Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

**Relations between basalts and adakitic/felsic intrusive
bodies in a soft-substrate environment:
The South Ouessant Visean basin in the Variscan belt,
Armorican Massif, France**

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2015-0230.R1
Manuscript Type:	Article
Date Submitted by the Author:	11-Feb-2016
Complete List of Authors:	Caroff, M.; UMR N 6538 Domaines Oceaniques Le Gall, Bernard; UMR N 6538 Domaines Oceaniques Authemayou, Christine; UMR N 6538 Domaines Oceaniques Bussien Grosjean, Denise; Musée cantonal de Géologie, Quartier UNIL- Dorigny, Bâtiment Anthropole Labry, Cyrill; UMR N 6538 Domaines Oceaniques Guillong, Marcel; Institute of Geochemistry and Petrology, Department of Earth Sciences, ETH Zurich, Clausiusstrasse 25
Keyword:	Armorican Variscides, Visean basin, adakite, peraluminous granite, peperite

SCHOLARONE™
Manuscripts

1 Relations between basalts and adakitic/felsic intrusive bodies in a soft-
2 substrate environment:

3 The South Ouessant Visean basin in the Variscan belt, Armorican
4 Massif, France

5
6
7 Martial Caroff^{a,*}, Bernard Le Gall^a, Christine Authemayou^a, Denise Bussien
8 Grosjean^{a,1}, Cyrill Labry^a, Marcel Guillong^b

9
10 ^aUMR/CNRS n°6538 « Domaines Océaniques », Institut Universitaire Européen de la Mer,
11 Université de Brest, Place Nicolas Copernic, 29280 Plouzané, France

12 ^b Institute of Geochemistry and Petrology, Department of Earth Sciences, ETH Zurich,
13 Clausiusstrasse 25, 8092 Zurich, Switzerland

14
15
16 * Corresponding author: caroff@univ-brest.fr

17
18
19 ¹ Present address : Musée cantonal de Géologie, Quartier UNIL-Dorigny, Bâtiment
20 Anthropole, 1015 Lausanne, Switzerland.

21

22 *Abstract*

23 The metasedimentary and magmatic terranes in the southern part of the Ouessant Island
24 (Western Brittany, France) are the offshore prolongation of the Léon Variscan metamorphic
25 domain. They mainly consist of micaschists and subordinate amphibolitic lenses (meta-
26 pillow lavas and volcanoclastic successions) cut by a swarm of trondhjemite sills, together
27 with a large porphyritic monzogranite body, newly dated at 336 Ma, and later syeno-
28 leucogranitic intrusions. A large spectrum of fluidal peperites, including spectacular
29 “flamme”-bearing breccias, is observable at the contact between metasediments and most of
30 the intrusives. The coexistence of amphibolitized basalts, adakitic trondhjemites, and
31 peraluminous granites in the inferred South Ouessant basin is assigned to a variety of deep
32 subcontemporaneous processes, including asthenospheric partial melting, high-pressure
33 fractionation in lithospheric reservoirs (or partial remelting of deep crystallized mafic
34 intrusions), and continental crust melting. Implications of these new results are discussed in
35 the Viséan basinal framework of the Armorican Massif, formed at an early stage of the
36 Variscan orogeny.

37

38 *Résumé*

39

40 Les formations métasédimentaires et magmatiques de la partie sud de l'île d'Ouessant
41 (Bretagne occidentale, France) correspondent au prolongement occidental du domaine
42 métamorphique varisque du Léon. Elles comportent essentiellement des micaschistes – dans
43 lesquels on trouve quelques lentilles d'amphibolites (anciennes laves en coussin et
44 successions volcano-sédimentaires) – traversés par un réseau de sills trondhjémiques et un
45 important corps de monzogranite porphyrique, nouvellement daté à 336 Ma, ainsi que par des
46 intrusions syéno-leucogranitiques légèrement plus tardives. Un large spectre de pépérites

fluidales, comprenant de spectaculaires brèches à « fiammes », peut être observé au contact entre les métasédiments et la plupart des roches intrusives. La coexistence de basaltes amphibolitisés, de trondhjémites adakitiques et de granites peralumineux dans les métasédiments d'Ouessant sud est attribuée à plusieurs processus profonds subcontemporains, incluant : une fusion partielle asthénosphérique, un fractionnement haute pression dans des réservoirs lithosphériques (ou une refusion partielle d'intrusions mafiques profondes) et une fusion de la croûte continentale. Ces nouveaux résultats sont discutés dans le cadre des bassins viséens armoricains, formés à un stade précoce de l'orogénèse hercynienne.

Mots clés: Chaîne varisque armoricaine, bassin viséen, adakite, granite peralumineux, pépérite

1. Introduction

Recent studies have shown that peperites are very widespread in volcano-sedimentary basins, regardless of the tectonic context, as for instance: outer shelf-slope basin (Coira and Pérez 2002), back-arc rift (Dadd and Van Wagoner 2002), continental half-graben (Galerne et al. 2006), and semi-arid lake in fault-bounded basin (Erkül et al. 2006). They include a large variety of clast morphologies from blocky to fluidal (globular, ameboidal and pillow-like varieties), as a result of sediment fluidization at the contact with the magmatic bodies (Skilling et al. 2002).

Bimodal magmatism usually occurs in fault-bounded pull-apart continental sedimentary basins, as mafic and silicic (or intermediate) magmas ascending through the boundary faults, before intruding or spreading out more or less simultaneously in the sedimentary infill (e.g., Caroff et al. 1996; Schaltegger et al. 1996). Associated basalts are generally anorogenic and display either a tholeiitic (e.g., Schaltegger et al. 1996) or a slightly alkaline affinity (e.g., Saadat et al. 2010).

Such a magmatic environment is documented in the low-grade metamorphic (metasedimentary) terranes of the Ouessant Island, western offshore continuation of the Léon Domain, Armorican Massif (Fig. 1). Emphasis is put here on the analysis and interpretation of still preserved fluidal peperite textures, including uncommon fiamme-bearing granitic breccias. In addition, various magmatic types, with affinities usually reputed inconsistent, such as anorogenic basalts, adakitic trondhjemites and peraluminous granites, are assumed to have emplaced subconcomitantly in the South Ouessant basin, Viséan in age.

2. Analytical techniques

2.1. U/Pb zircon dating

Zircon grains extracted from a monzogranitic sample by standard mineral separation were placed in epoxy resin, polished (equatorial plane), and then imaged by cathodoluminescence (CL; CamScan MV2300, Earth Sciences Institute, University of Lausanne, Switzerland). Avoiding perturbed zones and inherited cores, dating was performed by laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS ; Resonetics Resolution 155 excimer laser ArF 193 nm and Thermo Element XR magnetic sector; Institute of Geochemistry and Petrology, ETHZ), with the same analytical parameters as in Caroff et al. (2015).

A typical analytical sequence starts with the internal standard analyses (GJ-1), a maximum of 24 unknown grains, three natural zircons (Temora, Plesovice and 91500) as secondary standards, and ends with GJ-1. The Glitter software package (van Achtenberg et al. 2001) and Isoplot/Ex v. 4.15 (Ludwig 2008) were used to process and plot the data. Based on Concordia and Tera-Wasserburg diagrams, the analytical validity of each measurement was

98 estimated and the intercept age obtained, respectively. Repeated measurements on the GJ-1
99 show an age of 604.5 ± 2.0 Ma (2 sigma, n=17) and the Plesovice resultant age is 338.4 ± 2.2
100 Ma (2 sigma, n=5; certified value of 337.13 ± 0.37 Ma by Sláma et al. 2008).

101

102 *2.2. Whole-rock analyses*

103

104 Whole-rock major and trace elements and isotopic ratios were determined at the
105 PSO/IUEM (Pôle Spectrométrie Océan, Institut Universitaire Européen de la Mer, Brest,
106 France). Major elements were analyzed by inductively coupled plasma-atomic emission
107 spectrometry (ICP-AES) using a Horiba Jobin Yvon® Ultima 2 spectrometer and following
108 the analytical procedure of Cotten et al. (1995). Relative standard deviations are $< 2\%$ ($< 1\%$
109 for SiO_2), except for low values (< 0.50 wt%), for which the absolute standard deviation is $\pm$
110 0.01 wt%. Trace elements were determined by high-resolution ICP-MS, using a Thermo
111 Element 2 spectrometer, following the sample preparation and analytical procedure described
112 by Barrat et al. (1996). Relative standard deviations are $< 5\%$ for most of trace elements and $<$
113 10% for Nb, Gd, Tb, Ta, Ni, Zn and Rb. Sr isotopic ratios were measured by thermal
114 ionization mass spectrometry (TIMS), while Nd isotopic ratios were quantified using a
115 multicollector ICP-MS (PSO/IFREMER, Brest, France). The protocol for element separation
116 is described in White and Patchett (1984).

