



# From opening to subduction of an oceanic domain constrained by LA-ICP-MS U-Pb zircon dating (Variscan belt, Southern Armorican Massif, France)

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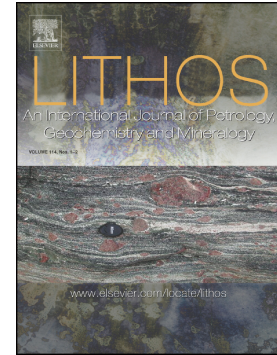
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**From opening to subduction of an oceanic domain constrained by LA-ICP-MS  
U-Pb zircon dating (Variscan belt, Southern Armorican Massif, France).**

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**Abstract**

In the Variscan belt of Western Europe, the lifetime and evolution of the oceanic domain is poorly constrained by sparse, outdated and unreliable multigrain ID-TIMS U-Pb zircon dating. In this article, we present a complete in situ LA-ICP-MS dataset of about 300 U-Pb zircon analyses obtained on most of the ophiolitic and eclogitic outcrops of Southern Brittany, comprising new dating of previously published zircon populations and newly discovered rock samples. In situ dating and cathodo-luminescence imaging of each zircon grain yields new absolute time-constraints on the evolution of the Galicia-Moldanubian Ocean. The new results confirm that the opening of this oceanic domain is well defined at about 490 Ma. In contrast, the generally-quoted 400-410 Ma-age for the high-pressure event related to the subduction of the oceanic crust is definitely not recorded in the zircons of the eclogites. In light of these new data, we propose that the obduction of oceanic rocks occurred

at about 370-380 Ma while the high-pressure event is recorded at 355 Ma in only a few zircon grains of some eclogite samples.

Additionally, this large scale dating project demonstrates that the zircons from eclogites do not systematically recrystallise during the high pressure event and consequently their U-Pb systems do not record that metamorphism systematically. These zircons rather preserve the isotopic memory of the magmatic crystallization of their igneous protolith. Another example of an eclogite sample from the French Massif Central illustrates the frequent mistake in the interpretation of the ages of the early hydrothermal alteration of zircons in the oceanic crust versus partial or complete recrystallization during eclogite facies metamorphism.

## **1. Introduction**

In ancient mountain belts, ophiolitic gabbros associated with plagiogranites record the opening and expansion of oceanic domains, whereas eclogite-facies rocks rather evidence their closure. Establishing the ages of ocean formation and subduction is a primary target for reconstructing past plate configurations, as well as their relative movements, and geologists consider that the most reliable method is the U-Th-Pb dating of zircon. Nevertheless, high-grade fluid-driven metamorphic events may strongly disturb the behaviour of the U-Pb isotopic system of zircons, eventually producing weak, complex or complete recrystallization of the grains. For that reason, in-situ analytical techniques associated with cathodoluminescence imaging are preferred because they allow deciphering of complex crystalline structures and corresponding ages. Our purpose here is not to match LA-ICPMS (or SIMS) against ID-TIMS analytical techniques. It is undoubtedly admitted that state-of-the-art CA-ID-TIMS reaches the highest analytical precision levels (i.e. Schaltegger et al., 2015).

Nevertheless, high spatial resolution associated with good precision on numerous analyses is a more favourable tool to accurately understand the behaviour of the U-Pb system in such complex minerals and rocks than very high precision on a few grains. Furthermore, "old-fashioned" multigrain U-Pb dating of the 1970s-80s, devoid of any mechanical or chemical abrasion pre-treatment (Krogh, 1982; Mattinson, 2005), is unable to challenge in producing accurate age constraints for such multi-episodic zircon crystals.

The late Palaeozoic Variscan belt is responsible for the construction and architecture of the continental crust in large parts of western and central Europe. The Variscan belt is generally thought to be the result of the collision between Laurussia to the north and Gondwana to the south, and this collision was preceded by the subduction of one or several oceans (e.g. Pin, 1990; Matte, 2001; Lardeaux, 2014; Franke et al., 2017), the largest one being the Rheic Ocean, separating Avalonia to the North from Armorica and other Gondwana-derived terranes to the South. The geological history of Southern Brittany in Western France records the rift-drift history of Armorica away from Gondwana and its late shearing during the oblique convergence between Laurussia (incorporating Avalonia) and Gondwana (Ballèvre et al., 2009 and 2014). This area comprises several worldwide-famous key geological domains such as Essarts (e.g. Lacroix, 1891; Brière, 1920; Godard, 1988) and Ile de Groix (e.g. Barrois, 1883; Triboulet, 1974; Audren et al., 1993; Barrientos and Selverstone, 1993; Ballèvre et al., 2003; El Korh et al., 2009) where eclogites and blueschists have been carefully described for several decades. Isolated samples from different massifs have been dated (e.g. Peucat et al., 1982; Paquette et al., 1985 and 1987), sometimes providing complex or enigmatic results. None large-scale dating of the oceanic rocks from South Brittany was performed so far. As we demonstrate in this article, the analytical limitations described above in combination with the challenge of dating mantle-derived

oceanic zircons and over-interpretation of the results led to a poorly constrained and consequently partly incorrect timescale of the geodynamic evolution of the Variscan belt.

Thirty years later, spectacular improvements in the analytical techniques have provided us with best-suited tools for addressing this geochronological challenge. We considered a global dating target including all the relevant complexes of Southern Brittany: Baie d'Audierne, Champtoceaux, the Essarts (Vendée), Ile de Groix, and Bois-de-Cené. Most of the formerly dated and published samples (including by two of us) were re-analyzed by LA-ICPMS using the same starting zircon separates in addition to newly discovered ocean-derived samples. Old and new results are compared and discussed to obtain a global scheme of the evolution of the Variscan belt based on a new and more accurate timescale. Additionally, the impact of metamorphism on the U-Pb system of the zircons is discussed.

## **2. Geological setting and studied samples**

Where not covered by younger (Mesozoic and Cenozoic) sediments, or reworked in Cenozoic orogenic belts (like the Alps and the Pyrenees), the Variscan basement may be studied in numerous massifs scattered from Spain and Portugal to Bohemia (Fig. 1). Dismembered ophiolite complexes are recognized throughout the belt, from Iberia to Bohemia (e.g. Dubuisson et al., 1989; Pin, 1990; Girardeau et al., 1994; Sánchez Martínez, 2009; Kryza and Pin, 2010; Arenas and Sánchez Martínez, 2015; Franke et al., 2017). In the absence of fossiliferous sedimentary sequences deposited on top of these ophiolite sequences, geochronology is the only tool available for assessing their age. In the Armorican Massif, several oceanic complexes have been recognized for several decades (e.g. Montigny and Allègre, 1974; Bernard-Griffiths and Cornichet, 1985; Godard, 1981; Ballèvre et al., 2009)

(Fig. 2). These are briefly reviewed below, and the samples taken for detailed dating in each complex are described and summarized in Table 1.

### *The Baie d'Audierne Complex*

In the Baie d'Audierne, a sequence of ultrabasic and basic rocks has long been recognized as a potential ophiolite complex in the Variscan belt (e.g. Peucat, 1973; Hanmer, 1977). It comprises, from top to bottom, (i) serpentized peridotites with chromite pods (Ty Lan Formation), (ii) metagabbros (Peumerit Formation), (iii) metabasalts (Tréogat Formation), and possibly (iv) metasediments (Trunvel Formation). Because of poorly-exposed outcrops, especially for the Peumerit Formation, it has not been possible to establish in the field the relations between the gabbros and the peridotites.

The metamorphic evolution of these rocks is characterized by an amphibolite-facies overprint. Mafic rocks preserving high-pressure granulite facies (i.e. coexisting garnet, Jd-poor clinopyroxene and plagioclase) or transitional granulite to eclogite facies parageneses (i.e. coexisting garnet, omphacite, plagioclase, quartz, kyanite and rutile) (Velde, 1972; Marchand, 1982; Schulz et al., 2002) form tectonic slices located on top of the ophiolite body. The latter displays amphibolite-facies parageneses, with no relics of a previous high-pressure stage.

We studied two samples from the Baie d'Audierne Complex. The first one (BA-8B), a loose block found close to the cemetery of the type locality, is a plagioclase-rich layer in a foliated metagabbro. It essentially consists of plagioclase ( $An_{26-32}$ ), a few elongated aggregates of green hornblende replacing the former magmatic clinopyroxene, with some apatite, ilmenite and zircon. The second one (BA-1) is a chlorite schist from the Ty-Lan Formation, made of Mg-rich chlorite, apatite, ilmenite, monazite and zircon. Comparable

drilled samples from sheared peridotites of the Mid-Atlantic ridge, containing zircon crystals as accessory phase, have been interpreted as altered plagiogranite melt impregnations originating from hydrous partial melting of gabbroic intrusions in an oceanic shear zone (Cornen et al., 1999; Jöns et al., 2009; Pietranik et al., 2017). Consequently, the Ty-Lan chlorite schist, as well as similar samples from Ile de Groix and Bois-de-Cené, can be considered as fragments of ancient oceanic crust exposed in ophiolitic complexes.

### *The Champtoceaux Complex*

In this area, a stack of thin units displaying contrasting lithologies and P-T histories has been recognized following detailed mapping and careful petrological descriptions (Marchand, 1981; Ballèvre et al., 1987 and 1989; Ballèvre and Marchand, 1991; Bosse et al., 2000; Ballèvre et al., 2002; Pitra et al., 2010).

The lowermost Cellier Unit is famous because it consists of fine-grained leucocratic Ordovician gneisses containing well-preserved, meter-sized eclogite lenses (Lacroix, 1891). Two eclogite samples from this Unit have been restudied. The first one (CX-14), already described in Paquette et al. (1985), is a fine-grained and very fresh rock showing no trace of amphibolitization. The paragenesis consists of sub-idioblastic zoned garnet, omphacite, large poeciloblasts of kyanite, quartz, rutile and rare zircon. Fine lamellae of paragonite crosscutting both omphacite and kyanite may represent the only trace of retrogression in this well-preserved eclogite. The second sample from the Cellier Unit (CX-5) is a fine-grained, unfoliated eclogite consisting of garnet-omphacite-glaucophane-quartz-phengite-rutile. Most garnet grains display an atoll structure and surround isolated crystals or aggregates made of phengite with minor omphacite and quartz. Glaucophane crystals are late-stage (but still eclogite-facies) porphyroblasts, which most probably developed at the time of garnet core



dissolution, promoted by the access of eclogite-facies fluids in this undeformed, brittle rock. This sample is representative of the eclogites defined in the Champtoceaux Complex as Le Cellier type. The petrology of similar samples from the same outcrop has been already detailed in Godard et al. (1981).

The Champtoceaux Unit essentially comprises migmatitic orthogneisses containing a few mafic lenses. Most of them are made of plagioclase and hornblende, but some display relics of garnet, and rutile. The eclogite-facies paragenesis is best preserved in sample SLA-1, a fine-grained unfoliated eclogite, consisting of garnet, omphacite (Jd<sub>30</sub>), kyanite, zoisite and rutile. Omphacite is largely replaced by diopside-plagioclase symplectites, a typical feature related to Na-clinopyroxene breakdown during decompression of eclogites (e.g; Joanny et al., 1991; Anderson and Moecher, 2007).

