Kinematics of subduction in the Ibero-Armorican arc constrained by 3D microstructural analysis of garnet and pseudomorphed lawsonite porphyroblasts from Ile de Groix (Variscan belt)

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Abstract

The small island of Groix in southern Brittany, France, is well known for its exceptional preservation of outcrops of Variscan blueschists, eclogites and garnetiferous micaschists that define a Late-Devonian suture between Gondwana and Armorica. The kinematics of polyphase deformation in these rocks is reconstructed based on 3D microstructural analysis of inclusion trails in garnet- and pseudomorphed lawsonite porphyroblasts using multiple, differently oriented thin sections of single samples and X-ray tomography. Three sets of inclusion trails striking NE-SW, NNW-SSE and WNW-ESE are recognized and interpreted to witness a succession of different crustal shortening directions orthogonal to these trends. The curvature sense of sigmoidal- and spiral-shaped inclusion trails of the youngest set is shown to be consistent with northward subduction of Gondwana under Armorica causing southward thrusting, provided that these microstructures developed by overgrowth of actively forming crenulations instead of the previously envisaged 'snowball' mechanism. The latter predicts an opposite thrusting direction which is at odds with the regional tectono-metamorphic zonation in the Ibero-Armorican Arc. Strongly non-cylindrical folds locally found on Ile de Groix are reinterpreted as fold-interference structures instead of having formed by progressive shearing. Six additional samples of lower-grade footwall units of the Groix ophiolite were also studied. The oldest inclusion trails in these rocks have similar trends as the youngest one in Ile de Groix, but formed later during the Carboniferous. Our new inclusion-trail data for southern Brittany bear a strong resemblance with those documented previously in the north-western Iberian Massif and suggest about 20° clockwise rotation of Iberia during the early Cretaceous opening of the Gulf of Biscay.

Key words: porphyroblast inclusion trails, FIA, Variscan subduction, Ibero-Armorican arc, Ile de Groix.

1. Introduction

Kinematic reconstructions in polydeformed metamorphic regions are traditionally based on a combination of geological mapping, study of structural relationships in outcrop and corresponding orientation measurements, study of thin sections which are usually cut parallel to the stretching lineation to determine a shear sense, and geochronological data for pre- and syn-tectonic minerals. Not rarely does this approach produce paradoxical results that insufficiently constrain different possible tectonic models. However, following a major conceptual shift concerning the formation mechanism and tectonic significance of porphyroblast inclusion trails (Bell et al., 1985, 1986; Bell & Johnson, 1989), a number of studies have shown how quantitative microstructural data for such microstructures can significantly improve the resolution of deformation histories whose complexity was previously not even recognized (e.g. Bell et al., 1998; Bell & Welch, 2002; Sayab, 2005; Ali, 2010; Shah et al., 2011; Aerden, 2013; Kim & Ree, 2013; Abu-Sharib & Sanislav, 2013; Aerden & Sayab, 2017). Aerden (2004) pioneered this approach in Variscan NW Iberia in a research project led by José Ramón Martínez Catalán and Ricardo Arenas (e.g. Martínez Catalán et al., 2000). He distinguished 4 inclusion-trail sets with specific, regionally consistent trends and relative timing. An E-W trend of the earliest formed set was interpreted to record N-S directed compression and subduction with unknown polarity. Subduction would have been followed by several changes in the direction of crustal shortening responsible for the 3 younger sets of inclusion trails. The youngest two sets with NE-SW and WNW-ESE trends were correlated with regional-scale fold-interference patterns developed throughout the Iberian Massif and this, in turn, was key to rediscovering a partially blind orocline in central Iberia, which was later endorsed by Martinez Catalán et al. (2012).

Here, we report a similar study of inclusion trails in the Armorican Massif focusing on high-pressure metabasites of Ile de Groix, but also including data from lower-grade rocks located in their footwall. The island of Groix (ca. 15 km^2) is a national reserve with excellent coastal outcrops of Variscan blueschists, eclogites and interlayered garnetiferous micaschists that are generally accepted to represent the remains of a narrow ocean that, in the late Silurian and lower Devonian separated Gondwana in the south from the Armorica microplate to the north. In NW-Iberia, a similar ophiolitic unit is since long recognized and correlated with the one exposed on Groix island (Arenas et al., 1995; Diaz-García et al., 1999; Ballèvre et al., 2009, 2015). Closure of this ocean involved subduction of the margin of Gondwana causing high-pressure metamorphism dated 370-360Ma on Ile de Groix (Bosse et al., 2005). The polarity and kinematics of ophiolite emplacement have remained poorly constrained by (micro)structural data. Indeed, not much has changed since Quinquis et al. (1978) wrote: "*the bulk sense of shear on Groix has not yet been determined unequivocally, but may perhaps be deduced from systematic analyses of fold asymmetry and of microstructures in and around syntectonic garnets. The significance of glaucophane orientation in the basic rocks of Groix also needs to be studied: the orientation is extremely variable and may not be simply related to a shear direction.*"

Precisely along these lines of suggested further research, we performed detailed 3D microstructural analysis, using oriented thin sections and X-ray tomography, of 10 garnetiferous blueschist samples of Ile de Groix, 4 samples of albite-porphyroblast bearing greenschists (Pouldu schists) cropping out along the coast of the mainland, and 2 kyanite-staurolite schists collected inland from the North-Armorican Zone (Fig. 1). Integration of the new data with that of previous field-based studies, and the above cited shear sense criteria provides a coherent picture of a complex deformation history hidden behind the false appearance of a simple L-S fabric. Implications for the mechanism of sheath folds (Ile de Groix is one of the main type locations for these structures) and for kinematics of Variscan subduction are also presented.

2. Geological setting and previous work

The Variscan (or Hercynian) orogeny took place in the Devonian and Carboniferous as a consequence of Gondwana-Laurussia convergence with 2 microcontinents occupying intermediate positions known as Armorica and Avalonia (e.g. Matte, 2001). The resulting closure of oceanic domains created multiple ophiolitic sutures whose precise location, timing and correlation continues to be a major research topic (e.g. Azor et al., 2008; Faure, 2008; Ballèvre et al., 2009; Arenas et al., 2016). The high-pressure rocks of Ile de Groix are part of a partially submerged ophiolitic klippen belonging to a thrust nappe that separates Armorican crustal units in the hangingwall, outcropping to the North- and Central Armorican Domains, from North-Gondwana derived crustal units below the suture outcropping in the South Armorican Domain and NW Iberia (Fig. 1). Because of this regional-scale zonation, a north-dipping subduction zone associated with south verging thrusts has been considered the most likely geodynamic scenario (Matte, 2001; Faure et al., 2008; Ballèvre et al., 2009; Ballèvre 2015). However, structural data have not allowed to independently confirm this model and in fact have yielded conflicting results.

