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Gold as a powerful proxy to trace gold and unravelling gold systems, an insight into French Guiana (France)

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Abstract. Despite of the gold exploration since 150 years, there is a limited understanding of gold deposits in the French Guiana. To improve our knowledge, alluvial, eluvial and primary gold grains from the Sophie-Repentir and Saint-Elie goldfields (French Guiana) have been characterised by EPMA and LA-ICP-MS analyses. Preliminary results show a good discrimination between the two orogenic gold districts. Whereas the gold grains population of the Saint-Elie is characterised by a low content of silver (*i.e.* mainly less than 6 wt%), a suite of Bi mineral inclusions and a Sb-Bi-Cd fingerprint, gold from the Sophie-Repentir is enriched in silver (up to ~ 20 wt%), Cu-poor and associated with a wider range of tellurides. These features also allow matching an alluvial gold population to its corresponding lode source with confidence and raise questions about the processes controlling the trace elements behaviour.

1 Introduction

The French Guiana represents the first French gold province and belongs to the Guiana shield in South America. It has produced at least 213 tons of gold since 1855 (Cassard et al. 2008 and references therein). Furthermore, because French Guiana has a deeply weathered landscape (*i.e.* lateritisation), primary gold deposits are rarely outcropping. In such conditions, the use of indicator mineral studies is necessary for exploration of undercover gold deposits. The best indicator mineral of gold deposits is gold itself (McClenaghan and Cabri 2011) because it is a dense mineral, chemically stable and easily found in the erosional products of gold systems (*i.e.* placers).

Gold displays a range of intrinsic mineralogical characteristics such as its shape, size or chemical composition (*i.e.* minor and trace elements). These features can be used to provide information for relationships between placer and lode deposits in exploration but also informing about ore-forming processes. Considering this, a powerful technique was largely developed by the British Geological Survey (*e.g.* Leake et al. 1997, Chapman et al. 2000) for gold exploration, named “microchemical analysis” of gold. It is based on two types of mineralogical information linked to the environment of formation (Chapman et al. 2000): (i) the determination of the minor alloying elements content (Ag, Cu and Hg) and (ii) the identification of mineral inclusions in gold grains. In addition, the improvement of analytical tools allows analyses of trace elements (*e.g.* Sb, Pd, Pt, Bi) of gold by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-

MS), mainly for tracing archeological gold objects (Watling et al. 1999), for traceability of ore gold (Dixon 2014, Augé et al. 2016) but also for tracing lode sources (Banks et al. 2018).

This project focus on the chemical characterisation of gold from French Guiana for which few data are known in comparison with others areas from the Guiana Shield or from the West-African craton. For this reason, LA-ICP-MS analysis of gold, coupled with the “classical” microchemical analysis, is applied to two gold grain populations from French Guiana in order to better understand the gold-forming processes and better constrain gold exploration.

2 Gold in French Guiana

The known gold deposits are located in the mid-north part of the French Guiana (Fig. 1). They are mainly hosted by the Paleoproterozoic Paramaca Greenstone Belt (PGB), interpreted as the remnant of a volcanic arc sequence formed during the Transamazonian orogeny (2.18 to 2.13 Ga). It forms two regional-scale synformal structures located to the north and south of the Mesorhyacian Central TTG (Tonalite Trondhjemite Granodiorite) complex (Delor et al. 2003, Enjoly 2008). Three types of primary gold deposits have been identified in the PGB (Milesi et al. 2003): (i) stratabound gold deposits hosted by the volcano-sedimentary rocks of the Paramaca Formation, where gold is associated with disseminated sulphides; (ii) gold-bearing conglomerates with disseminated gold within the Upper Detrital Unit of the North Guiana Trough; and (iii) “classical” orogenic gold deposits which consist of quartz-carbonate-sulphide veins and stockworks, essentially hosted by the Paramaca Formation and granitoids. The Sophie-Repentir (SR) and the Saint Elie (SE) gold districts discussed in this study belong to the orogenic type. To date, most of the gold production of the French Guiana is coming from placers of Pliocene to Quaternary age.