The Drain Unit consists of serpentinised peridotites and metagabbros, sometimes preserving magmatic textures and minerals. The studied rock (CX-6) has been sampled in a abandoned quarry along the left bank of the Loire River. A preliminary geochemical study of this sample (Paquette, 1987) has indicated its oceanic affinity, owing to the N-MORB-type shape of its REE pattern and the depleted mantle signature of the Nd isotopes. A full geochemical characterization of this Unit was recently provided by Aertgeerts (2016), who has confirmed the affinity with N-MORB basalts. The studied sample is a moderately foliated rock deriving from a gabbroic protolith, where the former sites of magmatic clinopyroxene and plagioclase have been replaced by aggregates of amphibole, zoisite and albite, respectively. The elongated shape of the aggregates defines the foliation.

*The Essarts Unit (Vendée)*

The Essarts Unit (Fig. 2) forms a NW-SE-trending body about 40 km long and 20 km wide, consisting of predominantly orthogneisses into which are scattered km-sized bodies of eclogites (Lacroix, 1891; Brière, 1920; Godard, 1981, 1988, 2001, 2009; Lahondère et al., 2009). Geochemical studies have shown a rather large mineralogical diversity of eclogites, with (i) zoisite and kyanite-bearing eclogites deriving from Al-Mg rich gabbros, (ii) quartz-rich eclogites, (iii) rutile-rich eclogites deriving from Fe-Ti rich gabbros, and (iv) a few more felsic rocks (Godard, 1981 and 1988). Primary magmatic minerals have not been preserved in the eclogites. By contrast, the distribution and shape of inclusions suggest that they derive from amphibolitized metagabbros (Godard, 2001).

Following early attempts at characterizing the geochemistry of the eclogites (Montigny and Allègre, 1974; Bernard-Griffiths and Cornichet, 1985), it was proposed that the Essarts eclogites derive from a subducted oceanic crust, later dismembered in a melange formation during the Variscan collision (Godard, 1983). Further studies, revealing HP parageneses in the enclosing gneisses (Godard, 2001 and 2009), have constrained the tectonic history of this unit, demonstrating that the mixing between the oceanic and continental crust was earlier or synchronous with the HP event.

The two samples studied here come from the famous Gerbaudière quarry, mapped in detail (Godard, 2001), and were previously studied by Peucat et al. (1982) and described by Godard (1981 and 2001). Samples 4980 and 4981 are quartz-bearing eclogites with zoisite, clinozoisite, rutile, ilmenite, pyrite and zircon as accessory minerals.

#### *The Ile de Groix Unit*

The Ile de Groix essentially consists of blueschist-facies metasediments and metabasalts (Barrois, 1883; Triboulet, 1974; Audren et al., 1993; Bosse et al., 2002 and 2005;

Ballèvre et al., 2003), with a few occurrences of albite gneisses derived from felsic dykes or tuffites of Early Ordovician age (El Korh et al., 2012). However, rare occurrences of ultrabasic rocks are found in its easternmost (and structurally deepest) part, the first one in the Tréhor area, the second one at Beg Melen. The former was sampled for this study and consists of a chlorite schist (sample GX-16A) composed mainly of Mg-rich chlorite, with minor amounts of apatite, ilmenite and zircon.

#### *The Bois-de-Céné Unit*

The Bois-de Céné Unit is very similar to the Ile de Groix Unit, and it consists of blueschist-facies metapelites and metabasalts (Guiraud et al., 1987; Lahondère et al., 2009). However, one difference with the Ile de Groix is the larger exposure of serpentinites, which have been quarried. The V1 chlorite schist studied sample comes from a small abandoned quarry located about 2 km south of Paulx and 8 km east of Bois-de-Céné (Lahondère et al., 2009), and essentially consists of magnesian chlorite, with minor amounts of magnetite, apatite, monazite and zircon.

#### *The la Bessennoits eclogite (French Massif Central)*

In the French Massif Central (FMC), a complex stack of nappes is intruded by numerous late-Carboniferous granitoids (e.g. Faure et al., 2009; Lardeaux, 2014; Chelle-Michou et al., 2017). Eclogites are found in several localities throughout most of the FMC, but they are generally poorly outcropping. This is the case in the studied locality, la Bessennoits, where eclogites are found as small blocks in the pastures and the forests (Monchoux and Couturier, 1987). As described in detail in Paquette et al. (1995), the dated

E3 samples is a Fe-Ti eclogite located in metre-thick layers within the orthogneisses. This rock is banded with a millimeter-scale grain size and comprises clinopyroxene kelyphites associated with plagioclase. Garnet is commonly altered (see Table 1), quartz is abundant and rutile is interlayered with biotite and ferroan pargasitic hornblende.

### 3. Analytical techniques

In situ U-Th-Pb isotopic data were obtained by laser ablation inductively coupled plasma spectrometry (LA-ICP-MS) at Laboratoire Magmas & Volcans (Clermont-Ferrand, France). The analyses involved the ablation of minerals with a Resonetics Resolution M-50 powered by an ultra-short-pulse (<4ns) ATL Atlex Excimer laser system operating at a wavelength of 193 nm (detailed description in Müller et al., 2009). Spot diameters of 26 to 44  $\mu\text{m}$  were used, associated with repetition rates of 3 Hz and a laser fluence of 4 J/cm<sup>2</sup> (Supplementary Table S1). The ablated material was carried by helium and then mixed with nitrogen and argon before injection into the plasma source of an Agilent 7500 cs ICP-MS equipped with a dual pumping system to enhance sensitivity (Paquette et al., 2014). The alignment of the instrument and mass calibration were performed before every analytical session using the NIST SRM 612 reference glass, by inspecting the signal of <sup>238</sup>U and by minimising the ThO<sup>+</sup>/Th<sup>+</sup> ratio (< 1%). The analytical method for isotope dating is similar to that developed and reported in Paquette and Tiepolo (2007) and detailed in Hurai et al. (2010). The signals of <sup>204</sup>(Pb+Hg), <sup>206</sup>Pb, <sup>207</sup>Pb, <sup>208</sup>Pb, <sup>232</sup>Th and <sup>238</sup>U masses were acquired. The occurrence of common Pb in the sample was monitored by the evolution of the <sup>204</sup>(Pb+Hg) signal intensity, but no common Pb correction was applied owing to the large isobaric interference from Hg. The <sup>235</sup>U signal was calculated from <sup>238</sup>U on the basis of the ratio <sup>238</sup>U/<sup>235</sup>U = 137.88. Single analyses consisted of 30 seconds of background integration

with the laser off, followed by 60 seconds integration with the laser firing and a 20 second delay to wash out the previous sample and prepare for the next analysis.

Data were corrected for U-Pb fractionation occurring during laser sampling and for instrumental mass discrimination (mass bias) by standard bracketing with repeated measurements of the GJ-1 zircon reference material (Jackson et al., 2004). Repeated analyses of the 91500 zircon reference material (Wiedenbeck et al., 1995) treated as an unknown independently control the reproducibility and accuracy of the corrections. Data reduction was carried out with the software package GLITTER® from Macquarie Research Ltd (van Achterbergh et al., 2001; Jackson et al., 2004). For each analysis, the time resolved signals of single isotopes and isotope ratios were monitored and carefully inspected to verify the presence of perturbations related to inclusions, fractures, mixing of different age domains or common Pb. Calculated ratios were exported and concordia ages and diagrams were generated using the Isoplot/Ex v. 2.49 software package of Ludwig (2001). The zircon analytical results were projected on  $^{207}\text{Pb}/^{206}\text{Pb}$  versus  $^{238}\text{U}/^{206}\text{Pb}$  diagrams (Tera & Wasserburg, 1972), where the analytical points plot along a mixing line between the common Pb composition at the upper intercept and the zircon age at the lower intercept. This method is commonly used to date Phanerozoic zircons using in situ techniques (Baldwin and Ireland, 1995). The concentrations of U-Th-Pb were calibrated relative to the values of the GJ-1 zircon reference material (Jackson et al. 2004).

Before dating, the zircon crystals were imaged by cathodoluminescence to investigate inner structure and zoning. Imaging was performed on a Jeol JSM-5910LV scanning electron microscope equipped with a detector operating at 15 kV current at Laboratoire Magmas & Volcans (Clermont-Ferrand, France).

#### **4. U-Pb zircon results**

The U-Pb zircon analytical results are plotted in the Figure 4 and reported in the Supplementary Table S2.

#### *4.1. The Baie d'Audierne Complex*

Sample BA-8B, a plagioclase-rich metagabbro, contains euhedral, pale-coloured, medium-elongated and oscillatory zoned zircon crystals (Fig. 3a). The centre part of the grains appears systematically darker, implying a higher U content than the margin. No inherited cores were detected. 27 analyses including zircon centres and margins yielded concordant to sub-concordant points defining a lower intercept age of  $481.7 \pm 3.2$  Ma (Fig. 4a). The mean Th/U ratio is  $0.25 \pm 0.11$ . The U contents are generally less than 100 ppm but with centre parts up to 270 ppm and margins as low as 10 ppm. Considering the igneous character of the grains, this age is interpreted as that of crystallization of the zircons.

The zircons from the BA-1 chlorite schist are yellow, medium to long prismatic with generally poorly translucent edges. The grains appear euhedral but their inner structure is commonly complex. This grain morphology is related to an outer oscillatory-zoned dark rim systematically occurring on all of the grains (Fig. 3b). These rims may be locally covered by a very thin ( $<5 \mu\text{m}$ ) and highly-luminescent rim and surround an inner highly luminescent core, itself sometimes containing another occasionally dark-zoned central core (Fig. 3b and c). The dark outer rims are commonly metamict as demonstrated by a very high U content up to 3000 ppm. Plotted together with synchronous cores (Fig. 3d), the dark rims yield a lower intercept age of  $376.8 \pm 2.5$  Ma (Fig. 4b), representing the major part of the zircon population. Inherited cores in some grains define multiple age patterns with concordant points dating at

$490.2 \pm 4.2$  Ma (Fig. 4b) and discordant points indicating Proterozoic upper intercept ages of  $1.89 \pm 0.08$  Ga and  $2.40 \pm 0.03$  Ga (Fig. 4c).

A comprehensive interpretation including all of this information is proposed. With a Th/U of about 0.3 and consistent core-rim ages, it can be deduced that the protolith of the chlorite veins was emplaced into the oceanic lithosphere at  $376.8 \pm 2.5$  Ma. This rock was slightly contaminated by inherited Cambrian and Proterozoic zircons preserved as inner cores within the analysed grains. That implies that this continental crust contamination occurred prior or simultaneously to the (re-) crystallization of the euhedral dark-zoned outer rim at c.a. 375 Ma. Finally, this latest event occurred synchronously within error limits with the magmatism of the oceanic protolith also recorded about 375 Ma (Fig. 3d). The outer rims display lower Th/U ratios with much higher U contents than the cores. They could have been produced by in situ hydrothermal alteration responsible for dissolution-reprecipitation processes affecting the whole zircon population (Schwartz et al., 2010). According to Jöns et al. (2009), Schwartz et al. (2010) and Pietranik et al. (2017) such events are not uncommon during the magmatic stage.

