feldspar + 2 H^+ = Muscovite + 6 Quartz + 2 K^+	-15.3
3 Albite + 2 H^+ + K^+ = Muscovite + 6 Quartz + 3 Na^+	-7.7
3 Biotite + 0.65 O_2 + 12.6 H^+ = 2 Muscovite + 3 Quartz + K^+ + 4.8 Fe^{2+} + Mg^{2+} + 7.3 H_2O	-8.8

The replacement of biotite by muscovite and quartz is characterized by a volume decrease of 8.8%. Alteration reactions of K-feldspars and plagioclase are respectively associated with 15.3% and 7.7% of volume decreases. Feldspars are the most abundant minerals in the Panasqueira granite, thus their breakdown is able to generate significantly porosity in greisen. These results are compatibles with the presence of (i) vugs in altered sections of feldspars (Fig. 2b) and (ii) the vuggy texture of the endmember quartz-muscovite greisen (Fig. 2a).

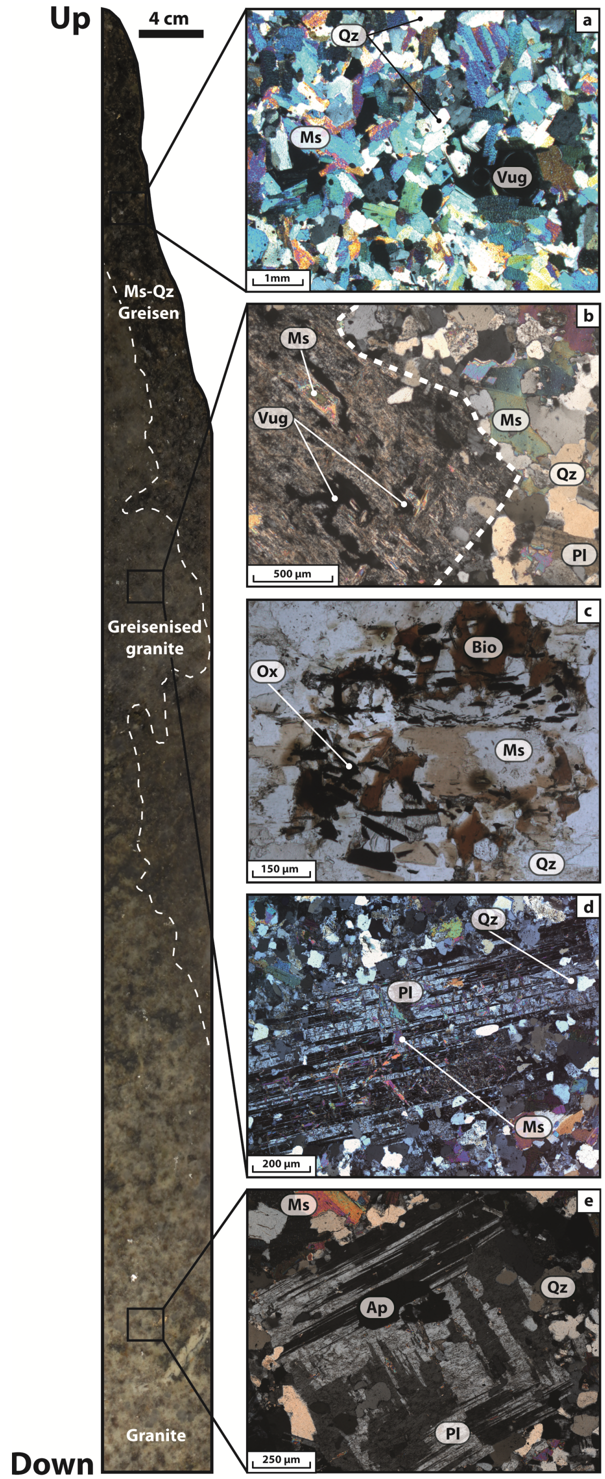

Figure 2. Zoned greisenisation of the Panasqueira granite in drill core section. **a** Section of the quartz-muscovite greisen endmember. **b** Section of K-feldspar replaced by muscovite. **c** Section of biotite bleached and partially transformed in muscovite. **d** Section of plagioclase partially altered and **e** section of fresh plagioclase in the unaltered granite.

4 Porosity and permeability changes with greisenisation

4.1 Experimental methods

Connected porosity and bulk density were measured by gravimetric method which consists of measuring mass changes when samples are saturated by a fluid. Mass of water in saturated samples allows calculating volumetric water contents and consequently the connected porosity of samples. Mass ratio between dry samples and difference between saturated and dry samples allow calculating the bulk density of samples.

