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# Thermal peak detected in gold-bearing shear zones by a thermo-structural study: a new tool to retrieve fluid flow?

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**Abstract.** Gold mineralizations of the northern part of the Canigou massif (Eastern Pyrenees, France) are localized along regional-scale shear zones. These structures connect the upper metapelitic greenschist facies unit (suprastructure) to the lower migmatitic unit (infrastructure) and are attributed to the late-Variscan tectonic evolution transposing earlier structures. Raman spectroscopy of carbonaceous materials (RSCM) approach documents thermal anomalies in these shear zones with a temperature peak [20 – 100 °C] above the host rocks values. These thermal anomalies are interpreted as recording the upward circulation of a hot fluid. These data point to gold mobilization and transfer controlled by localized deformation and fluid flow at the end of the Variscan orogeny. The nature and origin of the mineralizing fluids, the source(s) of gold, and the mechanisms of ore mobilization-transfer-deposition remain to be determined.

## 1 Introduction

Fluid flow is known to modify mechanical (Sibson 1992) and thermodynamic features of the crust (Ague 2014). Chemical mass transfer and heat transfer are associated to fluid circulation (Yardley 2005). However, the regional thermal influence of fluid flow remains difficult to retrieve (Ague 2014).

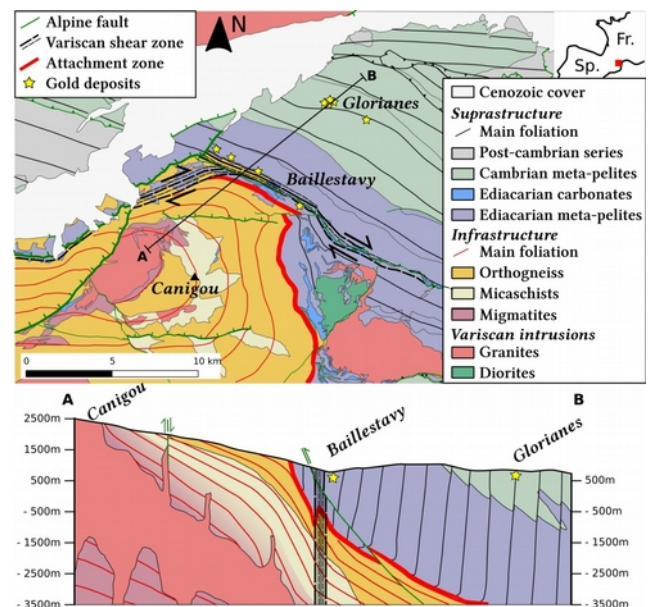
Gold deposits are good evidence of crustal fluid flow. They can provide insights into crustal evolution processes, such as fluid evolution or mass transfer (Philips and Powell 2009). The orogenic gold model implies that metamorphic fluids from the lower crust goes upward through transcrustal shear zones and form gold deposits in the middle and upper crust (Groves et al. 1998; Goldfarb and Groves 2015). However, lower crust levels, where fluids and metal could come from, are rarely exhumed near gold deposits, so their source is difficult to retrieve (Thomkins 2013).

In orogens, metamorphic domes are structures where both upper and lower parts of the crust are exhumed (Whitney et al. 2004). Therefore, they are good targets to retrieve the origin and pathways of former mineralized fluids. Thus, we focused our study on the Canigou dome, in the Axial Zone of the Eastern Pyrenees (France), a late-Variscan metamorphic dome, where the lower levels of the crust are exhumed (Gibson and Bickle 1994; Barbey et al. 2001; Aguilar et al. 2015). Gold mineralizations have been described in the upper crustal levels of this dome (Blès and Costargent 1985;

Polizzi 1990).

## 2 Geological settings of the Canigou massif

The Canigou massif is located in the Axial Zone of the Pyrenees, where the Variscan basement is exposed. The area consists of a metamorphic dome cored by migmatites designated as the infrastructure with a foliation delineating the shape of the dome. The dome is surrounded by Ediacarian-Cambrian metasediments dominated by metapelites designated as the suprastructure, marked by folding of an S0/1-2 foliation into upright F3 folds associated with the development of a subvertical axial planar S3 schistosity. The contact between suprastructure and infrastructure is marked by a zone of transposition interpreted to represent strain partitioning along an attachment zone (Cochelin et al. 2017) (Fig. 1).