#### 4.2. The Champtoceaux Complex

In the CX-14 eclogite, zircon crystals were already described (Paquette et al., 1985) as yellowish orange with a prismatic magmatic habit, commonly fragmented and highly corroded. The cathodo-luminescence images display complex inner patterns with abundant oscillatory zoned inherited cores surrounded by zoned or unzoned rims (Fig. 3g-h-i-j-k). These zircons were previously dated by ID-TIMS U-Pb analyses on unabraded multigrain size-fractions (Paquette et al., 1985). The discordant points defined a discordia line intersecting the Concordia at  $413 \pm 16$  Ma and  $2208 \pm 39$  Ma respectively.

New in-situ LA-ICPMS results sub-divide the zircons into two different populations.

- (1) The oldest population consists of Proterozoic zircon grains comprising crystals with synchronous cores and rims (Fig. 3e-f). When plotted in a Concordia diagram, these grains are consistent with the previously defined upper intercept age at about 2 Ga (Fig. 4d).
- (2) The second population mostly consists of discordant and composite Late Neoproterozoic to Cambrian zircon crystals (Fig. 3g-h-i) amongst which the youngest grains or outer rims are dated at  $480 \pm 5$  Ma (Fig. 4e) and characterized by magmatic Th/U ratios of  $0.4 \pm 0.1$ . It is noteworthy that absolutely no analysis confirms the lower intercept formerly calculated at 413 Ma (ID-TIMS; Paquette et al., 1985) since the youngest measured rims yield ages of about 480-490 Ma.

Owing to intermediate major elements chemical composition, a strongly LREE enriched pattern and a strongly negative initial  $\epsilon_{\text{Nd}}$  value (Paquette, 1987; Paquette et al., 1985), the protolith of this eclogite is not a mafic rock and its origin remains unconstrained. The prevailing inherited Proterozoic zircons evidence the occurrence of significant amount of recycled continental crust. The high-pressure metamorphic event is probably responsible for the corrosion-dissolution of the zircon faces but interestingly no newly crystallized rim is present that can be obviously related to the metamorphism. For that reason, the U-Pb dating of these zircons cannot provide any reliable constraint about the age of the high-pressure event. Consequently, it can be concluded that the previously published  $413 \pm 16$  Ma lower intercept age is meaningless and only related to a fortuitous data alignment combined with a complex behaviour of the U-Pb system in connection with the mixing of zircon grains yielding different (rim-core) ages.

In the CX5 glaucophane-bearing eclogite, the zircons were already characterized and dated by unabraded multigrain fractions ID-TIMS (dataset in Paquette, 1987). They were



yellow and ovoid in shape without any zoning or core identified by cathodo-luminescence. Their U content was very high, up to 1000 ppm, with a  $^{208}\text{Pb}/^{206}\text{Pb}$  ratio providing a proxy value of the Th/U ratio at about 0.04. Unfortunately, the quarry is now filled up and no more zircon grains remain available. When recalculating the published dataset with Isoplot, the slightly discordant analytical points yield an upper intercept age of  $355.4 \pm 4.1$  Ma (Fig. 4f).

When these zircon grains are included in glaucophane crystals, they have developed pleochroic halos reflecting their high U content. Considering that the glaucophane is strongly connected to the high-pressure event and in agreement with the low "Th/U" ratio of the zircons and their lack of any older age, this upper intercept at  $355 \pm 4$  Ma can be interpreted as the crystallisation age of the zircons during the eclogite-facies metamorphism. A Sm-Nd isochron at  $362 \pm 25$  Ma performed on garnet-omphacite-whole rock from the same sample (Bosse et al., 2000) confirms this interpretation. It cannot be excluded that older magmatic zircons could have been fully dissolved and recrystallized during the metamorphism. These glaucophane-bearing eclogites present LREE-enriched MORB-like patterns and initial  $\epsilon\text{Nd}$  values (calculated at 500 Ma) ranging from +3.4 to +6.0, which favour a depleted-mantle source (Paquette, 1987).

Several zircon morphologies occur in the SLA-1 eclogite sample, from euhedral or subhedral to rounded with generally colourless grains. Cathodo-luminescence reveals two main types of structures: zircons with well-developed oscillatory zoning (Fig. 3j-k) and others with irregular and patchy zoning (Fig. 3l). Most of the zoned crystals are sub-concordant to concordant and yield a mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2.55 \pm 0.02$  Ga (Fig. 4g). This late Archean population is characterized by high Th/U ratios of about  $0.8 \pm 0.2$  and U content often lower than 100 ppm. The other euhedral and zoned crystals (Fig. 3k) also show high Th/U ratios about 0.3-0.5 but significantly higher U content, from 200 to 900 ppm. Four spots were

analyzed, yielding a mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $471 \pm 12$  Ma (Fig. 4h). Finally, 13 analyses of the irregularly zoned grains yield a concordant age at  $353.2 \pm 2.6$  Ma (Fig. 4h). Interestingly, this younger zircon population is characterized by low U contents ( $< 100$  ppm) and extremely depleted Th contents implying very low Th/U ratios ( $<<0.01$ ).

Before interpreting the zircon ages, it is worth remembering that the small (metre-sized) eclogite lenses of the Champtoceaux Unit most probably represent boudinaged dykes which intruded the protolith of the orthogneisses. These latter are (poorly) dated at  $546 \pm 63$  Ma using the EPMA method on a single grain of xenotime (Cocherie et al., 2005). The Late Archean zircon grains are most probably related to a crustal component involved in a contamination process of the protolith of the eclogite. These zircons were unaffected by any Variscan overprint so it can only be established that this sample was contaminated by old continental material but the time of inheritance remains unknown. Few other zoned euhedral zircon crystals were dated at about 470 Ma. Very thin highly luminescent rims occur on these grains but cannot be dated. Consequently, it is difficult to distinguish between possible Cambrian-Ordovician inherited grains possibly incorporated into the mafic magmas from the enclosing granitoid or preserved magmatic zircons recording the emplacement of the eclogite protolith at  $471 \pm 12$  Ma. The third population is very homogeneous with very symptomatic morphological, chemical (Rubatto et al., 1998; Rubatto and Gebauer, 2000; Rubatto, 2002) as well as isotopic parameters which favour the hypothesis of fluid-driven (re)crystallisation of these zircons during the high-pressure event  $353.2 \pm 2.6$  Ma ago.

The zircon crystals from the CX-6 metagabbro are pale yellow, translucent and euhedral but are frequently broken. They were already described and dated by ID-TIMS on unabraded multigrain size fractions (Paquette, 1987). Cathodo-luminescence images evidence well-defined magmatic zoning patterns (Fig 3m-n). Interestingly a highly luminescent thin

outer rim is frequently distinguished, although these zircon crystals never experienced eclogite-facies conditions. Consequently, such fine outer rims cannot be systematically connected to a high-grade event. 29 spots were performed on 24 zircons grains producing 19 concordant analyses and a corresponding Concordia age of  $381.8 \pm 2.3$  Ma (Fig. 4i). The Th/U ratios are high with a mean value of 0.9 and a large range of the U contents are recorded, from 10 to 800 ppm. According to Paquette (1987), this gabbro displays geochemical features consistent with a N-MORB composition, particularly a LREE-depleted pattern and an initial  $\epsilon\text{Nd}$  value (calculated at 380 Ma) of +10.1. Consequently, this age of 382 Ma can be interpreted as the crystallization of the zircons during the magmatic emplacement of these gabbros, most probably in an oceanic environment.

#### 4.3. *The Essarts Complex (Vendée)*

Zircon crystals from sample 4980 were already described (Peucat et al., 1982). They are colourless, subhedral to rounded; cathodo-luminescence images reveal irregular and poorly visible zoning with locally preserved darker overgrowths (Fig. 3o-p). No inherited cores were identified. 29 analyses yield a lower intercept age of  $487 \pm 12$  Ma (Fig. 4j). The Th/U ratios of  $0.4 \pm 0.1$  are characteristic of magmatic zircons and the U content is particularly low at about 2-3 ppm. Except for a single concordant analysis at around 650 Ma, neither any trace of systematic Proterozoic inheritance nor any Silurian ages were detected in these zircon crystals. A few spots partly performed on the dark rims indicate similar ages to those focused on the central parts of the grains.

The geochemical study of similar eclogites was already published (samples 4566 and 5498 in Bernard-Griffiths and Cornichet, 1985). These authors provided evidence of LREE-depleted patterns (N-MORB type) and initial  $\epsilon\text{Nd}$  values of about +10 (recalculated at 487

Ma) demonstrating that these samples derived from a depleted mantle source such as the oceanic lithosphere. Zircons from the same sample analyzed in the present study were initially dated by U-Pb multigrain size-fractions ID-TIMS (Peucat et al., 1982) and plotted together with those of another eclogite sample 4981. When plotted separately or together, the three strongly discordant fractions of sample 4980 yielded a lower intercept at 436 Ma and an upper intercept at 1.3 Ga (see review in Paquette, 1987). Our LA-ICPMS in situ dating of the same zircon population does not support this 436 Ma lower intercept age and allow us to conclude that the gabbroic protolith of the 4980 eclogite was emplaced in an oceanic environment at  $487 \pm 12$  Ma. No significant crustal contamination was detected and the eclogite-facies metamorphism was not recorded by these zircon crystals. The very low U and Th contents suggest that their crystal lattice was very well preserved at the time of metamorphism, preventing these zircons from any significant dissolution-recrystallization processes. This extreme depletion in U and radiogenic Pb may also be responsible for the unreliable former ID-TIMS dating.

Another eclogite sample (#4981) was collected in the same area as #4980 (Peucat et al., 1982) and comprises two different subhedral zircon populations: one with oscillatory zoning and sometimes inherited cores (Fig. 3q-r) and another more rounded in shape without visible cores (Fig. 3s). 21 analyses were performed on 11 individual grains with significantly different results according to their morphology (Fig. 4k). Four analyses of the oscillatory zoned grains yield a Concordia age of  $467 \pm 8$  Ma with Th/U ratios of around 0.5-0.9. 15 analyses of the rounded population define a concordant cluster with an upper intercept at  $1.05 \pm 0.02$  Ga and an additional grain is concordant at  $1.45 \pm 0.01$  Ga. Interestingly, the core and rim of a single crystal plot at the beginning and the end of a discordia chord drawn between 467 Ma and 1.05 Ga (Fig. 3r and 4k). This demonstrates that the crustal contamination

occurred at the time of the crystallization of the zircon rim. Consequently, this lower intercept at  $467 \pm 8$  Ma is similar within error limits to that of sample #4980 and confirms the simultaneous crystallization of the protoliths of both eclogites. It is noteworthy that the eclogite-facies metamorphism was also not recorded by any zircon grains from sample #4981. Although sampled in the same quarry, #4981 eclogite contains inherited zircons at c.a. 1.05 Ga demonstrating its contamination by continental crust, whereas #4980 seems uncontaminated. This implies that an older continental crust or their detrital products were present in the vicinity of the intrusive bodies of the mafic protoliths, allowing some contamination.

