Journal of Structural Geology 31 (2009) 1308–1321

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Kinematic records of subduction and exhumation in the Ile de Groix blueschists (Hercynian belt; Western France)

Melody Philippon*, Jean Pierre Brun, Frédéric Gueydan

Géosciences Rennes UMR 6118 CNRS, Université de Rennes 1, 35042 Rennes Cedex, France

A R T I C L E I N F O

Article history:
Received 20 February 2009
Received in revised form
1 July 2009
Accepted 6 July 2009
Available online 16 July 2009

Keywords:
Subduction/exhumation processes
HP rocks
Shear criteria
Lawsonite

A B S T R A C T

Deciphering between deformations related to subduction and exhumation in HP metamorphic rocks represents a challenge for the understanding of the dynamic processes involved and more particularly, the exhumation mechanisms. An analysis of shear criteria in the Ile de Groix blueschists in the Hercynian Belt of southern Brittany (Western France) is carried out in terms of relative chronology and in relation to lithology (mainly micaschists and glaucophane-bearing metabasites). Structural mapping shows that foliations are flat-lying, bearing stretching lineations oriented in a N150°E ± 30° direction. Associated shear criteria are dominantly top-to-northwest and locally, in the southeast part of the island, both top-to-northwest and -southeast. Both shearing deformations lead to intense finite strains as demonstrated by the occurrence of sheath folds and the general orientation of fold axes parallel to the stretching lineation. Detailed mapping in this area showing opposite senses of shear, demonstrates that only top-to-southeast shear is observed in rocks containing well-shaped lawsonite pseudomorphs. In rocks affected by top-to-northwest shear, the lawsonite pseudomorph shape is destroyed by intense stretching. The top-to-southeast shear is coeval with prograde HP metamorphism and precedes a top-to-northwest shear coeval with a retrograde metamorphic path. In the frame of the hercynian belt of southern Brittany, the southeast directed shear is attributed to thrusting related to a northward dipping subduction and the northwest directed shear to exhumation controlled by a northward dipping extensional detachment.

1. Introduction

Whereas subduction offers a simple and widely accepted mechanism for the burial of crustal rocks down to mantle depths, the mechanisms invoked to explain the exhumation of HP–UHP rocks remain a debated question (Platt, 1993; Ring et al., 1999; Chopin, 2003). The deformations recorded by HP rocks represent one important set of criteria to be considered in this debate. Any researcher might suspect that during subduction, HP rocks must have undergone some type of thrusting shear, from brittle to ductile conditions, which is either localized or distributed. Then, during exhumation, they must have not only been subjected to metamorphic retrogression, but also deformations related to their rise towards the surface. Therefore, in an ideal case, HP rocks should display the superposition of at least two main sequences of deformation phases. However, what is most commonly described is, in fact, evidence for strong shearing during retrograde metamorphism along extensional detachments, as illustrated in most HP metamorphic belts of the Mediterranean orogens (Jolivet et al., 2003). This would suggest that, most commonly, exhumation related deformation tends to erase previous deformation related to subduction. However, it is likely that, even where the second deformation is intense, remnants of early deformation can be preserved in restricted areas that require particular attention to be detected. For the above reasons, attempting to decipher between the kinematics of ductile deformation related to prograde HP metamorphism (acquired during subduction, on one hand) and to HP rocks retrogression (developed during exhumation, on the other hand) represents a challenge for the understanding of the full subduction–exhumation cycle.

In the above perspective, we re-examine here the kinematics of ductile deformation in the Ile de Groix blueschists (Hercynian belt of southern Brittany; Western France), where a number of previous methodological developments concerning the deformation of HP metamorphic rocks has been carried out. The presence of sheath folds (Quinquis et al., 1978) was interpreted as evidence of progressive shear, possibly related to subduction or obduction. As, at that time, exhumation was always implicitly attributed to erosion, ductile deformation was only interpreted as a result of thrusting-type shear (Quinquis and Choukroune, 1981; Cannat,

* Corresponding author. Tel.: +33 60 364 4740.
E-mail address: melodie.philippon@univ-rennes1.fr (M. Philippon).

0191-8141/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2009.07.003

1985). Shear bands indicating opposite senses of shear, already identified but not interpreted by Quinquis (1980), were considered to result from a coaxial deformation during exhumation in extension (Shelley and Bossière, 1999). Recent detailed petrological and geochronological studies of the metamorphic history (Bosse et al., 2002, 2005; Ballèvre et al., 2003) offer a precise PTt framework to attempt a new analysis of deformation kinematics.

In this paper, we present a structural analysis of the Ile de Groix metamorphic rocks. A detailed mapping of shear senses is used to establish their relationship with lithology and with prograde and retrograde metamorphism. It is argued that the relationship of shear senses with prograde versus retrograde metamorphism characterizes the deformations related to subduction and exhumation, respectively. Finally, in the frame of the Hercynian belt of Brittany, the results provide a basis to discuss the possible configuration of subduction and the mode of blueschists exhumation.

2. Geological setting

Located to the south of the South Armorican Shear Zone (SASZ), a large HP unit outcrops over more than 300 km from northwest (southern Brittany) to southeast (Vendée; Fig. 1a). It is composed of a lower sub-unit of meta-rhyolites, the so-called ‘‘porphyroïdes’’, with a maximum recorded pressure of 9 kb (Le Hebel et al., 2002) and an upper sub-unit of blueschists outcropping in the Ile de Groix and at Bois de Céné in Vendée (Triboulet, 1974, 1991). In Vendée, the porphyroïdes are thrust onto low grade sediments (Bretignolle locality; Iglesias and Brun, 1976); whereas in southern Brittany, they are separated from underlying middle crust units, mostly micaschists and migmatites, by a Carboniferous extensional detachment (Fig. 1b).

The Ile de Groix metamorphic units consist mostly of micaschists (80%) with minor bodies of metabasites (20%), whose protoliths correspond to oceanic sediments with an occurrence of metacherts and oceanic island basalts (OIB), respectively (Bernard-Griffiths et al., 1986). Since the first mapping by Lamouche (1929), the large-scale structure of the island has often been described as a NW–SE trending upright anticline (Cogné, 1954; Quinquis and Choukroune, 1981; Bosse et al., 2002; Ballèvre et al., 2003). However, the detailed cross-sections of Jeannette (1965) and Boudier and Nicolas (1976) show a succession of west verging inclined folds with a 100–300 m wavelength, instead of a single kilometre-scale anticline. Boudier and Nicolas (1976), argued that i) glaucophane-bearing metabasites are more competent than micaschists and therefore, have preserved evidence of early deformations, ii) in retrogressed metabasites, the so-called prasinites, the development of albite during the greenschist overprint most often erase early deformations and iii) in micaschists, only the latest deformations can be observed. Consequently, they describe the structural history of the Ile de Groix metamorphic rocks as a succession of two main deformation stages. The first stage occurred in the blueschist facies conditions and is responsible for the epidote-glaucophane banding conserved in metabasites. During the second stage, in greenschist facies conditions, micaschists and metabasites layers are deformed in inclined folds that tightened eastward, as previously described by Jeannette (1965). Fold axes that trend N160°–170° are parallel to the glaucophane lineation (Boudier and Nicolas, 1976) and to the stretching direction indicated by sheath fold axes (Quinquis et al., 1978).