117 More details on analytical techniques and complementary references can be found in
118 Caroff et al. (2015).

119

120 **3. Geological setting and age framework**

121

The Variscan belt of Brittany (western France) consists of a mosaic of structural domains that have been amalgamated during Carboniferous times along a network of crustal-scale EW-trending ductile dextral fault zones, e.g. the North and South Armorican Shear Zones (NASZ and SASZ, Fig. 1a) (Gapais and Le Corre 1980). The Central Armorican Domain (CAD) is composed of a thick pile of gently folded and schistosed sedimentary rocks, ranging in age from Proterozoic up to Lower Carboniferous in the Châteaulin and Laval basins (Fig. 1a) (Le Hérissé and Plaine 1982; Rolet et al. 1986; Darboux and Le Gall 1988; Gumiaux et al. 2004). The composite block extending north of the NASZ mainly comprises Cadomian metamorphic and magmatic terranes that mostly escaped Variscan strain, excepted to the west in the highly strained Léon metamorphic domain. This area is separated from the CAD sedimentary rocks to the south by the NASZ system (Fig. 1a, b). To the east, the Léon metamorphic terranes are overlain by sedimentary rocks of the Morlaix Viséan basin (Fig. 1a) (Cabanis 1986).

The Léon domain is composed of a northerly-directed thrust stack of metamorphic units emplaced in the time range 440-340 Ma (Paquette et al. 1987). They were later exhumed during a long-lasting transtensional tectonic event, synchronously to granitic processes at 340-300 Ma (Schulz et al. 2007; Marcoux et al. 2009; Le Gall et al. 2014). Two successive ductile shearing episodes, with opposite senses of movement, took place in this time range. Early dextral shearing occurred along the E-W-trending NASZ, synchronously to the intrusion of the Saint-Renan granite at 316 ± 2 Ma (Le Gall et al. 2014). The emplacement of the younger and sinistral N70°E-oriented Plouguerneau-Guisseny ductile shear zone (PGSZ) further north was accompanied by the c. 300 Ma-old Aber-Ildut granitic complex (Caroff et al. 2015).

The Ouessant Island extends offshore of the Léon metamorphic domain (Fig. 1a, b). Its overall N70°-trending structural arrangement involves two distinct areas that differ in terms of both lithological contents and tectonic histories, but that share a common

metamorphic evolution with a HT peak at c. 305 Ma (monazite age from Schulz 2013). The northern area involves various c. 300 Ma-old granitic intrusions (Caroff et al. 2015). There, ductile strain is mainly expressed by the North-Ouessant sinistral shear zone (NOSZ) that forms the offset western offshore prolongation of the above-mentioned PGSZ. The Central-Ouessant shear zone (COSZ) separates the North Ouessant area from the metasedimentary and magmatic rocks of the 2-3 km-wide South Ouessant area, under study here (Fig. 1b and 2). There, highly strained micaschists are intensely intruded by a swarm of (micro)trondhjemite sills and by a K-feldspar porphyritic granitoid, extending as either a map-scale intrusion or thin sills. Slightly younger muscovite granitoid intrusions locally occur in contact with either porphyritic granitoid or micaschists. The latter also contain, to the south, subordinate amphibolitic layers and lenses (Fig. 2). The South Ouessant metasedimentary/metavolcanic formations recorded an amphibolite-grade metamorphism (Schulz 2013) that increased slightly southwards.

The porphyritic monzogranite 14DB01 yields a Concordia age of 336.3 ± 2.3 Ma (1 sigma, MSWD = 1.4), slightly older than its $^{206}\text{Pb}/^{238}\text{U}$ age of 335.7 ± 2.4 Ma (1 sigma, MSWD = 1.3) (Fig. 3 and Table S1). From field relationships (see section 4.2.), it is further argued that this magmatic event, which predated regional strain and metamorphism in the South Ouessant area, occurred synchronously to initiation of the so-called South Ouessant basin (SOB in the text). As assuming the Visean age of the SOB, our results supply quite new insights about the early Variscan basinal/magmatic history experienced by Lower Carboniferous terranes, west of the Leon metamorphic domain. The SOB is assumed to be part of the network of intra-continental sedimentary basins documented further east in the CAD (Châteaulin, Morlaix and Laval), and also in the South Armorican Domain (Ancenis) (Fig. 1a).

4. Field relationships

4.1. Pillow lavas and volcanoclastic successions

Metavolcanic formations crop out punctually in the form of amphibolitic intercalations in micaschists along the southern coast of the South Ouessant Island (Chauris 1994) (Fig. 2). Two early types are exposed, as lavas and volcanoclastic successions.

Despite intense strain and metamorphism (Schulz 2013), ancient effusives still show recognizable initial pillow-like structures in the Porz Doun sector (Fig. 2), in contact with micaschists. Most of them display an ovoid form (Fig. 4a), sometime stretched by tectonics, and some are bordered by a chilled margin (Fig. 4b, c). They are massive, showing no internal structures.

Ancient volcanoclastic successions are more common than the pillow lavas. They comprise alternations of light (quartz-dominant) and dark (amphibole-dominant) thin-layered (from a few millimeters to a few centimeters in thickness) clast-bearing volcanic-derived deposits (Fig. 4d). Either light or dark layers may be prevalent. The beds, generally regular, are sometimes of variable thickness, displaying undulated and beveled forms. Although their volcanic origin is not in doubt, the scarcity of original deposit features, together with significant metamorphic recrystallizations, make the interpretation of initial breccias very difficult. Nevertheless, it is here assessed that the layer thickness pattern, as well as the local presence of lenticular and corrugated (amphibole-bearing) thin beds (Fig. 4e), typically resemble the bedded eruption-fed submarine facies described elsewhere by McPhie and Allen (1992), Caroff et al. (2009), and Jutzeler et al. (2014).

4.2. Silicic intrusions

Trondhjemites and microtrondhjemites occur as a dense and folded sill/dyke network in the micaschists, north of the SOB (Fig. 2). The greatest body can be observed to the east, in the Stiff Bay. It is an ENE-WSW-trending 200 m-thick sill, more than 1 km in length, cut by a subvertical network of NS-trending normal faults (Chauris 1994). The other occurrences, in the Stiff Bay and, to the west, in the Lampaul Bay, are up to 10's m-thick intrusions. Contacts between (micro)trondhjemites and micaschists systematically display finger-shaped, rounded or lobate morphologies (Fig. 4f).

The main magmatic formation in South Ouessant is a schistosed K-feldspar porphyritic granitoid that forms either a map-scale intrusion in the micaschist host-rocks to the east or a dense sill/dyke swarm, of variable thickness, to the west (Fig. 2). Special attention has been paid to the remarkable porphyritic granitoid/metasediment contacts. That provides quite original new insights about the conditions of emplacement of the porphyritic intrusives in the SOB infill. In some places, the silicic intrusions form undulated sills, insulated amoeboid bodies (Fig. 4g), or even frozen descending crystal-bearing plumes (Fig. 5a) in the metasediment. Elsewhere, contacts are more diffuse and metasediment appears to be loaded with isolated feldspar crystals, whilst magmatic intrusions only occur as small-sized undulated lodes or veinlets (Fig. 5b). Such features undoubtedly show analogies with magma/sediment mingling facies (peperites) described elsewhere (e.g., Skilling et al. 2002; Martin and Németh 2007). Additional interaction facies corresponds to fiamme-bearing breccias (see 4.3).

A third type of felsic intrusions is evidenced in the SOB metasedimentary infill. It consists of a largely-distributed sill/dyke network of a schistosed muscovite granitoid. The main intrusion has a thickness of c. 100 m. To the south-west, sills and dykes cut through the micaschists, the porphyritic granitoid and/or the mingling facies (Fig. 2). From these mutual

cross-cutting relationships, further completed by the observation of undulate, finger-shaped (Fig. 4h) and lobate contacts between the muscovite-bearing granitoid and metasediment (less marked than about the porphyritic granitoid), it is firmly assumed that the intrusion of the muscovite granitoid predated the complete lithification of the sediment and postdated the emplacement of the porphyritic granitoid.

4.3. *Fiamme-bearing peperitic breccias*

Remarkable interaction facies between porphyritic granitoid and micaschist can be observed in a small embayment of the coastline south of the south-western headland (Porz Ejen, Fig. 2). There, elongate metasedimentary clasts are embedded within a mingled matrix where granitoid and micaschist materials are hardly distinguishable, hence forming fiamme-bearing schistosed breccias (Fig. 5c and d). Some metasedimentary “flame-like” lenses extend parallel to the regional schistosity, others not. Consequently, tectonics does not seem to be at the origin of the clast elongation, even if it could have locally contributed to it. The lense-shaped metasedimentary clasts of the SOB mingled breccias are confidently regarded as fiammes, i.e. elongate lenses or domains of similar mineralogy, texture and composition within a contrasted material, hence resulting in an early (pre-tectonic) foliation-like structure (following the definition of Bull and McPhie 2007).

Approximately 500 m east of the previous sector, a mingling facies between porphyritic granitoid and metasediments encloses lenses of graphite-bearing micaschists, similar to the abovementioned fiammes but not oriented, in the process of detaching from the main metasedimentary bodies (Fig. 6). Such specific magma-sediment features might be regarded as highly evolved peperitic facies (Skilling et al. 2002; Caroff et al. 2009), in turn arguing for the syn- (or slightly post-) depositional emplacement of the porphyritic granitoid

intrusions. As the other magmatic units of the SOB also display peperitic contacts, all of them can thus be considered as subcontemporaneous at c. 336 Ma.