The SR gold district is located along the SR shear zone, which is a major metalotect for gold deposits in this area (Machairas 1963). This N130°E trending structure of 19 km long, hosts numerous gold-bearing quartz vein-type zones and derived placers. The northern part of the structure, the Sophie-Dagobert area, hosts several lodes distributed around the Sophie, Salomon, and Absinthe creeks (*e.g.* the Tabou, the Gros Chantier, and Dagobert lodes). The southern part of the structure, the Saint Léon-Repentir area, is characterised by numerous lodes distributed around the Saint Léon

creek (e.g. Repentir and Félix lodes). The historical production of the SR district is estimated at 25 t of alluvial gold and 3.3 t of primary gold. The SR shear zone is located at the contact between the Paramaca formation and the Central TTG complex. Primary mineralisation consists of sulphides-bearing quartz veins with associated alteration halos (*i.e.* silicification). Pyrite is the most dominant sulphide and can be found (i) as isolated crystals inside quartz, (ii) as impregnations in the crushed zone at the wall rock of mylonites or (iii) in veinlets within mylonites. Gold appears frequently as free grains (up to 1 mm in size) within quartz veins or in cracks, as inclusions and/or in the crystal lattice of pyrite. Pyrite and gold are commonly associated with subordinated galena, chalcopyrite, covellite, sphalerite, bismuthinite, Bi- and Au-Ag tellurides. The paragenetic evolution could be resumed by an early ductile stage with gold-rich sulphides formation within mylonitic zones followed by a brittle deformation stage forming a dense network of quartz veins with free gold.

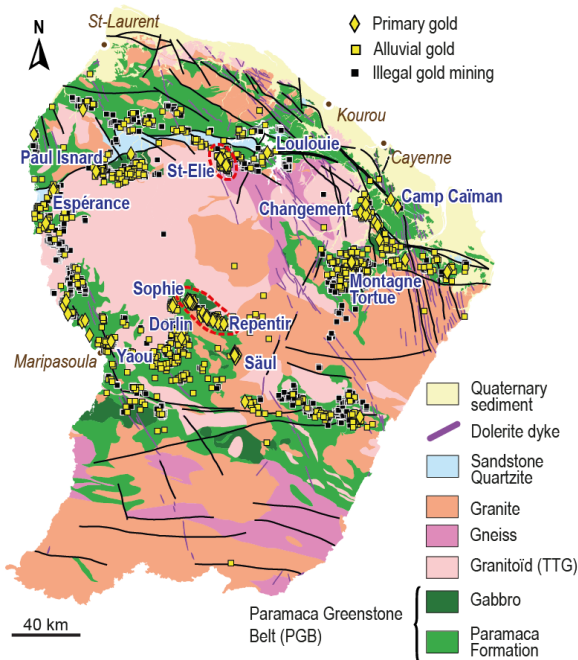


Figure 1. Simplified geological map of the French Guiana adapted from Delor et al. (2003) with the location of known gold deposits and the two studied districts (red dashed ellipse).

The SE gold district is located in the Paramaca formation in the northern part of French Guiana and a few kilometers south of the North Guiana Trough, a major sinistral structure (Milési et al. 2003). Mainly exploited for alluvial gold (e.g. St-Auguste creek), there are also numerous lodes known in this district such as Devis, Michel or Dieu-Merci lodes. Two types of quartz veins are recognised, sub-horizontal and sub-vertical auriferous veins. The latter are associated with NW-SE trending shear zones. The geometric relationships indicates that the vein sets occurred in a single deformation episode. Pyrite and pyrrhotite are the main sulphides in the paragenesis of the SE district. They are associated with minor amounts of chalcopyrite, galena,

Bi-tellurides and traces of Ag-Au tellurides, greenockite and molybdenite. Gold commonly occurs along contacts between pyrite and pyrrhotite, within cracks in pyrite and as inclusions in galena and tellurides.

