



MINERAL PROSPECTIVITY

current approaches
and future innovations

MINERAL PROSPECTIVITY CONTEST

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Introduction

This document describes the mineral prospectivity contest organized within the Mineral Prospectivity conference (24-26 October 2017, Orléans, France; visit <http://www.brgm.eu/mineral-prospectivity> for detailed information on the conference), its organization, the data set provided and the geological context of the case study. For any additional information, please contact the organizing committee at mineral.prospectivity@brgm.fr

Purpose of the contest

All registered participant to the Mineral Prospectivity conference can participate to the contest at no additional cost. The main objective of this mineral prospectivity contest is to encourage discussion and contacts between researchers of the mineral prospectivity scientific community. It will be achieved through the realization of predictive maps by all interested participants, using the methodologies of their choice, but on a unique case study (same area, same targeted commodity, same dataset for all participants). During the conference, resulting maps will be displayed, evaluated and compared, and methodologies will be discussed. Best predictive maps (in terms of performance) will be awarded during the conference. After the conference, all contributions will be compiled in a synthetic document for distribution to all participants. This will certainly trigger fruitful discussion and hopefully foster interactions and future collaborations within the scientific community.

Deliverables and deadlines

The goal of the contest is to produce the best (i.e. most accurate and selective) predictive map for gold in French Brittany. Each participant will produce a predictive map using only the provided dataset (not additional data is allowed) and using the methodology of his/her choice.

Participants to the contest will have to provide the following files:

- One georeferenced TIFF file (UTM WGS84, zone 30N) with maximum resolution (i.e. minimum pixel size) of 250 m; predictivity values will be normalized between 0 and 1; This file will be used by the organizing committee to evaluate the quality of predictivity;
- One printable layout of their map, 1/500 000 scale, in raster format (gif, tiff, jpg, png); This image will be printed and displayed during the conference for discussion;
- One text file (doc, docx, txt or equivalent) of maximum one page, explaining the methodology/approach used to produce the map;

These 3 files will be placed in a .zip archive named with “first name”, underscore and “surname” of participant (example : John_Doe.zip).

The .zip archive will have to be transferred via WeTransfer service (<https://wetransfer.com/>) to the organizing committee email (mineral.prospectivity@brgm.fr).

The deadline for participating to the contest (i.e. providing the .zip archive) is October 15th 2017.

Evaluation of the results

The maps submitted by all participants will be printed and displayed during the conference, for discussion and comparison.

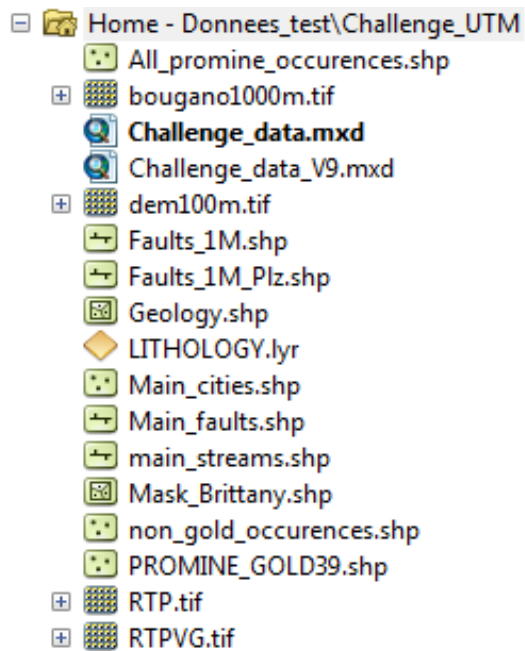
The organizing committee will evaluate the accuracy of each map with a “controlling set” (set of deposits that were removed from the dataset) and using Prediction Rate (also known as ROC) curves based on percentage of “controlling set” deposits vs. percentage of prospective area. The best predictive map will be awarded during the conference.

Dataset

Vector data layers are in ESRI Shape format (.shp) and all raster data layers are in .tif format. Projection system of the whole dataset is UTM WGS84, zone 30N.