5. Textural and petrological notes

5.1. Sampling and nomenclature

Most samples were collected in 2014 and 2015 along the southern coast of the Ouessant Island. In addition, new data on lavas from the northern edge of the Châteaulin basin and the southern part of the Laval basin, respectively sampled in 1994 and 1999, are also presented here (Table 1).

The petrographic nomenclature of lavas and (pre-metamorphic) amphibolites is based on the total alkali-silica (TAS) classification scheme of Le Maitre et al. (2002) (not shown). The granitoid nomenclature is based on the Q' vs. ANOR diagram (not shown), derived empirically by Streckeisen and Le Maitre (1979) from the IUGS classification of Streckeisen (1976) and considered as its CIPW normative equivalent. The samples OS10 and OSB30, which plot in the right part of the granodiorite field of the Q' vs. ANOR diagram, display a mineralogy of (micro)trondhjemite (see below) and, thus, will be considered as such.

5.2. Micaschists

Texture and mineralogy of the SOB micaschists change progressively from north-west to south-east in the area. In the central part of the island, micaschists are glossy and mainly made up of muscovite, chlorite and quartz. Great chloritized biotite crystals are sparsely secant to the schistosity planes. Other minerals are plagioclase, >2 mm-long helicitic

almandine, 1-2 mm-long staurolite, sparse andalusite, and euhedral tourmaline (Chauris 1994). Quartzite beds are observable in several places in the glossy micaschists. Along the southern coast, micaschists are distinguished by the presence of numerous great poikiloblastic muscovite crystals, secant with respect to schistosity. Other minerals are, in order of decreasing abundance: biotite, quartz, garnet – red almandine and yellow grossular – with lengths ranging from 3 mm to 4 cm (Chauris 1994), late poikiloblastic tourmaline, and plagioclase. Graphite is locally present in significant quantities, as shapeless patches in the poikiloblastic micaschist or as clasts in the granitoid/micaschist fiamme-bearing mingled breccias (Fig. 5c). An intermediate facies between glossy and poikiloblastic micaschists occurs along the north-west coast of the south-western headland.

5.3. Amphibolites

The highly stretched amphibolitized pillow lavas, basaltic in composition, have a nematoblastic texture. They contain aligned green hornblende, quartz, sericitized plagioclase, ilmenite, apatite and subordinate titanite (Fig. 7a). A few retromorphosed pillow lavas typically contain greenschist facies assemblage of actinolite, chlorite and epidote, in addition to altered plagioclase, quartz, ilmenite and apatite.

The volcanoclastic layered breccias are characterized by a succession of beds alternately light and dark. The light layers are mainly formed of quartz and plagioclase (either one of these two minerals is the most abundant), then also green hornblende, Fe-Ti oxides and apatite. Texture is either clastic or granoblastic. The dark layers contain mainly green hornblende with a nematoblastic texture. Subordinate minerals are quartz, plagioclase, biotite, muscovite, Fe-Ti oxides, and apatite. Light layers are sometimes disturbed by the presence of millimeter-sized nematoblastic amphibolitized clasts. A hornblende-dominant bedded breccia

from Porz Doun (Fig. 2) contains a remarkable clast, several centimeters in size, which still shows a preserved primary texture and mineralogy. It is mainly constituted of augite and plagioclase, making layers that range from macro- to microgranular textures.

5.4. Trondhjemites and microtrondhjemites

Rocks of this type usually display a highly porphyritic microgranular texture in South Ouessant (Fig. 7b), excepted the 200 m-thick trondhjemitic dyke in the Stiff Bay (Fig. 2) that instead shows a porphyritic coarse-grained texture. In both cases, phenocrysts are euhedral square-section Na-rich plagioclase crystals, up to 7 mm-long (Fig. 7b). Their twins often display mechanical distortions. Groundmass minerals are quartz with undulose extinction, rare chloritized biotite and late muscovite.

Sample OSB30 has been taken from a 5-10 m-thick microtrondhjemitic intrusion located west of the island, whereas sample OS10 is from the 200 m-thick trondhjemitic sill in the Stiff Bay (Fig. 2).

5.5. Granites

The porphyritic granitoid is a monzogranite following the classification scheme of Streckeisen and Le Maitre (1979). Its porphyritic texture is supported by 1-2 cm-long square-section feldspar crystals (microcline or orthoclase, and oligoclase) (Figs. 4g and 5b), with local myrmekite structures (Fig. 7c). Quartz is also present as large crystals with undulose extinction and small contiguous recrystallized crystals, as well as biotite, apatite, and late tourmaline. Muscovite is lacking or very rare. In the Porz an Ejen mingled complex (Fig. 2),

intense fragmentation of the monzogranite results in K-feldspar megacrysts embedded within the graphite-bearing poikiloblastic micaschist host rock (Fig. 8a).

Following the Q' vs. ANOR diagram of Streckeisen and Le Maitre (1979), the muscovite granitoid divides into two contemporaneous petrographic types, both with a granular texture, i.e. syenogranite and K-feldspar leucogranite. The first one is made up of K-feldspar, quartz, plagioclase, muscovite, biotite, and apatite. In the second type, very light colored, the mica population is dominated by muscovite (Fig. 7d). Leucogranitic intrusions often contain disseminated tourmaline and garnet. Pegmatite occurrences are frequently associated with them. An example of microtexture of the lobed contacts between coarse-grained tourmaline-bearing leucogranite and fine-grained metasediment is shown in Fig. 8b. There is no clear limit between both lithologies, but a 2-4 mm-large biotite-rich transition zone.

6. Geochemistry

6.1. Major elements

Glossy and poikiloblastic micaschists, occurring respectively north and south of the SOB, display contrasted major element compositions. The glossy micaschist LC1 is more siliceous and more aluminous than the poikiloblastic micaschist LC5, which is, by contrast, enriched in CaO and K₂O. The local presence of grossular in the latter type may be related to relatively high CaO contents.

The South Ouessant amphibolites plot in the basalt field in the TAS diagram of Le Maitre et al. (2002). They are characterized by high content in TiO₂ (> 1.8 wt%, Table 1 and Fig. 9a) and by P₂O₅ values ranging from 0.2 to 0.4 wt% (Table 1 and Fig. 9b). Their major

element composition is compared in Fig. 9 with that of mafic lavas from contemporaneous basins in the CAD and of Visean dolerites from Saint-Malo (North Armorican Domain). The highest TiO_2 values concern the mafic rocks from Laval, Châteaulin and Saint-Malo, whereas the lowest TiO_2 contents correspond to the Morlaix and South Ouessant amphibolites (Fig. 9a). P_2O_5 is especially high in the Laval basalts (> 0.6 wt%) and low in the Morlaix amphibolites (< 0.3 wt%); the other mafic rocks plot between these values (Fig. 9b). The andesite sample KR22 from the Châteaulin basin shifts to the right in both diagrams ($\text{SiO}_2 = 61.80$ wt%, Table 1). All the Visean mafic rocks from the Central and North Armorican Domains plot at the intersection between the Ocean Island, Ocean Ridge and Continental basalts fields in the triangular discrimination diagram of Pearce et al. (1977) (Fig. 9c). Accordingly, all of them have a clear anorogenic affinity.

The SOB felsic rocks are characterized by high SiO_2 contents (> 67 wt%, Table 1 and Fig. 9a, b). The syenogranite OS3c has a $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio higher than that of the monzogranites (1.57 vs. 0.96-1.02, Fig. 9d). All the granites from the SOB are peraluminous, i.e. with ratios of molecular $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ or 'A/CNK' exceeding 1: 1.07-1.13 for the porphyritic monzogranites, 1.16 for the syenogranite OS3c, and > 1.15 for the tourmaline-bearing leucogranite LC29. Syeno- and leucogranites from South Ouessant can even be considered as strongly peraluminous rocks, following the criterion of Sylvester (1998): $\text{A/CNK} \geq 1.1$. In the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs. SiO_2 diagram of Fig. 9d, the South Ouessant (micro)trondhjemites plot within the of the high-silica adakite (HSA) field, close to the trondhjemites from the Morlaix Visean basin (Fig. 9d).

6.2. Trace elements

The South Ouessant and Morlaix amphibolites are characterized by low La/Eu and La/Tb ratios (Fig. 10a). The Laval basalts have the highest La/Eu and La/Tb ratios, while mafic rocks from Châteaulin and Saint-Malo areas plot between them. These features are also evidenced in the chondrite-normalized rare earth element diagram of Fig. 11a. As such, all mafic rock patterns display a negative slope from middle to heavy rare earth elements (MREE and HREE), with the steepest negative slope about the Laval basalts. The SOB and Morlaix amphibolites again show a specific signature, with their light rare earth elements (LREE) concave-down shaped patterns (Fig. 11a). In the discrimination diagram of Cabanis and Lecolle (1989) (Fig. 10b), all the Visean mafic rocks from the Central and North Armorican Domains show an anorogenic affinity, as plotting close to the E-MORB field for South Ouessant and Châteaulin, in the alkali basalt field for Laval, and in the intracontinental tholeiite field for Saint-Malo (Morlaix not plotted).