#### 4.4. *The Ile de Groix*

In the GX-16A chlorite schist, the zircon grains are yellow, euhedral and poorly translucent. In cathodo-luminescence images, the crystals appear oscillatory or sector zoned. No rim-core structure was identified, nevertheless, the outer part of the grains is systematically dark (Fig. 3t). Most of the grains are crosscut by a lattice of late, thin and highly luminescent veins, which is also present as a very thin and irregular outer rim. Some rare crystals (Fig. 3u) exhibit better preserved magmatic structures. 23 analyses were performed on 17 zircon crystals. The analytical points are concordant or sub-concordant and yield a lower intercept age of  $492.7 \pm 3.2$  Ma (Fig. 4l). The U contents range from 300 to 400 ppm and the Th/U ratios of  $0.29 \pm 0.13$  are consistent with the magmatic morphology and structure of the zircon grains. Consequently, we conclude that the age of  $492.7 \pm 3.2$  Ma can be interpreted as the time of crystallization of the zircons from a melt.

#### 4.5. *The Bois-de-Cené Unit (Vendée)*

Zircon crystals from V1 chlorite schist sample are clear, pale yellow and generally euhedral or subhedral. Most of the grains display an oscillatory zoned centre part while the outer domain appears as a highly luminescent rim growing at the expense of the magmatic starting grain (Fig. 3v-w). 22 analyses on these zircons yield a lower intercept age of  $488.8 \pm 2.7$  Ma (Fig. 4m). An additional spot performed on a highly luminescent rim (on the left tip of zircon 3w) produced a discordant but synchronous ellipse error (see discordant filled grey-dotted ellipse in Fig. 4m). More often, these rims are systematically enriched in common Pb and very discordant producing unreliable data points. Nevertheless, synchronous cores and rims confirm that the rims were most probably produced during a strong syn- to post-magmatic fluid interaction, likely similar to that reported by Schwartz et al. (2010) for modern mid-ocean ridge gabbros. The U content is high at  $800 \pm 300$  ppm and magmatic Th/U ratios are close to 0.2, even in the rims. The 8 remaining analyses indicate crustal contamination with inherited zircons of Paleoproterozoic and Neoproterozoic ages (Fig. 4n).

#### 4.6. *La Bessenois éclogite E3 (French Massif Central)*

These analyses were performed to provide additional constraints for the discussion about the significance of the U-Pb zircon ages in the eclogites. They also represent new dating by LA-ICP-MS of zircon crystals originating from a population previously dated by multigrain ID-TIMS from the #E3 Fe-Ti eclogite sample (Paquette et al., 1995). A set of 48 zircon crystals were selected and imaged. Some are subhedral with complex sector zoning (Fig. 5b) but most are anhedral with rarely developed crystal faces and complex zoning (Fig. 5a and c). The latter could be interpreted as grains belatedly crystallized in the remaining free spaces at the end of the formation of a mafic magma. A total of 59 analyses (Table 3) were

performed in contrasted centres and borders or dark and light zones. When plotted together, these 59 analytical points yield a discordia line with a lower intercept at  $472.4 \pm 2.0$  Ma (MSWD = 1.4). A more accurate investigation of the analyses distinguishes three types of results. First, 32 analyses are concordant (light grey ellipses) and yield a concordia age of  $474.5 \pm 2.2$  Ma (Fig.6) which represents the best estimate for the crystallization of the zircons of the gabbroic protolith. Second, 24 other analyses were variously affected by common Pb contribution (open small-dotted ellipses), but yield a consistent lower intercept age  $472.4 \pm 3.8$  Ma (MSWD = 0.2). Finally, three analyses are slightly discordant (open large-dotted ellipses) and were not considered in these calculations. In addition, ID-TIMS multigrain fraction results from the same zircon separate published by Paquette et al. (1995) are shown as red points in Figure 6. In spite of the sub-concordant position of the four analysed grain-size fractions, a discordia line yielded an upper intercept age of  $478 \pm 18$  Ma and a poorly defined lower intercept age of  $394 \pm 51$  Ma. This latter date was interpreted as being related to the eclogite-facies event (Paquette et al., 1995). Whatever the analytical techniques, old and new data well agree on the 470-480 Ma age of the early crystallization of the zircons during the formation of the mafic protolith. In contrast, the new in-situ analyses do not confirm the occurrence of a metamorphic recrystallization at about 400 Ma. A weak discordance of a few analytical points is observed (open large-dotted ellipses), nevertheless it never corresponds to whole grain or rim recrystallization but rather to local alteration or cracks. Furthermore, Th/U ratios systematically yield high magmatic values of  $0.9 \pm 0.2$  in all analyzed parts of the crystals. Consequently, the occurrence of a 400 Ma metamorphic event is absolutely not evidenced in these zircons and probably reflects an over-interpretation of the old data.

## 5. Discussion

### 5.1. *Geodynamic implications*

At the scale of the Variscan belt of western and central Europe, there is an amazing spread of ages reported for both ocean opening and ocean closure. For example, ophiolitic complexes define an age range of more than 250 Ma, the oldest being the Letovice Complex (530 Ma: Soejono et al., 2010) and the youngest being the Beja-Acebuches in SW Spain (330-340 Ma: Azor et al., 2008). This range encompasses the life of more than one ocean (e.g. Condie, 1997), and thus invites us to carefully and cautiously interpret the age data. The same remarks apply to eclogite formation in the Variscan belt, with the oldest ages at about 440Ma in the French Massif Central (Gebauer et al., 1981; Ducrot et al., 1983) and the youngest ages at about 315Ma in the Montagne Noire (Whitney et al., 2015), spanning more than 120 Ma of life for the same orogeny.

These age spreads may result from different causes. One potential bias has a geological foundation, in the sense that a long-lived ocean or several diachronous oceans may provide widely different ages. Similarly, a long-lived subduction zone, or several subduction episodes, may be responsible for the spread of the ages for the HP event across the Variscan belt. However, another potential bias in our reasoning may be due to the fact that we aggregate dates obtained at different sites using different methods, some of them being now outdated. This aspect will be the main line of the following discussion, because of its evident geodynamic implications.

Some of the new ages presented above were reported (but not discussed) as unpublished data to establish a geodynamic reconstruction scheme of the Variscan evolution in the Ibero-Armorican arc. The reader is encouraged to refer to Ballèvre et al. (2014) for more details on petrological and structural descriptions and interpretation of these geological units. Nevertheless, a synthesis scheme for the evolution of the Variscan belt in southern



Brittany is proposed in Fig. 10. The target here is to discuss the geological implications deduced from these new geochronological results.

*Timing of opening of the oceanic basins*

The new zircon ages obtained on a plagioclase-rich metagabbro (Audierne), eclogite-facies metagabbros (Essarts) and chlorite schists (Ile de Groix and Bois de Cen  ) from the different sites are summarized in the Fig. 7. They evidence the formation of an oceanic lithosphere in the range 490-470 Ma. Most analytical errors yield enough precision to deduce that the formation of these rocks possibly occurred during several successive episodes:  $490 \pm 2$  Ma (Audierne chlorite schist),  $482 \pm 3$  Ma (Audierne plagioclase-rich metagabbro) and  $467 \pm 8$  Ma (Essarts eclogite), i.e. during Late Cambrian to Lower Ordovician times. These samples frequently contain inherited zircons of varied ages from 0.6 Ga, 1.0 Ga, 1.5 Ga and 1.9-2.0 Ga to 2.4-2.6 Ga. These zircons probably derive from the erosion and recycling of Gondwanan terranes. Consequently, the emplacement of this oceanic lithosphere is strongly connected to significant crustal contamination, which implies that this episode of oceanic accretion at 490-470 Ma took place in the vicinity of continental rocks. Therefore, these ages could correspond to an early opening phase of an oceanic rift in the geological context of a thinned continental crust rather than the accretion of a mature oceanic segment. It is noteworthy that this mafic mantle-derived magmatism is synchronous of a felsic magmatism largely developed in this South Armorican domain (for a review, see Ball  vre et al., 2012; Pouclet et al., 2017).

Another set of zircon ages has been provided by the Drain metagabbro, with ages at  $382 \pm 2$  Ma (i.e. at the Middle to Upper Devonian boundary). The Drain Unit occupies a higher structural position with respect to those providing Cambro-Ordovician ages.

Consequently, this implies that a second ocean was formed in the Variscan realm at about 380 Ma. However, its size is not well constrained, and it may be interpreted as a back-arc basin developed during subduction of the Cambro-Ordovician ocean, or as a supra-subduction ophiolite.

The data from the Armorican Massif may be tentatively integrated at a larger scale, i.e. at the scale of the Variscan belt. The two age-groups of ophiolites (Cambrian and Early-Ordovician, and Devonian) recognized in the Armorican Massif have also been identified in the other parts of the Variscan belt in western and central Europe (Fig. 8). The first group is represented in Galicia (Vila de Cruces: Arenas et al., 2007; Bazar: Sánchez Martínez et al., 2012), Brittany (Baie d'Audierne, this paper), Bohemia (Mariánské-Lázně: Bowes and Aftalion, 1991; Timmermann et al., 2004; Faryad, 2012; Letovice: Soejono et al., 2010) and the Alps (Chamrousse: Pin and Carme, 1987; Ménot et al., 1988). The second group includes ophiolitic complexes from Galicia (Careón: Diaz Garcia et al., 1999; Pin et al., 2002; Purrido: Sánchez Martínez et al., 2011; Moeche: Arenas et al., 2014), Brittany (Drain: this paper), England (Lizard Complex: Nutman et al., 2001), Vosges (Skrzypek et al., 2012) and Sudetes (Slezna Complex: Dubinska et al., 2004; Kryza and Pin, 2010).

However, despite these progress in geochronological characterization of the ophiolitic complexes, the identification and correlation of oceanic sutures in the Variscan belt remain largely elusive, as shown by an array of contrasting proposals recently published (e.g. Díez Fernández and Arenas, 2015; von Raumer et al., 2015; Arenas et al., 2016; Murphy et al., 2016; Simancas et al., 2016; Franke et al., 2017). We favour a model where the ophiolitic complexes from southern Brittany derive from a Cambro-Ordovician ocean (the Galicia-Southern Brittany Ocean of Matte (2001), equivalent to the Galicia-Moldanubian Ocean of Franke et al. (2017) (Fig. 10). Subduction of this Cambro-Ordovician Ocean was possibly

associated to the development of Devonian ophiolites, either in narrow back-arc basins or in a supra-subduction position (Fig. 10).