Lagarde (1980) concluded NW directed thrusting from shear criteria in the Champtoceaux Complex (Fig. 1), implying south-east subduction. A similar kinematic was deduced on Ile de Groix by Quinquis (1980), Quinquis & Choukroune (1981) and Cannat (1985) from rotated snowball garnets and quartz c-axes fabrics. Recognizing the conflict with respect to northward subduction, these authors proposed that this shear sense corresponds to backthrusting and obduction of ophiolites in opposite direction as subduction.

Quinquis (1980), however, noticed that shear bands (C and C' planes) on Ile de Groix indicate opposite shear senses that cannot be clearly linked to different metamorphic conditions and therefore were interpreted as conjugate sets. Shelley and Bossière (1999) reported opposite shear senses also indicated by quartz fabrics studied in 57 oriented samples. This led them to conclude bulk vertical shortening in Ile de Groix related to crustal thinning. In contrast, Philippon et al. (2009) recently argued for a consecutive origin of opposite shear-bands in Ike de Groix. The older set would have developed during prograde metamorphism and top-to-the SW (N140) shearing, followed by a younger recording quasi-opposite top-to-the-north (N350) shearing during retrogression.

3. Inclusion-trail data from thin sections

A total of 132 oriented thin sections were studied of 33 samples: 20 from Ile de Groix, 9 from the Pouldu schists and an equivalent unit in the Baye d'Audièrne (Tréogat formation), and 4 from the Central Armorican Zone (Fig. 1). Initially, a single horizontal thin section was cut of each sample to assess the interest of the rock for further study and to measure the strike of inclusion trails. The latter only proved possible in about half of the samples, the other half containing garnets that are too altered or whose inclusion trails are too poorly developed. Seven Ile de Groix samples containing the most promising inclusion trails were further studied in 6 vertical thin sections striking N0, N30, N60, N90, N120 and N150 aimed at determining inclusion-trail curvature axes also known as 'FIA' ('Foliation Intersection- or Inflexion-Axes'; Bell et al., 1992; Bell et al., 1995; Stallard et al., 2003; Kim & Sanislav, 2017). Five Ile-de-Groix samples (G3, G11, G12, G14 and G20) were studied in even greater detail using X-ray computed tomography (XCT) allowing study of virtual sections of any orientation and location in scanned rock volumes, as well as quantitative analysis of the 3D shape of different minerals and their preferred orientations.

3*.1. Preferred orientations of inclusion trails and genetic implications*

Inclusion trail strikes were measured in 10 samples from 3 main areas in Ile de Groix (Fig. 2a) and plotted in moving-average rose diagrams made with the Excel Workbook MARD (Munro & Blenkinsop, 2012; Fig. 2b). The matrices of these rocks contain a mineral/stretching lineation that, although locally exhibiting significant variation, overall trends N-S in the south-east of the island, changing gradually to NW-SE further north and west. Bosse et al. (2002) inferred a thrust contact separating garnetiferous eclogites, blueschists and micaschists in the eastern half of the island from underlying lower-grade (albite-epidote facies) rocks outcropping in the western half (Triboulet, 1974; Schulz, 2001).

In the eastern part of the island, stretching lineations are associated with a gently dipping or subhorizontal foliation so that shearing-induced porphyroblast rotation can be expected to have resulted in inclusion trails broadly striking orthogonal to the lineation (Fig. 3a). Our measurements, however, show precisely the opposite: a NNE-SSW maximum of inclusion-trail strikes subparallel to the stretching lineation. This is only a first indication that the classic interpretation of internal foliations based on Zwart (1960), Spry (1963) or Roosenfeld (1970) may not be applicable and that the alternative model of Bell (1985), Bell et al. (1986) and Bell & Johnson (1989) has to be considered, according to which sigmoidal and spiral-shaped inclusion trails form by punctuated overgrowth of one or multiple crenulation cleavages by non-rotating porphyroblasts (Fig. 3b). The lack of rotation results from the preferential nucleation of porphyroblasts in microlithon domains and the partitioning of shearing components in surrounding cleavage planes. Thus, FIA represent 'fossil' crenulation axes in this model and this explains FIAs being commonly parallel to crenulation- and fold-axes in the matrix (Aerden, 1995, 2004, 1998, Sayab, 2005, Aerden et al., 2013; Bell & Sanislav, 2011).

Additional support for a 'non-rotational' origin of the inclusion trails of Groix Island is provided by internal truncations within garnets of samples G7 and G14 (Fig. 4). These exhibit similar subvertical and subhorizontal preferred orientations as reported in other metamorphic belts (e.g. Bell et al., 1992; Hayward, 1992; Aerden, 1994, 1998, 2004; Mares, 1998; Bell & Sapkota, 2012; Sayab, 2005; Shah et al., 2009; Aerden and Ruiz Fuentes, 2020), where it is interpreted to witness alternating compression and (synorogenic) gravitational collapse. We are unaware of any alternative explanation for this data.

3.2. Inclusion-trail curvature sense and implications for subduction polarity

Quinquis & Choukroune (1981) reported that out of a total of 29 thin sections they studied, presumably cut parallel to the stretching lineation, 26 contained sigmoidal or spiral-shaped inclusion trails that would indicate top-to-the north shearing. Since they assumed the traditional 'rotational' model, it follows that their inclusion trails predominantly curve anticlockwise when viewed in westward direction. In effect, we found the same predominance in our samples after counting the number of clockwise vs. anticlockwise trails in all vertical thin sections striking N-0, N30, N120 and N150, that is is, in all thin sections lying at a small angles with the regional stretching lineation. This resulted in 99 anticlockwise and 27 clockwise inclusion trails (viewing westward); a ratio of about 4:1.