The SOB (micro)trondhjemites plot clearly within the HSA fields of Fig. 10c and d. Their REE patterns, although grossly parallel to those of the granites, are quite distinct as being lower and devoid of Eu negative anomaly (Fig. 11b).

6.3. Isotopes

The new Sr and Nd isotopic ratios from the SOB and North Châteaulin basin are presented in Table 2 (only the Sr ratio is available for the syenogranite OS3c) and reported in the ϵ_{Nd}^t vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ ($t = 336 \text{ Ma}$) diagram of Fig. 12. The $^{87}\text{Sr}/^{86}\text{Sr}_i$ value of the microtrondhjemite OSB30 is obviously aberrant (0.73417, Table 2), possibly because of alteration processes, and as such is not plotted in the Fig. 12 diagram. The field of the c. 300 Ma Aber-Ildut/North-Ouessant (AI-NO) complex is also indicated, for comparison.

The monzogranite 14DB01 and the syenogranite OS3c have isotopic compositions comparable to those of the equivalent lithologies in the AI-NO complex (Caroff et al. 2015). Microtrondhjemites are characterized by lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and positive – or slightly negative – initial ϵ_{Nd} ($^{87}\text{Sr}/^{86}\text{Sr}_i$ [OS10] = 0.70426; $-0.5 < \epsilon_{\text{Nd}}^{336} < 2.2$). The initial ϵ_{Nd} of the amphibolite OS8 (3.0) is close to those of the microtrondhjemite OSB30 / North Châteaulin andesite KR22 ($\epsilon_{\text{Nd}}^{336} = 2.2$ in both cases). The North Châteaulin basalt KR3 shows a very high $\epsilon_{\text{Nd}}^{336}$ value of 5.9. The relatively high $^{87}\text{Sr}/^{86}\text{Sr}_i$ of sample OS8 with respect to KR3 and KR22 (Table 2 and Fig. 12) might result either from an early seawater alteration process (pillow lava stage) or fluid circulations during metamorphism.

7. Discussion

7.1. Visean fault-bounded basins in the Léon and Central Armorican Domains

Carboniferous basins from the CAD display striking similarities in terms of sedimentary infill and syndepositional magmatism. Indeed, their respective basal deposits, Tournaisian-Visean in age, are dominated by terrigenous sequences, coeval to a mafic/silicic (or intermediate) effusive volcanism (Le Hérissé and Plaine 1982; Cabanis 1986; Le Gall 1992; Caroff et al. 1996; Ducassou et al. 2014). Since these initial sedimentary and magmatic features consistently occur along the margins of the developing basins, they can be assigned to boundary fault-induced processes. The inferred early fault networks are also usually thought to have controlled the emplacement of the Châteaulin and Laval basins as pull-apart structures (Rolet 1984). With respect to this long-lived and EW-trending crustal-scale fault pattern, the submeridian Morlaix Carboniferous basin occupies a specific location, as separating the Léon metamorphic domain (west) from the North Armorican Cadomian block

(east), north of the NASZ (Fig. 1a). Its emplacement might have been controlled by a submeridian zone of crustal weakness that expresses at the surface by the restricted map-scale distribution of a trondhjemite dyke swarm, Carboniferous in age (Chauris 1992).

The SOB currently lies as a narrow structure (2-3 km wide) bounded by two EW-trending ductile shear zones (Fig. 1b) that thus prevent any precise restoration of its initial geometry and dimensions. Given the age yielded by the monzogranite 14DB01 and the geochemical resemblances displayed by the basaltic(/amphibolitic) compositions in the entire Visean basin network (Figs. 9, 10, 11, and 12), the SOB is here assumed to be the westernmost fault-bounded intracontinental basins in the Armorican belt, possibly initiated in a transtensional regime (Fig. 13). The chemical differences between glossy and poikiloblastic micaschists within the SOB (Table 1) likely reflect either contrasted lithological content in the sedimentary infill (Fig. 13) and/or hydrothermal effect linked to magmatism along the inferred southern basin boundary.

A restored basinal template of the CAD between c. 340 and 330 Ma is attempted in Fig. 14. The corresponding sedimentary depocenters are known to have been partly controlled by N70°E-trending extensional boundary faults, subsequently reactivated as dextral ductile shear zones during the Variscan shortening (green arrows in Fig. 14). The Saint-Malo doleritic dyke swarm corresponds to contemporaneous intrusions, with geochemical features very close to those of the North Châteaulin basalts (Figs. 9, 10, and 11; see also Caroff et al. 1996). According to this restored Visean basinal framework, the South Ouessant and Morlaix basins occupied comparable structural positions, at the western and eastern edges of the Leon Domain, respectively. That basinal setting matches with the very close chemical composition of their respective amphibolites, especially in REE elements (Figs. 10a and 11), and also with the presence of trondhjemite intrusions in both basins (Fig. 9d).

7.2. Formation of peperites

“Peperite” is a generic term applied to the rocks formed *in situ* by disintegration and/or mingling of magma (lava or intrusion) at the contact with unconsolidated or poorly consolidated, typically wet sediments (White et al. 2000). Magma fragmentation produces two types of peperites, which are called fluidal and blocky, in reference to the dominant shape of the clasts (Skilling et al. 2002). Clasts in fluidal peperites have globular or amoeboid morphology, with complex outlines; blocky clasts are polyhedral to tabular, with subplanar surfaces (Skilling et al. 2002). While blocky clasts imply disintegration of magma in the brittle regime, fluidal peperites are, in contrast, fragmented in the ductile regime, with stable vapor films along magma-sediment preventing direct contact with the pore fluid (Skilling et al. 2002).

In the SOB under study here, peperites are predominantly fluidal. A large range of morphologies can be observed from lobed margins in dykes and sills (Fig. 4f, h) to fiamme-bearing breccias (Fig. 5d) through globular and amoeboid bodies (Fig. 4g). Microtrondhjemites and leucogranites display only moderately corrugated contacts with the metasedimentary host rocks, whereas monzogranites are locally entirely disintegrated within sediment (Fig. 5a, b, d). These features suggest that the emplacement of the monzogranitic intrusions within the sedimentary material took place at an early stage, prior to the other granitoids, and when the sediment was in a less consolidated state. This is consistent with the field cross-cutting relationships showing that syeno-leucogranites obviously post-date monzogranites (see section 4.2).

Three features are especially remarkable in the South Ouessant peperites: (1) the high degree of monzonite disintegration; (2) the local presence of fiamme-bearing breccias; and (3) the fact that most peperitic magma bodies have a coarse-grained texture, even near magma-

sediment contacts. The first two features are listed in the summary of characteristics of peperite domains by Skilling et al. (2002), as “close-packed peperites” and “oriented sediment grains”, respectively. One of the most striking features about the close-packed peperites documented here is that the fragmented monzonite is highly porphyritic, hence resulting in apparent K-feldspar crystals isolated within the metasediment (Fig. 8a). In the east sector of Porz an Ejen (Fig. 6 insets), we can observe detachment of fiammes from coherent sedimentary bodies and incorporation within monzonite. In this sector, the metasediment clasts are elongate but not oriented (Fig. 6), contrary to little further west (Fig. 5c, d). This implies that the monzonitic magma intruded very soft sediment, flaked off and incorporated elongate sedimentary fiamme-shaped fragments and, sometimes, moved forward, which oriented them. The striking coarse-grained texture of monzonite and syeno-leucogranite near the contacts with metasediment (Fig. 8b) has, to our knowledge, never been so far described in peperitic context. One should have rather expected to observe quenched or microgranular textures. Such an unexpected feature may result from (i) influx of fluid in the early stage of emplacement, which can have in turn affected the textural coarsening by maintaining a low degree of undercooling in magma (Yang 2012), (ii) subsequent formation of sustainable insulating vapor films at the magma-sediment contacts, which can have inhibited fluid loss, explosion and/or quenching, and (iii) metamorphic recrystallizations. Biotite-rich transition zones at the leucogranite/metasediment contacts (Fig. 8b) may have been the consequence of these processes.

7.3. Contemporaneous mantle- and crust-derived magmas

The positive $\epsilon^{336}_{\text{Nd}}$ value of the amphibolitized basalt OS8 shows that it is undoubtedly a mantle-derived product. By contrast, the Sr-Nd isotopic compositions of the SOB

peraluminous granites fit with those of the AI-NO granitoids, which have been recently interpreted by Caroff et al. (2015) as entirely – or predominantly – crust-derived materials. Lastly, adakitic trondhjemites display isotopic compositions midway between those two. Field relationships indicate that these three syn- (or slightly post-) depositional magmatic groups are overall contemporaneous. Simultaneous emplacement of magmas having such contrasting affinities in a very narrow area is, at the least, surprising and implies a specific range of genetic processes.