Permeability measurements were performed with Paterson apparatus following the method described by Coelho et al. (2015). Experiments were performed at 400°C, 1 kbar of confinement pressure (Pc) and with 500 bar of pore fluid pressure (deionized water). Permeability was measured using steady-state flow method for Darcian flow which defines the flow rate (Q) proportional to the permeability (k) for an imposing pressure difference ($\Delta P \approx 5$ MPa) across the core sample:

$$k = (\mu * L * Q)/(A * \Delta P)$$

Where μ is the water viscosity at 400°C and 500 bar L (in m) and A (in m²) are respectively the length and the cross-sectional area of core samples. Fluid flow (Q in $m^3.s^{-1}$) across samples was calculated from the volume of fluid injected in samples over experiment time.

4.2 Results

Evolution of density and connected porosity are plotted in function of alteration index of the rock (Al_2O_3/Na_2O+K_2O) based on the progressive transformation of feldspars in muscovite during greisenisation (Fig. 3a and 3b). The initial granite is characterized by a bulk density of 2.65 $g.cm^{-3}$ and a low connected porosity of 0.56%. Evolutions of bulk density and connected porosity are positively correlated with index of alteration (Fig. 3a and 3b). Value of bulk density increases from 2.65 to 2.87 $g.cm^{-3}$ and connected porosity strongly increases from 0.56 to 5.86%. As expected, the endmember quartz-muscovite greisen is more porous than unaltered granite. Permeability evolution is reported in function of the connected porosity (Fig. 3c). The unaltered granite is impermeable and presents a permeability value of 10^{-20} m², comparable to the average of permeability in granitic rocks. The porosity increase induced by hydrothermal alteration progression causes an important permeability increase following the theoretical relation between permeability and porosity of rock proposed by Wark and Watson (1998). Consequently, the important increase of connected porosity in greisen clearly implies a significant increase of permeability in the muscovite-quartz greisen (10^{-17} m²).

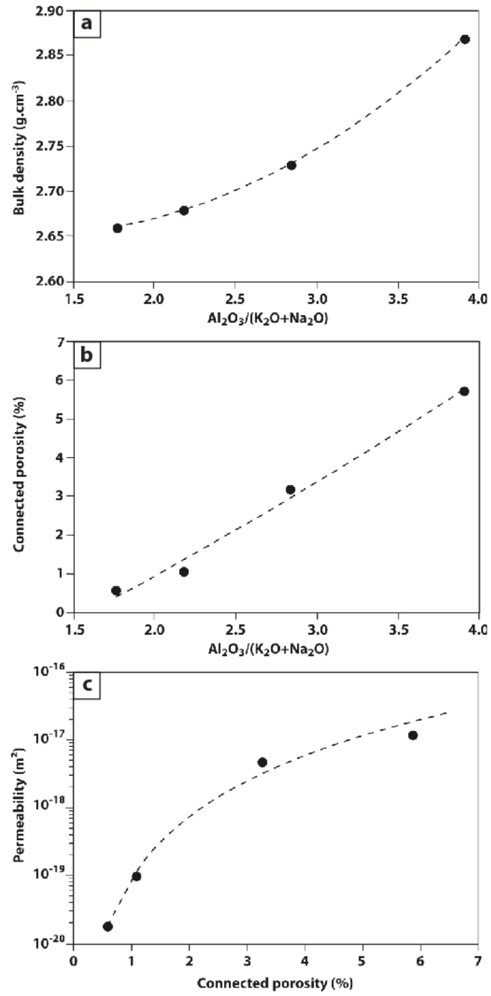

Figure 3. Evolution of **a** bulk density and **b** connected porosity in function of the alteration index $Al_2O_3/(Na_2O+K_2O)$. **c** Evolution of permeability in function of connected porosity.

5 Numerical modelling of greisenisation effect on fluid flow

5.1 Model geometry and parameters

Previous results suggest that permeability of granitic intrusion evolves significantly during greisenisation. This permeability change have been integrated in numerical modelling performed with Comsol Multiphysics™ by coupling Darcy's law and heat equation to determine effect of greisenisation on Sn-W fluid flow. The granite is characterized by an initial temperature of 850°C and an initial permeability of 10^{-20} m². With time, the granite cools progressively and its permeability increase in function of the pressure gradient which constrain preferential sites of hydrothermal alteration. The parameters of the matrix are based on schist properties. A fixed pressure is imposed on top boundary while no flow is allowed on others and there is no heat flow on lateral boundaries.