The complete dataset is available for download in the web site of the conference, at <http://www.brgm.eu/mineral-prospectivity>

The dataset contains the following files:



Data files are all located in the Challenge_UTM directory. They are listed and briefly described below:

- **Challenge_data.mxd**: ArcGis project (V10.2) with all data
- **Challenge_data_V9.mxd**: ArcGis project (V9.2) with all data
- **Mask_Brittany**: study area
- **Faults_1M.shp**: faults extracted from the 1 million scale geological map of France – mean orientation is stored in attribute ORI180. Other attributes : Nature_ENG : Nature of the fault, Important_ : Importance of the fault
- **Faults_1M_Plz.shp**: faults extracted from the 1 million scale geological map of France; faults oriented between 150° and 170° related to Tertiary events have been eliminated of the dataset.
- **Main_faults.shp**: synthetic major faults
- **Geology.shp** : geological map synthetized from the 1:50 000th scale geological maps of France. Attibutes are : Area (in sq km) Lithology, System (from Paleoproterozoic until Quaternary), RMK (remarks), Veins (1 if true) and Code (coded concatenation of lithology and system as described in the tables) – see Geological coding
- **All_promine_occurrences.shp**: all occurrences of any commodity and of any type from the Promine database – Attributes : INDEX : number of the occurrence, NAME: name of the occurrence, TYPOLOGY: metallogenic type, COMMODITIES : main known metallic commodities. The gold occurrences that will be used for control have been removed from that dataset.
- **Non-gold_occurrences.shp**: a selected dataset of primary no-gold bearing occurrences – Attributes : INDEX : number of the occurrence, NAME: name of the occurrence, TYPOLOGY: metallogenic type, COMMODITIES : main known metallic commodities,

- **PROMINE_GOLD39.shp**: a set of Promine Gold occurrences than can be used as a dataset for predictivity mapping – Attributes : INDEX : number of the occurrence, NAME: name of the occurrence, TYPE : size of the occurrence, TYPOLOGY: metallogenetic type, COMMODITIES : main known metallic commodities, RELIABILIT : reliability of the occurrence.
- **Main-streams.shp**: main rivers of Brittany
- **Main_cities** : a selection of main cities of Brittany
- **Grids**:
 - **boug_ano.tif**: 1000m grid Bouguer anomaly
 - **dem100.tif**: 100m Digital Elevation Model from SRTM
 - **rtp2.tif**: 250m grid of mag survey, magnetic field reduced to the pole
 - **rtpvg.tif**: vertical gradient of the reduced to the pole magnetic field.