#### *Timing of subduction and closure of oceanic basins*

Eclogite-facies rocks record the subduction of oceanic and continental rocks. Dating them may be a clue for deciphering the age of the oceanic subduction when ophiolite-bearing rocks host the dated zircons, or of the oceanic closure if the dated rocks are of continental crustal derivation. This is because continental subduction most probably follows oceanic subduction. The oceanic complexes from southern Brittany are either devoid of high-pressure overprint (Audierne, Drain), or display blueschist-facies parageneses (Ile de Groix, Bois-de-Cené). Conversely, some of the dated eclogites belong to continentally-derived units (Cellier, Champtoceaux): they do not derive from ophiolitic rocks, but from gabbroic plutons or doleritic dykes intruding the continental crust. Because of this duality, we are therefore potentially able to constrain both the subduction and the closure of the oceanic basins.

In both locations where eclogites were sampled in the Champtoceaux and Vendée complexes, no high grade metamorphic event at 420-400 Ma was recorded by the U-Pb zircon system (Fig. 7). Based on old dating results, it was generally assumed that an eclogite-facies metamorphic event occurred at this time in the Variscan belt of Western Europe. This hypothesis cannot be completely ruled out; nevertheless our new in situ U-Pb zircon dataset does not confirm this statement in the context of South Brittany. To our knowledge, this Siluro-Devonian period rather corresponds to the maximum expansion of the oceanic domain (Ballèvre et al., 2014).

Two samples from the Baie d'Audierne and Champtoceaux complexes recorded the thrust over the continental basement of mafic and ultramafic rocks from the upper part of the

oceanic lithosphere during the Upper Devonian. The complex age pattern obtained in the zircons of the BA-1 chlorite schist with successive crustal contaminations does not favour a simple interpretation. At the contrary, the Drain metagabbro overthrust on top of the Champtoceaux Unit witnesses the occurrence of oceanic rocks crystallized at 380 Ma. The age of the tectonic (obduction?) process itself, since it was unrelated to any zircon (re-) crystallization, remains unconstrained. The results of the Audierne chlorite schist that the gabbroic protolith crystallized at 375 Ma, may suggest that the emplacement and thrusting of these units may happened within a close time interval.

Finally, two eclogite samples from the Champtoceaux Complex (Cellier and Champtoceaux Units) are characterized by the occurrence of a very peculiar zircon population displaying symptomatic features such as extremely low Th/U ratios with high Th depletion (Rubatto, 2002) which are systematically associated with a patchy and irregular zoning. This illustrates that the crystallization or complete dissolution-recrystallization most probably takes place under very specific conditions which seem drastically different from those controlling the formation of magmatic zircons. Both Champtoceaux samples yield concordant ages at about 355 Ma. Except for Precambrian inherited zircons and those related to the Cambro-Ordovician formation of the gabbroic protoliths, these 355 Ma grains represent the only reliable metamorphic age recorded in the eclogites by the U-Pb zircon system. The inclusion of some of these Lower Carboniferous zircon grains into glaucophane in the CX5 sample demonstrates that this age can be interpreted as the best estimates for the high-pressure event (Godard et al., 1981) in this part of the Variscan belt. Consequently, one major piece of information provided by this new U-Pb zircon dataset is that the subduction then closure of the Galicia-Moldanubian Ocean is dated at 355 Ma in Southern Brittany. The occurrence of a 420-400 Ma high pressure event deduced from former multigrain ID-TIMS U-Pb zircon

analyses can be from now ruled out based on this new dataset and the reappraisal of the older ones.

### *5.2. Implications for U-Pb zircon geochronology*

It is often considered by the earth sciences community that the U-Pb system in zircon (and monazite among other minerals) is systematically disturbed by high grade metamorphic events. Consequently, the ages measured on such minerals sampled in high-temperature eclogites (i.e. those devoid of hydrous phases like lawsonite and glaucophane, and not preserving garnet growth zoning) or granulites are frequently translated directly as metamorphic ages. This point is absolutely not demonstrated by some of our new results, which in complete agreement with Tilton (1960) confirm that this assertion could be fully erroneous. The "Les Essarts" Complex in Vendée is world famous owing to its beautiful and thoroughly studied eclogites from the Variscan belt of Western Europe (Lacroix, 1891; Brière, 1920; Godard, 1988). Both dated samples from this area contain zircons whose U-Pb isotope systems were fully unaffected by the eclogite facies metamorphism. Of course, the morphology of the zircons from Vendée, as well as those from the CX14 eclogite from the Champtoceaux Complex, clearly displays dissolution features in the outer part of the grains. Nevertheless, the U-Pb zircon system of the eclogite protoliths remained completely closed to the metamorphic overprint and still records Cambro-Ordovician ages connected to the primary oceanic magmatism. Again, this confirms that the U-Pb zircon method is a geochronometer and not a thermochronometer. In metamorphic rocks, zircons are principally affected by dissolution-recrystallization processes which are strongly connected to the composition of the fluid phase and/or of the melt when present. In such conditions, zircon behaviour will depend on the preservation of its crystal lattice at the time of fluid-mineral

interaction. For instance, the Th and U contents in the zircons sampled in the #4980 eclogite from Vendée are very low and produce negligible radiation damage to the crystal lattice. These zircons were not significantly affected by the eclogite-facies metamorphism. On the contrary, metamict zircons display a highly damaged crystal lattice and thereby do not behave any longer as a closed system, allowing fluids to strongly interact with the grains (Seydoux-Guillaume et al., 2015). In favourable cases, temperature and maybe pressure may also trigger such complex behaviour, but temperature alone cannot reset the U-Pb system even in very high temperature metamorphic facies (Paquette et al., 2004).

We have demonstrated that the U-Pb zircon date of an eclogite sample does not necessarily constrain the age of the high-pressure event. Another important point should be discussed on the differences between true metamorphic zircons and hydrothermally altered magmatic zircons preserved in metamorphic rocks. In modern oceanic gabbros and related alteration products, the occurrence of highly luminescent and sometimes porous rims, generally characterized by high Th/U ratios and preserving comparable ages to the undamaged igneous parts, is well documented (Jöns et al., 2009; Grimes et al., 2009; Schwartz et al., 2010). These features are commonly interpreted as dissolution-reprecipitation aqueous fluid-driven alteration processes at high-temperature, occurring at shallow levels and in the vicinity of a mid-ocean ridge. In our study, similar zircon crystals were sampled in gabbros and chlorite schists, preserving their primary magmatic Th/U ratios and ages. When such gabbroic rocks are metamorphosed under eclogite-facies, the alteration rims acquired quite synchronously with the primary magmatic processes may be preserved or partly resorbed, as illustrated in #4980 eclogite from Vendée. Nevertheless, their U-Pb isotope system can remain closed during the metamorphic overprint as in Vendée, or its behaviour may be more complex owing to the probable porosity of the crystal lattice in these rims associated with frequent interaction with common Pb-bearing fluids. In any case, these

magmatic zircons are clearly distinct from the recrystallized metamorphic zircons sampled in the SLA-1 eclogite from the Champtoceaux Complex. In the French Massif Central, several dates for Variscan eclogites were reported (Gebauer et al., 1981; Ducrot et al., 1983, Paquette et al., 1995; Berger et al., 2010) and metamorphic ages about 420-400 Ma were proposed. It is tempting to speculate a similar Variscan geodynamic evolution in both the Armorican Massif and the Massif Central. Nevertheless, even if the formation of the oceanic units appears to be effectively synchronous during Cambro-Ordovician times, the age of the eclogite-facies metamorphism seems to be significantly discordant between the Armorican Massif on the one hand, and the French Massif Central on the other hand. It would now be particularly interesting to re-examine the published dating of the high-pressure event in the French Massif Central, taking into account the observations developed in this paper.

## Conclusion

This study represents a comprehensive U-Pb zircon dataset produced on geological samples witnessing of the evolution of an oceanic domain, from its birth to its subduction. These samples come from the Variscan belt of Southern Brittany, which is with Northern Spain one of the best exposures of the Variscan basement in Western Europe. These new ages were mostly obtained by the best-suited LA-ICPMS in situ analytical technique on individual zircon grains and in close connection with their cathodo-luminescence images. The study comprises samples previously dated 30 years ago by multigrain fractions ID-TIMS and new ones.

The formation of the Galicia-Moldanubian Ocean is dated at 470-490 Ma on several ocean-derived rock-types. In many cases, inherited zircon grains or inner cores evidence the

contribution of older Gondwana-derived continental crust components to the magmas at this early stage.

The overthrusting of the oceanic rocks also occurred later in the evolution of this ocean, at 370-380 Ma. This may represent the obduction of oceanic crust onto the continental palaeo-margin.

The high-pressure metamorphism related to the subduction of the oceanic crust is dated at 355-360 Ma. Absolutely no high-pressure event at the previously assumed date of 400-410 Ma was confirmed in any studied zircon grain. This old concept of a Siluro-Devonian eclogite-facies event is most probably related to analytical limitations of the published ages in the 80s, which led to geodynamic over-interpretations.

Many magmatic zircons were affected by hydrothermal alteration in the oceanic environment, close to their primary formation time. This was misinterpreted as recording the high-grade metamorphic event in many studies whereas these zircons were in fact unaffected by this event.

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### Figure Captions

**Fig. 1.** Location of the South Armorican domain within the Variscan Belt of Western Europe. The main structural boundaries within the Variscan Belt are indicated. The studied samples

are coming from the South Armorican domain (see Fig. 2), except one sample from the Massif Central (see filled star).

**Fig. 2.** Structural scheme of the South Armorican domain. The location of the samples dated in this study are shown by yellow stars.

**Fig. 3.** Cathodo-luminescence images of representative zircon crystals from the studied samples from the South Armorican domain. Spot size, location and corresponding individual age with errors quoted at the  $2\sigma$  level are reported.

**Fig. 4.** The U-Pb dating results of the studied samples from the South Armorican domain are reported in Tera & Wasserburg or Wetherill concordia diagrams. Error ellipses and calculated ages are quoted at the  $2\sigma$  level.

**Fig. 5.** Cathodo-luminescence images of representative zircon grains for the DEC-3 eclogite from the French Massif Central. White open circles represent the spot size and location with Th/U ratio and individual concordia age (full line) or apparent  $^{206}\text{Pb}/^{238}\text{U}$  age for discordant analyse (large dotted line) and common Pb contribution (small dotted line).

**Fig. 6.** Tera & Wasserburg U-Pb diagram for in situ analyses of zircon crystals from DEC-3 sample. Error ellipses and corresponding age are quoted at the  $2\sigma$  level. Symbols are the same than in Figure 5. The red-filled circles represent published ID-TIMS analyses (Paquette et al., 1995).

**Fig. 7.** Summary of the La-ICP-MS U-Pb ages obtained in this study on the South Armorican domain. (For source of data, please refer to Table 3-I in the Electronic Supplementary material).

