Sb-Deposits in the Variscan Armorican Belt (France) - Potential Relationships with Basic Intrusions and High-Density Magnetic Lithologies at Depth

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Anthony Pochon, Denis Gapais
Géosciences Rennes - UMR6118, Université de Rennes 1, Campus de Beaulieu, 35042 Rennes Cedex

Charles Gumiaux, Yannick Branquet
Institut des Sciences de la Terre d'Orléans (ISTO) – UMR7327, Campus Géosciences, 1A rue de la Ferollerie, 45100 Orléans

Eric Gloaguen, Florence Cagnard, Guillaume Martelet
Bureau de Recherche Géologique et Minière (BRGM), 3 avenue Claude-Guillemin, BP 36009, 45060 Orléans Cedex 02

Abstract. Sb-deposits in the Variscan Armorican belt constitute a large part of this resource in France notably with the La Lucette deposit (42000 tons of Sb). Although these mineralizations are known since the 19th century, relationships between geological features and antimony deposits remain unclear. Here we perform a spatial statistical analysis using Geographic Information System software (GIS), geophysical and geological data (Ripley's function, spatial distribution analysis of geophysical values, and distance to the nearest neighbour) in order to identify particular geophysical zones where Sb-deposits are potentially clustering and to assess affinity with different geological objects. We show that there are specific ranges of gravity and magnetic values associated to Sb-deposits. These characteristic ranges outline several zones of high density and relatively high magnetic susceptibility that cover only 17.6 % of the surface of the Armorican Massif and contain or are close to more than 50 % of Sb-deposits. Moreover, Sb-deposits far from these zones are related with major faults. Our results reveal spatial relationships between Sb-deposits, major faults and high-density and magnetic zones that are interpreted as reflecting the occurrence of basic rocks at depth. The use of such a statistical approach enables to highlight geological controls of the mineralization.

Keywords. Sb-deposits, High-density magnetic lithologies, Spatial analysis, Variscan Armorican belt

1 Introduction

Mineralizations from the Armorican Massif constitute the most important resource for antimony in the French Variscan belt. Mineralizations are hosted by several lithologies of late Proterozoic and Paleozoic age. Usually Sb-deposits are considered to be related to a large-scale, late Variscan hydrothermal mineralizing event (Bouchot et al. 2005). In spite of numerous works, geological controls (e.g. origin of fluids, heat flux, fluids trap) still remain unclear.

In this study, we develop a new approach using Geographic Information System software (GIS), geophysical data and mapping data to analyse potential correlations between mineralizations and geological features, like intrusive magmas or lavas, lithologies, or major faults. First, we examined gravity and magnetic anomaly values where deposits are known and referenced. Statistical calculations further allowed us to determine geophysical anomalies associated with Sb-deposits. Then, a proximity analysis between Sb-deposits and various geological objects like major faults or basic rocks was performed.

The analysis reveals useful to outline first-order geological feature attached to mineralizations and thus provide tools to locate zones with high potential for mining exploration or scientific understanding (Bonham-Carter 2002; Carranza 2011).

2 Geological Setting

2.1 The Armorican Massif

The Armorican Massif is a part of the Variscan belt located in the western part of France. It comprises three main domains: North- (NAD), Central- (CAD) and South Armorican Domain (SAD). These domains are separated by two major crustal-scale shear zones (Gumiaux et al. 2004): the North Armorican Shear Zone (NASZ) and the South Armorican Shear Zone (SASZ).

The NAD was mainly structured during the Cadomian orogeny (late Proterozoic) and basically belonged to the upper brittle crust during Variscan times. The CAD is mostly composed of late Proterozoic to upper Paleozoic sediments deformed during Carboniferous times by regional dextral strike-slip under low-grade / greenschist facies metamorphic conditions (Gapais and Le Corre 1980; Gumiaux et al. 2004). Deformation is characterized by E-W striking upright folds and by a coeval vertical schistosity bearing a sub-horizontal stretching lineation. The SAD represents the internal zones of the belt that were thickened during the Variscan orogeny and are marked by large strains, high-grade metamorphic conditions and numerous intrusions of per-aluminous leucogranites.

2.2 Sb-mineralization

Most of the Armorican belt antimony deposits are stibnite-bearing quartz lodes. They are locally associated with gold and are mainly spatially associated with major shear zones (Chauris and Marcoux 1994). Numerous Sb-occurrences are known, but only four districts represents all of the antimony resources in the Armorican Massif (Chauris and Marcoux 1994): the La Lucette district, the Vendée district, the Le Semnon district and the Quimper-

Cap Sizun district).