3 Sampling and methods

Some 450 gold grains from the studied areas were collected during a BRGM in-house project funded by WWF (World Wildlife Fund), aiming to assess the traceability of gold of French Guiana (Augé et al. 2016). When possible, a representative population of each grains type (alluvial, eluvial, and primary) were mounted in polished sections, in order to determine the microchemical signatures of gold.

Optical microscope (reflected light) and scanning electron (SEM) microscope were used to identify the nature of mineral inclusions within gold alloy. The minor alloy composition (Table 1) have been determined using a Cameca SXFive electron microprobe (operating at 20 KeV and 40 nA with a counting time of 20 s for each element) at the ISTO facilities (Orléans, France). The content of Ag within a population of gold grains is displayed in cumulative percentile plots (Fig. 2), which allows a direct and best comparison of populations with different numbers of grains (Chapman et al. 2000). Trace elements of gold were determined by *in situ* LA-ICP-MS at the BRGM laboratory (Orléans, France) using an excimer laser (193 nm) CETAC Excite coupled to ThermoScientific X serie II quadripole ICP-MS. Ablation spot of 85 µm with a laser fluence of 12 J/cm² and a repetition rate of 8 Hz were used. Quantification of gold is carried out using Ag as internal standard. A large spot size has been used in order to increase the signal because most elements are close to the detection limits (LOD). Moreover, the value of LOD is assigned to each values below the latter.

4 “Microchemical signature” of gold

Sophie-Repentir district. Primary gold grains from the Dagobert lode, observed in this study and recovered from shaking table, range in size from 50 to 500 µm. They are associated with base-metal sulphides (pyrite, galena and chalcopyrite) and tellurides (hessite, calaverite, petzite altaite, Table 1). The Ag content of gold grains is ranging between 4.20 and 11.36 wt%. Copper is frequently below LOD but detected up to 0.19 wt%, whereas Hg is always below LOD. Alluvial gold grains, from the Marc creek, are classically coarser than primary gold grains and range in size from 100 to 3000 µm. Galena, Bi- and Pb tellurides represent the main mineral inclusions contained in these gold grains. In contrast to primary gold grains from the Dagobert lodes, alluvial grains from the Marc creek are characterised by highly variable Ag content (from 1.96 to 22.60 wt%) and rather similar Cu and Hg content (up to 0.18 wt% and below LOD, respectively). Figure 2 illustrates the statistical distribution of the Ag content of primary and alluvial gold. There are strong similarities of the Ag content between all the samples. Primary gold grains

from the two Dagobert lodes are extremely similar and only 20 % of the population show a different composition. The statistical distribution of the Ag content of primary and alluvial gold grains also shows strong similarities. About 70 % of alluvial population fit well with the primary population indicating that almost gold from Marc creek could come from the Dagobert lodes.

Table 1. Characteristics of studied gold grains from French Guiana

Sample	No.	EPMA composition (wt %)				Ore mineral association*
		Ag		Cu		
		LOD	0.3 %	0.05 %	0.2 %	
Sophie-Repentir district						
Dagobert lode 1	120	4.20-11.36	6.87	bdl-0.19	0.08	bdl
Dagobert lode 2	52	4.61-8.36	6.50	bdl-0.19	0.06	bdl
Marc creek (Upstream)	42	1.96-22.60	7.34	bdl-0.18	0.07	bdl
Marc creek	48	2.57-19.93	6.46	bdl-0.18	0.09	bdl
Saint-Elie district						
Unk. lode (SE concession)	41	1.79-7.87	3.92	0.03-0.27	0.11	bdl
Unk. lode (St-Auguste area)	56	1.80-4.88	2.58	bdl-0.29	0.12	bdl
St-Auguste creek	105	1.57-4.85	3.00	0.03-0.31	0.13	bdl