A garnet isograd (Fig. 2), trending NNE–SSW (Carpenter, 1976; Quinquis, 1980) divides the island into two parts: with and without garnet to the east and west, respectively. In the eastern part, *P* and *T* conditions are estimated as 16–18 kbar and 450 °C (Bosse et al., 2005) from Mn and Mg-rich garnets and as 18–20 kbar, 450 °C (Ballèvre et al., 2003) from lawsonite pseudomorphs in metabasites (Felix, 1972; Felix and Fransolet, 1972). In the western part, *P* and *T* conditions are estimated at 12–16 kbar, 450 °C (Bosse et al., 2002). The two metamorphic events are dated as 360–370 Ma for the HP metamorphism and as 345–353 for the greenschist overprint (Rb/Sr on whole rock and $^{40}Ar/^{39}Ar$ dating on phengite and epidote; Bosse et al., 2005). Considering the pressure gap between the two parts and the location of the highest pressure conditions on top of the metamorphic pile, Bosse et al. (2002) interpreted the garnet isograd as a thrust, as previously suggested by Cannat (1985; Fig. 9). On the contrary, Shelley and Bossière (1999) described the whole lithological pile as a unique metamorphic series, retromorphosed from eclogite facies to greenschist facies, without any internal discontinuity.

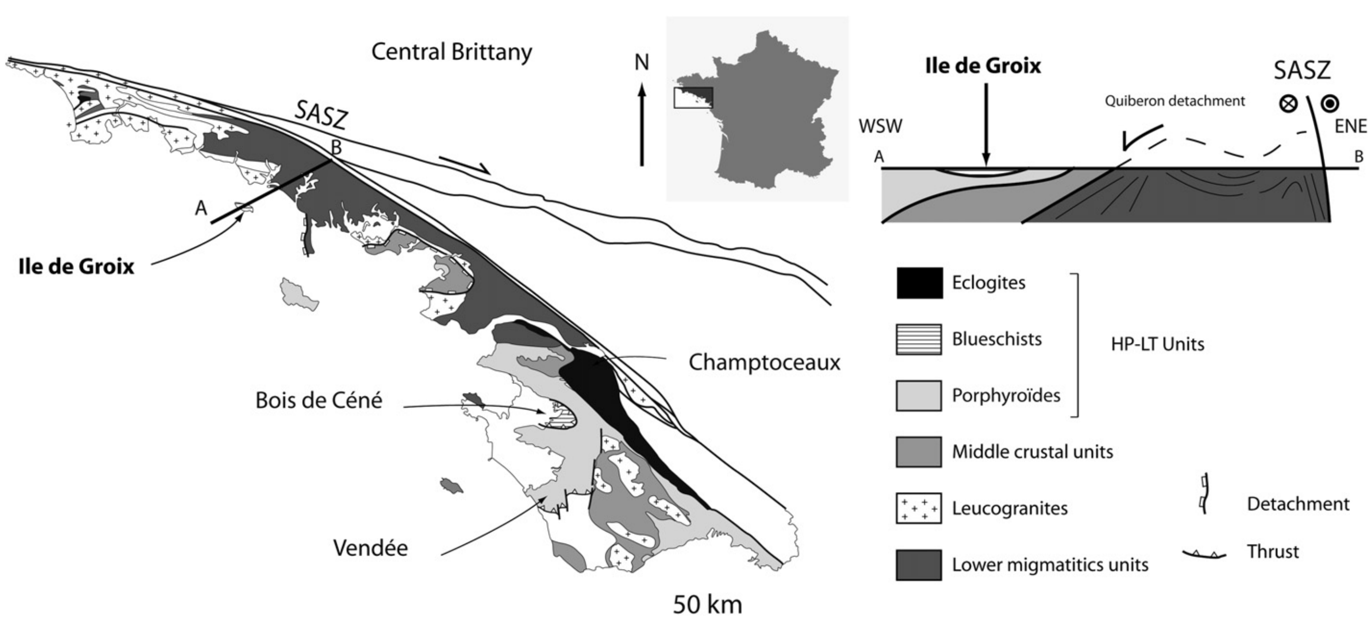

Fig. 1. Geological setting of the Ile de Groix in the frame of the Hercynian belt of southern Brittany. a. Simplified geological map of the metamorphic domain of southern Brittany with the location of the Ile de Groix. SASZ = South Armorican Shear Zone. b. Cross section AB (see location in a) showing the structural position of the Ile de Groix blueschists (modified after Cagnard et al., 2004).

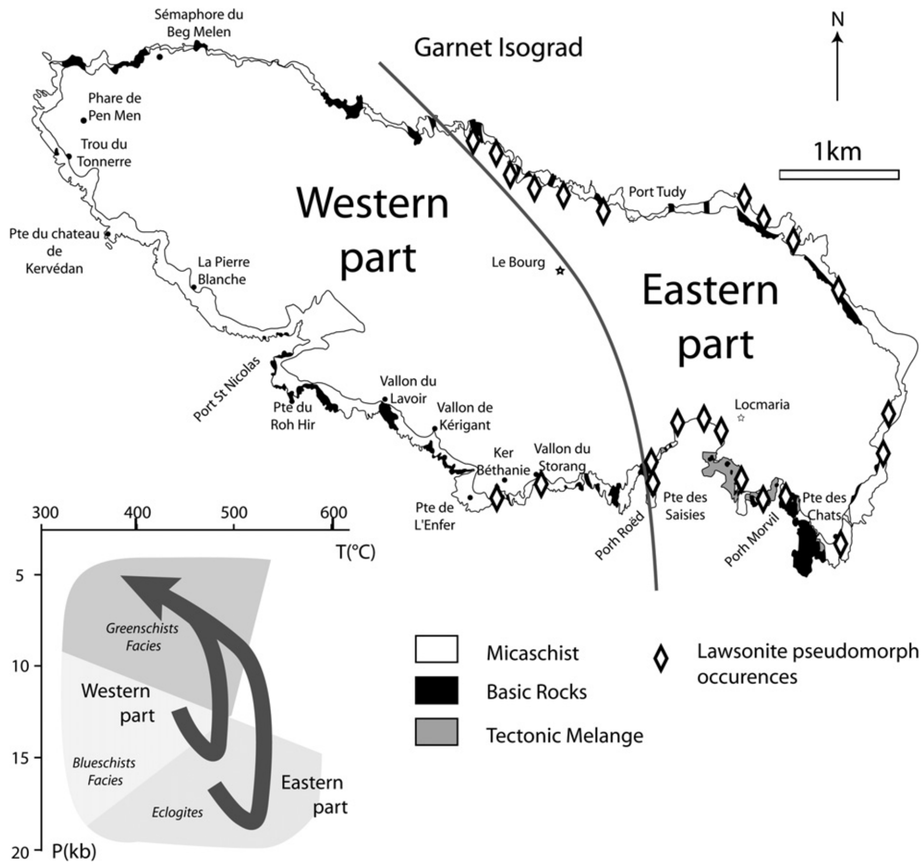

Fig. 2. Metamorphic map of the Ile de Groix showing the location of the garnet isograd (after Quinquis, 1980) and the occurrence of lawsonite pseudomorphs (after Ballèvre et al., 2003). The lithological contours are only shown along the seashore. The PT paths for the western and eastern part of the island are shown in the insert (after Bosse et al., 2002).

The rotation of garnet porphyroblasts, in the stability field of glaucophane, (Quinquis, 1980) and the asymmetry quartz fabrics (Cannat, 1985) indicate a top-to-NW sense of shear attribute to thrusting towards the NW, antithetic to a southward dipping subduction. Top-to-NW and top-to-SE shear criteria observed in equal proportions in thin sections led Shelley and Bossière (1999) to conclude that the whole deformation is co-axial and corresponds to the exhumation of the metamorphic series in extension.