The La Lucette district, which is located in CAD, consists of a swarm of meter-thick, N030°E trending quartz-carbonate veins hosted by Ordovician to Upper Silurian metapelites and sandstones (Chauris and Marcoux 1994). The paragenesis consists of dominant stibnite, arsenopyrite and native gold. In the Le Semnon district, the mineralization is characterised by berthierite-stibnite-arsenopyrite and gold-bearing quartz veins with carbonate (Chauris and Marcoux 1994) hosted by dolerite dykes that intruded Lower Ordovician slates.

In the Vendée district, more than 20 lodes have been recognized and mined up to 1992.The mineralization consists of dominant stibnite and quartz in tension gashes and shear fractures mainly hosted by Cambrian and Brioverian slates (Marcoux et al. 1984).

The Quimper-Cap Sizun district is the only one located in the western part of the Armorican Massif. There, Sb-deposits consist of stibnite-bearing quartz veins with locally Sb-sulfosalts, hosted by Ordovician and Variscan granitoids. They are associated with the SASZ, which contrasts with the three others district in the Armorican Massif (Chauris and Marcoux 1994).

Currently, Sb-deposits are related with a late Variscan belt-scale hydrothermal mineralizing event around 300 Ma (Bouchot et al. 2005) but no precise mineralization age has been obtained to date.

3 Spatial analysis

3.1 New Sb classification

In order to analyse available Sb-deposit data, a classification was first made on the base of three main criteria: main mineralogical assemblages, mineralization morphology, and presence or lack of Sb-sulphides / Sb sulfosalts. According to Chauris and Marcoux (1994), three types of mineralizations exist in the region: stibnite-gold type (La Lucette), stibnite-quartz type (Rochetrejoux) and stibnite-cinnabar type (La Rouxiere). After an exhaustive review of several works, four additional types are highlighted here (Fig. 3): stibnite-stratabound (Rosnoen), stibnite-galena (Montjean), sulfosalts without stibnite (Pointe de Plogoff) and sulfosalts without stibnite and with gold (St-Aubin-des-Châteaux). The conditions of formation for these different types of mineralizations are sensibly the same except for sulfosalts-type without stibnite and with gold. Indeed, the depositional temperature of this last is around 275 ± 9 °C (Gloaguen et al. 2007) whereas others are around 140 up to 175 °C (Bailly et al. 2000; Bellot et al. 2003). However conditions of formation of numerous Armorican Sb-deposits remain without data.

3.2 Data processing

Using statistical analysis, this study focussed on the quantification of spatial relationships between peculiar geophysical signatures and Sb-occurrence.

Data used are i) gravity data from the "Banque Gravimétrique de la France" (Martelet et al. 2009): including the Bouguer anomaly and its vertical gradient upward continued to 2.5 km (with a mesh grid of 1 x 1 km), ii) an airborne magnetic anomaly reduced to the pole with a mesh grid of 1 x 1 km (Bonijoly et al. 1999; Truffert et al. 2001), and iii) mining inventory which result from numerous works on the Armorican Massif (e.g. Meloux 1978).

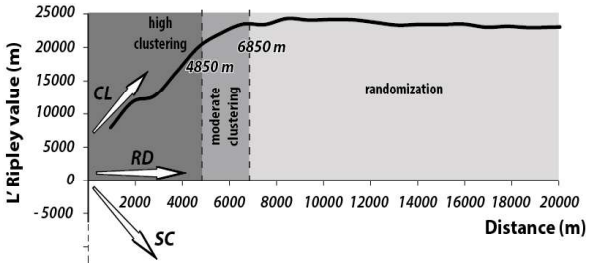

Figure 1. Ripley's L'- function computed to detect spatial deviations from a homogenous Poisson distribution. The computed Ripley's L'-function value = 20000 m corresponds to a high clustering rate of the Sb occurrence distribution, with a clustering distance of 4850 m and Ripley's L'-function value = 23570 m for a maximum distance equal to 6850 m (See fig. 3 in Deveaud et al. (2013) for further explanation). CL = clustering, RD = random distribution and SC = scattering.

The overall distribution pattern of Sb-deposit is illustrated here by the Ripley's L' function that shows a positive slope which highlights a cluster distribution of data set (Deveaud et al. 2013), up to 6850 m of inter-distance with two rates of clustering distinguished (Fig. 1).