Most workers agree that the general tectono-metamorphic zonation in the Ibero-Armorican Arc is best explained in terms of a northward subduction of Gondwana below Armorica-Avalonia and hence south-verging thrusting. In order to reconcile this with top-to-the-north shearing apparently indicated by 'rotated' porphyroblasts, Quinquis & Choukroune (1981) envisaged a geodynamic model including major backthrusting and obduction in the Ile de Groix, contrary to the direction of subduction. However, a 'non-rotational' interpretation of the same inclusion trails hey studied resolves the problem without need for this rather *ad-hoc* solution as the model predicts north-side-up shearing on vertical foliations alternating with top-to-the south shearing on horizontal foliations compatible with north directed subduction (Bell & Johnson, 1989, their Figs. 16 and 17). Therefore, the curvature sense of inclusion trails in Ile de Groix is an extra argument in favour of the 'non-rotational' model.

3.*3. Average FIA trends measured from radial thin-section sets*

Hayward (1990) devised a method for determining the average orientation of FIAs in a sample using sets of radially cut thin sections with regular angular spacing. The method exploits the fact that asymmetric inclusion-trails (or folds) exhibit either an S- or Z-asymmetry in cross-section depending on the orientation of the section relative to the fold- or inclusion-trail axes. This allows the average trend of FIAs defined by sigmoidal or spiral-shaped trails in a sample to be constrained between the strikes of thin-sections exhibiting opposite asymmetries of these microstructures. Once the FIA trend is known, the average plunge can also be determined by cutting a new radial set of thin sections, this time about a horizontal axes oriented normal to the FIA trend. The method was refined by Bell et al. (1995) to potentially allow determination of multiple FIA sets in samples with complex deformation histories.

We successfully applied the method to 5 Ile de Groix samples. The average FIAs for these are given in Fig. 2b as pie-cake symbols. All were constrained to within 30° trend ranges, but 10° for sample G7 as 2 extra thin sections were cut with 10° spacing. The plunge direction could also be determined from the asymmetry of inclusion trails in the horizontal thin sections, but the plunge angle was not further constrained because of the large amount of extra thin sections and time this would have required. The method did jot produce results in samples G18, G19 and G20, which contain relatively few porphyroblasts with inclusion trails that show inconsistent asymmetries in some thin sections. X-ray data for G20 presented further suggest that this inconsistency is due to the presence of 2 differently oriented sets of FIA sets that could not be resolved with thin sections. Samples G3, G13 and G15 mostly contain garnets with straight inclusion trails and too few asymmetric ones to confidently apply the technique.

3.*4. Mainland samples: Pouldu schists, Tréogat formation and Central Armorican Domain*

The 'Pouldu schists' are greenschists of volcano-sedimentary origin cropping out along the southern coast of mainland Brittany (Triboulet, 1992; Fig. 1). Inclusion-trails preserved within abundant albite porphyroblasts in this unit were measured in 3 samples (PO2, PO3, PO5) and in a fourth sample (AU-1) of similar rocks cropping out in the Baye d'Audièrne (Tréogat Formation; Luck et al., 2002). Inclusion-trails in all these samples broadly strike E-W (Fig. 2b), subparallel to the generally steeply dipping macroscopic cleavage. A N060 striking crenulation cleavage is visible in the matrix of PO2 and PO5 (Fig. 2c).

N-S striking vertical thin sections of PO2, PO3 and PO5 show that the main foliation ('S2' in Fig. X1a) itself crenulates an older fabric (S1) and inclusion-trail geometries indicative of porphyroblast growth syn- to post-D2 (Fig. X1b). Radiometric ages of 330-320Ma obtained for nearby granites affected by S2 (Béchennec et al., 2012) imply that these inclusion trails formed in the Carboniferous and hence post-date the ones of Ile de Groix where metamorphism peaked in the Late-Devonian (360-370Ma; Bosse et al., 2005).

Two staurolite-kyanite schists from the Central Armorican Domain located about 5km NNE of Quimper were also studied but only in horizontal thin sections. The age of metamorphism in these rocks is roughly constrained by granite ages to the period of 350-320Ma (Schulz et al., 1998). The broadly N060 trend of inclusion trails in these samples (Fig. 2d) suggests a correlation with the late earlier mentioned N060 crenulation cleavage in the Pouldu schists.

4. Inclusion-trail data from X-ray tomography

4.*1. Data acquisition and processing method*

X-ray computed tomography (XCT) scans were acquired at the University of Granada with an Xradia 510 (Versa Zeiss) microtomographer at resolutions of 13-15 um using 140kV voltage and 2500-3200 projections. Four thin-section blocks measuring 10-15 cm3 were scanned of samples G3, G11, G12, and G14 plus a more irregular piece of G20 of similar volume. Geographic orientation arrows made of metal wire were stuck on the samples to aid reorientation of the Tiff image-stacks generated by the scanner such that geographic north coincides with the Y-axes, and true vertical with the Z-axes. Image stacks were processed with the Fiji software package (Schindelin et al., 2012). After reorientation, the spatial orientation of all straight inclusion-trails or inclusion-trail segments visible in the stacks were determined by recording the strike and pitch of these microstructures as seen in XY-, YZ- and XZ-slices, then plotting these angles in a stereonet and fitting them to great circles.

Furthermore, the curvature axes of sigmoidal or spiral-shapes inclusion-trails (FIA) were measured by slicing individual porphyroblasts in radial patterns, analogous to the radial thin-sectioning technique of Hayward (1990) and Bell et al. (1995) already described in section 6. The trend of the FIA defined by sigmoidal or spiral-shaped trails is first constrained by interactively rotating a vertical slice about a vertical axes through the porphyroblast and recording where the switch of inclusion-trail curvature sense occurs. Once the FIA trend is determined, a horizontal slice is interactively rotated about a horizontal axes trending normal to the FIA trend and allows to constrain the FIA plunge and plunge direction from a similar asymmetry switch.

The 3D image stacks also allowed us to study preferred orientations of both garnet porphyroblasts and relatively large opaque minerals present in all 5 samples. The BoneJ plugin of Fiji (Doube et al., 2010) was used for this purpose. This plugin allows rapid calculation of best-fit ellipsoids for a large number of 'objects' in a binary (black & white) image stack. Image stacks were first segmented by thresholding top, only leaving the range of grey-scale values corresponding to garnet or opaque minerals, and then binarized (i.e. all grey tones are set to black). Subsequently, a size-filter was applied to remove small particles and in some cases the 'dilate' tool in order to re-join parts of single garnets that had become separated during thresholding due to the presence of fractures and related alteration. In all samples studied except G20 this procedure revealed strong preferred orientations of opaque minerals but not of garnets, whereas in sample G20 the reverse situation was found with only preferred orientation of garnets. The following subsections describe our main microstructural results for each sample in detail.