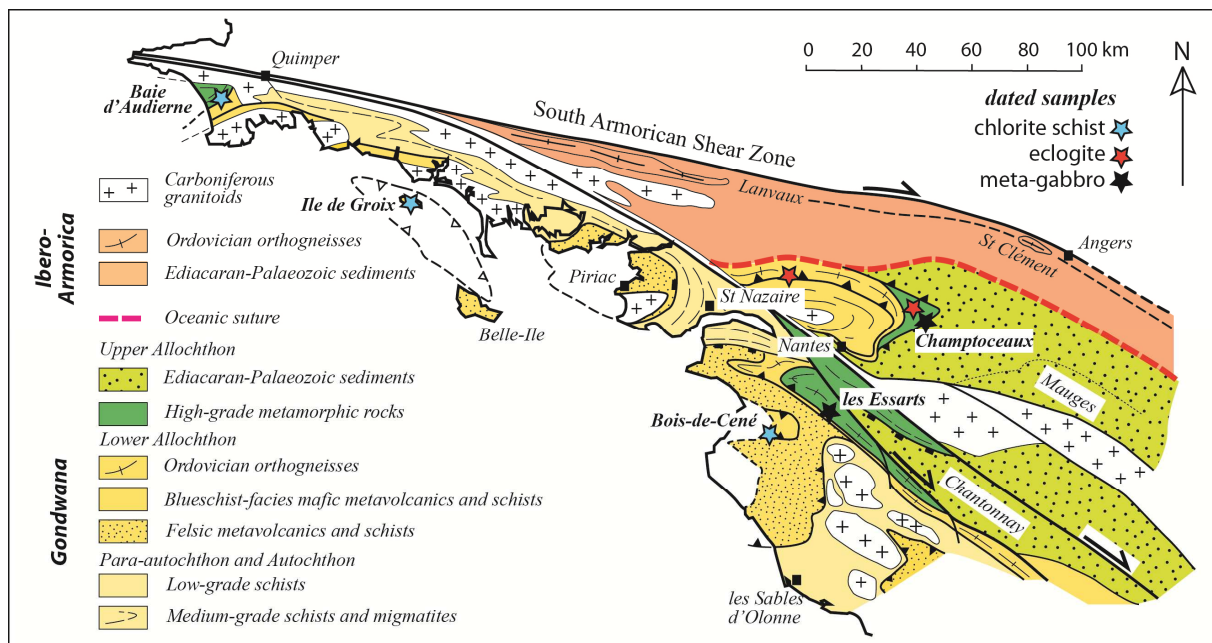
**Fig. 8.** Distribution and ages of ophiolitic complexes in the Variscan belt. References for specific localities are found in the main text. Note that only LA-ICP-MS (and in a few cases SHRIMP) data are here considered. The age of some ophiolitic complexes remains unknown (open symbols). (For source of data, please refer to Table 3-I in the Electronic Supplementary material).

**Fig. 9.** Distribution and ages of the high-pressure metamorphic rocks (eclogites and blueschists) in the Variscan belt. (For source of data, please refer to Table 3-II to 3-V in the Electronic Supplementary material).

**Fig.10.** A tectonic scenario for the South-Armorican domain. This scenario highlights the subduction (and then loss) of the Cambro-Ordovician oceanic lithosphere (pale violet), followed by continental subduction associated to development of eclogites (Cellier Unit) in the former palaeo-margin. The Devonian ophiolites from the Drain Unit (dark violet) are much better preserved because they did not enter the subduction factory.

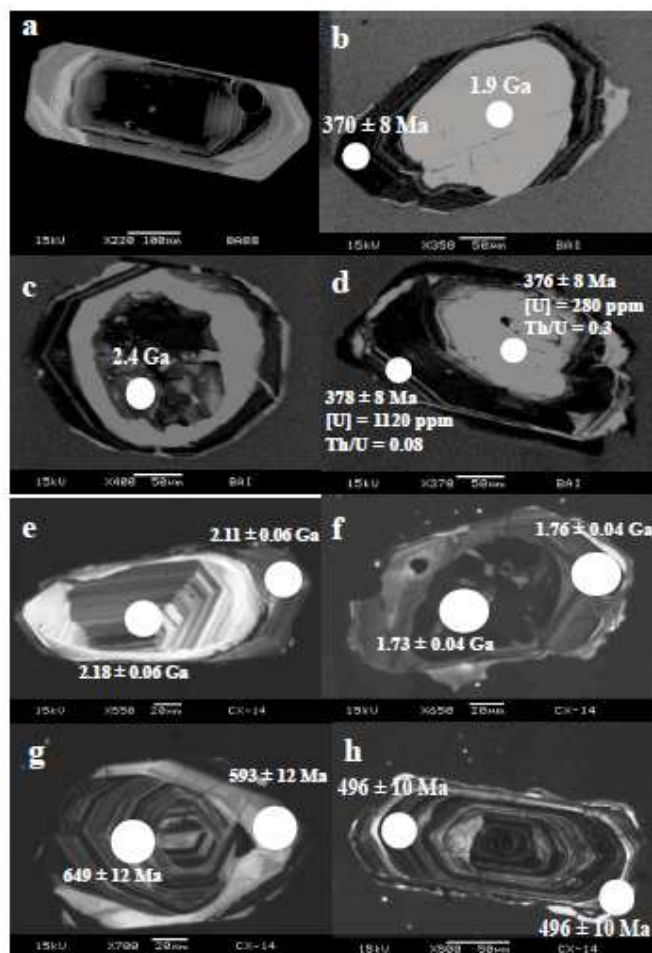


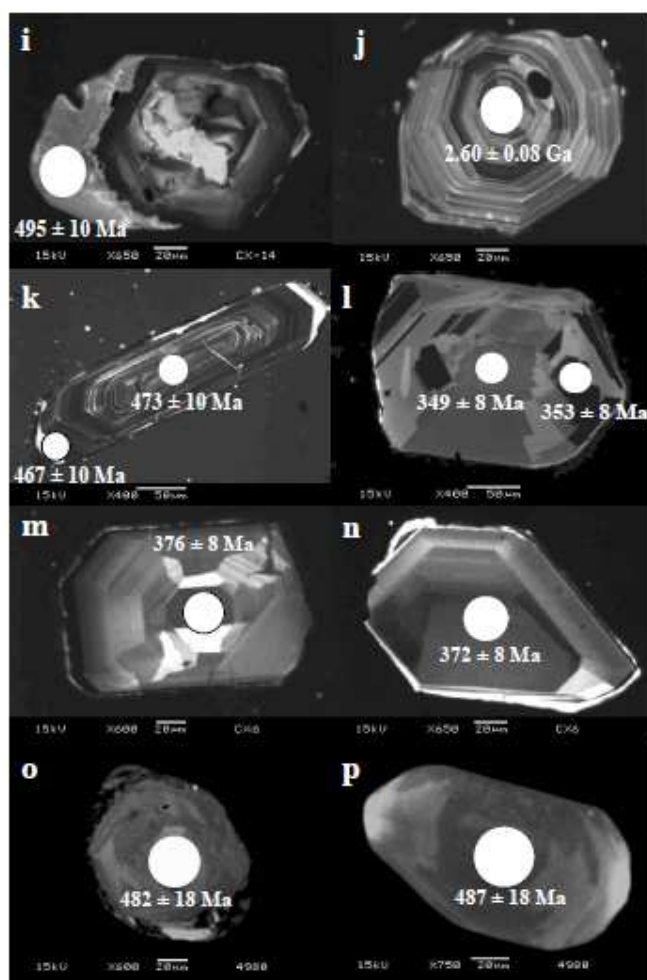


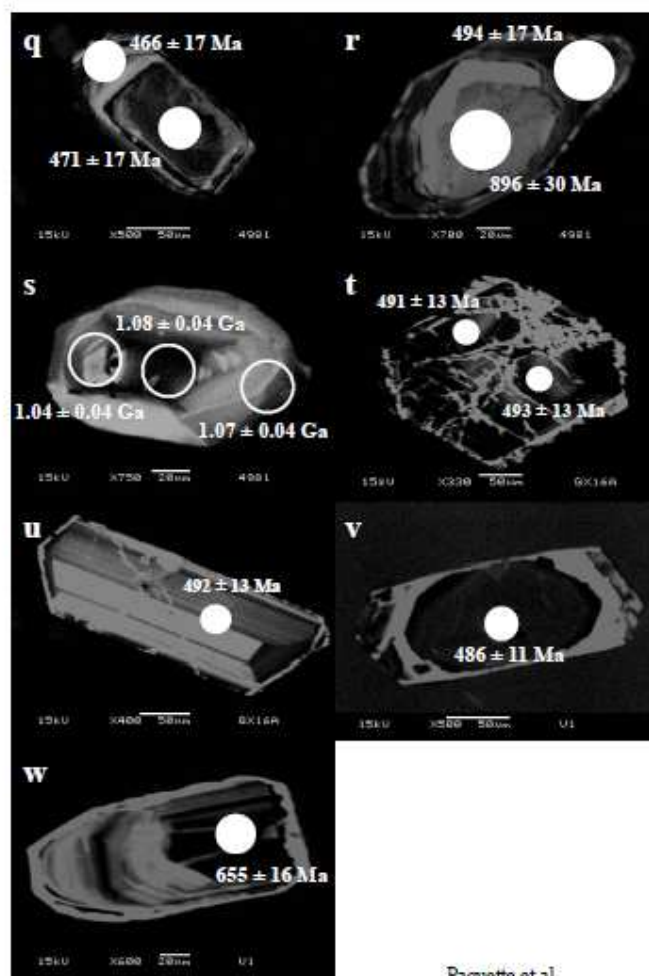


Paquette et al.