Assuming that the SOB was a transtensional basin, as similarly applied to most of Visean basins in the CAD, suggests that its syndepositional basalts probably rose up from deep levels through its border faults, as already discussed by Caroff et al. (1996) for the North Châteaulin basalts. The fact that these latter have major and trace element compositions very close to those of Hawaiian oceanic tholeiites (Caroff et al. 1996) rather suggests an asthenospheric source for them and, more generally, for all the Visean CAD mafic rocks. The increasing alkalic character of the Visean basalts/dolerites/amphibolites from SOB/Morlaix (E-MORB) and Châteaulin/Saint-Malo (transitional basalts) to Laval (alkali basalts) (Figs. 9a, b, 10a, b, and 11) is consistent with decreasing degrees of partial melting of the mantle source eastwards, concomitantly with an inferred lithospheric thickening (Fig. 14). Peraluminous granitic magmas are reputed to be chiefly crust-derived melts (Frost et al. 2001; Caroff et al. 2015). On the other hand, the most likely ways to generate HSA-type adakitic magmas are either (i) by partial melting of metabasalts or metagabbros in the field of garnet stability (Moyen 2009 and references herein) or (ii) by deep fractionation of a garnet-dominated assemblage (Macpherson et al. 2006). The lack of Eu anomaly in the SOB (micro)trondhjemites can be explained in different ways: (1) plagioclase was absent during high pressure melting or crystallization; (2) plagioclase was in competition with phases having positive distribution coefficients for Sm and Tb (e.g., amphibole or apatite), leading,

by compensation, to no Eu anomaly; or (3) oxygen fugacity was high during melting or crystallization (Shearer and Papike 1989).

The origin the SOB magmatic intrusions should be strictly assigned to the following processes (depicted in Fig. 14), given the petrologic and geochemical constraints listed above. (1) Asthenospheric partial melting resulted in basaltic liquids that rose and erupted, or crystallized in deep reservoirs. (2) Partial remelting of deep mafic intrusions resulting from stage (1) – or high-pressure fractionation in deep reservoirs – produced adakitic liquids. Such a lithospheric partial melting could have been caused by asthenospheric advective heating associated with the Léon exhumation event (Schultz 2013; Le Gall et al. 2014; Caroff et al. 2015). (3) Heating of the continental crust by mafic injections might have produced silicic melts that rose and emplaced as peraluminous granites. Assuming that the genetic model proposed by Caroff et al. (2015) for the North Ouessant granitic complex can be applied to the SOB granitoids implies that syeno-leucogranites likely originated from pure crustal melting, whereas monzogranitic products would result from mixing between crustal melts and mantle-derived mafic liquids.

8. Conclusions

1. Though the South Ouessant metasedimentary and magmatic rocks are highly tectonized and metamorphized under amphibolite facies conditions, their age, petrology and geochemistry have been precisely defined, hence leading us to identify an early basin, Viséan in age, at the western offshore extremity of the Léon and Central Armorican Domains.

2. Contacts between metasedimentary materials and magmatic bodies display a large spectrum of quite original fluidal peperitic features, from lobed or amoeboid sill/dyke rims to fiamme-bearing polygenic breccias. One of the most noticeable aspects of these unusual

peperites is that they include coarse-grained granites. The South Ouessant composite magmatic complex as a whole is thus assumed to have emplaced at a relatively high crustal level, into not yet indurated and lithified Visean sediments.

3. From a magmatic point of view, the South Ouessant basin comprises three types of subcontemporaneous rocks, issued from very different sources, i.e. (1) sparse amphibolitized basaltic pillow lavas and associated volcanoclastic breccias, (2) a sill/dyke swarm of adakitic (micro)trondhjemites, and (3) large intrusions of peraluminous granites. Emplacement of such a contrasted magmatic complex within a very narrow basin and in a brief time period necessarily requires the following subconcomitant mechanisms: (1) asthenospheric partial melting prone to generate basaltic liquids that later rose up through the basin border faults, (2) high-pressure fractionation in deep reservoirs (or partial remelting of deep gabbroic intrusions) leading to adakitic products, and (3) continental crust melting from which originated peraluminous silicic melts.

Supplementary data to this article can be found online at...

Acknowledgements

Detailed and constructive comments by Dr. Yener Eyuboglu and by two anonymous reviewers helped us to improve the text. The authors are grateful to C. Bollinger (ICP-MS Brest), P. Nonnotte (TI-MS), C. Liorzou (ICP-AES), M.-L. Rouget (chemistry lab assistant, UMS n°3113), A. von Quadt (U/Pb geochronology, ETH Zurich), P. Vonlanthen (Scanning electron microscopy, Institut des Sciences de la Terre, Lausanne), G. Chazot (photomicrographs), P. Tieffenbach (thin sections), and J.-P. Oldra (sample preparation).

References

569

570 Barrat, J.A., Keller, F., Amossé, J., Taylor, R.N., Nesbitt, R.W., Hirata, T., 1996.

571 Determination of rare earth elements in sixteen silicate reference samples by ICP-MS

572 after Tm addition and ion exchange separation. *Geostandards Newsletter* 20, 133-139.

573 Barrat, J.A., Zanda, B., Moynier, F., Bollinger, C., Liorzou, C., and Bayon, G. 2012.

574 Geochemistry of CI chondrites: Major and trace elements, and Cu and Zn isotopes.

575 *Geochimica et Cosmochimica Acta*, **83**: 79-92.

576 Bioret, F., David, L., Darboux, J.-R., Gourmelon, F., Guermeur, Y. et al. 2012. Ouessant.

577 Atlas environnemental. ISBN: 978-2-9534262-3-6. Les cahiers du CEMO, **4**. hal-

578 00797158.

579 Bull, K.F., and McPhie, J. 2007. Fiamme textures in volcanic successions: Flaming issues of

580 definition and interpretation. *Journal of Volcanology and Geothermal Research*, **164**:

581 205-216.

582 Cabanis, B. 1986. Identification des séries magmatiques dans les socles métamorphiques sur

583 la base de critères géologiques, pétrographiques et géochimiques. Exemples

584 d'application dans le Massif Armoricain. Implications géodynamiques. Contribution à

585 une méthode d'étude basée sur les éléments traces. Thesis, Université Pierre et Marie

586 Curie, Paris.

587 Cabanis, B., and Lecolle, M. 1989. Le diagramme La/10-Y/15-Nb/8: un outil pour la

588 discrimination des séries volcaniques et la mise en évidence des processus de mélange

589 et/ou de contamination crustale. *Compte Rendus de l'Académie des Sciences, Paris, II*,

590 **309**: 2023-2029.

591 Caroff, M., Labry, C., Le Gall, B., Authemayou, C., Bussin Grosjean, D., and Guillong, M.

592 2015. Petrogenesis of late-Variscan high-K alkali-calcic granitoids and calc-alkalic

- 593 lamprophyres: the Aber-Ildut/North-Ouessant complex, Armorican massif, France.
594 *Lithos*, **238**: 140-155.
- 595 Caroff, M., Le Gal, X., Rolet, J., Cotten, J., and Thonon, P. 1996. Magmatisme tholeiitique
596 continental en contexte orogénique hercynien : l'exemple du volcanisme viséen de
597 Kerroc'h, Massif armoricain (France). *Comptes Rendus de l'Académie des Sciences*,
598 Paris, II, **322**: 269-275.
- 599 Caroff, M., Vidal, M., Bénard, A., and Darboux, J.-R. 2009. A late-Ordovician
600 phreatomagmatic complex in marine soft-substrate environment: The Crozon volcanic
601 system, Armorican Massif (France). *Journal of Volcanology and Geothermal Research*,
602 **184**: 351-366.
- 603 Chauris, L., 1992. Intrusions sodiques à affinité trondhjémiques dans le Nord-Ouest de la
604 Bretagne (France). *Comptes Rendus de l'Académie des Sciences*, Paris, II, **315**: 705-
605 710.
- 606 Chauris, L. 1994. Notice explicative, Carte géologique de la France (1/50 000), feuille
607 Plouarzel – Île d'Ouessant (237). Orléans, BRGM Éditions.
- 608 Coira, B., and Pérez, B. 2002. Peperitic textures of Ordovician dacitic synsedimentary
609 intrusions in Argentina's Puna Highland: clues to emplacement conditions. *Journal of*
610 *Volcanology and Geothermal Research*, **114**: 165-180.
- 611 Cotten, J., Le Dez, A., Bau, M., Caroff, M., Maury, R., Dulski, P., Fourcade, S., Bohn, M.,
612 and Brousse, R. 1995. Origin of rare-earth element and yttrium enrichments in subaerial
613 exposed basalts: evidence from French Polynesia. *Chemical Geology*, **119**: 115-138.
- 614 Dadd, K.A., and Van Wagoner, N.A. 2002. Magma composition and viscosity as controls on
615 peperite texture: an example from Passamaquoddy Bay, southeastern Canada. *Journal of*
616 *Volcanology and Geothermal Research*, **114**: 63-80.