3. Structural setting

3.1. Foliation

The foliation that is generally parallel or close to parallel to lithological boundaries is defined i) in micaschists by the preferred orientation of micas and flattened quartz veins and ii) in metabasites by a metamorphic layering dominantly made of epidote and glaucophane or by chlorite preferred orientation in prasinites. At the island-scale, the foliation that is most often flat lying with an average dip of 15° (stereoplot in Fig. 3a) can locally reach dip values of 70°. From east to west, the foliation attitude defines two main domains to the east and west of Le Trou de l'Enfer (see foliation trajectories in Fig. 3a). To the east, foliation trends are dominantly N–S with eastward dips; whereas, to the west, it trends NW–SE with dips either to the NE or to the SW.

Following the first structural mapping by Lamouche (1929), several studies (Cogné, 1954, 1960; Quinquis, 1980; Bosse et al., 2002) have advocated the presence of an island-scale anticline in the western domain. This could have been suggested by the regular southwestward dip of foliation along the western coastline in the vicinity of Pen Men. However, instead of a large-scale anticline, the high cliffs between Port St Nicolas and the Trou de l'Enfer displays a series of inclined folds underlined by thick layers of metabasites with characteristic wavelengths of about 200–300 m (Fig. 3a), in agreement with previous structural interpretations by Jeannette (1965) and Boudier and Nicolas (1976).

3.2. Lineations

Most rocks display prominent mineral and/or stretching lineations. In metapelites, they are often represented by stretched and corrugated quartz veins. In metabasites that have preserved blueschist parageneses, mineral lineations defined by glaucophane crystals are parallel to the stretching direction given by pressure shadows around garnets porphyroblasts (Quinquis, 1980). In retrogressed metabasistes, the so-called prasinites, stretching lineations are defined by aligned and stretched patches of albite and epidote crystals.

Mineral and stretching lineations are most often shallow plunging with a mean N150°E trend and a dispersion in orientation within a sub-horizontal plane between N–S and N120°E (stereoplot and map in Fig. 3b).

3.3. Shear criteria

In the present study we systematically mapped the sense of shear using C′-type shear bands that are present in all rock types at all scales up to 100 m. However, it was verified that shear senses

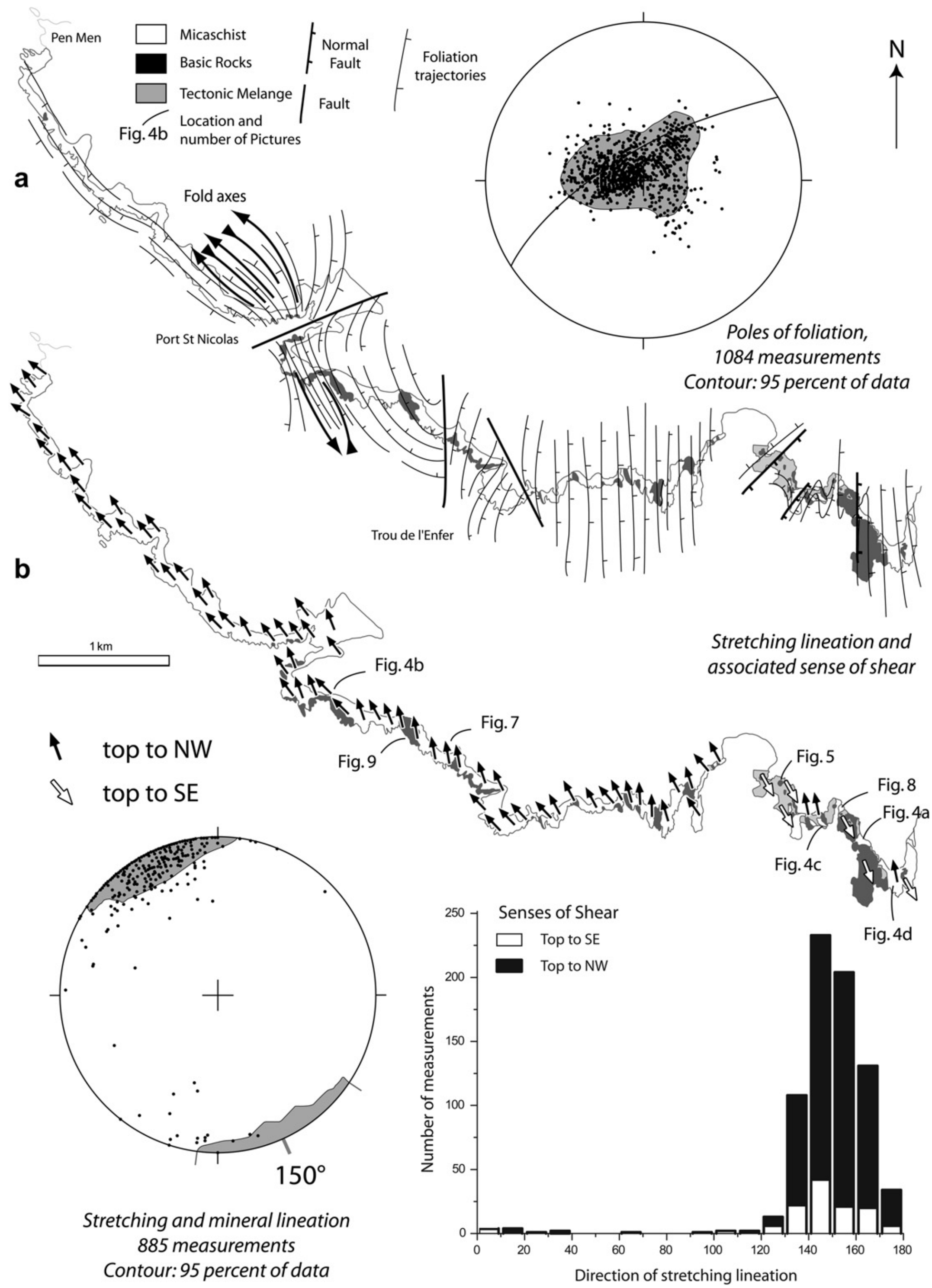

Fig. 3. Structural map of the island's southern coast. a. Foliation trajectories and stereoplot of 1084 foliation measurements b. Stretching lineations and stereoplot of 885 measurements. Associated senses of shear are indicated by black and white arrows for the top-to-northwest and -southeast, respectively. The histogram represents the statistical distribution of lineation directions and senses of shear. Stereoplots: lower hemisphere projection on a Schmidt net with contours for 95% of data.

deduced from shear bands they were consistent with those deduced from rotations of garnet porphyroblasts (Quinquis, 1980) and asymmetrical quartz fabrics (Cannat, 1985). Fig. 4 shows typical aspects of shear bands patterns in micaschists with a dominant sense of shear towards either the southeast (Fig. 4a) or the northwest (Fig. 4b) or with both senses towards the southeast and the northwest (Fig. 4c). In the micaschists, shear bands length and spacing vary according the type of lithology and in particular, as a function of the density of quartz veins (low in Fig. 4b and high in Fig. 4c). In metabasites, where foliation is dominantly marked by glaucophane, the growth of lawsonite crystals is synchronous with SE directed shearing (Fig. 5a). Lawsonites pseudomorphs (Ep–Chl–Ab) have well conserved lozenge shapes even after lawsonite breakdown. At outcrop scale (Fig. 5b, c), in the Amer area,