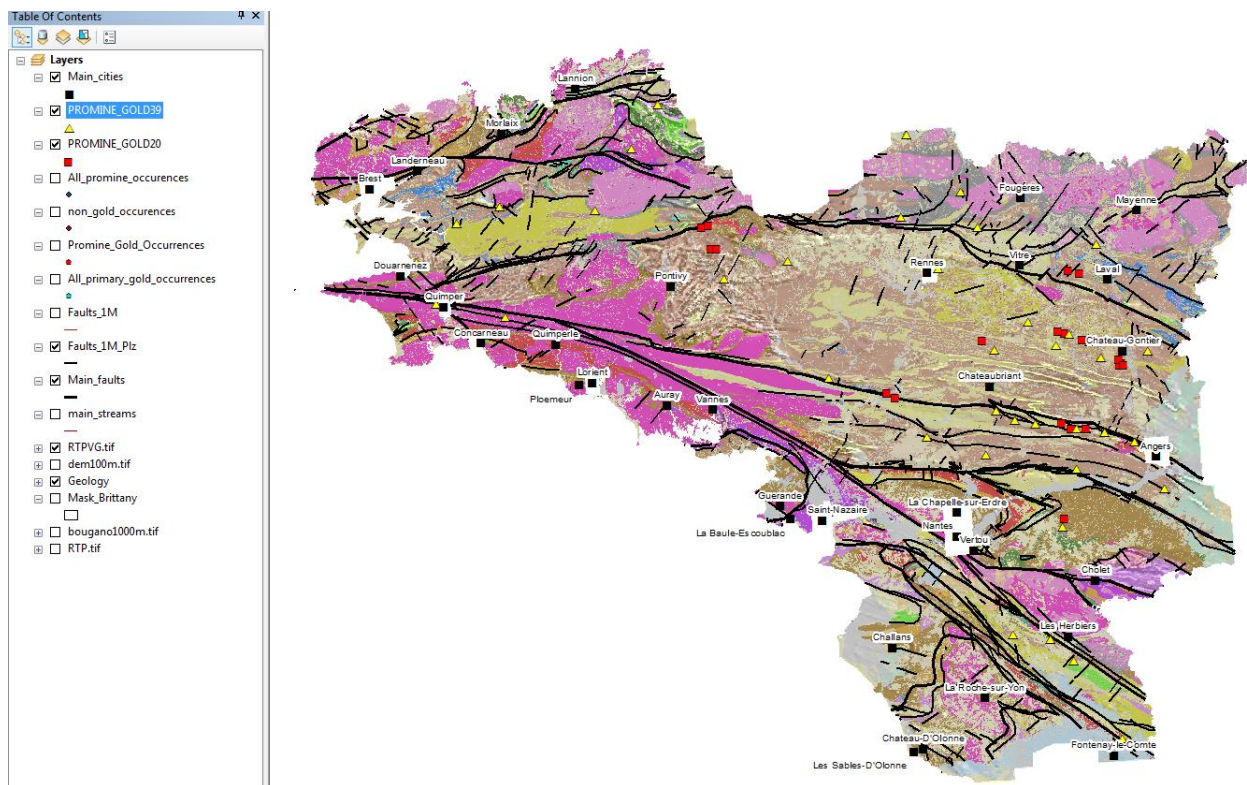


Figure 1 – overview of the “contest dataset” provided.

Geological coding

The systems below have been used to code geological information

Index for stratigraphic codes:

System	Ages	Code
Quaternary	less than 2.5My	Q
Eocene-Oligocene-Miocene-Pliocene	65-2.5My	T
Jurassic- Cretaceous	199-65My	M
Triassic	251-199My	9

Permian	299-251My	8
Carboniferous	359-299My	7
Devonian	416-359My	6
Silurian	443-416My	5
Ordovician	488-443My	4
Cambrian	542-488My	3
Neoproterozoic	1000-542My	2
Paleoprotéozoic	2500-1600My	1
Unknown Ante-Mesozoic	????	0

Index for lithological codes:

Magmatic rocks	Metamorphic rocks
ALBT: Albitites ANOR : Anorthosites DIOR : Diorites DOLE : Dolerites GABB : Gabbros GDIO : Granodiorites GRAN : Granite MCGR : Microgranites MDIO : Microdiorite MSYE : Microsyenites MZGR: Monzogranites PEGM : Pegmatites UMAF: Ultra mafic rocks	AMPH : Amphibolites GNEI: Gneiss HORN : Hornfels LEPT: Leptynites MCSH : Micaschistes MIGM: Migmatites ORTG: Orthogneiss SCHS: Schistes
Other basement rocks	Post paleozoic sedimentary formations
IRCA : Iron Cap LIME : Limestone SDST : Sandstone GRWK : Greywackes ACVO: Acid volcanics BAVO: Basic volcanics VDET: Volcano-sedimentary rocks VOLR: Volcanic rocks QUTZ : Quartz vein	ALLU : Alluvium COLL : Colluvium CRET : Cretaceous formations JURA : Jurassic formations EOC : Eocene formations MIOC: Miocene formations OLIG: Oligocene formations PLIO : Pliocene formations QUAT : Quaternary formations XXXX : Anthropic waste WATR : Rivers & lakes

Example: in the attribute code of the Geology Shapefile, the value "LIME5" means "Silurian limestone".

Regional geological context

The case study chosen by the organizing committee is gold in the French Armorican massif (Brittany).

The Armorican Massif is that part of western France where the Palaeozoic basement is presently cropping out, either because it had never been covered by Meso- Cenozoic sediments or because these sediments were removed by erosion. This Massif is part of the Late Paleozoic Variscan belt that extends throughout western and central Europe. This belt resulted from the convergence of Laurussia (= Laurentia + Baltica) and Gondwana, with