**Figure 1.** Simplified geological map and cross-section of the Canigou dome and position of main gold deposits.

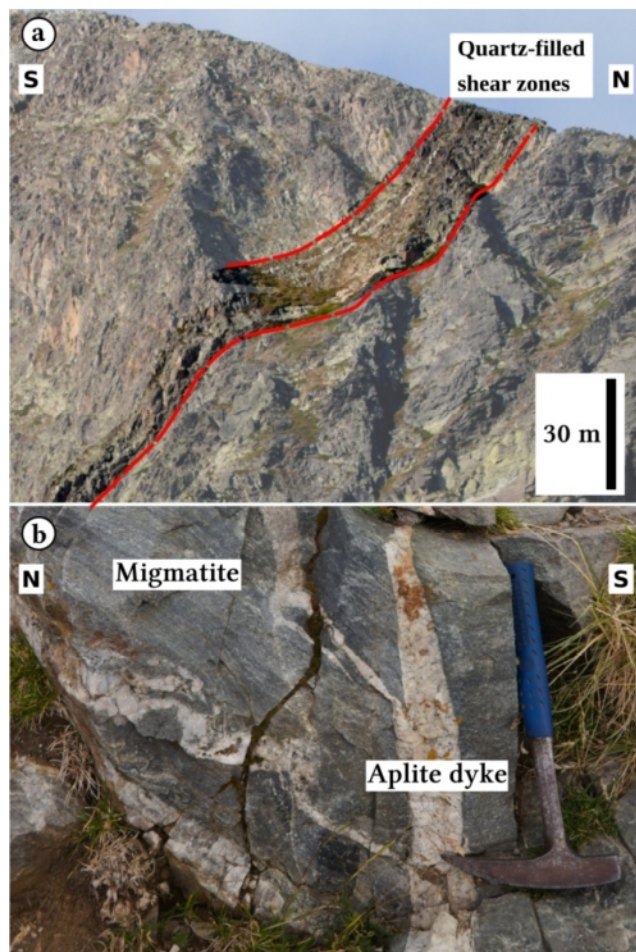
In the suprastructure, many gold veins have been described (Blès and Costargent 1985; Polizzi 1990). They are localized along vertical retrogressive mylonite zones (Baillestavy) and reverse faults zones (Glorianes), attributed to the last Variscan deformation stages (Blès and Costargent 1985; Polizzi 1990). The

gold veins are mainly filled with siderite, quartz and arsenopyrite. Native gold (electrum) is present in arsenopyrite cracks (Polizzi 1990).

### 3 Structural position of gold deposits

#### 3.1 Shear zones and migmatites of the infrastructure

The infrastructure is principally made of metapelites and orthogneiss intruded by the Canigou leucogranite, made of coarse-grained quartz-feldspars-muscovite. The presence of leucosome concordant to the synmigmatitic foliation in textural continuity with discordant leucosomes localized along W-E trending subvertical shear zones indicates that partial melting and melt segregation were coeval with deformation (Fig. 2b). Moreover, the localization of leucogranite dykes and major quartz veins together with solid-state mylonitic deformation of the Canigou leucogranite along these shear zones suggests that magma emplacement and differentiation occurred during this deformation event (Fig. 2a).

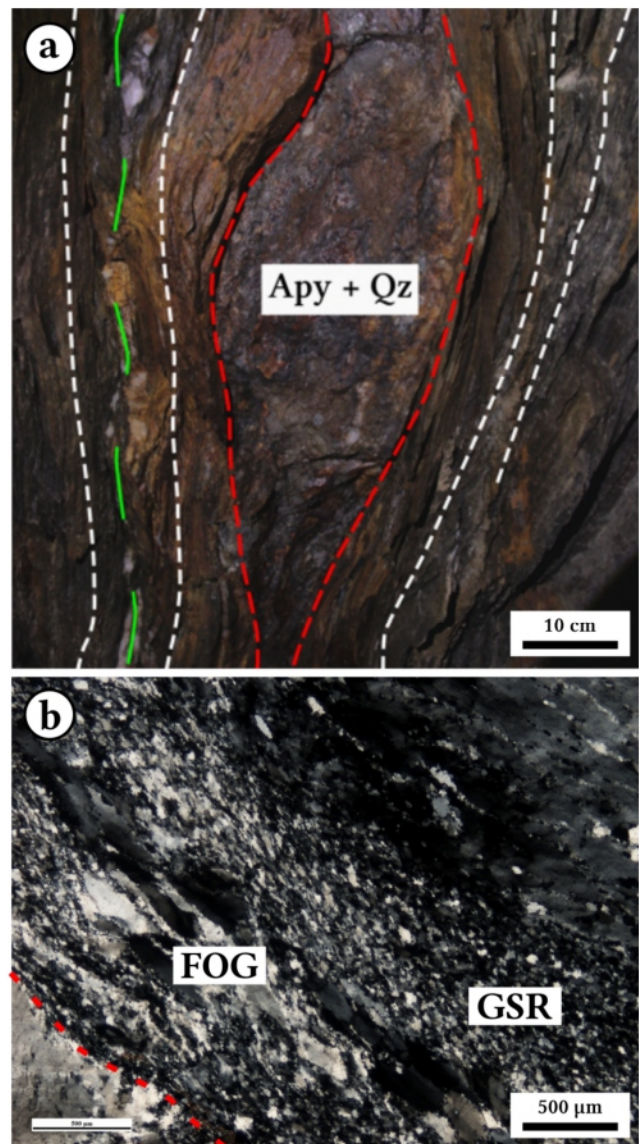


**Figure 2.** (a) Vertical quartz vein and leucogranite dyke along vertical shear zones on the Canigou summit. (b) Aplitic leucogranite dyke and migmatite collecting zone along vertical shear zone.