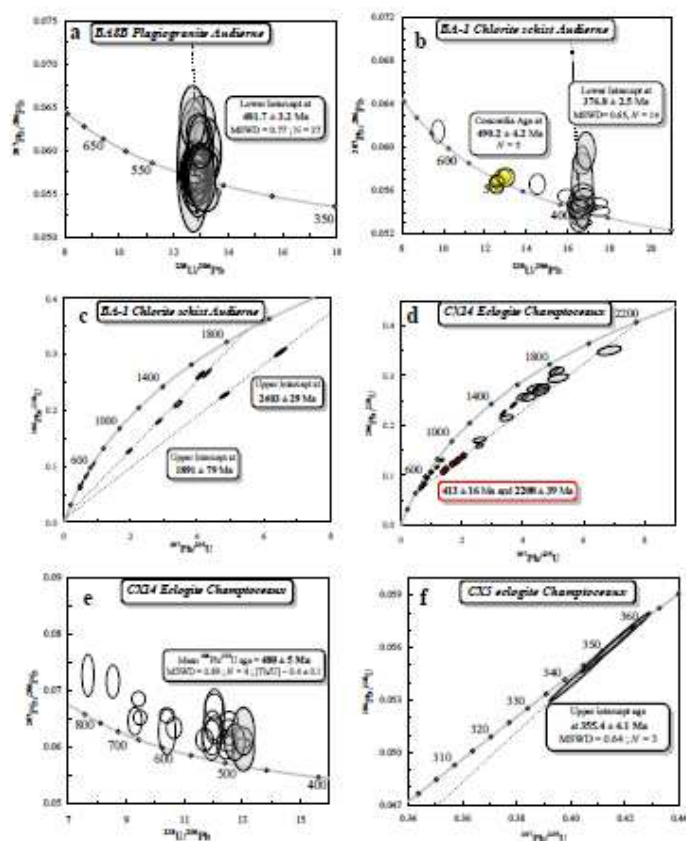
Fig. 2





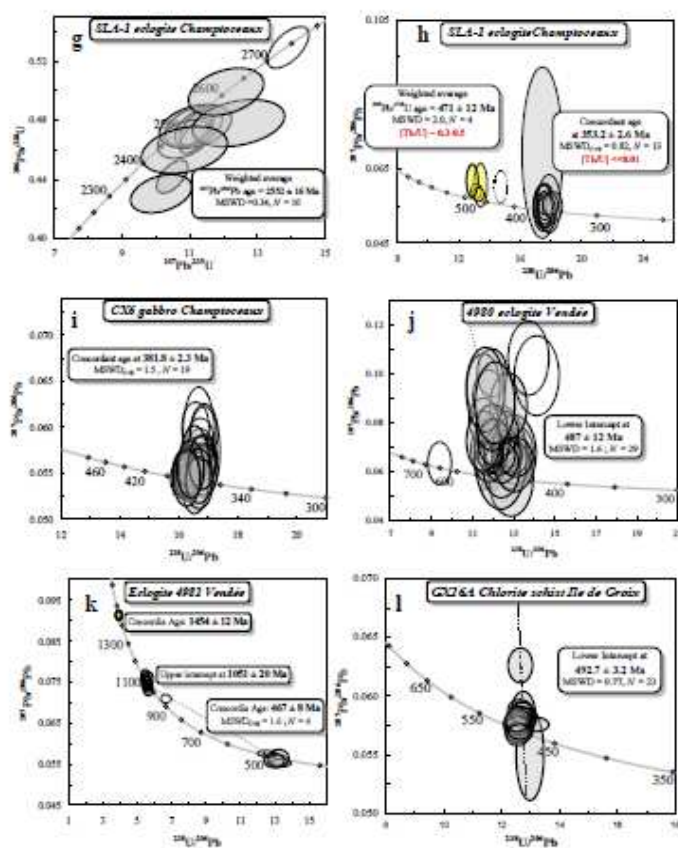


Paquette et al.  
Figure 3



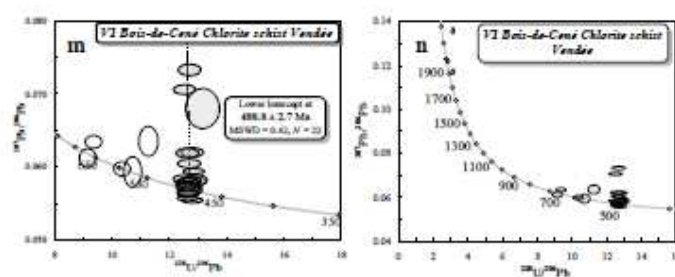
Paquette et al.

Figure 4



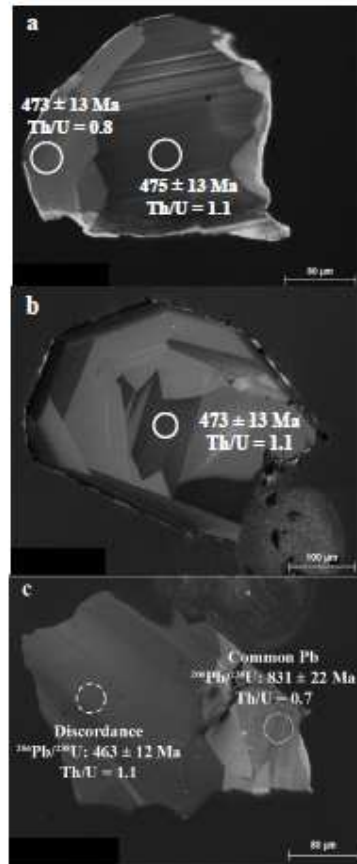
Paquette et al.

Figure 4 (continued)

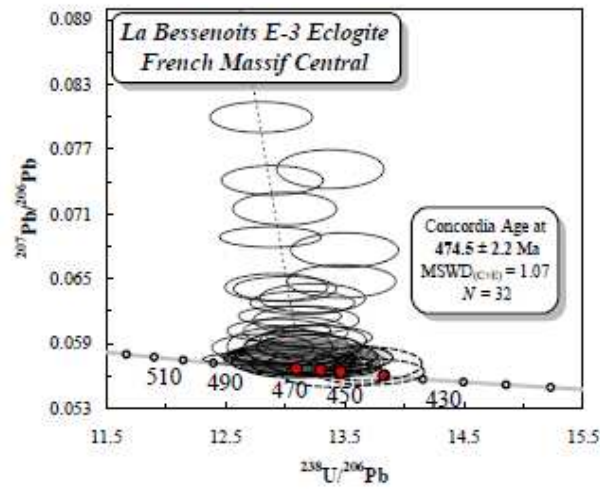


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Figure 4 (continued)