*= observed in this study, AgTe= Ag tellurides, Apy= arsenopyrite, AuTe= calaverite, bdl= below detection limit, BiTeS= tetradymite group, BiTe= Bi tellurides, Cpy= chalcopyrite, Gn= galena, No.= Number of gold grains, PbTe= altaite, Py= pyrite, Unk= unknown, LOD= limit of detection

Saint-Elie district. Primary gold grains are coming from two different lodes of the SE district, an unknown lode from the SE concession, and a lode from the St-Auguste area. Grain size ranges between 600 and 1200 µm. About 35 % of gold grains contain inclusions, mainly represented by Bi-tellurides (e.g. hedleyite), tetradymite, Bi alloy (probably maldonite) and native Bi. Gold grains from the two lodes are characterised by different Ag content from 1.97 to 7.87 wt% for grains coming from the SE concession and from 1.80 to 4.88 wt% for those coming from the St-Auguste area (Table 1).

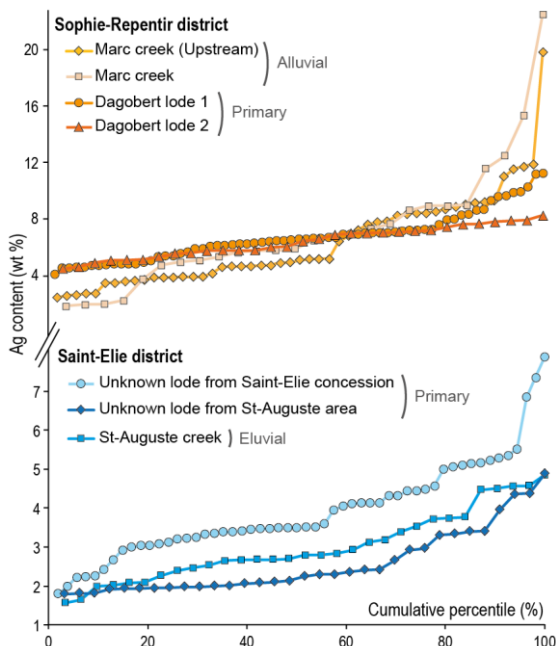


Figure 2. Cumulative plots of Ag content of gold particles from the the SR district and the SE district.

However, the Cu content is similar with a maximum value of 0.29 wt% and mean values around 0.12 wt%. The Hg content is always below LOD. Eluvial gold from the St-Auguste creek only contains 9 inclusions in despite of large grains collection (i.e. 105 grains) and corresponding to pyrite, Bi tellurides and Co-bearing sulpharsenides. Thus, bismuth appears to be the predominant element in the microchemical signature of the SE district. This eluvial gold shows a range of Ag content comprised between 1.57 and 4.85 wt%, a Cu content comprised between 0.03 and 0.31 wt% and Hg content below LOD. The two populations of primary gold from the SE concession are different (Fig. 2). Gold from the lode around the St-Auguste area is poorer in Ag and seems to be a good candidate as the source of eluvial gold from the St-Auguste creek. However, the light misfit in the distribution of the Ag content does not exclude a contribution of another source of gold.

5 LA-ICP-MS signatures

Preliminary results of the trace elements analysis (Fig. 3) show that Cu is well detected in LA-ICP-MS whereas this is not always the case with EPMA. However, the Cu content measured by LA-ICP-MS is consistent with the Cu content obtained by EPMA.