4.*2. Sample G11*

G11 is a blueschist from 'Amer' in the SE of the island (Fig. 2a). It contains garnet porphyroblasts as well as rectangular pseudomorphs probably after lawsonite composed of a mixture of white mica, chlorite, albite and epidote (Cogné et al., 1966; Felix & Fransolet, 1972; Ballèvre et al., 2003). Lawsonite relics have never been found, though, and some authors have argued that the replaced mineral could have been plagioclase (Shelley & Bossière, 1999). Lawsonite, is a high-pressure mineral and should have grown partially synchronous with garnet on a prograde path, whereas plagioclase is more likely to have formed during retrogression. Thus, the relative timing of the pseudomorphed mineral relative to garnet growth is highly relevant to this question.

Inclusion trails in garnet porphyroblasts of G11 vary from simple to sigmoidal to spiral-shaped but never curve more than about 90° from the centre to the rim (Figs. 5a, b, c, g and 6). The X-ray scan also revealed relatively large elongate crystals with high X-ray attenuation (higher than garnet) and hence density, which in thin section were identified as Fe-rich opaques partially or completely replaced by brown-reddish goethite (Fig. 5d, h). Some of these opaques attain porphyroblastic sizes and contain scarce silicate inclusions. Reflected-light imaging showed that the opaque phase is a mixture of ilmenite and magnetite, the latter possibly replacing the former. Best-fit ellipsoids calculated for these crystals with *BoneJ* (see section 7.1.) have their long-axes (X) strongly aligned with the macroscopic mineral/stretching/intersection lineation, whereas XY planes lie in the plane of the matrix foliation (Fig. 6).

Sigmoidal- or spiral-shaped inclusion trails were measured both in the centre and in the rims where they become sharply deflected or truncated by younger inclusion trails. The porphyroblast-rim measurements tightly define a steeply SW dipping plane, whereas porphyroblast-core foliations vary significantly from steeply NE dipping to shallowly W-dipping. The intersection lines of core- and rim inclusion-trail planes agree well with 10 FIAs that were measured independently with the above mentioned radial-slicing technique. Simple (straight) inclusion trails have variable orientations that coincide either with the ones in the cores or the rims of porphyroblasts with sigmoidal and spiral-shaped trails.

Based on this data it can be confidently interpreted that the bimodal inclusion-trail strikes seen in the rose diagram for G11 in Fig. 2b represent two sets of inclusion trails: an older set striking NNW-SSW and a younger one striking WNW-ESE. The FIAs measure din individual porphyroblasts also confirm the average FIA that was initially determined using thin sections (Fig. 2b).

Lawsonite pseudomorphs in G11 also exhibit visible inclusion trails in the X-ray scan (Fig. 5e, f, and h) although less finely defined as in garnet. They have a straight to weakly sigmoidal geometry oblique to the matrix foliation and are subparallel to the inclusion trails of garnet-rims suggesting that the pseudomorphed mineral grew synchronous with garnet rims. This agrees with earlier reported garnet inclusions within the pseudomorphs (e.g. Ballèvre et al., 2003). Thus our new microstructural evidence for synchronous growth with garnet rims supports prograde lawsonite growth rather than retrograde plagioclase. The asymmetry or curvature sense of inclusion trails in the pseudomorphs is opposite as in garnets viewed in N-S vertical sections, implying a change from top-to-the south shearing during the growth of garnet cores, to top-to-the north shearing during formation of garnet rims and lawsonite, as further discussed in section 6.3.

4.*3. Sample G12*

G12 is a similar blueschist as G11 and from the same outcrop in which one possible lawsonite pseudomorphs could be identified in X-ray scan but not clearly showing an internal fabric. The tomographic data for this sample reveal an early NNW-SSE striking foliation preserved in porphyroblast cores and as simple inclusion trails, which was overprinted by a steeply S-dipping foliation preserved in garnet rims (Fig. 6). The garnet-rim foliation is in turn deflected or truncated by a subhorizontal crenulation cleavage that causes transposition in the matrix and constitutes the composite macroscopic foliation. The same opaque minerals as described in G11 are present in the matrix but in this case also as relatively large inclusions within garnets, often occupying a central position suggesting that the garnets nucleated on those grains. Best-fit ellipsoids demonstrate strong elongation of the matrix opaques in NW-SE direction, subparallel to the strike of inclusion trails in garnets and the macroscopic lineation.

These data allow to correlate the different peaks exhibited by the rose diagrams for inclusion-trail strikes in G11 and G12 (Fig. 2b). These peaks correspond to (1) an early NE-SW striking foliation which preserved in the cores of spiral-shaped inclusion trails, (2) a younger NNW-SSE striking foliation included in the cores of sigmoidal inclusion trails with variable dip angles, and (3) a still younger ESE-WNW foliation preserved in garnet rims and in lawsonite pseudomorphs. It is noteworthy that, in spite of the similar microstructural evolution of G11 and G12, the average FIA trends that were initially determined for both samples differ significantly and without the tomographic data would have been probably misinterpreted as corresponding to different deformation periods.

4.*4. Sample G14*

G14 is another blueschist sample from Amer containing numerous relatively small (1-2 mm) garnets with straight, sigmoidal or spiral-shaped inclusion-trails. The spiral patterns exhibit significantly greater curvature (up to 180°; Fig. 4b) as in G11 and G12. Unfortunately, only a few garnets had clearly visible inclusion trails in the tomographic scan because of their very fine grain size and profuse fracturing of garnets. A few inclusion-trail planes could be measured plus 5 FIAs that plunge steeply in different directions (Fig. 7a).