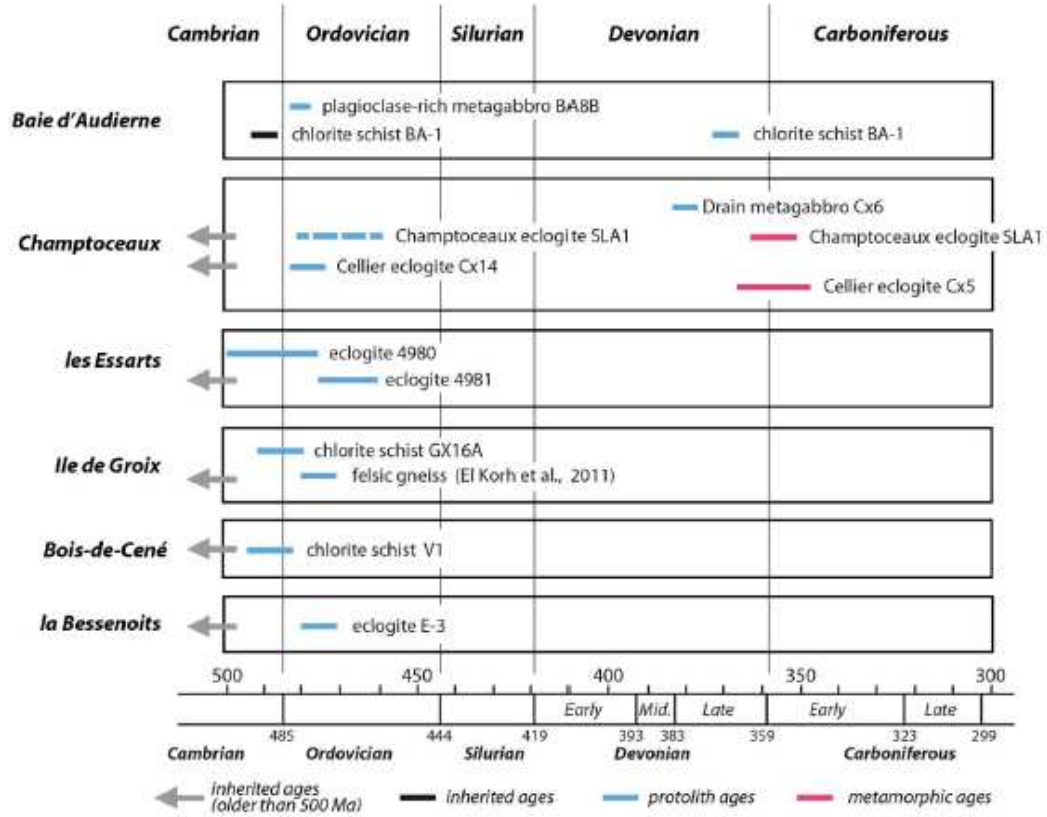




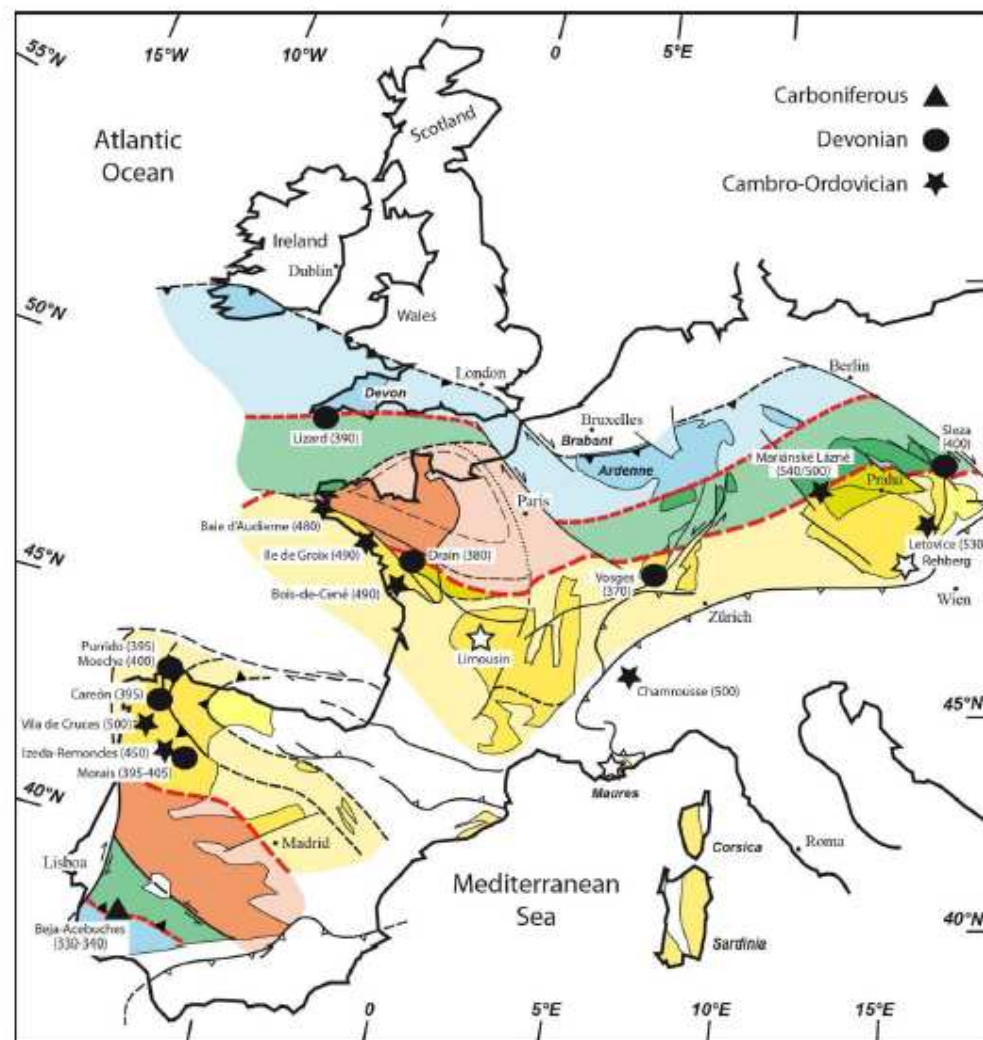
Paquette et al.  
Figure 5



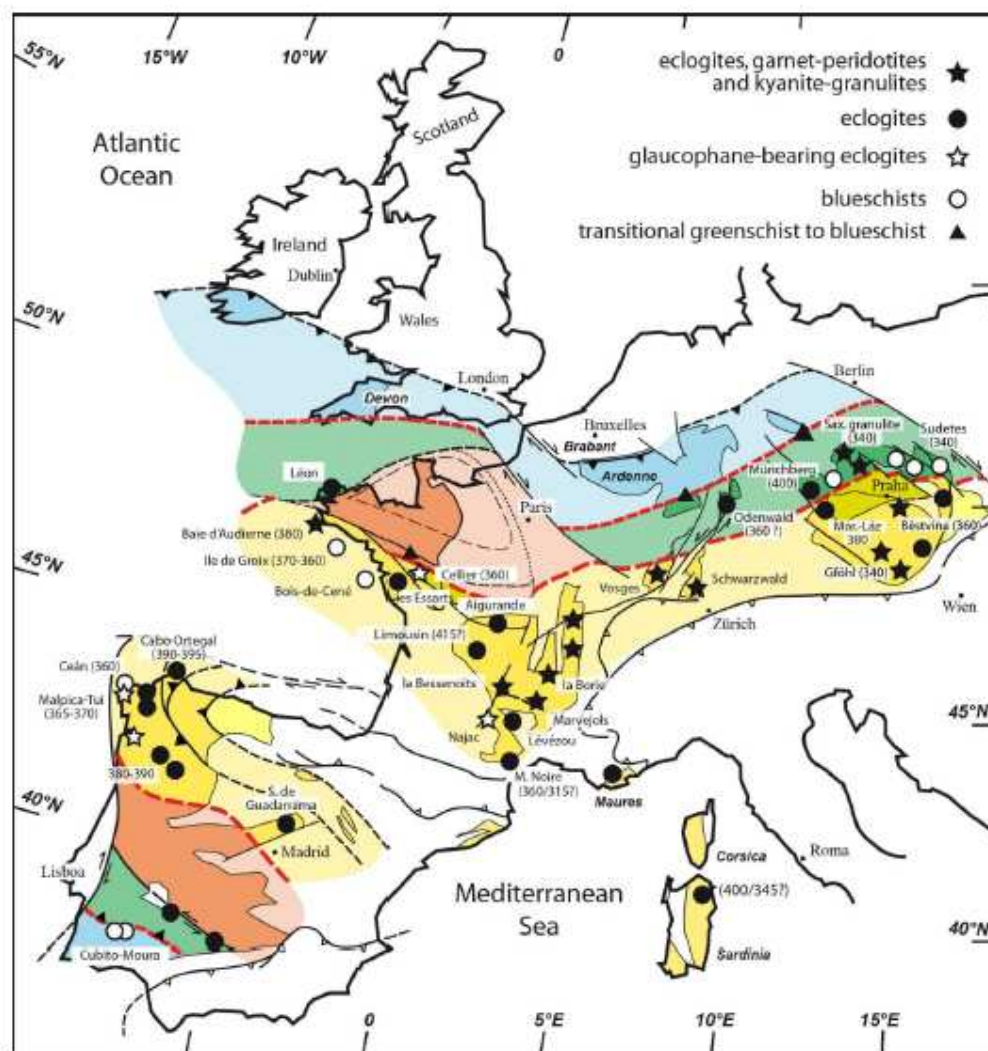
Paquette et al.  
Figure 6



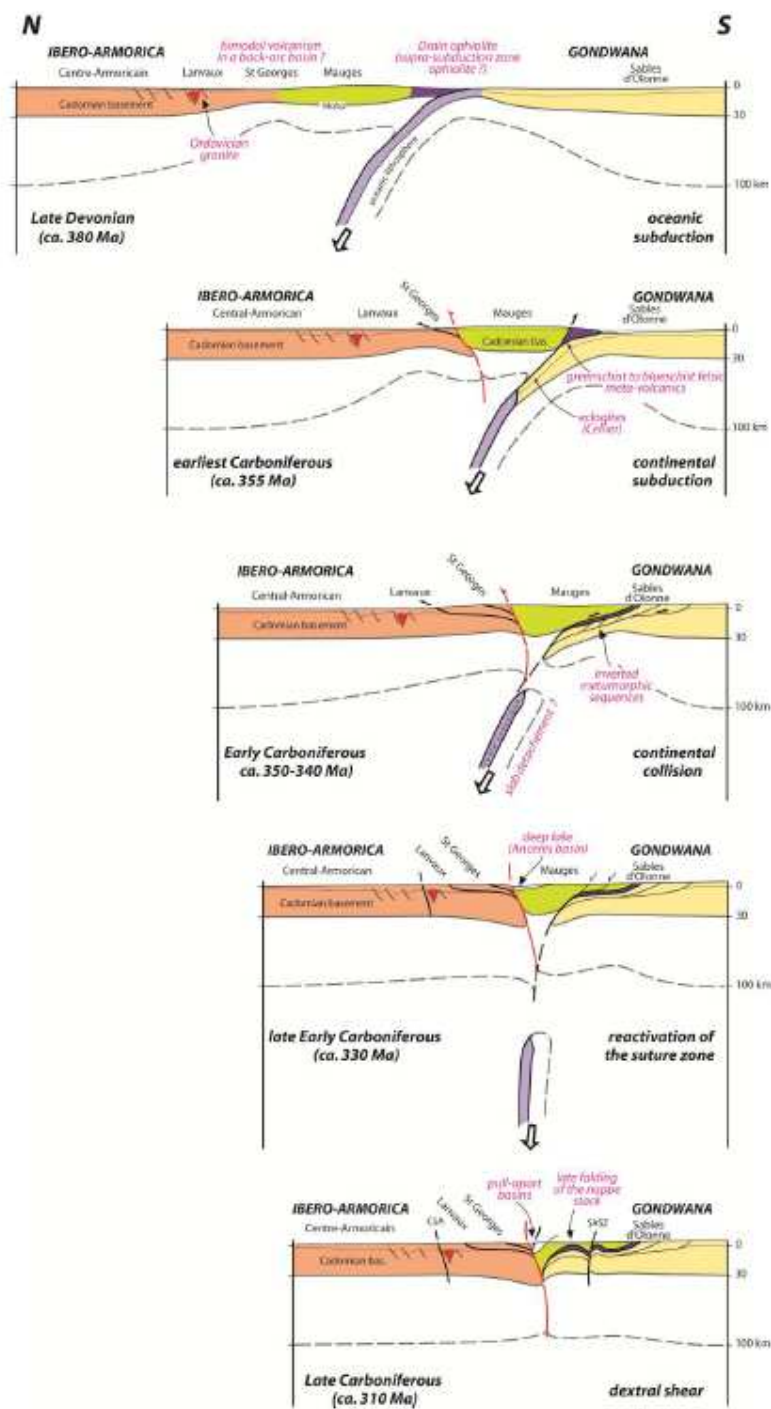
Paquette et al. Figure 7



Paquette et al. Figure 8



Paquette et al. Figure 9



Paquette et al. Figure 10

Table 1: Synthesis table displaying sample provenance (with GPS geo-localization), lithology, nature of the protoliths when available, metamorphic evolution and alteration features of the dated samples.

	<b>Tectonic Unit</b>	<b>Outcrop</b>	<b>Lithology</b>				<b>Protolith</b>	<b>Metamorphic history</b>	
			<b>Sample N°</b>	<b>Geographical coordinates</b>				<b>Peak paragenesis</b>	<b>Alteration</b>
				<b>Latitude N</b>	<b>Longitude E</b>				
<b>Baie d'Audierne</b>	Ty-Lan Formation		BA-1	47.943585	-4.341635	chlorite schist (shear zone in the ultramafics)		foliated rock essentially consisting of Mg-rich chlorite, with minor amounts of apatite, ilmenite, monazite and zircon	
	Peumerit Formation	loose blocks in a cultivated parcel	BA-8B	47.941245	-4.307263	plagioclase-rich amphibolite, with clasts of Fe-Mg	leucogabbro	foliated (mylonitic) rock essentially consisting of	

						minerals		plagioclase (An26-32), apatite, ilmenite and zircon	
<b>Champtoceaux Complex</b>	Cellier Unit	loose blocks in a cultivated parcel	CX-14	47.424 239	- 1.7888 68	medium-grained eclogite		unfoliated rock essentially consisting of garnet, omphacite, kyanite, quartz and rutile	retrogression is absent, except for some unoriented paragonite flakes
	Cellier Unit	eclogite lenses in fine-grained leucocratic orthogneisses	Cx-5	47.302 406	- 1.3262 21	fine-grained eclogite		unfoliated rock consisting of garnet, omphacite, rutile and idioblastic glaucophane porphyroblasts; a large number of garnet grains have	retrogression is absent, except along narrow (< 1mm) fractures



								atoll shapes , with phengite and/or quartz infilling the atoll	
	Champ toceau x Unit	outcrop along a road	SLA-1	47.285227	- 1.205894	metre-sized lens of a fine-grained eclogite enclosed in foliated leucocratic, fine-grained, orthogneisses	dolerite dyke in a Cambro-Ordovician granite ?	unfoliated rock consisting of garnet (sometimes with atoll structure) and omphacite (a few inclusions in garnet, and matrix grains) , with minor amounts of quartz, zoisite and rutile	omphacite is replaced by diopside-plagioclase symplectites, some amphibole coronas around garnet grains
	Drain Unit	abandoned quarry	CX-6	47.343825	- 1.182877	foliated meta-gabbro (with textural relics	gabbro	poorly-foliated rock consisting of zoisite aggreg	

						of plagioc lase and clinopy roxene domai ns)		ates (replac ing the magn atic plagioc lase) and amphi bole aggreg ates (replac ing the magn atic clinopy roxene )	
<b>Essart s Comp lex</b>		la Gerba udière quarry (see detaile d map in Godar d et al., 2001)	4980	46.985 619	- 1.5304 72	eclogit e	gabbro	garnet + ompha cite + quartz + rutile	
		idem	4981	idem	idem	eclogit e	gabbro	garnet + ompha cite + quartz + rutile	
<b>Ile de Groix</b>	Lower Unit	coastal outcro p at Beg Melen	GX-1	47.651 816	- 3.5035 85	chlorit e schist			
	Lower Unit	coastal outcro p at le Tréhor	GX- 16A	47.652 702	- 3.4920 65	chlorit e schist			
	Upper	coastal		47.628	-	felsic	felsic		

	Unit	outcrop at Plage des Sables Rouges (El Korh et al., 2012)		490	3.418567	gneiss	dyke or tuff		
<b>Bois-de-Cené</b>		abandoned quarry	V1	46.941375	-1.758887	chlorite schist		foliated rock essentially consisting of Mg-rich chlorite, with minor amounts of magnetite, apatite, monazite and zircon	
<b>la Besse nois</b>	Upper Gneiss Unit	loose blocks	E3	44.575473	2.319718	fine-grained eclogite	Fe-Ti rich gabbro	garnet, clinopyroxene (altered), quartz, rutile, and minor apatite, zoisite and zircon	diospide-plagioclase symplectites at the expense of clinopyroxene, brown amphibole, a few biotite

									crystal s
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ACCEPTED MANUSCRIPT