amalgamation of various continental domains of peri- (or north-) Gondwanan origin, and the resorption of the intervening oceanic domains. One such continental domain, namely Armorica (Perroud et al., 1984; Van der Voo, 1982), has been distinguished and constitutes the main part of the Armorican Massif, North of the South Armorican Shear Zone (see details below). In the Armorican Massif, the Variscan collision began during the Late Devonian and continued until the Early Carboniferous (Matte 1986; Ballèvre et al. 2014). The Armorican Massif is part of the Ibero-Armorican Arc, a major syntaxis of the Hercynian belt of western Europe. It comprises three main domains with contrasted structural styles and deformation/metamorphic histories. The northern part of Brittany shows external parts of the orogen, marked by moderate thickening and metamorphism. It consists in the North Armorican and the Central Armorican Domain, two main units separated by the NASZ, The South Armorican Domain corresponds to internal parts of the orogen. These domains are bounded by two dextral crustal-scale shear zones, the North Armorican Shear Zone and the South Armorican Shear Zone (NASZ and SASZ, respectively).

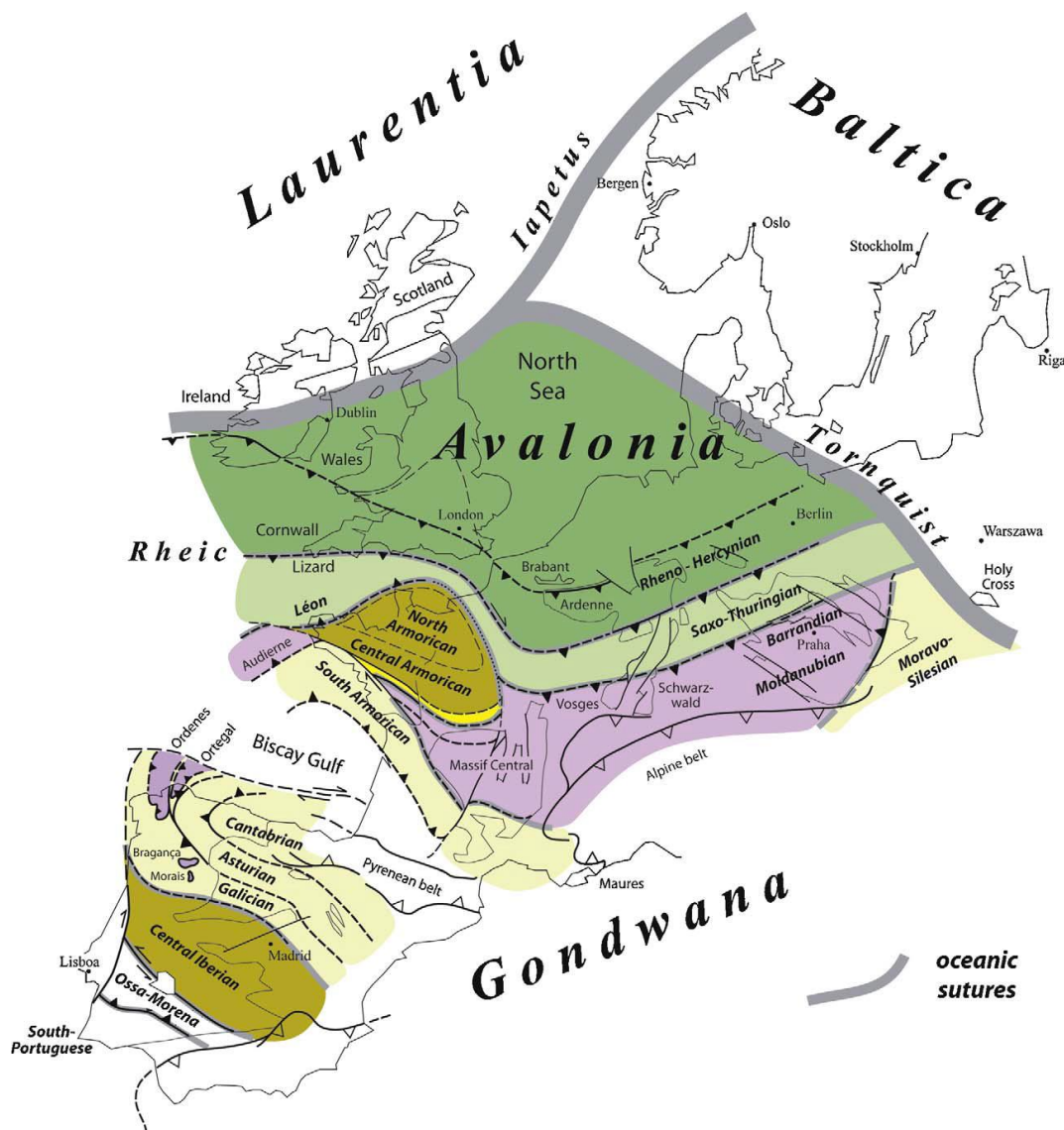


Figure 2 (after Ballèvre et al., 2009) - The Armorican Massif is one of several areas where Palaeozoic rocks deformed during the Variscan orogeny, crop out. The main domains in the Variscan belt vary along strike, their correlation being a matter of debate because of the non-cylindrical nature of the belt. Different colors are used to overcome the difficulties of the parochial nomenclature, and highlight potential correlations within the Variscan belt.

Pre- Variscan collision history

A common feature of all domains within the Armorican Massif is the occurrence of a Proterozoic basement that has been deformed at the end of the Neoproterozoic, during an orogenic event that is locally known as the Cadomian orogeny (Chantraine et al., 2001). It is now widely accepted that the Armorican Massif was located at this time close to the West African craton (Nance and Murphy, 1994), and therefore the Cadomian orogeny would be an integral part of, the Panafrican orogeny.

The Early Palaeozoic was a time of continental rifting and oceanic opening, as recorded in the Armorican Massif. Indeed, the Early Palaeozoic sequences record two main episodes of continental rifting. Cambrian rifting is well-documented in the North-Armorican domain (Le Gall, 1993), and in the Mauges Unit (Le Métour and Bernard-Griffiths, 1979; Thiéblemont et al., 1987, 2001). Early Ordovician rifting is more widespread than the Cambrian rifting, being reported in the whole Armorican