#### 3.2 Shear zones and gold ore-bodies of the suprastructure

Nearby the NE edge of the Canigou dome, the Baillestavy NW-SE trending dextral shear zone crosscuts the amphibolite facies meta-pelites and carbonates and affects the attachment zone.

Many small ductile to brittle-ductile shear zones are also present in the suprastructure. They crosscut the  $S_0$ ,  $S_1$  and  $S_2$  foliations and they are syn- to post- $S_3$ . Like vertical shear zones of the infrastructure, the shear zones of the suprastructure have a W-E orientation and are mainly filled by quartz veins. The brittle-ductile shear zones are particularly concentrated in the Glorianes-Serrabona area that we designate as the Glorianes-Serrabona shear bands.



**Figure 3.** (a) Vertical quartz-arsenopyrite vein (red) along the  $S_3$  main foliation (white), in Glorianes gold deposit. (b) Quartz microstructures in vertical quartz-arsenopyrite auriferous vein showing grain-size reduction (GSR) and flattened old grains (FOG); in red, contact between strongly deformed vein and weakly deformed vein

Gold ore-bodies of the suprastructure are located along the Baillestavy shear zone and the Glorianes-Serrabona shear bands. They consist of siderite-quartz-arsenopyrite vertical veins (Fig. 3a). Microstructures of quartz show an abundant dynamic recrystallization by dislocation creep with strong grain-size reduction (GSR) and flattened old grains (FOG) (Fig. 3b). These microstructures show that the quartz deformed under ductile conditions ( $T > 400\text{ °C}$ ) (Passchier and Trouw 2005). Moreover, microstructural textures show that, at least two quartz filling events occurred in the vein. Indeed, the second deformed quartz vein crosscuts the first deformed quartz vein (Fig. 3b). It suggests that fluid flow was active during the shear strain.

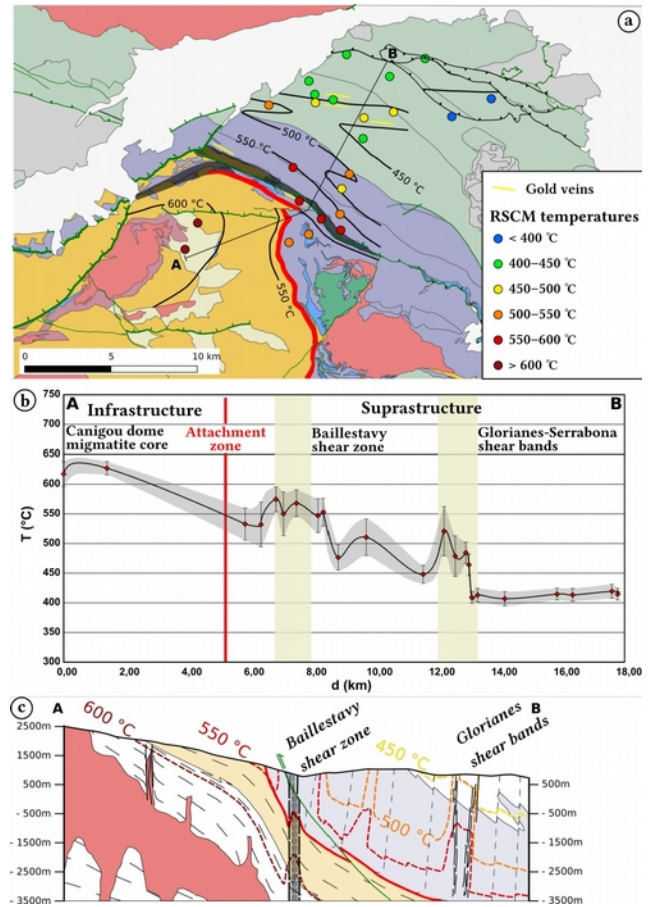
#### 4 Regional thermal gradient

The regional thermal gradient has been determined by the Raman spectroscopy of carbonaceous material (RSCM) method (Beysac et al. 2002). This geothermometer is based on the structural organization of carbonaceous material. It provides the maximum temperature reached by the rock. Previously obtained RSCM temperatures for the Axial Zone of the Pyrenees are considered to record the Variscan thermal peak (Cochelin et al. 2018). Measurements have been carried out on metapelite samples from the suprastructure and the infrastructure.