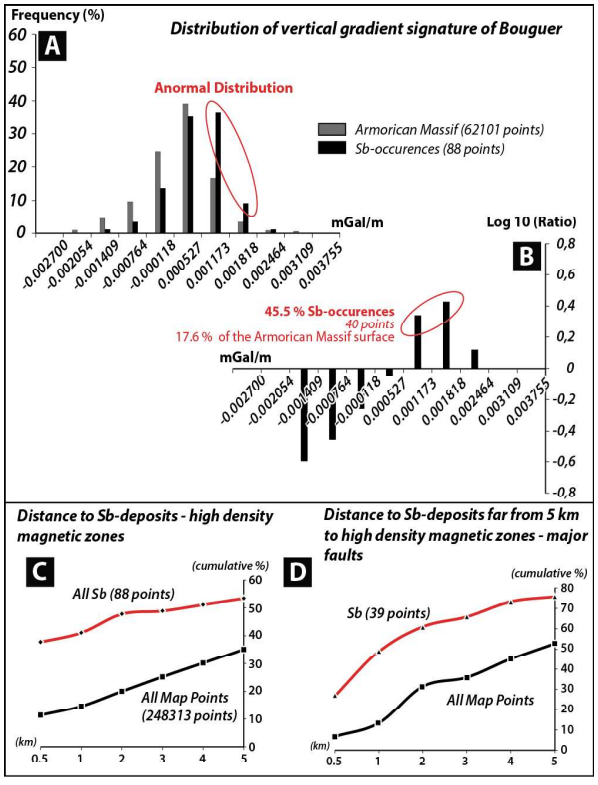

Figure 2. A. Frequency histogram of vertical gradient of Bouguer anomaly signature. **B.** Frequency log10 (Sb-values/ Armorican Massif-values) histograms. **C.** Spatial proximity analysis calculated among Sb-deposits and all map points and high density magnetic zones. **D.** Spatial proximity analysis calculated among Sb-deposits located at more 5 km to high-density magnetic zones and to all map points and major faults.

In order to detect potential links between geophysical anomalies and deposits, we then statistically compared the distributions of geophysical anomaly values near Sb-deposits with the ones for the entire Armorican Massif (considered as a reference) (Deveaud et al. 2013). This technique allows determining the geophysical signature of zones of potential Sb-deposits. According to the frequency histogram (Fig. 2A), an abnormal distribution of Sb-values for values of the vertical gradient of Bouguer anomaly is comprised between 0.000527 (exclude) to 0.001818 (include) mGal/m with a high ratio (Fig. 2B). This range covers only 17.6 % of the Armorican Massif surface and the corresponding areas contain 45.5 % of Sb-deposit. A similar statistical approach was performed on magnetic anomaly values reduced to the pole and Bouguer anomaly values. Thereby, several favourable geophysical signatures have been identified from the statistical analysis. In short, zones favourable for mineralization are correlated with zones of high density and relative high magnetic susceptibility.

A statistical analysis was also performed to examine geographical relationships between Sb-deposits and several geological objects (such as major faults, granitoids, basic rocks or the strong magnetic-gravity zones). As a reference, the same calculations were done for points of a grid covering the entire region (spaced every 500 m). Here only the shortest frequency with high density zones and major faults are shown (Fig 2C and 2D). The analysis shows that approximately 55 % of Sb-deposits are located at less than 5 km from high density and magnetic zones whereas only 35 % of reference points are closer than 5 km from these zones. When Sb-deposits are farther than 5 km of these zones, 76 % of them are less than 5 km of major faults.

3.3 Geophysical zones

Main results of our statistical analysis are displayed in Figure 3. They show a spatial link between Sb-deposits and high density / high-density and magnetic zones. This link may explain why Sb-deposits in the Le Semnon district occur in the middle of the CAD where there are no major faults. Three of the four main antimony districts are actually localized directly above high-density magnetic zones. Only the Quimper-Cap Sizun district, which is the smallest district, is not localized nearby such zones. Moreover, Sb-deposits that are neither near high-density magnetic zones nor near major faults are localized in distal aureoles of granites. The map (Fig. 3) also shows that 99 % of antimony resources and 90 % of antimony reserves known in the Armorican Massif are localized above the high-density magnetic zones. Finally, the deposit of Rosnoen, of Stb-Stratabound type, is located above the wider high density magnetic zones. This deposit has at least potentially antimony reserves of 10000 t (see Fig. 3 for references).