- 617 Ducassou, C., Poujol M., Ruffet, G., Bruguier, O., and Ballèvre, M. 2014. Relief variation and
618 erosion of the Variscan belt: detrital geochronology of the Paleozoic sediments from the
619 Mauges unit (Armorican massif, France). Geological Society, London, Special
620 publications, **405**. doi 10.1144/SP405.6
- 621 Darboux, J.R., and Le Gall, B. 1988. Les Montagnes Noires: Cisaillement bordier méridional
622 du bassin carbonifère de Châteaulin (Massif armoricain, France). Caractéristiques
623 structurales et métamorphiques. *Geodinamica Acta*, **2**(3): 121-133.
- 624 Erkül, F., Helvacı, C., and Sözbilir, H. 2006. Olivine basalt and trachyandesite peperites
625 formed at the subsurface/surface interface of a semi-arid lake: An example from the
626 Early Miocene Bigadiç basin, western Turkey. *Journal of Volcanology and Geothermal*
627 *Research*, **149**: 240-262.
- 628 Galerne, C., Caroff, M., Rolet, J., and Le Gall, B. 2006. Magma-sediment mingling in an
629 Ordovician rift basin: the Plouézec-Plourivo half-graben, Armorican Massif, France.
630 *Journal of Volcanology and Geothermal Research*, **155**: 164-178.
- 631 Gapais, D., and Le Corre, C. 1980. Is the Hercynian belt of Brittany a major shear zone ?
632 *Nature*, **288**: 574-576.
- 633 Gumiaux, C., Gapais, D., Brun, J.-P., Chantaine, J., and Ruffet, G. 2004. Tectonic history of
634 the Armorican Shear Belt (Brittany, France). *Geodynamica Acta*, **17**: 289-307.
- 635 Jutzeler, M., McPhie, J., and Allen, S.R. 2014. Submarine eruption-fed and resedimented
636 pumice-rich facies: the Dogashima Formation (Izu Peninsula, Japan). *Bulletin of*
637 *Volcanology*, **76**:867. doi:10.1007/s00445-014-0867-x.
- 638 Lahaye, Y., Blais, S., Auvray, B., and Ruffet, G. 1995. Le volcanisme fissural paléozoïque du
639 domaine nord-armoricain. *Bulletin de la Société géologique de France*, **166**(5): 601-612.
- 640 Le Gall, B. 1992. Notice explicative, Carte géologique de la France (1/50 000), feuille Gourin
641 (311). Orléans, BRGM Éditions.

- 642 Le Gall, B., Authemayou, C., Ehrhold, A., Paquette, J.-L., Bussien, D., Chazot, G., Aouizerat,
643 A., and Pastol, Y. 2014. LiDAR offshore structural mapping and U/Pb zircon/monazite
644 dating of Variscan strain in the Léon metamorphic domain, NW Brittany.
645 *Tectonophysics*, **630**: 236-250.
- 646 Le Hérissé, A., and Plaine, J. 1982. Volcanisme basique dans le Carbonifère inférieur du
647 Synclinorium de Laval (Massif armoricain, France). *Comptes Rendus de l'Académie*
648 *des Sciences, Paris, II*, **294**: 1199-1202.
- 649 Le Maitre, R.W., Streckeisen, A., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P., Bellieni,
650 G., Dudek, A., Efremova, S., Keller, J., Lamere, J., Sabine, P.A., Schmid, R., Sorensen,
651 H., and Woolley, A.R. 2002. *Igneous Rocks: A Classification and Glossary of Terms,*
652 *Recommendations of the International Union of Geological Sciences, Subcommittee*
653 *of the Systematics of Igneous Rocks.* Cambridge University Press.
- 654 Ludwig, K. R. 2008. User's manual for Isoplot 3.70, a geochronological toolkit for Microsoft
655 Excel. Berkeley Geochronology Center Special Publication, **4**.
- 656 Macpherson, C.G., Dreher, S.T., and Thirlwall, M.F. 2006. Adakites without slab melting:
657 high pressure differentiation of island arc magma, Mindanao, the Philippines. *Earth and*
658 *Planetary Sciences Letters*, **243**(3-4): 581-593.
- 659 Marcoux, E., Cocherie, A., Ruffet, G., Darboux, J.R., and Guerrot, C. 2009. Géochronologie
660 revisitée du dôme du Léon (Massif armoricain, France). *Géologie de la France*, **1**: 19-40.
- 661 Martin, U., and Németh, K. 2007. Blocky versus fluidal peperite textures developed in
662 volcanic conduits, vents and crater lakes of phreatomagmatic volcanoes in Mio/Pliocene
663 volcanic fields of Western Hungary. *Journal of Volcanology and Geothermal Research*,
664 **159**: 164-178.

- 665 McPhie, J., and Allen, R.L. 1992. Facies architecture of mineralized submarine volcanic
666 sequences: Cambrian Mount Read Volcanics, Western Tasmania. *Economic Geology*,
667 **87**: 587-596.
- 668 Moyen, J.-F. 2009. High Sr/Y and La/Yb ratios: The meaning of the “adakitic signature”.
669 *Lithos*, **112**: 556-574.
- 670 Paquette, J.L., Balé, P., Ballèvre, M., and Georget, Y. 1987. Géochronologie et géochimie des
671 éclogites du Léon: nouvelles contraintes sur l'évolution géodynamique du Nord-Ouest
672 du Massif armoricain. *Bulletin de Minéralogie*, **110**: 683-696.
- 673 Pearce, T.H., Gorman, B.E., and Birkett, T.C. 1977. The relationship between major element
674 chemistry and tectonic environment of basic and intermediate volcanic rocks. *Earth and*
675 *Planetary Science Letters*, **36**(1): 121-132.
- 676 Rolet, J. 1984. Grabens losangiques (pull-apart) en régime de décrochement. Le rôle des
677 coulissements hercyniens dans l'individualisation des bassins carbonifères du Massif
678 armoricain. *Bulletin de la Société géologique du Nord*, **103**: 209-220.
- 679 Rolet, J., Le Gall, B., Darboux, J.R., Thonon, P., and Gravelle, M. 1986. L'évolution
680 géodynamique dévono-carbonifère de l'extrémité occidentale de la chaîne hercynienne
681 d'Europe sur le transect Armorique-Cornwall. *Bulletin de la Société Géologique de*
682 *France*, **8**, 43-54.
- 683 Saadat, S., Karimpour, M.H., and Stern, C. 2010. Petrochemical characteristics of Neogene
684 and Quaternary alkali olivine basalts from the Western Margin of the Lut Block, Eastern
685 Iran. *Iranian Journal of Earth Sciences*, **2**: 87-106.
- 686 Schaltegger, U., Schneider, J.-L., Maurin, J.-C., and Corfu, F. 1996. Precise U – Pb
687 chronometry of 345-340 Ma old magmatism related to syn-convergence extension in the
688 Southern Vosges (Central Variscan Belt). *Earth and Planet Science Letters*, **144**(3-4):
689 403-419.

- 690 Schulz, B. 2013. Monazite EMP-Th-U-Pb age pattern in Variscan metamorphic units in the
691 Armorican Massif (Brittany, France). *German Journal of Geosciences*, **164**: 313-335.
- 692 Schulz, B., Krenn, E., Finger, F., Bratz, H., and Klemd, R. 2007. Cadomian and Variscan
693 metamorphic events in the Léon Domain (Armorican massif, France): P-T data and
694 EMP monazite dating. *In* The evolution of the Rheic ocean from Avalonian-Cadomian
695 active margin to Alleghenian-Variscan collision. *Edited by* U. Linneman, R. Nance and
696 P. Kraft. Geological Society of America Special Papers, **423**: 267-285.
- 697 Shearer, C.K., and Papike, J.J. 1989. Is plagioclase removal responsible for the negative Eu
698 anomaly in the source regions of mare basalts? *Geochimica et Cosmochimica Acta*, **53**:
699 3331-3336.
- 700 Skilling, I.P., White, J.D.L., and McPhie, J. 2002. Peperite: a review of magma-sediment
701 mingling. *Journal of Volcanology and Geothermal Research*, **114**: 1-17.
- 702 Sláma, J. et al. 2008. Plesovice zircon – A new natural reference material for U-Pb and Hf
703 isotopic microanalysis. *Chemical Geology*, **249**(1-2): 1-35.
- 704 Streckeisen, A.L. 1976. To each plutonic rock its proper name. *Earth Science Reviews*, **12**: 1-
705 33.
- 706 Streckeisen, A.L., and Le Maitre, R.W. 1979. A chemical approximation to the modal QAPF
707 classification of the igneous rocks. *Neues Jahrbuch für Mineralogie, Abhandlungen*,
708 **136**: 169-206.
- 709 Sylvester, P.J. 1998. Post-collisional strongly peraluminous granites. *Lithos*, **45**: 29-44.
- 710 van Achterberg, E., Ryan, C.G., Jackson, S.E., and Griffin, W. 2001. Data reduction software
711 for LA-ICP-MS. *In* Laser Ablation- ICPMS in the Earth Science: Principles and
712 Applications. *Edited by* P. Sylvester. Mineralogical Association of Canada, Short
713 Course Series, Ottawa, Ontario, Canada, **29**: 239-243

- White, J.D.L., McPhie, J., and Skilling, I.P. 2000. Peperite: a useful genetic term. *Bulletin of Volcanology*, **62**: 65-66.
- White, W.M., and Patchett, J. 1984. Hf-Nd-Sr isotopes and incompatible element abundances in island Arcs: implications for magma origins and crust-mantle evolution. *Earth and Planetary Sciences Letters*, **67**: 167-185.
- Yang, Z.-F. 2012. Combining quantitative textural and geochemical studies to understand the solidification processes of a granite porphyry: Shanggusi, East Qinling, China. *Journal of Petrology*, **53**(9): 1807-1835.