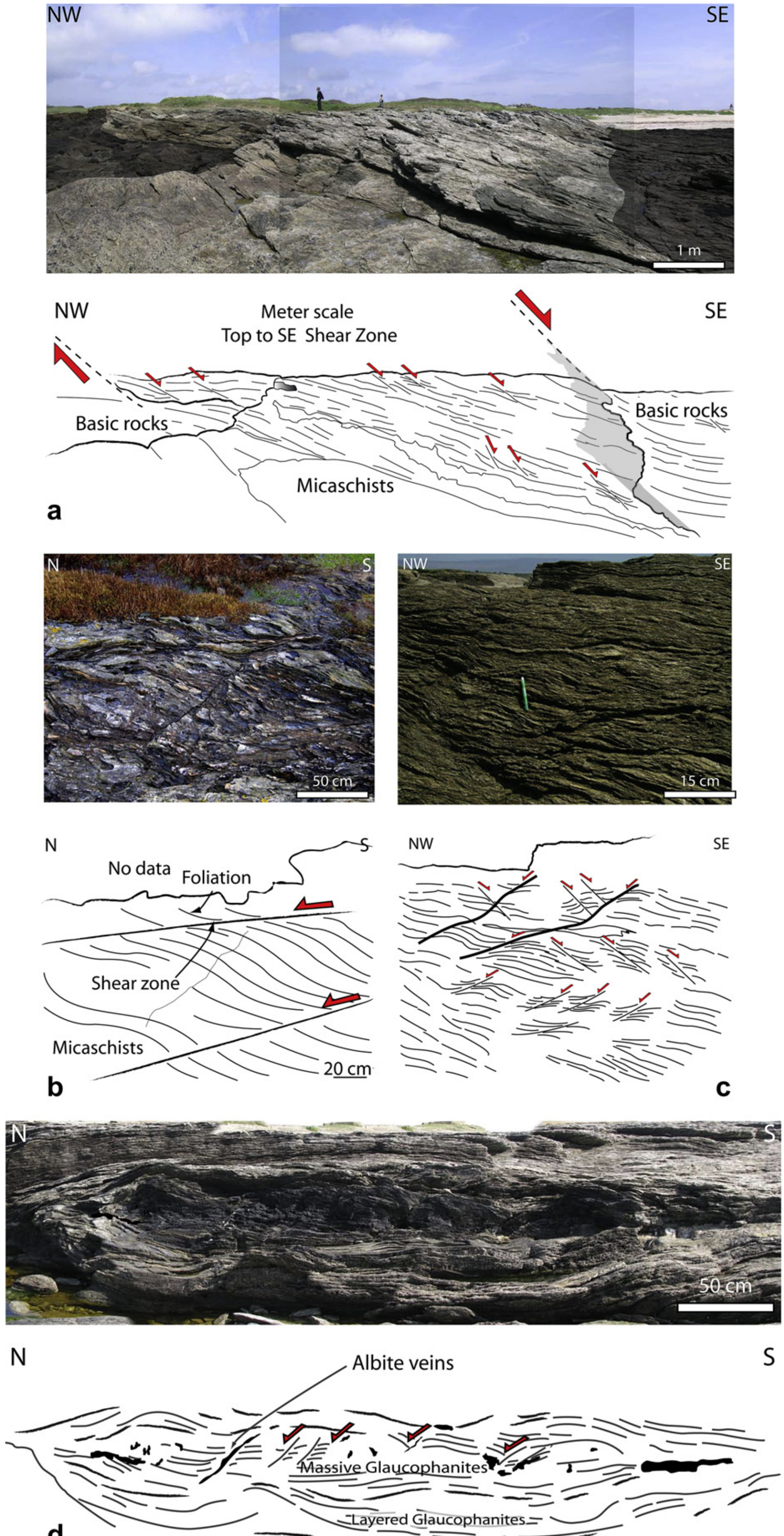

Fig. 4. Examples of shear bands in micaschists. Metre-scale top-to-SE shear bands at (a) the Pointe des Chats and (b) Kerbethanie. Top-to-SE and top-to-NW shear bands at Porh Morvil. d. Photograph and line drawing of a metre-scale glaucophanite boudin in micaschists at the Pointe des Chats.

metabasites show narrow spacing shear bands associated to cm-scale lawsonite pseudomorphs.

Mapping of the senses of shear (Fig. 3b) exemplifies that a top-to-northwest shear is represented in the whole island, whereas a top-to-southeast shear is only observed in the southeast part of the island. From a statistical point of view, a difference of around 10° exists between the mean direction of lineation associated to shearing top-to-northwest and -southeast, respectively (histogram in Fig. 3b). Shear sense indicators close to large reverse to isoclinal folds marked by metabasites inside micaschists were not taken into account to avoid apparent reversal in shear sense in inverted limbs.

4. Relationships between senses of shear and rock types

Detailed geological and structural mapping has been carried out in the southeast part of the island (Fig. 6), between the Pointe des Chats and the Pointe des Saisies, where the two opposite senses of shear are observed. Three kinds of rock types or rock assemblages are distinguished. (1) Metabasites are represented by two main metamorphic facies: glaucophanites (Lawsonite + Glaucophane + Epidote + Garnet) and greenschists, the so-called "prasinites" (Epidote + Albite + Chlorite). The local occurrence of omphacite in the parageneses indicates that the rock has attained the glaucophane-bearing eclogite facies. The presence of lawsonite pseudomorphs gave an estimate of PT conditions at about $P = 18–20$ kbar, $T = 450$ °C. (2) Micaschists, in addition to quartz and white micas, i.e. phengite and paragonite, contain garnet + Chloritoid + rutile ± glaucophane, which provided an estimate of PT conditions at about $P = 16–18$ kbar, $T = 450–500$ °C (Bosse et al., 2002). Retrogressed micaschists characterized by an assemblage containing Albite + Chlorite + Paragonite + Biotite + Ilmenite gave $P = 14–16$ kbar, $T = 400–450$ °C (Bosse et al., 2002). (3) Micaschists containing numerous metre-scale metabasite blocks, or boudins, were mapped as a separate type of rock unit, the so-called tectonic melange in Figs. 2, 3 and 6.

In this area, the foliation (Fig. 6a) is predominantly oriented NS and dips to the east by 0–20°. It is affected by a series of post metamorphic N–S or NE–SW trending normal faults that dip to the east or southeast, and which are also responsible for large open folds.