The Cu content ranges from 10 to 1620 ppm in the SR district (mean value of 690 ppm) and from 270 to 3205 ppm in the SE district with a 1085 ppm mean value (Fig. 3a, b). The content of PGE (Fig. 3b, c, d), mainly controlled by the Pd content, is close between gold from the two district with mean values of 0.75 ppm (SR district) and 1.15 ppm (SE district), respectively. This similarity is likely because gold mineralisation is hosted by the PGB, mainly composed of ultramafic-mafic rocks. On the other hand, bivariate plots show a distinct behavior of Sb between the two gold districts (Fig. 3a, c, e), with a median value of Sb (1.01 ppm) at least 20 times greater in gold grains of the SE district compared to the SR gold (0.052 ppm). Same observation can be made about the cadmium content (Fig. 3f), with a mean value of 2 ppm for the SE gold grains, 40 times greater than the mean value of SR gold. This is supported by the observation of greenockite in the paragenesis from the SE district (Lafrance et al. 1999). The Bi content graphically appears as similar between the SR and SE gold grains with a close mean value (0.11 ppm for SR gold and 0.17 ppm for SE gold); however, 52% of Bi values are below LOD (0.009 ppm) for SR gold, compared with 95% of values above LOD for the SE gold grains. This indicates that the gold coming from the SE district is relatively more enriched in Bi, which is consistent with the abundance of Bi mineral inclusions observed in gold grains.

In the same way that cumulative Ag percentile (Fig. 2), trace elements can assist to distinguish a gold population from another. Displayed diamonds on the Figure 3, representing alluvial SR gold and eluvial SE gold, confidently fall in the field of their supposed source (Fig. 3).

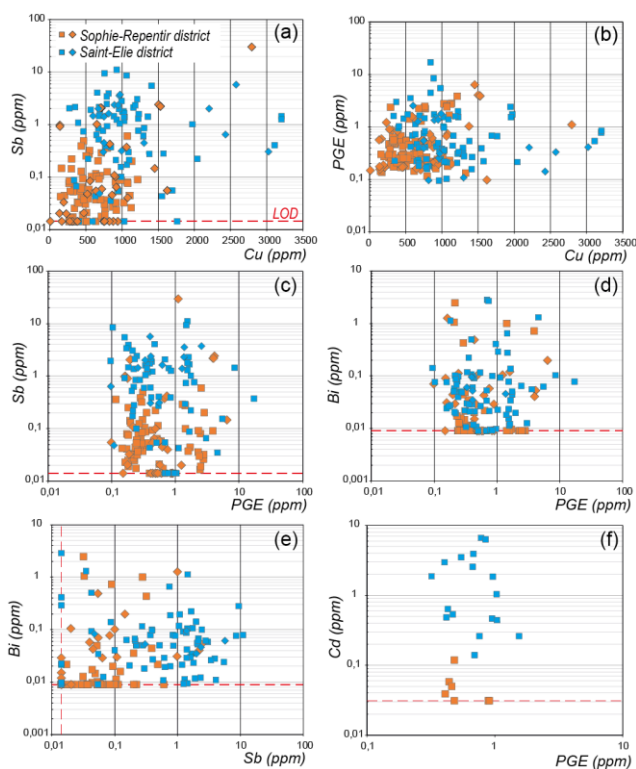


Figure 3. Bivariate plots showing trace elements content of gold grains from the studied areas. (a) Sb vs. Cu contents, (b) PGE vs. Cu contents, (c) Sb vs. PGE contents, (d) Bi vs. PGE contents, (e) Bi vs. Sb contents, (f) Cd vs. PGE contents. PGE (*i.e.* Platinum Group Elements) correspond to rhodium (Rh), palladium (Pd) and platine (Pt). Square represents primary gold, whereas diamond represents alluvial/eluvial gold. LOD = limit of detection.

6 Concluding remarks

Preliminary results of the chemical characterisation of alluvial-eluvial gold and the gold from their supposed lode source have shown several distinction between two orogenic goldfields hosted in the same greenstone belt. The signature of gold from the SE district is defined by the strong presence of bismuth in both gold alloy and inclusions of Bi-tellurides or tetradymite. Cadmium is also a specific feature of the SE gold as evidenced by the relative high Cd content and the greenockite in the paragenesis. Trace elements analysis by LA-ICP-MS therefore has a powerful potential for elements, such as Sb, Cd, Bi or PGE, rarely detected by the EPMA method. Additional data from others goldfields in French Guiana are needed to go further in the understanding of ore-forming processes related to gold systems.

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