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Granite petrogenesis revealed by combined gravimetric and radiometric imaging

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ABSTRACT

In peneplaned terranes, it is often impossible to get a full 3D view of geological objects. In the case of granitic plutons, for which intrusive relationships between constituent units can provide first order information regarding their petrogenesis, this lack of 3D field evidence is a major issue. Indirect observations can be provided by geophysical surveys. Here, we interpret field gravity data and airborne gamma ray radiometric maps with whole rock geochemistry data in order to obtain information on granite petrogenesis. First, we test our proposed combined geophysical and geochemical approach on the Huelgoat Variscan intrusion (Armorican Massif, France) and we show that ternary radiometric maps are a good proxy for the distribution of K, U and Th radioelements. Then, we apply our method to the Lizio and Questembert Variscan granitic intrusions (Armorican Massif) and show that some features characteristic of the intrusions, such as the feeding zones, can be localised by geophysical imaging. Indeed, radiometric maps constitute a frozen image of the latest stage of the magmatic building of plutons.

1. Introduction

Petrological and geochemical field-based studies of granite petrogenesis in old and eroded areas often preclude direct 3D observations, especially for the deepest part of those massifs. Nevertheless, geophysical imaging is known to be a powerful tool to determine the 3D shape and the deep structure of the plutons (e.g. Benn et al., 1999; Vigneresse, 1990). Combined radiometric, magnetic and gravity data have also been used to study emplacement mechanisms (Castro et al., 2002; Clemens et al., 2009; Oliveira et al., 2008).

Recently, Tartèse and Boulvais (2010) showed that the petrological and geochemical differences between two Variscan granites emplaced at distinct depths along the South Armorican Shear Zone (SASZ; Jégouzo, 1980; Fig. 1a) could be related to the fractionation of K-feldspar (Kfs), plagioclase (Pl), biotite (Bt), zircon and monazite during magma migration toward the surface. The model also implies that feeder zones for highly differentiated granitic plutons should be enriched in these minerals, though the present-day level of exposure precludes direct observation of the deepest parts of the plutons. The validity of the model can nevertheless be tested by integrating the available geophysical data obtained throughout the area (Bonijoly et al., 1999), especially an airborne gamma ray spectrum that images the radioactive heterogeneity at the present surface level.

This paper suggests that airborne radiometric maps can be used as an efficient tool to investigate petrogenetic processes acting during magma emplacement and leading to heterogeneities in the distribution of K, U and Th in granitic plutons. First, the accuracy of aerial measurements is tested on a pluton well covered by whole rock geochemical analyses (Huelgoat granite, Armorican Massif, Fig. 1b). Airborne data are then compared with the gravity-derived image of its shape at depth in order to examine whether the surface data and the information about floor depth can be correlated. Then we apply this approach to two synkinematic leucogranites (Lizio and Questembert granites, Armorican Massif, Fig. 1b) and we argue that the K-relative rich zones (high $K/(K+Th+U)$) displayed on the ternary radiometric map are the surface witnesses of the vertical deep conduits that fed the plutons. Radiometric maps thus image the latest stages of the magmatic construction of plutons.

2. Geological setting

The studied granitic plutons (Fig. 1b) belong to the European Variscan belt, which is part of the Variscan orogen central domain (Fig. 1a), where numerous Carboniferous plutons were emplaced. The collision initiated in the late Devonian and evolved until early-Carboniferous times (e.g. Ballèvre et al., 2009; Matte, 1986). The Huelgoat granite is a composite intrusion emplaced 340 ± 9 Ma ago (whole rock Rb–Sr isochron; Georget, 1986) in the western part of the region (Fig. 1b), at a depth corresponding to a pressure of 3–4 kbar (Georget, 1986). It is partly related to the NASZ (Fig. 1). The other major feature in this part of the

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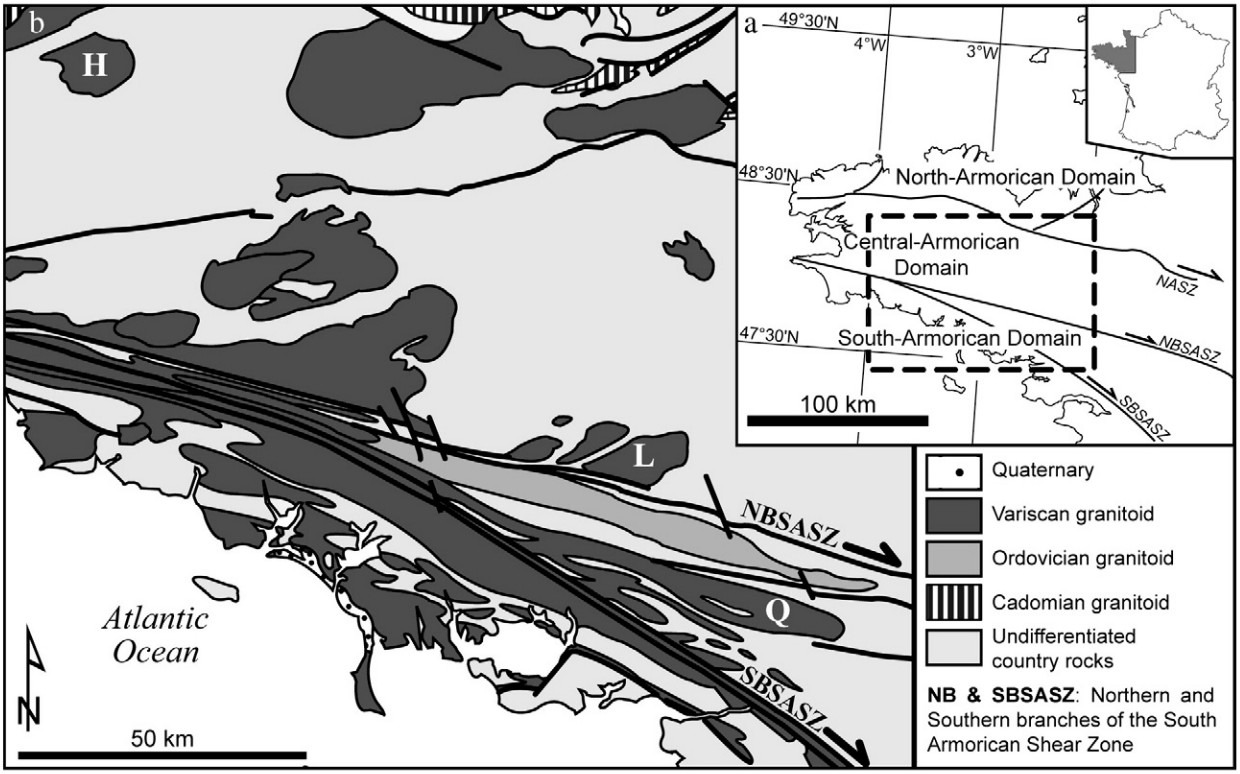