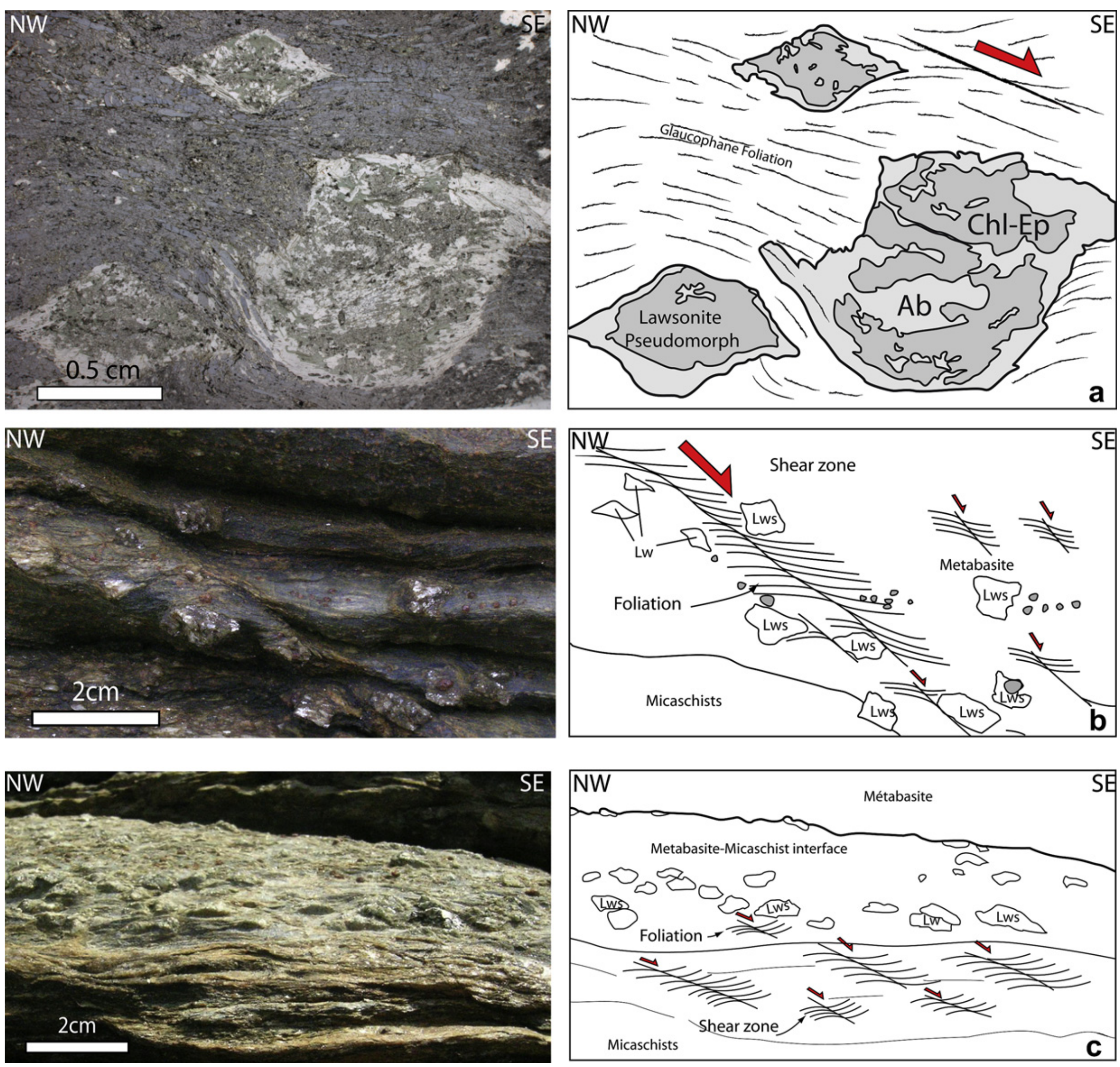

Fig. 5. Lawsonite pseudomorphs in thin section (a) and at outcrop scale (b) in glaucophane-bearing metabasites (a and b) and micaschists (c), between Locmaria and Porh Morvil. Shear bands are top-to-southeast.

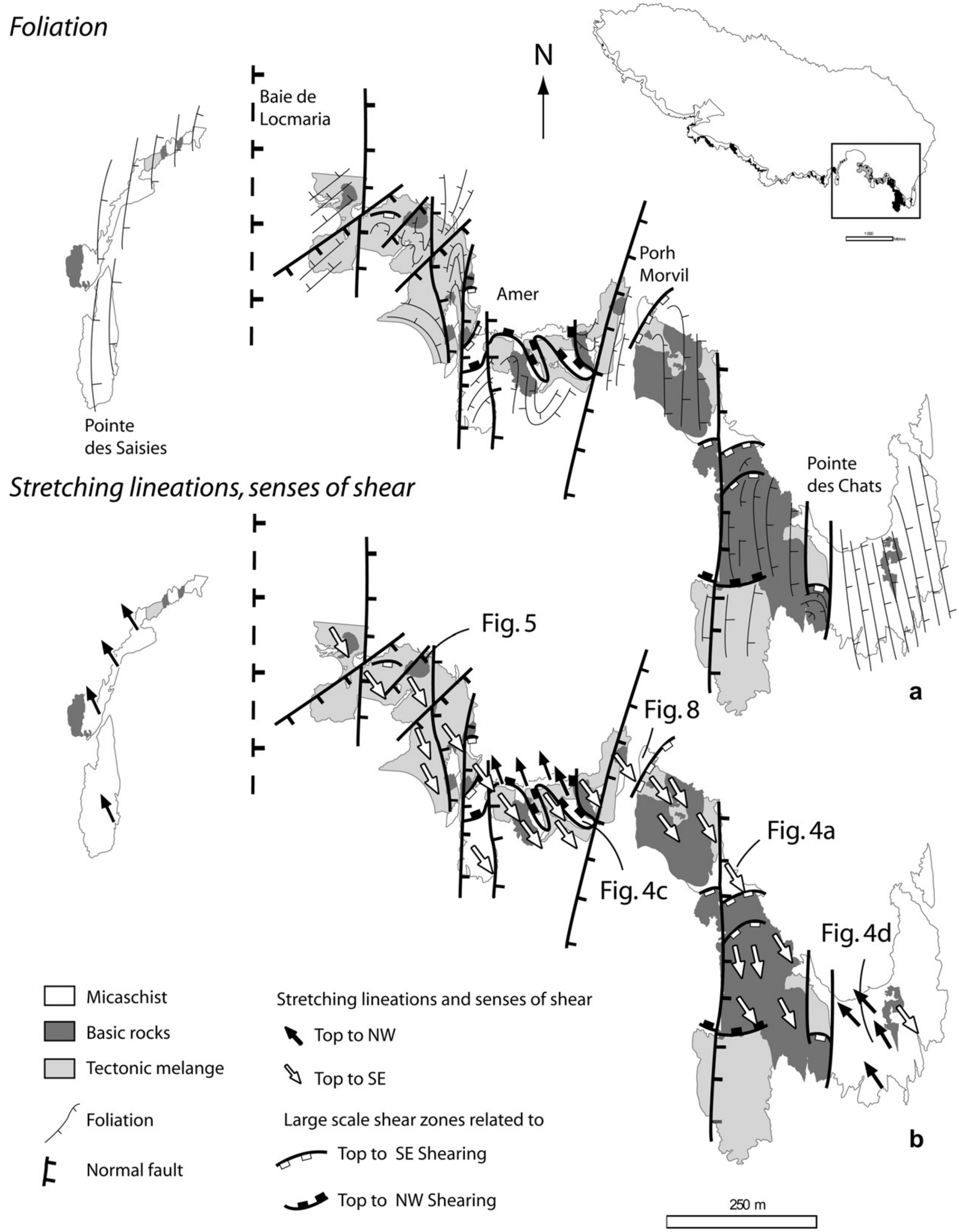

Fig. 6. Detailed structural map of the eastern part of the island between the Pointe des Saisies and the Pointe des Chats. a. Foliation trajectories. b. Stretching lineations. Associated senses of shear are indicated by black and white arrows for the top-to-northwest and -southeast, respectively. The map shows domains of basic rocks or mixed basic rocks and micaschists – i.e. mélange – with only a southeast directed sense of shear.

Lineations have a mean N140°E trend (Fig. 6b). Associated senses of shear show a systematic relation with rock types. A top-to-N140°E sense of shear is observed in all types of mapped units, whereas a top-to-N350°E sense of shear is never observed in metabasites containing lawsonite pseudomorphs (Fig. 6b). Fig. 5 shows an example of a lawsonite pseudomorph closely associated with top-to-N140°E shear bands. Detailed mapping shows the occurrence of shear bands with two senses of shear at 10–100 m scales. Strong shearing at micaschist–metabasite interfaces is responsible for the mixed lithological pattern, i.e. what is called a tectonic melange in this work (Figs. 4a and 6). It results from the dislocation by boudinage and/or shear zones of large metabasite units and their incorporation inside a micaschist matrix.