5.2 Numerical results

Preliminary results show that greisenisation can play a key role on fluid flow in and around granitic intrusion. Dynamic time-varying permeability in the apex and along the roof of the intrusion increases significantly and is self-sustaining during the greisenisation (Fig. 4a). This permeability increase causes the enlargement of the fluid pathways in the upper part of the granitic intrusion and increases significantly fluid velocity above the apex (Fig. 4b), and consequently enhances metal transport (Sn-W) in the apical part of granitic intrusion.

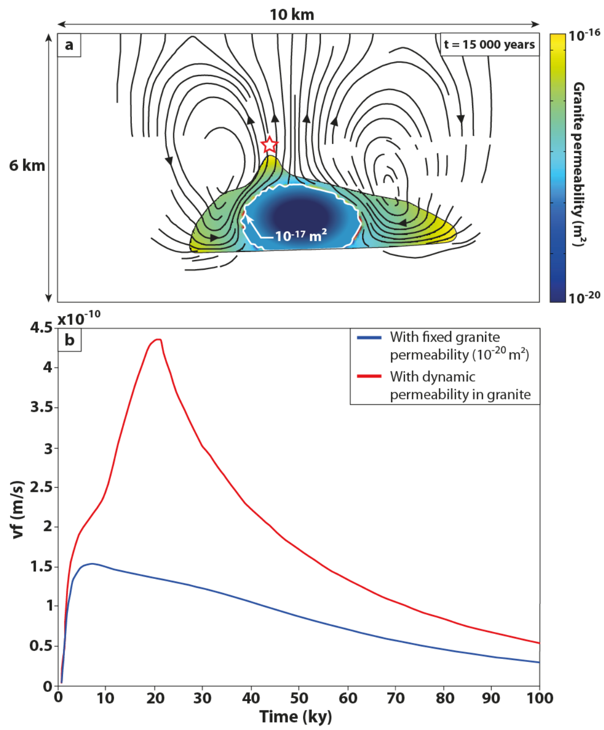

Figure 4. **a** Numerical solution (at 15 000 years) of fluid flow around granitic intrusion with dynamic permeability in the granite **b** fluid velocity above the apex (red star) between with fixed and dynamic permeability in the granite.

6 Discussion and conclusion

In the W-Sn veins-greisen system of Panasqueira, the intense fluid flow in the upper part of the granitic intrusion strongly changes the mineralogy of the granite. The total breakdown of feldspars during greisenisation causes a mineral volume reduction of 6%. This process of mineral volume reduction has direct effects on petrophysical and hydrodynamic features of granitic rock. First, the remaining mass of rock is reduced in a lower mineral volume, consequently the rock density increases progressively with progression of greisenisation. Second, the mineral volume decrease implies connected porosity creation and expansion in greisen, thus increasing the permeability of the intrusive body. As a result, greisenisation induced by W-Sn fluid flow in granite enhances fluid circulation by enlarging the network of fluid pathway. In this case, hydrothermal alteration has a positive feedback on permeability and consequently on metal transport by focussing of fluid in the most permeable zone of granitic intrusion. Presence of cassiterite (Fig. 5a) and sulfides (Fig. 5b) which infill partially the porosity confirms that fluids which transport metals have flowed in the greisen via the neo-formed porosity.

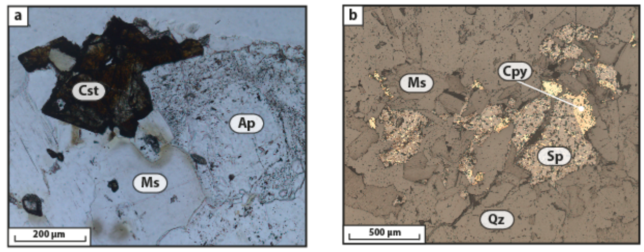

Figure 5. Infilling of vugs generated during greisenisation by **a** cassiterite and apatite **b** sphalerite and chalcopyrite.

In conclusion hydrothermal fluids at the origin of the Panasqueira deposit made their own pathway in the granite via greisenisation reactions which improve significantly fluid circulation and focusing it in the apical part of granitic intrusion. The greisenisation is not just a passive process of hydrothermal circulation but can play a key role during fluid flow in Sn-W ore deposit system.

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