Fig. 1. (a) Location of the studied area in France and in the Armorican Massif. NASZ: North Armorican Shear Zone; NBSASZ and SBSASZ: Northern and Southern branches of the South Armorican Shear Zone. (b) Simplified geological map of the studied area. H: Huelgoat granite; L: Lizio granite; Q: Questembert granite.

Armorican Massif is the South Armorican Shear Zone (SASZ; Jégouzo, 1980), a composite crustal shear zone which localised dextral wrenching that affected the region during the Carboniferous (e.g. Gumiaux et al., 2004). Along its northern branch (NBSASZ), numerous syntectonic Carboniferous granitoids (Bernard-Griffiths et al., 1985; Berthé et al., 1979) have been emplaced into the Pre-Variscan basement (Fig. 1b), which is also characterised by base metal ore deposits (Gloaguen et al., 2007). Among them, the Lizio leucogranite is dated at ca. 338 Ma (whole rock Rb–Sr isochron; Bernard-Griffiths et al., 1985). Southward, the Questembert leucogranite was emplaced at around 329 Ma (whole rock Rb–Sr isochron; Bernard-Griffiths et al., 1985) between the two branches of the SASZ (Fig. 1b). Based on the regional stratigraphy and on syntectonic metamorphic assemblages of the surrounding country rocks, Tartèse and Boulvais (2010) argued that the Lizio and Questembert granites were emplaced at ca. 3–4 kbar and 1–2 kbar, respectively.

3. Geophysical surveys

A detailed airborne magnetic and radiometric survey was carried out over the Armorican Massif (Bonijoly et al., 1999; Truffert et al., 2001) in order to provide improved mapping for a region that is largely covered by surficial and weathered formations. The data set was collected along 117 700 km of lines on N–S flight lines with a spacing of 500 to 1000 m, a sample rate of 0.1 s for magnetic data and 1 s for radiometric data at an altitude of 120 m and a flying speed of 240 km/h. E–W control lines were recorded every 10 km. Operating procedures as well as calibrations followed the recommendation of the International Atomic Energy Agency (I. A. E. A., 2003). Airborne geophysical data were interpolated using the minimum curvature method with a 250 m regular grid spacing. The ternary K–Th–U radiometric map has been obtained by red–green–blue additive chromatic combination applied point by point for the three radiometric measurements. On these ternary K–Th–U radiometric maps, the geological features are well displayed, despite the fact that the area is affected by weathering and soil development. One can thus consider that gamma ray radiometric maps actually image the substratum rather than superficial features.

Gravity also helps to determine the deep structures of a granitic pluton. Because the density of acid igneous rocks is lower than that of the surrounding country rocks, the gravity signature of a granitic intrusion is often negative, which allows us to deduce its shape at depth. A detailed gravity survey has been acquired by Georget (1986) on the Huelgoat granite (Fig. 1b), comprising more than 200 data stations, which resulted in an average coverage of more than one measurement per square kilometre. After raw data processing and subtraction of the regional field, the 3D structure of the pluton has been derived by inversion of the residual Bouguer anomaly. In order to obtain the best shape approximation, the density contrast varied according to the different petrographic types within the intrusion. The calculation followed the procedure described by Vigneresse (1999), and the precision of isodepth lines obtained is estimated at $\pm$15%.

4. The Huelgoat granite: establishing the method

4.1. Shape of the intrusion

Several studies have shown that important information can emerge when compositional zoning in plutons is regarded in relation to the granite shape at depth, notably information on magma flow and granite petrogenesis (e.g. Hecht et al., 1997). The shape of the Huelgoat pluton has been investigated by Georget (1986) using gravity inversion. The resulting isodepth lines are presented on Fig. 2a, together with the cartographic outline of the pluton and its constituent units. Fig. 2a also shows a 3D visualisation of the shape of the pluton. The granite is seen to have a major 6–7 km deep root zone in its central part, while in its northeastern part, there is another 5 km deep root zone. Together, these roots define a N030° direction. The contact between the Huelgoat and the La Feuillée units is well marked by the 2 km isodepth line.