Elongate opaque crystals similar as present in G11 and G12 align with the macroscopic stretching/mineral lineation. Their XY planes have variable dips but consistent N-S to NE-SW strikes parallel to that of most inclusion-trails (Fig. 2b). An interesting fold structures outlined by an epidote-rich layer was found, whose axial trace also trends NE-SW suggesting a genetic link with the inclusion trails that is further supported by the 3D microstructural data (Fig. 7a). E-W sections through the fold (Fig. 7c) show that it was refolded with a subhorizontal axial plane probably when the horizontal crenulation cleavage in sample G7 developed (Fig. 4a). In plan view, the fold is transected by N-S striking cleavage zones accentuated by irregularly folded quartz lenses (Fig. 7d).

4.*5. Sample G3*

G3 was collected close to Fort Nosterven on the east coast of the island, about 1 km south of G7 from Plage du Trech. Garnets in this glaucophane-epidote schist have well developed straight and sigmoidal inclusion trails whose strikes were measured in thin section. Unfortunately, the trails were poorly visible in the tomographic scan. The few that could be measured dip steeply NW, similar as the inclusion trails in garnet cores of samples G11 (Fig. 8a; compare with Fig. 6). A correlation can also be proposed with average FIA trend determined in sample G7 (Plage du Trech) from radial thin sections and with the gently SSW plunging folds measured there by Audren (1974, unpublished data; Fig. 8b). One garnet FIA defined by sigmoidal inclusion trails could be constrained by radial slicing. Inclusion-trails in the rim of this porphyroblast are approximately subvertical with N120 strike and hence can be correlated with the garnet-rim inclusion trails of G11 and G12.

4.*6. Sample G20*

G20 was collected at Port Lay on the central-north coast (Fig. 2) where the macroscopic cleavage dips about 50° NE associated with a subhorizontal mineral lineation parallel to fold axes. Despite numerous (>100) garnets in the scanned volume, only 6 FIAs could be determined with confidence for sigmoidal inclusion trails. Five of these plunge moderately NE and correspond to the intersections between early NE-SW striking inclusion trails and a younger set of NW-SE striking ones, subparallel to the macroscopic cleavage. The 6th FIA is subhorizontal with NW-SE trend and must have formed later by inclusion of the younger set of inclusion trails.

Abundant opaque minerals in the sample conspicuously cluster around garnet crystals suggesting a genetic relationship, but best-fit ellipsoids calculate from them did not reveal significant preferred orientation and their axial ratios are also lower as in other samples. In contrast, best-fit-ellipsoids for garnet porphyroblasts did confirm a strong preferred shape orientation already appreciable by eye with garnet long-axes (X_Gt) subparallel to fold axes, mineral lineation, and the late subhorizontal FIA (Fig. 8c). Aerden & Ruiz-Fuentes (2020) and Aerden et al. (Submitted manuscript, Tectonics) recently showed that garnets commonly grow elongate normal or parallel to their FIA, and explained this in terms of preferential nucleation of porphyroblasts in actively forming microlithon domains, whose ellipsoidal shapes are mimicked by the garnet. In G20, all 6 measured FIAs lie within the set of younger inclusion trail planes and macroscopic foliation. The 5 older FIAs (NE plunging) are hosted by garnets that are elongate in the direction of the the stretching lineation. The younger (subhorizontal) FIA is parallel to the stretching lineation but the corresponding garnet long axis plunges NE suborthogonal to the stretching lineation. In principle, one could consider the possibility that the elongate porphyroblasts in G20 rotated towards the flow plane and stabilized their position once they reached a small angle with it (Pennacchioni et al., 2000; Ceriani et al., 2003). However, the average axial ratio of the garnets (R=2.1) is well below the reported threshold value of R>3 for stabilization to occur, and apart from that the model does not explain the shape elongation in the first place.

5. Tectonic interpretation

Evidence has been presented for 3 sets of differently oriented inclusion-trails in Ile de Groix, which we interpret to witness 3 episodes of crustal shortening perpendicular to the their strikes. Although the ratios of clockwise vs. anticlockwise trails could not be resolved for each set separately, it is likely that in thin sections striking N330, N0, N30 and N60 this ratio is determined mainly by the oldest (NE-striking) and youngest (E-W striking) sets as these intersect the thin section at a high angle. The intermediate inclusion-trail set strikes subparallel or at a low angle to the same thin sections and can be expected to produce inconsistent curvature senses (cf. Hayward, 1990). Indeed, this may be the reason why about 25% of all counted garnet porphyroblasts exhibit opposite curvature (i.e. clockwise) as the others. Therefore, the oldest NE-SW striking inclusion trails are interpreted to witness early NW directed subduction. The polarity of an intermediate subduction stage has not been determined from inclusion trails, but was probably towards the WSW (cf. Martinez Catalán et al., 1997). The asymmetry of the youngest WNW-ESE striking trails (included in garnet rims of G11 and G12) corresponds the latest stages of northward subduction, followed by exhumation. All internal fabrics probably formed during a single prograde path reaching peak conditions of about 18–20 kbar, 450 °C (Ballèvre, 2003 and references cited therein). Schulz et al, (2001) presented interpreted 2 metamorphic cycles that perhaps merit further study with relation to the multiple generations of garnet porphyroblasts and FIAs distinguished herein.

The average dip of all 106 inclusion-trail planes measured in 6 samples with X-ray tomography is 57° (σ=21°) and the average plunge of all 32 measured FIAs is 43° (σ=15°). These relatively high dip and plunge angles imply only a minor role of the intermitted gravitational phases that are suggested by subhorizontal truncations within garnets of samples G14 and G7 (Fig. 4). These events did not significantly rotate pre-existing steeply dipping fabrics as that would have resulted in a preponderance of subhorizontal FIAs caused by the intersection of subhorizontal and subvertical foliations (e.g. Bell et al., 1995).

The penetrative subhorizontal crenulation cleavage in the matrix of G3, G7, G11, G12, and G14 is not continuous with the above mentioned subhorizontal truncations and therefore must have formed later. Based on what is known about the control of crenulation cleavage development on porphyroblast nucleation and growth (e.g. Bell & Hayward, 1991), we interpret that incipient development stages of the subhorizontal transposition foliation at Groix triggered the growth of lawsonite crystals and the latest stages of garnet growth in samples G11 (Fig. X2) both preserving the previous subvertical WNW-ESE striking foliation. Porphyroblast growth would have ceased as soon as the newly forming cleavage intensified against porphyroblast margins, followed by continued intensification, folding and transposition in the matrix.