Figure captions

Fig. 1. Geological features of the western extremity of the Léon Domain. (a) Shear-zone patterns, structural domains and Tournaisian-Visean basins in the Armorican Massif. (b) Ouessant geological context. The map of the offshore studied area is from Le Gall et al. (2014). COSZ, NASZ, NOSZ, and PGSZ are for Central Ouessant, North Armorican, North Ouessant, and Porspoder-Guissény shear zones, respectively.

Fig. 2. Geological sketch of South Ouessant Island, based on Chauris (1994) and Bioret et al. (2012). The reader could refer to Caroff et al. (2015) about the North Ouessant area.

Fig. 3. U-Pb analyses and ages of the porphyritic monzogranite 14DB01 given with 1 sigma level error (ellipses and error bars): a) Tera-Wasserburg diagram intercept age (line and frame) based on the black ellipses. Dotted ellipses are disregarded analyses. b) Weighted average $^{206}\text{Pb}/^{238}\text{U}$ ages with the resultant age. Details in Table S1. c) Representative cathodoluminescence images of sample 14DB01 zircons, with localisation and number of the

analytical spots (see Table S1), with their resultant $^{206}\text{Pb}/^{238}\text{U}$ ages and 1 sigma error in Ma.

Scale bar represents 50 microns.

Fig. 4. Emplacement structures of the main magmatic bodies. (a) Amphibolitized pillow lava, Porz Doun. (b) (c) Details of the precedent photograph. Coin for scale. (d) Amphibolitized volcaniclastic succession, Porz an Ejen. Mace handle for scale. (e) Detail of the precedent photograph. (f) Micaschist/trondhjemite contacts in the Lampaul Bay. Pencil for scale. (g) Amoeboid porphyritic monzogranite in micaschists, Porz Doun. Coin for scale. (h) Micaschists (grey) / leucogranite (yellow) contacts, south of Lampaul Bay. Coin for scale.

Fig. 5. Peperitic facies. (a) Frozen crystal-bearing monzogranitic plume descending into metasediment (micaschist), Croix de Saint-Paul. Inset: detail. Coin for scale. (b) Metasediment loaded with monzogranite-derived K-feldspar crystals, Porz an Ejen. Pencil for scale. (c) Monzogranitic breccias bearing metasedimentary fiammes and graphite clasts, Porz an Ejen. Coin for scale. (d) Fiamme-bearing breccia, Porz an Ejen. Encircled coin for scale.

Fig. 6. Photographic assemblage showing intimate mingling of porphyritic monzogranite and graphite-bearing micaschist, east of Porz an Ejen. We can also observe lenses of micaschist, similar to the fiammes of Fig. 5c, d, becoming detached from the main metasedimentary bodies.

Fig. 7. Photomicrographs of the four main types of (more or less metamorphized) magmatic rocks from South Ouessant (crossed nicols). (a) Amphibolite (ancient basaltic pillow lava) OS8. (b) Microtrondhjemite OSB30. (c) Monzogranite 14DB01. (d) Syenogranite OS3c. Bi:

biotite; Hb: hornblende; Mi: microcline; Mu : muscovite ; My : myrmekite ; Pl: plagioclase;
Q: quartz.

Fig. 8. Drawings of photomicrographs of mingled structures. (a) Monzogranitic K-feldspar (Afs) megacrysts embedded within graphite-bearing poikiloblastic micaschist. Location of sample OSB16a in Fig. 6 (Porz an Ejen). (b) Microtexture of lobed contacts between coarse-grained tourmaline-bearing leucogranite and fine-grained metasediment. There is no clear limit between both lithologies, but a 2-4 mm-large biotite-rich transition zone. Sample OSB5 is positioned in Fig. 5a (Croix de Saint-Paul).

Fig. 9. Major element diagrams for samples from South Ouessant and other Central Armorican Carboniferous basins (Morlaix: Cabanis 1986 and Chauris 1992; North Châteaulin: Caroff et al. 1996; South Châteaulin: Le Gall 1992; Laval: Bonnefoy 1999, unpublished Master report), together with Saint-Malo dolerites (Lahaye et al. 1995). Analyses in Table 1 and S2. (a) (b) TiO_2 and P_2O_5 vs. SiO_2 diagrams. (c) $\text{MgO-FeO}^*\text{-Al}_2\text{O}_3$ triangular discrimination diagram of Pearce et al. (1977), for mafic samples. (d) $\text{K}_2\text{O/Na}_2\text{O}$ vs. SiO_2 diagram, with the high-silica adakite (HSA) field of Moyen (2009).

Fig. 10. Trace element diagrams for samples from South Ouessant and other Central Armorican Carboniferous basins (Morlaix: Cabanis 1986; North Châteaulin: Caroff et al. 1996 and this study; Laval: Bonnefoy 1999, unpublished Master report, and this study), together with Saint-Malo dolerites (Lahaye et al. 1995). Analyses in Table 1 and S2. (a) La/Eu and La/Tb vs. SiO_2 diagrams. (b) La/10-Y/15-Nb/8 triangular discrimination diagram of Cabanis and Lecolle (1989), for mafic samples. (c) (d) Sr/Y and La/Yb vs. SiO_2 diagram, with the high-silica adakite (HSA) fields of Moyen (2009).

788

789 Fig. 11. CI-chondrite normalized trace element patterns of rocks from South Ouessant and
790 other Central Armorican Carboniferous basins, together with Saint-Malo dolerites (references
791 as in Fig. 10). Analyses in Table 1 and S2. Normalization values: Barrat et al. 2012. (a) Mafic
792 rocks. (b) South Ouessant silicic rocks and North Châteaulin basalt and andesite.

793

794 Fig. 12. ϵ_{Nd}^t vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope diagram showing South Ouessant and North
795 Châteaulin samples, compared with the Aber-Ildut/North-Ouessant (AI-NO) field (Caroff et
796 al. 2015). Symbols as in Fig. 11.

797

798 Fig. 13. Block diagram showing a 3D-restored view of the South Ouessant Visean basin.

799

800 Fig. 14. Restored lithosphere/asthenosphere block diagram of the Central Armorican Domain
801 at 340-330 Ma. Orange-colored dashed lines: possible extension of the Visean basins; green-
802 colored dashed lines and arrows: future Variscan shear zones.

803

Fig. 1
299x225mm (300 x 300 DPI)

Fig. 2
210x144mm (300 x 300 DPI)

Fig. 3 rev
168x223mm (300 x 300 DPI)

Fig. 4
233x243mm (300 x 300 DPI)

Fig. 5
233x162mm (300 x 300 DPI)

Fig. 6
397x241mm (300 x 300 DPI)

Fig. 7 rev
231x174mm (300 x 300 DPI)

Fig. 8 rev
144x169mm (300 x 300 DPI)

Fig. 9 rev
244x185mm (300 x 300 DPI)

Fig. 10 rev
238x185mm (300 x 300 DPI)

Fig. 11 rev
233x105mm (300 x 300 DPI)

Fig. 12 rev
199x149mm (300 x 300 DPI)

Fig. 13 rev
144x96mm (300 x 300 DPI)

Fig. 14 rev
298x135mm (300 x 300 DPI)

Draft

Table 1. Selection of major and trace element data on whole rocks.