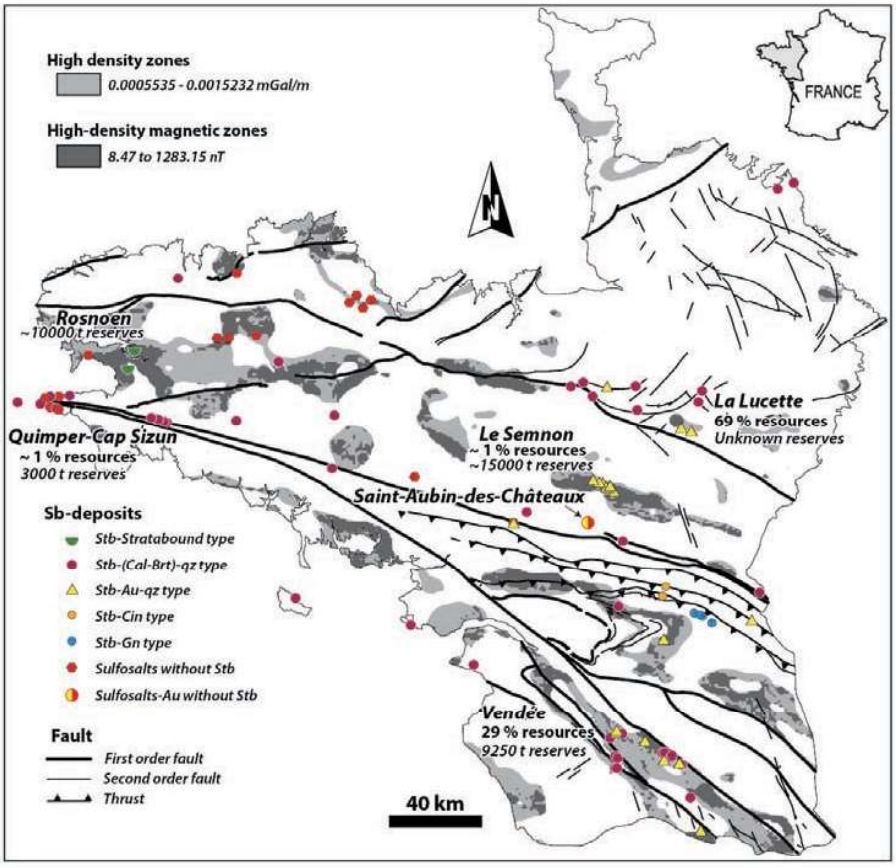

Figure 3. Map of spatial relationships between new classification of Sb-deposits high-density and magnetic zones throughout the Variscan Armorican belt. High density magnetic zones have the same range of gravimetric values as high density gravimetric zones. Data production from Audion (2012) in collaboration with European Strategic Intelligence Company (CEIS). Stb = stibnite, Cal = calcite, Brt = barite, Au = gold, Cin = cinnabar, Gn = galena.

4 Concluding remarks

This study has shown that Sb-occurrences in the Armorican Massif have a spatial clustering pattern. Indeed, there is a spatial link between these occurrences and localised high density and magnetic zones. Characteristics of these favourable zones determined by statistical analysis may be explained in several ways. Considering high density feature combined with relatively high magnetic susceptibility, only basic rocks or iron-mineral deposits (like pyrrhotite-bearing VMS or magnetite-bearing deposits) are possible as geophysical anomaly "sources". Few pyrrhotite-bearing VMS are known in the Armorican Massif but their associated magnetic anomalies are narrower. Few iron-mineral deposits are also known like Palaeozoic oolitic ironstone. In the Saint-Aubin-des-Châteaux area, there are Sb-mineralizations with sulfosalts (Gloaguen et al. 2007) within oolitic ironstone layers but these are too thin to generate a high positive vertical gravity gradient. On the other hand, Sb-mineralizations in the Le Semnon district are hosted by dolerite dykes and in the La Lucette district by Upper Silurian black shales intruded by numerous sills of dolerite. Therefore, a promising working hypothesis is that the high-density magnetic zones associated with mineralization are related to basic rocks localized in depth, probably in the upper part of the continental crust, feeding dykes and sills in near-surface. Nevertheless the origin of such spatial links remains to be further analysed. It is possible that basic rocks played a thermal role in the mobility of Sb-rich fluids or a leaching role in the composition of Sb-rich fluids. Several additional studies will be performed on the geochemistry and geochronology on basic rocks samples, especially dolerites.

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