The top-to-N350°E sense of shear that affects all types of rocks is observed at the whole island-scale (Fig. 3b). It is synchronous with retrograde metamorphism, as demonstrated by its common association with Ab + Chl + Qz veins in basic rocks and micaschists. Fig. 4d shows Ab + Chl + Qz veins developed within a glaucophanite boudin within a micaschist matrix at the Pointe des Chats, in an area characterized by top-to-N350°E senses of shear. Shear bands are present inside the boudin itself. The lack of clear evidence for N140°E shear criteria at the island-scale suggest that they have likely been erased by a shearing top-to-N350°E. This is in agreement with the lack of lawsonite pseudomorphs in most of the island (Fig. 2). In the Ile de Groix, the existence of lawsonite is only demonstrated by pseudomorphs whose mineral composition is in fact chlorite + epidote + paragonite (Ballèvre et al., 2003; Felix and Fransolet, 1972). However, the shape of lawsonite crystals is locally preserved (Fig. 5a; Felix, 1972). The pseudomorph composition is such that, as soon as they are deformed, they become extremely difficult to identify from their matrix. Consequently, the absence of lawsonite pseudomorphs can be interpreted as a consequence of deformation rather than proof of a non-development of lawsonite. Ballèvre et al. (2003) argued that "lawsonite growth took place at increasing *P* and *T*" and that the lawsonite breakdown recorded "the final part of the history after cessation of the ductile deformation and recording of the earliest stages of exhumation". In agreement with this statement, our structural observations and detailed mapping (Figs. 3b and 6b) show that well-shaped pseudomorphs are closely associated to N140°E shearing (Fig. 5) but, conversely, deformation continued after lawsonite PT breakdown conditions, with a quasi-opposite sense of shear top-to-N350°E. Consequently, the top-to-N140°E sense of shear is associated with the high pressure metamorphism and therefore, precedes the top-to-N350°E sense of shear.

5. Sheath folds

Sheath folds are rather common in all rock types and have been observed at various places in the island (Quinquis and Cobbold, 1978; Quinquis, 1980). Their size directly depends on the thickness of the folded layers. In micaschists, in which they most often affect thin graphitic quartzite layers, they are observed at a 10 cm-scale and their sheath shapes range from symmetrical (Fig. 7a) to asymmetrical (Fig. 7c). In metabasites that represent thick layers embedded in micaschists, the size of sheath folds can reach several tens of metres, parallel to the stretching lineation. The well exposed metabasites of the Vallon du Lavoir display a complex association of symmetrical and asymmetrical sheath folds (Fig. 8).

Sheath folds that develop in a broad spectrum of geological environments (see review in Alsop et al., 2007) generally indicate intense stretching (Cobbold and Quinquis, 1980; Brun and Merle, 1988). As stretching can reach high values in shear zones, they are commonly observed in highly sheared rocks, but shearing is not a necessary condition for their development. It has been suggested long ago that the presence of sheath folds in the Ile de Groix blueschists likely results from intense shearing within a subduction zone (Quinquis et al., 1978). Accordingly, sheath folds have since then been described in many HP metamorphic rocks related to either subduction or exhumation (e.g. Pennine Alps: Lacassin and Mattauer, 1985; Cuba: Stanek et al., 2006; Oman: Searle and Alsop, 2007). However, as argued in the present paper, two superposed events of shearing affect the Ile de Groix blueschists: the top-to-N140°E, related to the prograde HP metamorphism, and the top-to-N350°E, related to the retrograde metamorphism. The present study reveals that sets of sheath folds were generated during both of the shearing events.

To understand the processes of fold axes reorientation that are at the origin of sheath folds, it is especially interesting to examine the geometrical relationships between fold axes and lineations. Fig. 8 presents a metre-scale mapping of fold axes and lineations in metabasites close to the contact with micaschists at Porh Morvil in the southeast of the island (see location in Fig. 6a). Fold axes trend close to N–S (Fig. 8), parallel to the metabasite-micaschist contact, whereas stretching lineations present a strong dispersion in orientation from nearly N–S to E–W (Fig. 8b). E–W trending lineations only occur in relation with folds or boudins close to lithological interfaces. They constitute local and small-scale anomalies with reference to the lineation trend at the kilometre-scale (Fig. 6b). Folds and boudins result from mechanical instabilities due to strong competence contrasts in the contact strain zones between metabasites and micaschists. In fold limbs dipping at a low angle, lineations trend close to N90°E. The geometrical relationship between fold axes and lineations (Fig. 8b, c) indicates that folds likely formed with axes trending roughly N50°E, perpendicular to the N140°E direction of shearing, and rotated towards a N–S direction during progressive shearing. The obliquity that stretching lineations in fold limbs make with the regional trend of lineations indicates that they have undergone the same amount of rotation as the fold axes. Similar rotation of lineations associated with reorientation of fold axes is observed in other examples of sheath folding (see Fig. 10 in Alsop and Carreras, 2007). In the southeast of the island, as exemplified at Porh Morvil, reorientation of fold axes and lineation occurred during the earliest event of the shearing top-to-N140°E (Fig. 6b).

In the western part of the island, metabasite bodies are ductilely deformed during the second top-to-N350°E shearing event and form 100 m-wide reversed folds. The Vallon du Lavoir anticline presents a series of 10 m-scale symmetrical and asymmetrical sheath folds in a core of layered glaucophanite embedded in greenschists (Fig. 9a), whose complex 3D structure has been delineated by detailed mapping (Fig. 9b). A large sheath closure is observed in 3D at the SE extremity of the structure (Fig. 9d). In the core of the structure, sheath folds deform a pre-existing foliation bearing a glaucophane lineation that consequently appears to be strongly dispersed on the stereoplots (Fig. 9c, e). In the sheath closure (labelled l and m in Fig. 9c), the lineation dispersion occurs along a plane oriented N160°E, which is also very close to the mean stretching lineation in the surrounding greenschists (star symbol on the stereoplot). In the fold hinges that define the lateral arms of the large structure (labelled n, o, p and q in Fig. 9) the dispersion is such that no particular locus can be defined (Fig. 9e). In the field, it was observed that, around each individual fold hinge, lineations are dispersed in a plane strongly oblique to the fold axis. On the stereoplot (Fig. 9e), fold axes are close to the mean stretching lineation in the surrounding greenschists, indicating a strong reorientation. In Fig. 9f, we have rotated the fold axes in a direction β_0, perpendicular to the mean stretching direction, which likely represents their initial direction. With the same amount of rotation, most of the lineations become close to the plane of dispersion that is observed in the sheath closure (dotted line in Fig. 9c, f). This indicates that the fold hinges of the glaucophanites are rotated in parallel with the stretching direction without a significant superimposed strain. It also implies that glaucophanites are significantly more competent than the surrounding greenschist matrix.