Sample	OS8	LC6	LV4	KR3	KR22	14DB01	LC12	LC13
Location	SO	SO	Laval	NC	NC	SO	SO	SO
Type	Amph.	Amph.	Basalt	Basalt	Andes.	Mzgr.	Mzgr.	Mzgr.
Emplacement	Pillow	Pillow	Flow	Flow	Breccia	Pluton	Pluton	Pluton
<i>Major elements (wt.%)</i>								
SiO ₂	46.27	46.40	44.80	49.20	61.80	68.00	67.30	68.20
TiO ₂	2.68	1.89	3.05	3.51	1.96	0.51	0.60	0.50
Al ₂ O ₃	15.44	16.00	14.45	13.40	13.40	15.80	15.20	15.45
Fe ₂ O ₃ ^{tot}	12.12	11.70	12.70	13.82	7.20	3.20	3.20	3.18
MnO	0.14	0.19	0.15	0.20	0.07	0.04	0.05	0.05
MgO	7.06	8.40	9.30	5.78	2.41	1.32	1.50	1.60
CaO	9.16	11.70	7.25	9.66	3.75	2.25	1.85	2.25
Na ₂ O	2.73	~2.5	1.78	2.48	5.90	3.60	3.90	3.85
K ₂ O	0.33	< 0.5	0.16	0.34	0.20	3.68	3.95	3.70
P ₂ O ₅	0.39	0.25	0.76	0.40	0.37	0.15	0.20	0.20
LOI	1.24	-	5.10	1.21	1.64	0.85	1.80	0.95
Total	97.58	-	99.50	100.00	98.70	99.40	99.55	99.93
<i>Trace elements (ppm)</i>								
Li	50.5	27.0	36.9	32.3	17.6	140	-	-
Be	1.3	-	1.3	1.4	3.8	6.5	-	-
Rb	9	-	2	13	4	167	-	-
Cs	0.67	-	0.97	8.34	1.86	15.2	-	-
Sr	297	343	512	304	176	236	-	-
Ba	18	77	205	209	68	726	-	-
Sc	28	-	26	33	22	8	-	-
V	276	303	245	352	165	46.1	-	-
Cr	62.5	336	429	117	34.5	21.5	-	-
Co	50	51	52	39	15	7	-	-
Ni	49.7	89.0	227	76.1	12.4	11.5	-	-
Cu	4.7	10.0	71.8	125	21.7	7.5	-	-
Zn	164	158	111	125	93	80	-	-
Y	30	22	34	43	56	13	-	-
Zr	36	-	344	274	383	188	-	-
Hf	1.2	-	6.7	6.1	9.0	4.9	-	-
Nb	25	-	83	30	45	9	-	-
Ta	1.2	-	5.4	2.1	3.2	0.6	-	-
W	14.1	-	0.6	0.7	1.9	2.0	-	-
Ga	23	-	22	26	17	24	-	-
Pb	59.6	13.0	1.6	1.1	3.7	31.4	-	-
La	8.2	-	36.5	21.5	36.3	46.1	-	-
Ce	24.1	-	83.0	51.7	83.9	88.6	-	-
Pr	4.4	-	10.5	7.1	10.6	9.6	-	-
Nd	22.2	-	44.6	32.1	44.4	33.8	-	-
Sm	6.1	-	9.3	8.1	10.4	6.0	-	-
Eu	2.21	-	3.11	2.66	2.16	1.06	-	-
Gd	6.99	-	8.26	8.47	10.42	4.19	-	-
Tb	1.01	-	1.20	1.36	1.67	0.52	-	-
Dy	5.43	-	6.63	7.96	9.86	2.60	-	-
Ho	1.04	-	1.22	1.54	1.92	0.47	-	-
Er	2.79	-	3.14	3.97	5.28	1.23	-	-
Yb	2.05	-	2.55	3.29	4.48	1.13	-	-
Lu	0.28	-	0.35	0.44	0.61	0.16	-	-
Th	1.7	-	3.1	2.1	7.4	24.7	-	-
U	0.3	-	0.7	0.7	2.7	5.0	-	-

Table1. (*continued*)

Sample	OS3c	LC29	OSB30	OS10	LC1	LC5
Location	SO	SO	SO	SO	SO	SO
Type	Syenogr.	T-Leucogr.	μ Trondhj.	Trondhj.	Glossy Mic.	Poik. Mic.
Emplacement	Pluton	Pluton	Dyke	Dyke		
<i>Major elements (wt.%)</i>						
SiO ₂	72.57	72.30	71.70	72.57	51.70	62.45
TiO ₂	0.16	0.02	0.16	0.17	1.05	0.95
Al ₂ O ₃	13.77	15.20	16.60	16.10	26.50	18.50
Fe ₂ O ₃ ^{tot}	1.27	0.50	1.00	0.97	7.80	6.00
MnO	0.01	0.02	0.01	0.01	0.15	0.10
MgO	0.19	0.20	0.56	0.52	2.05	1.75
CaO	1.06	1.00	1.43	1.26	0.25	1.05
Na ₂ O	3.04	~3.0	6.26	6.16	1.30	1.45
K ₂ O	4.76	5.40	1.04	1.05	4.60	5.65
P ₂ O ₅	0.16	0.09	0.08	0.06	0.20	0.15
LOI	1.01	-	0.98	1.05	4.45	1.15
Total	97.99	-	99.83	99.91	100.05	99.20
<i>Trace elements (ppm)</i>						
Li	73.9	-	42.7	48.7	-	-
Be	4.2	7.0	1.7	1.5	-	-
Rb	182	-	17	21	-	-
Cs	4.45	-	1.18	1.39	-	-
Sr	169	126	648	609	-	-
Ba	446	164	230	205	-	-
Sc	3	-	2	2	-	-
V	4.0	-	14.2	15.1	-	-
Cr	4.7	42.0	11.7	13.7	-	-
Co	1	6	2	2	-	-
Ni	0.3	17.0	4.6	3.4	-	-
Cu	0.4	-	4.7	2.3	-	-
Zn	31	22	30	36	-	-
Y	13	-	3	4	-	-
Zr	76	-	76	46	-	-
Hf	2.5	-	2.5	1.9	-	-
Nb	9	-	3	1	-	-
Ta	0.5	-	0.1	0.1	-	-
W	17.3	-	0.3	8.1	-	-
Ga	24	-	25	18	-	-
Pb	48.0	42.0	8.4	11.6	-	-
La	23.9	-	4.6	7.0	-	-
Ce	49.2	-	10.6	14.6	-	-
Pr	5.9	-	1.4	2.1	-	-
Nd	20.9	-	5.7	8.4	-	-
Sm	4.9	-	1.2	1.6	-	-
Eu	1.00	-	0.40	0.49	-	-
Gd	4.46	-	0.83	1.27	-	-
Tb	0.60	-	0.11	0.15	-	-
Dy	2.84	-	0.56	0.73	-	-
Ho	0.50	-	0.10	0.13	-	-
Er	1.20	-	0.27	0.32	-	-
Yb	0.84	-	0.24	0.24	-	-
Lu	0.12	-	0.03	0.03	-	-
Th	13.5	-	1.0	1.1	-	-
U	8.0	-	0.6	0.7	-	-

Amph.: amphibolite; Andes.: andesite; Mzgr.: monzogranite; Syenogr.: syenogranite; T-Leucogr.: tourmaline-bearing leucogranite; (μ)Trondhj.: (micro)trondhjémite; (Poik.) Mic.: (poikiloblastic) micaschist. SO: South-Ouessant; NC: North-Châteaulin basin.

Major elements were analyzed by ICP-AES (IUEM, Brest, France) following the analytical method described by Cotten et al. (1995), except LC1, LC5, LC6, LC12, LC13 and LC29 (AAS/AES Brest, Chauris, 1994), LV4 (ICP-AES Brest, Bonnefoy, 1999: unpublished Master report), KR3 and KR22 (ICP-AES, Caroff et al., 1996); trace elements were analyzed by ICP-MS (IUEM, Brest, France) following the sample preparation and analysis method of Barrat et al. (1996), except the LC samples (AAS/AES Brest, Chauris, 1994).

Table 2. Isotopic data on whole rock samples.

Type	Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$ ($\times 10^{-6}$)	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$ ($\times 10^{-6}$)	$\varepsilon^t_{\text{Nd}}$
							($t=336\text{ Ma}$)						($t=336\text{ Ma}$)
Basalt	OS8	9	297	0.09	0.710424	4	0.71001	6.14	22.2	0.1673	0.512728	3	3.0
Basalt	KR3	13	304	0.12	0.704427	5	0.70386	8.15	32.1	0.1533	0.512846	3	5.9
Andesite	KR22	4	176	0.07	0.705779	4	0.70544	10.38	44.4	0.1415	0.512627	3	2.2
Monzog.	14DB01	167	236	2.05	0.716122	3	0.70631	6.00	33.8	0.1074	0.512300	5	-2.8
Syenogr.	OS3c	182	169	3.13	0.725639	4	0.71068	-	-	-	-	-	-
Trondhj.	OSB30	17	648	0.07	0.734522	5	0.73417	1.18	5.7	0.1248	0.512595	3	2.2
Trondhj.	OS10	21	609	0.10	0.704739	5	0.70426	1.63	8.4	0.1174	0.512439	3	-0.5
Micaschist	OSB26c	260	176	4.29	0.734924	4	0.71442	40.67	202	0.1214	0.512440	4	-0.6

Monzog.: monzogranite; Syenogr.: syenogranite; Trondhj.: trondhjemite.

All Sr and Nd isotope ratios are reported at the 2σ confidence level. The Sr isotopic data were determined by thermal ionization mass spectrometry (TIMS) using a Thermo ElectronTM Triton T1 at the IUEM, Brest, France. Nd isotopic data were determined using a Thermo ElectronTM Neptune MC-ICP-MS at Ifremer, Brest, France. Sr isotopic ratios were normalized to the NBS 987 standard ($^{87}\text{Sr}/^{86}\text{Sr}=0.710264$) and Nd ratios to JINDI330 standard ($^{143}\text{Nd}/^{144}\text{Nd}=0.512094$). Measured blanks for OS8 and OS10 are 3.9 ppb for Sr and 0.198 ppb for Nd; $\varepsilon^t_{\text{Nd}}$ values have been calculated with the following CHUR values: $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd}=0.1967$. 336 Ma is used as approximate age of crystallization.