Massif on the basis of: (i) a large amount of aerial to subaquatic volcanics, like the Early Ordovician “porphyroids” of the Vendée (Le Hébel et al., 2007), or the fine-grained “leptynites” of high-grade metamorphic complexes, some of them having an alkaline chemistry (Ballèvre et al., 2002); (ii) coeval granodioritic to granitic plutonism (Jégouzo et al., 1986), intruding the Neoproterozoic to Cambrian sequences (e.g. the Lanvaux granite); and (iii) lateral changes in sediment thickness and facies, interpreted as resulting from deposition on tilted blocks (Brun et al., 1991). Therefore, the Early Palaeozoic is interpreted as a period of widespread continental rifts coexisting with narrow oceanic domains (Gondwana break-up). No oceanic suture is recognized within or between the central- and North-Armorican domains which thus both own to the Armorica microplate (see above). By contrast, despite Variscan deformation and metamorphism, ophiolitic sequences (of Cambro-Ordovician to Devonian age) can be recognised in the South-Armorican domain, namely the Audierne Complex (Bernard-Griffiths and Cornichet, 1985), to the West, and the Drain-le Havre Unit in the Champtoceaux Complex (Bernard-Griffiths and Cornichet, 1985), to the East. Geochemical data on the Audierne and Drain Complexes indicate that the mafic rocks are akin to mid-ocean ridge basalts.

Variscan Structure of the Armorican Massif

The Hercynian belt of Brittany can be divided into different domains separated by crustal- and regional-scale shear zones (the NASZ, to the North, and the SASZ, which displays two distinct branches, to the South).

- 1) North of the NASZ, The North Armorican domain is mainly made of Cadomian (Proterozoic) basement and was essentially affected by Neoproterozoic deformations and metamorphism (between ca 600 and 540 Ma; it constituted a part of the upper brittle crust un-metamorphosed and almost un-deformed, behaving as a rigid continental block during the Variscan orogeny (Brun et al. 2001).
- 2) The Central Armorican domain and Ligerian domain are made of Late Neoproterozoic to upper Paleozoic detrital sediments affected by moderate deformations (Gumiaux et al. 2004a, 2004b) and a low-grade regional metamorphism during the Variscan orogeny. The maximum temperature reached is estimated to be close to 250–300 °C, based on vitrinite reflectance (Donnot et al. 1973), chloritoid-bearing slate occurrences (Le Corre 1969), the illite crystallinity (Le Corre 1975), and the chlorite geothermometer (Gloaguen et al. 2007). This emphasizes that these domains suffered only limited thickening during the Hercynian collision and that erosion has been limited in this domain of the range.