In the eastern half of the island, the subhorizontal crenulation fully transposed older fabrics and is responsible for the overall flat-lying position of the macroscopic composite cleavage. In lower-grade western Groix the same cleavage appears to be more weakly developed as the main foliation there dips moderately to steeply NE or SW due to upright folding. These contrasting structural styles are clearly reflected in the orientation data of Cogné et al. (1966) which are compiled in Fig. X3a. Structural relationship between the high-grade and lower-grade domains are further clarified by sketches of Cogné et al. (1966) and Boudier & Nicolas (1976) of an outcrop at Vallon du Lavoir (central south coast; Fig. 2a) showing a decametre-scale upright anticline overprinted by a horizontal crenulation cleavage with associated refolding suggesting a component of vertical shortening (Fig. X3c and X3d). Indeed, Shelley & Bossière (1999) already deduced vertical shortening from quartz fabrics and conjugate shear bands indicating opposite shear senses. The sketch of Cogné et al.'s (1966) includes a zone where the horizontal cleavage appears overprinted itself by a steeply SE dipping foliation.

Samples G18, G19 and G20 were collected at an outcrop in Port Lay (central north coast; Fig. 2a) where the main cleavage dips 55° NE without traces of a subhorizontal crenulation cleavage. This foliation strike parallel to the younger of 2 sets of inclusion trails present in sample G20 (Fig. 8c) suggesting a genetic relationship. Therefore, the main foliation at this outcrop is interpreted to predate the subhorizontal transposition cleavage in eastern Ile de Groix.

The above micro- and macro-structural relationships, summarized in the conceptual sketch of Fig. X3b, are consistent with a gravitationally spreading thrust nappe. We envisage an emplacement mechanism similar as modelled experimentally by Bucher (1956) or Merle (1989), and as proposed earlier for Variscan nappes in the Montagne Noire (Aerden, 1998; Aerden & Malavieille, 1999).

The steeply dipping E-W striking foliation in the Pouldu schists and associated inclusion trails (see section 3.5.) record continued N-S plate convergence during the Carboniferous causing shortening in the footwall of the Ile de Groix ophiolitic nappe. This deformation could have produced the late chevron-style folds with E-W trending axes recognized on Groix island (Fig. X2a).

6. Discussion

6.1. Inclusion trail data vs. structural sequences in the field

Cogné et al (1966) collected numerous structural data along the entire coast of the island and distinguished 3 deformation phases. The first phase corresponds to tight to isoclinal folds (called 'fundamental folds') with NW-SE to N-S trends. The second deformation caused local refolding of the 'fundamental' folds associated with a SW dipping crenulation cleavage striking N130-140. A third set of E-W trending chevron-type folds were interpreted as post-metamorphic structures. They reported further that stretching/mineral lineations defined by glaucophane prisms exhibit variable relationships with respect to fold axes, commonly being parallel with them and apparently coeval, but locally oblique and clearly predating the folding, or still elsewhere associated with 2nd-phase folds, in which case 2 sets of oblique glaucophane lineations were observed (their Fig. 12, p 70).

Boudier and Nicolas (1976) distinguished 4 deformation phases (D1-D4), the youngest one of which corresponds to the late chevron-type structures of Cogné et al. (1966). D1 refers to the mineral-lineation (L_1) , which they interpreted to have formed with a N120 trend. D2 and D3 correspond to N165 trending folds that would have partially reoriented L_1. Thus, an opposite relative timing was concluded of N120 vs. N165 trending folds as Cogné et al. (1966).

The orientation data collected by Boudier and Nicolas (1976) remarkably well match the strikes of our 3 sets of inclusion trails (Fig. 9c, 10a). However, our tomographic data for G11 and G12 indicate an opposite timing as they deduced for N165- vs. N120-trending fabrics and folds, and hence agree with Cogné et al (1966), and with an unpublished sketch by Claude Audren (1974) kept at the 'Maison de la Reserve Naturelle Le Bail' on Ile de Groix showing refolding of a N165 lineation by a N120 fold (Fig. 9a). Quinquis & Choukroune (1980) endorsed a late origin of N120 folds but considered them post-metamorphic. They considered that the N120 orientation maximum of L1 in Boudier & Nicolas' data (1976) from Vallon du Lavoir (Fig. 9c) is not representative for the entire island and has no regional-tectonic significance. They predicted instead that, on a regional scale L_1 varies symmetrically between N120 and N200 as a consequence of sheath folding driven by top-to-N340 progressive shearing. However, their ideas were heavily influenced by analogue modelling of sheath folds in the lab (Cobbold & Quinquis, 1980) rather than being based on new structural or microstructural data.

The above outlined contradictory interpretations of folding phases, their original orientations and relative chronology are not surprising considering the polyphase nature of 'L_1' revealed in this study and indeed recognized earlier by Cogné et al. (1966). This lineation, defined by glaucophane, epidote and opaque minerals is associated with at least 3 sets of foliations formed at different times with different orientations, but difficult to distinguish in the field due to the effects of repeated folding, rotation and transposition.

6.2. Formation mechanism of sheath folds

Based on a detailed study of quartz fabrics in 57 samples, Shelley and Bossière (1999) concluded that most folds of Ile de Groix island must nucleated with their axes immediately subparallel to the maximum stretching direction (X) instead of parallel to Y and then rotating towards X by progressive shearing (cf. Quinquis and Choukroune, 1981). Both models assume a single deformation event with subhorizontal flow plane and ignore the polyphase character of the "main foliation" and lineation, which is not a simple L-S fabric, but a foliation that transposed and modified earlier structures. This places the significance of fold-axes parallel stretching lineations and non-cylindrical folds in a quite different light. We interpret that these formed by vertical flattening of folds with originally steeply dipping axial planes and variably plunging fold-axes (Fig. 10). Depending on the precise geometry of precursor folds, new folds nucleated with straight axes parallel to X, or with strongly curved axes oblique to X.

6.3. Inclusion trail data vs. shear-bands

The reversed inclusion-trail curvature sense in lawsonite pseudomorphs with respect to garnets in sample G11 records a change from top-south to top-north shear sense (see section 4.2.) reminiscent of the change in regional-scale vergence interpreted by Philippon et al. (2009) from two sets of shear bands, as was already mentioned in section 2. They claimed that rocks conserving well shaped lawsonite pseudomorph exclusively contain top-south shear bands and that the lack thereof in other rocks also containing, or exclusively containing top-to-the north criteria or is due to a higher degree of retrogression, which would have destroyed the pseudomorphs. N-S sections of our lawsonite-bearing sample G11 cast doubts on these claims by showing both asymmetries with the majority indicating top-to-the north (Fig. X3). The sample comes from an area where according to Fig. 6 of Phillipon et al. (2009) only top-to-the south criteria should be found.