6. Relation between deformation and metamorphism

As documented in Section 4, well-shaped lawsonite pseudomorphs are closely associated to the N140°E shearing (Fig. 5), but

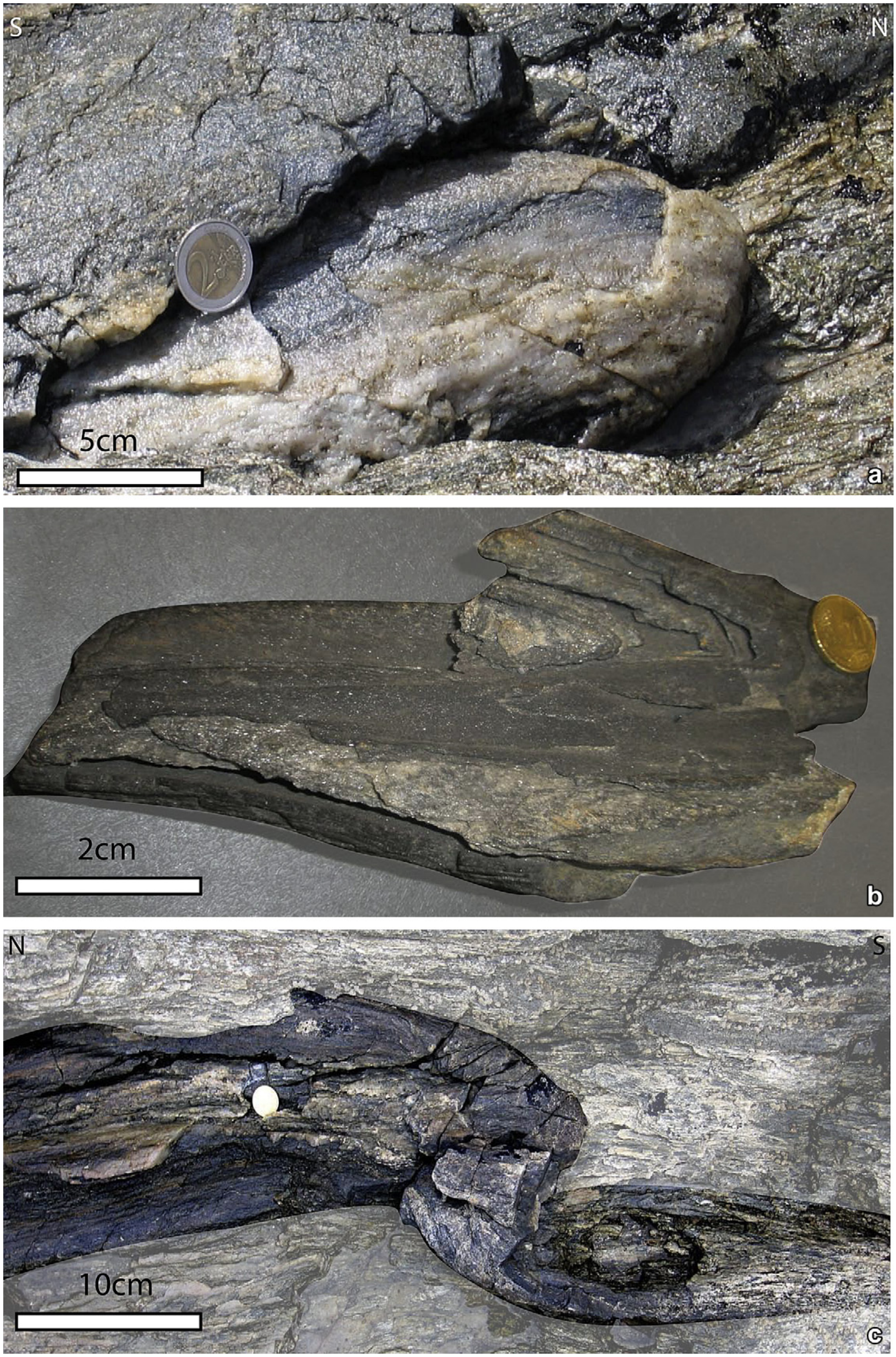

Fig. 7. Sheath folds affecting graphitic quartzite layers in the micaschists of the Vallon de Kerigan (a, c) and sample from Pen Men (b). The shape of sheaths is either symmetrical (a, b) or asymmetrical (c).

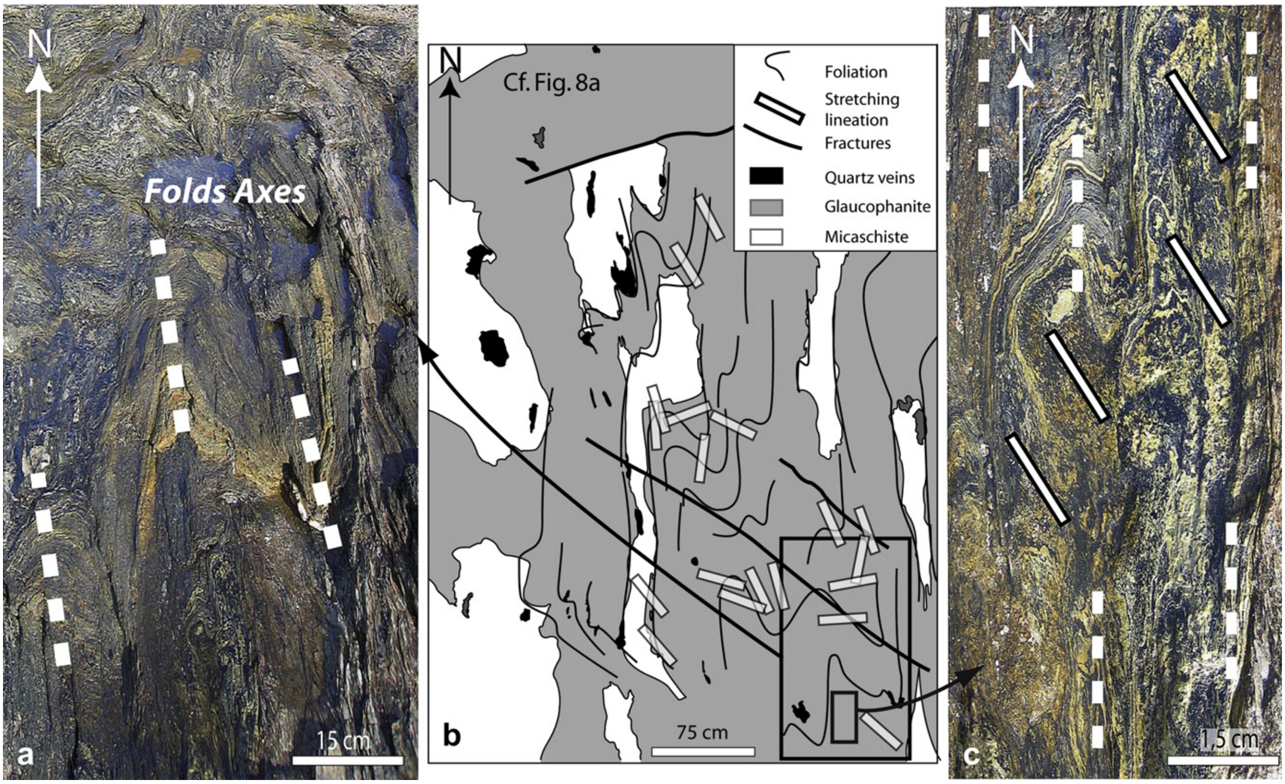

Fig. 8. Reoriented folds axes in glaucophane-bearing metabasites at Porh Morvil. a. Photograph of an outcrop detail. b. Line drawing of the mapped outcrop. c. Photograph of an enlargement of a. White bars in b and c show the orientation of glaucophane lineation. Black thick lines in c underline the fold axes. The location of photographs a and c is shown in b.

deformation continued after lawsonite PT breakdown conditions, with a quasi-opposite top-to-N350°E sense of shear.