From Mid-Ordovician to the Lower Devonian, a continuous sequence of marine sediments deposited. Sediments younger than mid-Devonian appear less continuous

and localized within domains bounding Eastern Central Brittany (e.g. Laval-Menez-Belair area, Brest area, or Ligerian Domain). During the Carboniferous, sedimentation became restricted to isolated basins located along fault zones bounding Central Brittany (Châteaulin, Laval and Ancenis basin) which mark the onset of Variscan shortening within the Central Armorican Domain. Deformation is basically continuous throughout the entire Eastern Central Brittany (Gapais and Le Corre, 1980; Gumiaux et al., 2004a). The upright folds that affect the sediments have horizontal and EW striking axes. The first order fold wavelength is controlled at regional scale by the thickest competent unit of the sedimentary sequence, the lower Ordovician Armorican sandstone. Folds that affect the Armorican sandstone are of limited amplitude and their overall envelope is sub-horizontal at regional scale.

Following early works arguing for strike-slip across Central Brittany (Gapais and Le Corre, 1980; Percevault and Cobbold, 1982), strain removal throughout this region has shown that it was deformed by overall dextral strikeslip simple shear (Gumiaux et al., 2004a, b). Shearing was partly synchronous with the emplacement of leucogranite plutons (see below for details on geochemistry and timing) (Berthé et al., 1979; Vignerresse and Brun, 1983).