In any event, shear-bands, pressure shadows and quartz c-axes fabrics are all related to the latest intense deformation associated with a subhorizontal transposition foliation. It has been shown that this foliation deformed a series of earlier steeply dipping foliations, and is probably related to the exhumation history. This rather supports the original interpretation of

Quinquis (1980) and Shelley & Bossière (1999) who considered opposite shear bands as conjugate pairs formed during the retrograde path.

6.4. Comparison with inclusion-trail data from NW-Iberia

Figure 10 compares our new inclusion-trail data from Brittany with that of Aerden (2004) for the Basal Unit of the allochthonous complexes of NW-Iberia. This unit comprises orthogneisses and high-pressure micaschists retrogressed in greenschist facies representing the subducted margin of Gondwana (Arenas et al, 1995; Martínez-Catalán, 1996) with a similar structural position as the Pouldu Schists, below an ophiolitic unit. Three sets of inclusion trails striking E-W, NE-SW and NNW-SSE were distinguished in this unit preserved in plagioclase and garnet porphyroblasts. The oldest of these with E-W trend were related to the high-pressure event dated 370-360Ma (Van Calsteren et al., 1979; Santos Zalduegui, et al. 1995; Abati et al., 2010; Li & Massonne, 2017), and hence synchronous with the metamorphism of Ile de Groix (Bosse et al., 2005). The 2 younger internal foliations sets formed at lower pressures and their age was only loosely constrained to pre-320 Ma.

To account for the Cretaceous anticlockwise rotation of Iberia during formation of the Gulf of Biscay, the current northern margin Iberian is placed back against the conjugate margin of south Brittany in Fig. 10 implying 20° clockwise back-rotation of Iberia. Although this reconstruction produces a good match of inclusion-trail strikes in both massifs (Fig. 10b), it poses question around the relative timing evidence of Aerden (2004). He interpreted that the (presently) NNW-SSE striking inclusion trails in the Basal Unit (coloured blue in Fig. 9) postdate E-W striking ones (yellow), opposite to what has been concluded herein. As he based this on only a sample with bimodal strikes of inclusion trails (sample 1. - Fig. 9a) we believe there is scope for re-assessing the relative timing of Aerden (2004) using X-ray tomography.

In contrast, the relative timing of NW-SE striking inclusion trails in NW Iberia (marked with red lines in Fig. 9) was based on more abundant microstructural and field criteria. Consequently, these microstructures cannot be correlated with the much older NW-SE trails in samples of Ile de Groix. However, a correlation can be proposed with the internal foliations of the 2 samples from the Central Armorican Domain, and the crenulation cleavages that is present in the Pouldu schists (Fig. 2c and d).

We checked the curvature sense of inclusion trails in Aerden's (2004) thin sections associated with the W-E to NW-SE FIAs (marked yellow in Fig. 10a) this author determined in 6 samples of the Basal Unit. In samples 3-4, 10, 14 and 20, inclusion trails curve anticlockwise viewing west. In samples 2 and 19 they curve clockwise. The larger number of anticlockwise trails is as observed in Ile de Groix, but we realize that more samples need to be studied before firm conclusions can be drawn regarding thrusting directions in NW Iberia.

7. Conclusion

(1) The blueschist-eclogite facies rocks of Ile de Groix experienced 4 successive tectonic events potentially reflected in a also complex PT path (Schulz et al., 2001). Corresponding fabrics are preserved as inclusion trails that maintained their original orientations due to limited or no rotation of porphyroblasts during ductile deformation.

(2) In specific orientations and dominant curvature sense of inclusion trails allow the following reconstruction. (Stage-I) Early NW-directed subduction of Gondwana. (Stage-2) E-W crustal shortening with unconstrained subduction polarity, but probably to westward given the preceding subduction direction. (Stage III) Northward subduction until peak metamorphic conditions were reached. (Stage IV) Exhumation associated with vertical shortening and a component of top-to-the-north shearing indicated by the asymmetry of inclusion trails in

lawsonite pseudomorphs as well as late shear bands (Philippon et al, 2009). A subhorizontal crenulation cleavage associated with this event transposes all earlier fabrics. Inclusion-trails studied in 4 additional greenschist samples from the lower-grade footwall of the Groix ophiolite strike E-W, parallel to the youngest set of inclusion trails in the blueschist samples from the island.

(3) The curvature sense of sigmoidal and spiral-shaped inclusion trails indicates top-to-the south thrusting which agrees with regional-geological evidence only when a 'non-rotational' original of these microstructures is accepted. The traditional 'rotational' interpretation implied an opposite and shear sense conflicting with the regional tectono-metamorphic structure of southern Brittany.

(4) The strikes of 3 sets of inclusion trails documented herein can be tentatively correlated with 3 similar sets reported earlier in NW-Iberia (Aerden, 2004). The coincidence of microstructural directions between both regions is maximized assuming only 20° rotation of Iberia during opening if the Gulf of Biscay, significantly less as ca. 35° rotation generally concluded from paleomagnetic data (Gong et al., 2009).

(5) Fold axes parallel to stretching lineations and rare sheath folds reported on Groix did not form by progressive unidirectional shearing, but by vertical shortening and horizontal shearing superposed on steeply dipping pre-existing foliations and folds with variable plunges.

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FIGURE CAPTION

Fig. 1. Simplified geological maps of southern Brittany and NW-Iberia showing the location of ophiolite outcrops and samples studied herein and by Aerden (2004) in NW Iberia.

Fig. 2. (a) Stretching lineation pattern of Ile de Groix and sample locations. (b) Moving-average rose diagrams for inclusion-trail strikes. Encircled pie-cake symbols represent average FIA trends in samples determined from radial thin sections and the FIA plunge direction. Also the sense of inclusion-trail curvature is indicated viewing down the FIA plunge (anticlockwise in G14, G12, G11; clockwise in G19 and G7). (c) Data for samples from the Pouldu schistes (PO2, 3, 5) and the Tréogat formation (AU1). Arrows represent crenulation axes in the matrix. (d) Data for 2 staurolite-kyanite schists from the Central Armorican Domain. The 4 inclusion-trail sets proposed in this paper are marked with magenta, blue, yellow and red trend lines, from the oldest to the youngest set.