The thermal profile from the migmatitic dome core (ca.  $620 \pm 20\text{ °C}$ ) and the external parts of the suprastructure (ca.  $380 \pm 20\text{ °C}$ ) shows a regular decreasing gradient of ca.  $30\text{ °C/km}$  (Fig. 4a, b). However, two thermal anomalies are present along the Baillestavy and the Glorianes-Serrabona shear bands (Fig. 4b, c). The temperature value strongly increases along these structures. It is comprised between  $550 \pm 37\text{ °C}$  and  $575 \pm 21\text{ °C}$  in the Baillestavy shear zone and between  $464 \pm 18\text{ °C}$  and  $521 \pm 41\text{ °C}$  in the Glorianes-Serrabona shear bands. They contrast with the thermal peak recorded in the surrounding rocks, where temperature reach  $[476 \pm 21\text{ °C} - 532 \pm 38\text{ °C}]$  and  $[413 \pm 12\text{ °C} - 448 \pm 15\text{ °C}]$ , respectively (Fig. 4a, b). Notably,  $\Delta T$  interval is very similar in both Baillestavy and Glorianes-Serrabona shear zones:  $[20 - 100\text{ °C}]$ .

#### 5 Discussion and conclusion

Temperature values obtained by RSCM approach on metapelites are consistent with petrological observations of LP/HT paragenesis. The temperature peaks identified could reflect local extrusion accommodated by conjugate faults. However, such faults have not been identified in the field. According to recent studies, shear heating may also be invoked to explain thermal anomalies identified by RSCM approach (Souche et al. 2013; Fauconnier et al. 2014). However, this process might be only valid for major crustal shear zones or supradetachments (Duprat-Oualid, pers. comm., 2018). Another possible source for anomalously high temperatures at depth may be represented by exothermic reactions during chloritization of biotite, but it seems difficult to generate temperature anomalies



**Figure 4.** (a) Position of RSCM analysis and distribution of isograds. Same legend as Fig. 1. (b) Paleotemperatures obtained by RSCM along A-B cross section. Errors bars are standard deviation. (c) Interpreted position of isograds in A-B cross section, based on RSCM datas and structural observations.

reaching tens of degrees C. As an alternative, we thus propose that the Baillestavy and Glorianes-Serrabona thermal anomalies reflect localized heating caused by circulation of a hot fluid in the shear zones. This interpretation is consistent with quartz microstructures in the mineralized veins, which show a deformation under ductile regime during fluid circulation.

Such fluids could originate from different sources that are not mutually exclusive. Indeed, they could represent meteoric fluids penetrating the upper crust down to the brittle-ductile transition, where they were heated before to go upward, as typically identified in Metamorphic Core Complexes (Morrison and Anderson, 1998; Siebenaller et al. 2013). The fluids could also be generated by dehydration metamorphic reactions as proposed for mineralizations in the Vall de Ribes district, on the south flank of the Canigou dome, where fluid inclusions revealed an  $\text{H}_2\text{O-NaCl}$  chemistry and trapping conditions under  $350\text{--}400\text{ °C}$  and 2 kbar (Ayora et al. 1992). In that case, upwelling fluids probably incorporated gold from disseminated sulphides of the meta-sedimentary pile. Such auriferous disseminated sulphides have been observed in the Vall de Ribes district too (Ayora and Casas 1986). Moreover, this

model involves a preexisting gold metal stock in metapelites and carbonates (Gaboury 2013), as proposed for the nearby Salsigne gold deposit (Montagne Noire, France) (Courjault-Radé et al. 2001). At last, the mineralizing fluids might originate from crystallization of the migmatites and granites forming the core of the Canigou dome. Constraining the origin of the mineralizing fluids requires fluid inclusions analyses.

In conclusion, our study shows that gold deposits of the Canigou massif formed during the late tectonic evolution of the Variscan orogenesis. Upward gold-forming fluid flow used vertical shear zones, which crosscut both the infrastructure and the suprastructure, as pathways. According to our structural model, the crustal thickness between gold deposits and migmatites is ca. 5 km. This contrasts with transcrustal fault system controlling fluid flow and gold mobilization-transfer-deposition invoked in the orogenic gold model proposed by Groves et al. (1998).

By combining structural observations and RSCM data, we were able to detect the thermal signature of fluid flow along structures which were difficult to retrieve by a classical petro-structural study. Using this thermo-structural approach at regional scale could be a useful tool for detection of ore deposits in faults and shear zones and to a better understanding of former fluid flow in the orogenic crust. It could also be a useful tool to identify areas with potential ore deposits for exploration.

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