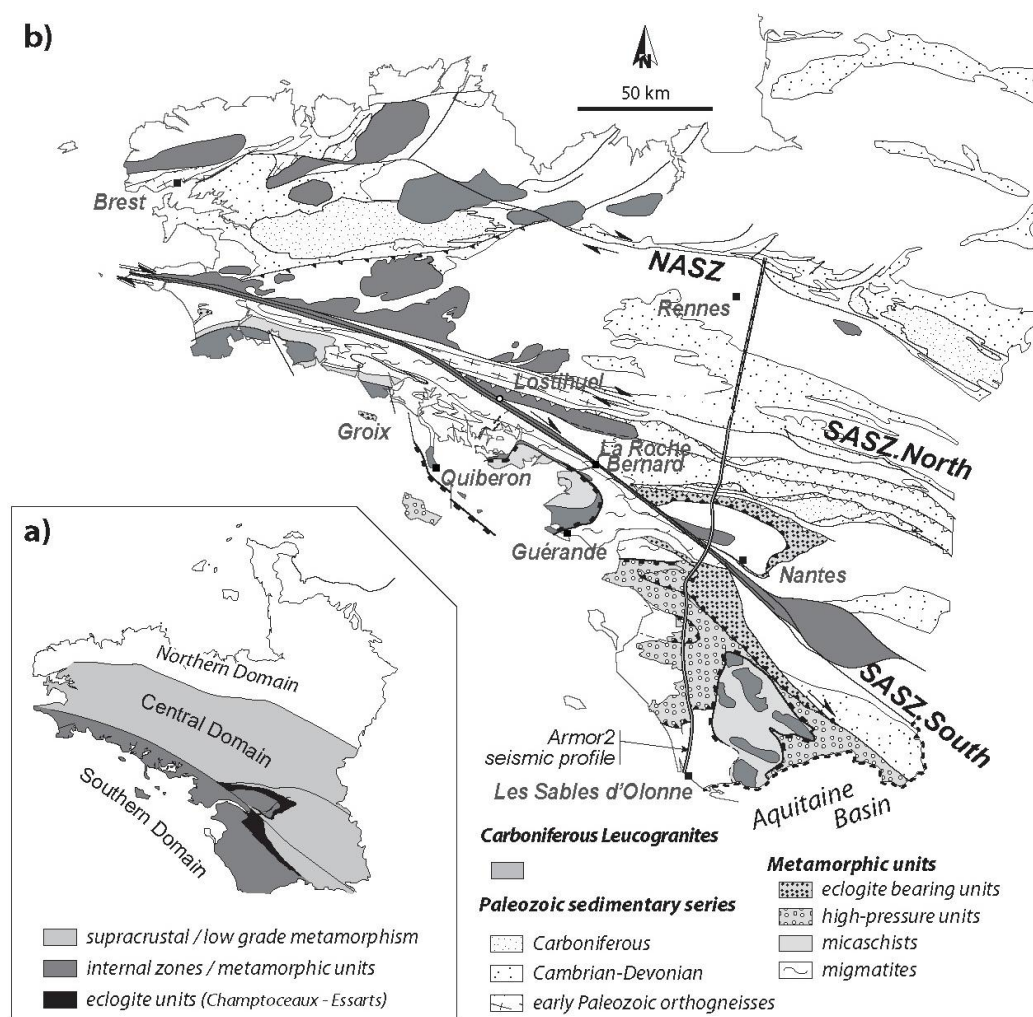


Figure 3 (from Gapais et al., 2015) - General geological features of the Armorican Hercynian belt. (a) Main structural domains; (b) General geology illustrating the important crustal derived magmatism of Carboniferous age. The line in (b) marks the trace of the Armor 2 deep seismic reflection profile.

3) The South Armorican domain belongs to the internal metamorphic zones of the Variscan belt. It was affected by crustal thickening during Late Devonian to Carboniferous times, with a high-pressure–low-temperature event at ca. 360 Ma (Bosse et al. 2000, 2005), followed by Late Carboniferous extension (Gapais et al. 1993, 2015). Extension induced in particular the exhumation of lower-crustal units below detachment zones and along the SASZ. Main geological units of the South Armorican Domain are as follows:

- Uppermost units are marked by metamorphic histories of HP–LT type. They are from top to bottom: (1) blueschists (Bois de Céné and Ile de Groix blueschists, 1400–1900 MPa, 500–550 8C; Bosse et al., 2002), and (2) metamorphosed volcanics and black shales (Vendée and Belle-Ile-en-Mer porphyroids, 700–900 MPa, 350–400 8C; Le Hébel et al., 2002).
- Intermediate units mainly consist of micaschists marked by Barrovian metamorphism, increasing downward from greenschist facies to amphibolite facies conditions (Triboulet and Audren, 1988; Goujou, 1992 and references therein).
- Lowermost units consist of high-grade rocks, with large volumes of migmatites, and correspond to the lower part of the Barrovian pile. Local estimates of peak metamorphic conditions have yielded values of the order of 700–750 8C and 1000 MPa (Golfe du Morbihan area; Jones and Brown, 1990).
- Several sheets or laccoliths of two-mica granites are emplaced below the HP–LT group, generally within the micaschists (e.g. Quiberon, Sarzeau, or Gue´rande granites). Available ages indicate that they emplaced and cooled between 310 and 300 Ma (Bernard-Griffiths et al., 1985; Le Hébel, 2002).

At regional-scale, the overall structural pattern of South Brittany is thus that of windows of high-temperature rocks overlain by lower temperature domains. Where exposed, contacts between these units are rather flat or gently dipping. In the migmatite cores, the foliation can have variable attitudes. Above them, the regional fabric is flat-lying to moderately dipping. It bears a generally strong stretching lineation that strikes dominantly E–W (Brun and Burg, 1982).

Highest grade metamorphic rocks in South Brittany are eclogite bearing units that mark the northern boundary of the South Armorican Domain, and outline a major suture zone of the belt. This limit between upper-crustal domains and high-grade zones is cut by the southern branch of the SASZ and a segment of this suture zone is presently located just north of the southern branch of the SASZ, within the Champtoceaux Domain.