Fig. 3. (a) Rotational interpretation of sigmoidal and spiral-shaped inclusion trails from Ile de Groix and the range (purple) of inclusion trail strikes predicted by this model. (b) 'Non-rotational' interpretation of the same inclusion trails according to Bell et al (1986) and Bell & Johnson (1989) consistent with orthogonal truncations and inclusion trails striking subparallel to stretching lineations, crenulation- and fold-axes. (c) Strikes measured in all 10 samples from Groix agree better with the non-rotational model.

Fig. 4. (a) Sketches of well developed 'rotational' inclusion trails in oriented vertical thin sections of samples G7 and G14 showing vertical and horizontal alignment of internal truncations (purple lines). (b) Rose diagram plotting the orientations of all individual dashes that make up the dashed lines representing inclusion trails in the drawings measured with the image/analysis program *Fiji*. The plot demonstrates bimodal orientations of the inclusion trails related to the orthogonal sets of truncations.

Fig. 5. All photographs of G11. (a and b) Garnet porphyroblast (parallel and crossed polars) with sigmoidal trails in a N-S striking vertical section. Barb of N-arrow points upward. Note top-to-the south shear sense suggested by asymmetric strain shadows, inconsistent with porphyroblast rotation. (c) Garnet with spiral-shaped truncation inclusion trails a porphyroblast core and rim zone. (d) Opaque mineral with elongate shape replaced by Goethite. (e and f). Lawsonite pseudomorphs (parallel and crossed polars) showing weakly sigmoidal inclusion trails oblique to the matrix foliation. (g) Tomographic image of a strongly curved inclusion trails garnet in G12. (h) Tomographic image of an elongate lawsonite pseudomorph, garnet (Gt) and opaque large opaque crystal.

Fig. 6. Stereoplots (equal angle, lower hemisphere) of internal foliations and FIAs measured in garnet and lawsonite pseudomorphs in samples G11 and G12. Also shown are 2 contoured stereoplots plotting maximum and minimum elongation directions of relatively large opaques present in the matrix of G11 and G12. See legend. The data can be matched to different sets of inclusion trails drawn with corresponding colors in garnets and a representative lawsonite pseudomorphs. The Mn concentration map is for one of the porphyroblasts with truncational inclusion trails.

Fig. 7. Tomographic images and microstructural data for sample G14. (a) Stereoplot of internal foliation planes, FIAs (grey boxes), long- and short axes of opaque minerals, and the axial plane of cm-scale folds. (b and c) Map- and cross-section views of a fold outlined by an epidote-rich layer. Its axial trace trends NNE-SSW oblique to N-S trending cross-cutting cleavage zones also visible in (d). The cross-section shows refolding with subhorizontal axial planes suggesting a component of vertical flattening associated with the main cleavage (compare with Fig. 4a, b).

Fig. 8. (a) 3D microstructural data for sample G3. See legend for explanation. (b) Field data collected by Claude Audren near sample G7 (Plage du Trech; about 1 km north of G3) and the average FIA trend that we determined for this sample from radial thin sections (magenta pie-cake segment). The FIA trend coincides with fold axes. Note that this conflicts with progressive sheath folding and porphyroblast rotation. Stretching lineations vary greatly due reflecting the polyphase nature of this fabric. (c) Microstructural data for G20. See legend and main text for explanation. The 6 garnet long axes with red fill in the right stereoplot correspond to the 6 garnet whose FIA were measured as indicated in the left stereopot. These garnet long-axes consistently make lie at a high angle to their FIAs (the moderately NNE plunging long-axes with red fill belongs to the subhorizonhtal NW-SE FIA.

Fig. 9. (a) Structural data collected by C. Audren and a corresponding sketch of isoclinal folds he drew at Vallon de Kérigant (location marked in Fig. 2a). The sketch is accurately redrafted and data re-plotted in lower hemisphere, equal angle projection (Audren used upper hemisphere, equal angle). Refolding of a N165 trending lineation around the nose of a N120 trending fold is demonstrated. (b) Lineations (L1) measured nearby (a) by Boudier & Nicolas (1976) at Vallon du Lavoir showing a N120 trend maximum of L1 (yellow lines) oblique to B2 fold axes in the same outcrop (blue lines). (c) Structural data from the same authors for the entire island. Note the bimodal pattern of L1. Magenta, blue and yellow trend lines show how this data can be correlated with the 3 sets of inclusion trails given the same colors in Figs 2, 5, 7 and 8.

Fig. 10. (a) Inclusion trails-strikes in the newly studied rocks and those measured by Aerden (2004) in 18 samples form the Basal Unit of NW-Iberia. The microstructures are correlated as 4 age sets marked with magenta, blue, yellow and red trend bars (from older to younger sets). Field data from Boudier and Nicolas (1976) and that of Engels (1972) and van Zuuren (1969) also show a good match. (b) Rose diagrams plotting inclusion-trail directions marked blue and yellow for different amounts of Iberia back-rotation. The directions line up best with 20° back-rotation, which is the current angle between the North-Iberia margin and that of southern Brittany.

Fig. 11. Conceptual models showing how vertical shortening and horizontal stretching can produce highly variable fold geometries depending on the original orientations of folded planes or pre-existing folds. Note how strongly curved fold axes can form without need of

extremely large shears trains. Adding a (horizontal) shearing component in the direction of X and/or Y can be expected to further modify the fold-interference patterns.tt

Interestingly, Béchennec et al. (2012) report that some albite porphyroblasts in the Pouldu schists include tiny garnets. In princiuple, these could be coeval with garnet growth in Ile de Groix.

All stereoplots are made with R. Allmendinger's program 'Stereonet'.

a Carboniferous age of the inclusion trails, corresponding to the continental collision stage of the Variscan orogeny when also the major dextral shear-zone system developed that dissects Armorican Massif (Béchennec et al. (2012).

The blueschist and eclogite metamorphism of Ile de Groix peaked in the late-Devonian in the context of oceanic subduction.

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