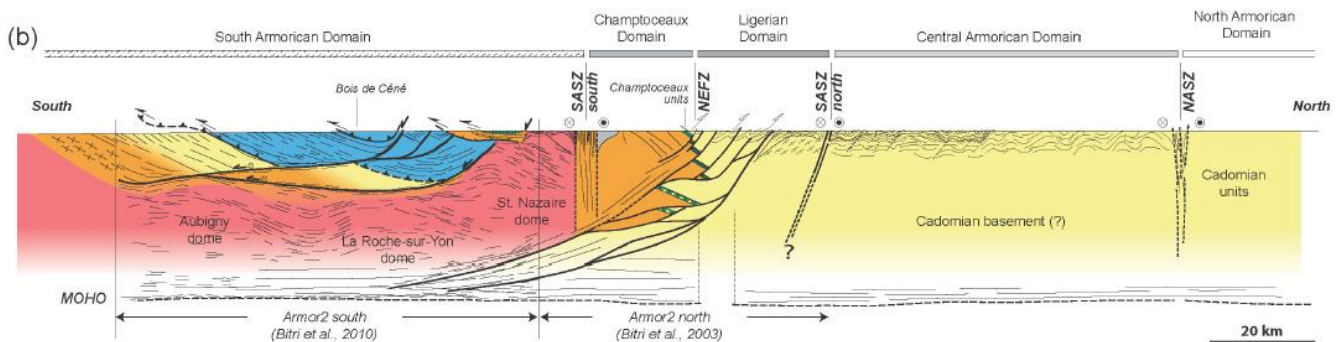


Figure 4 (from Gapais et al., 2015) - Summary of seismic information from the Armor2 Géofrance 3-D program. Interpreted seismic profile attached to a northern cross-section through Central Brittany.

Paleozoic magmatism through the Armorican Massif

Several magmatic events occurred during the Paleozoic in the Armorican Massif. These are first represented by bimodal magmatism and volcanism during the Late Cambrian-early Ordovician, featuring calc-alkaline and rare peraluminous series (Ballèvre et al. 2014 and references therein). The Late Cambrian event is best developed in the North Armorican domain, whereas the Early Ordovician event is best developed in the Central and South Armorican domains. Numerous Variscan granitoids have been emplaced in the Armorican Massif and are characterized by different geochemical associations (Capdevila 2010; Tartèse and Boulvais 2010; Tartèse et al. 2011a, 2011b; Ballouard et al. 2015). According to Capdevila (2010), five main associations are currently recognized: (1) a ca. 370 Ma (U-Pb method on zircon; Cuney et al. 1993) calc-alkaline association containing orogenic biotite-hornblende granites resulting from the partial melting of an enriched mantle; (2) a ca. 330 Ma Mg-potassic metaluminous association that includes mafic to intermediate rocks and porphyroid biotitehornblende monzogranites (e.g., Plouaret granite, 329 ± 5 Ma, whole-rock Rb-Sr, Peucat et al. 1984); (3) a Mg-potassic peraluminous association made up of monzodiorite with a mantle origin, monzogranite, and cordierite granite from partial melting of metasediments; and (4) a ca. 316–310 Ma two mica peraluminous leucogranites formed by the partial melting of a similar metasedimentary sources (Tartèse and Boulvais 2010), e.g., the Guérande leucogranite (309.7 ± 1.3 Ma by U-Pb method on zircon and monazite; Ballouard et al. 2015) and the Lizio granite (316 ± 1.3 Ma by U-Pb on zircons, Tartèse et al. 2011b); and (5) ca. 300 Ma red monzogranites and porphyroid syenogranites (e.g., the Ploumanac'h granite, 303 ± 15 Ma, whole-rock Rb-Sr, Vidal 1980).

The North and Central Armorican domains are also marked by a dense swarm of dikes and sills of dolerite that intrude the Late Proterozoic to Devonian sediments (Velde 1970; Ruffet et al. 1992; Lahaye et al. 1995; Aïfa et al. 1999; Le Gall 1999). They are spatially distributed in several groups defined by Le Gall (1999), namely the Mancellia, Saint-Malo, Laval Basin and Martigné-Ferchaud groups. According to Le Gall (1999), the dolerites of these groups present homogeneous geochemical compositions and appear to be similar in composition to the thick mafic and felsic volcano sedimentary sequences of the Châteaulin Basin in the western part of the Armorican Massif (Pelhate 1994). While mafic rocks are generally difficult to date due to a lack of suitable minerals, a recent paper presents U-Pb LA-ICP-MS dating of apatite applied to seven different dike and sill samples of dolerite from the above mentioned groups. These results demonstrate that, in all cases, the apatite grains do carry enough radiogenic Pb to be dated by in situ U-Pb analyses and yield a 207Pb -corrected mean age of 363.4 ± 5.8 Ma. These results reveal the existence of a major and short-lived magmatic event in the Variscan belt of Brittany during the Devonian-Carboniferous transition.

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