In addition to this observation, rock samples that lead to the highest pressure estimates (Bosse et al., 2002) are located in areas characterized by top-to-N140°E senses of shear (samples number 2, 3 and 5* in Fig. 10a). They belong to the prograde part of the PT path and they are located in the stability field of the lawsonite (Fig. 10b). This implies that the top-to-N140°E sense of shear is characteristic of a pressure increase. Conversely, samples 13 and 14 from Bosse et al. (2002), which are strongly retrogressed, are located in areas with a top-to-N350° sense of shear (Fig. 10a). They belong to the retrograde part of the PT path and they are located outside the stability field of the lawsonite (Fig. 10b).

7. Discussion

7.1. Record of subduction and exhumation in the Ile de Groix blueschists

In the Ile de Groix, shear senses deduced from different shear criteria have been interpreted in various ways: both in kinematics terms at the island-scale and in tectonic terms in the frame of the Hercynian belt. Analysis of snowball garnets rotation in thin sections was used by Quinquis (1980) to argue for a top-to-northwest sense of shear. Soon after, the same conclusion was reached by Cannat (1985) from quartz *c*-axes fabrics. Nearly 30 years ago, Quinquis (1980) observed that shear bands had opposite senses of shear but concluded that their significance was too uncertain. More recently, Shelley and Bossière (1999) argued that opposite senses of shear, observed in thin sections, are present in equal proportions and thus, concluded a co-axial deformation.

The rotation of snowball garnets towards the northwest was related by Quinquis and Choukroune (1981) to an "obductive offscrapping" (Moore and Allwardt, 1980) – i.e. a northwest verging thrust associated with a northwest dipping subduction. Quartz *c*-axes fabrics were also interpreted in the frame of a northwestward thrusting by Cannat (1985). However, at the time of these early works, the specific problems related to the exhumation of HP rocks were not clearly identified. All intense deformations and associated ductile fabrics observed in mountain belts were supposed to have resulted from thrusting and therefore, the exhumation of metamorphic rocks was implicitly attributed to erosion. Shelley and Bossière (1999) argued for a pure shear deformation which they attributed entirely to an exhumation in extension, synchronous to a retrogressive sequence from eclogite to greenschists facies. According to this interpretation, the Ile de Groix blueschists were exhumed by crustal thinning.

The detailed mapping of shear senses presented here shows that opposite shear senses are not present in equal amounts, whatever the scale considered, and that a southeast directed shear is only observed in basic rocks in the eastern part of the island, synchronous with a prograde HP metamorphism, and that it precedes the northwest directed shear, synchronous with retrogression (Fig. 12). This is in full agreement with the occurrence of lawsonite pseudomorphs only in rocks showing evidence of southward shearing.

In the frame of the Hercynian belt of South Brittany (Fig. 1), the tectonic interpretation of the kinematic analysis presented here is straightforward. Available field data, in particular from Vendée (see location in Fig. 1), shows that thrust units always root to the north or northeast (Brun and Burg, 1982). In the thrust pile, the upper units that have undergone HP metamorphism – i.e. porphyroïdes (Le Hebel et al., 2002) and the Bois de Céné blueschists (Triboulet, 1991) – are thrust on top of sediments affected only by low grade metamorphism (Iglesias and Brun, 1976). Further north, in the Champtoceaux area (see location in Fig. 1), eclogitic units are thrust on top of low to medium grade metamorphic rocks and also root to

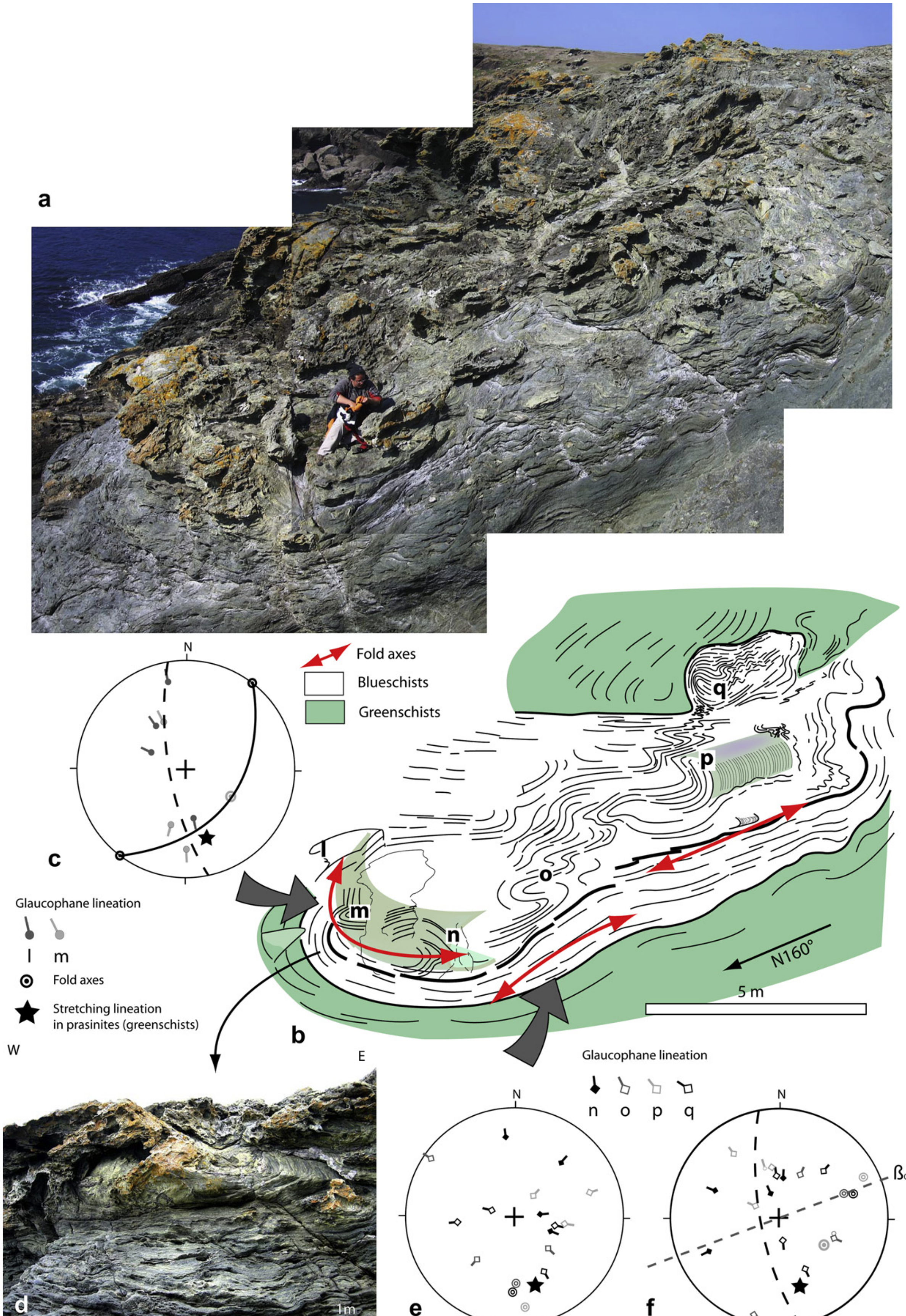

Fig. 9. Pluri-metric sheath fold at the Vallon du Lavoir. a. Photograph showing the bulk structure. b. Line drawing of a. c. Stereoplot showing the relative position of fold axes, glaucophane lineations and the direction of shear (star). d. Photograph of the meter-scale eye-type closure affecting an interface between banded glaucophanites and "prasinites" (Greenschists). e. Stereoplot of fold axes and glaucophane lineations. f. Same data as in e restored in their position prior to fold axes reorientation in the shear direction. Stereoplots: lower hemisphere projection on a Schmidt net.

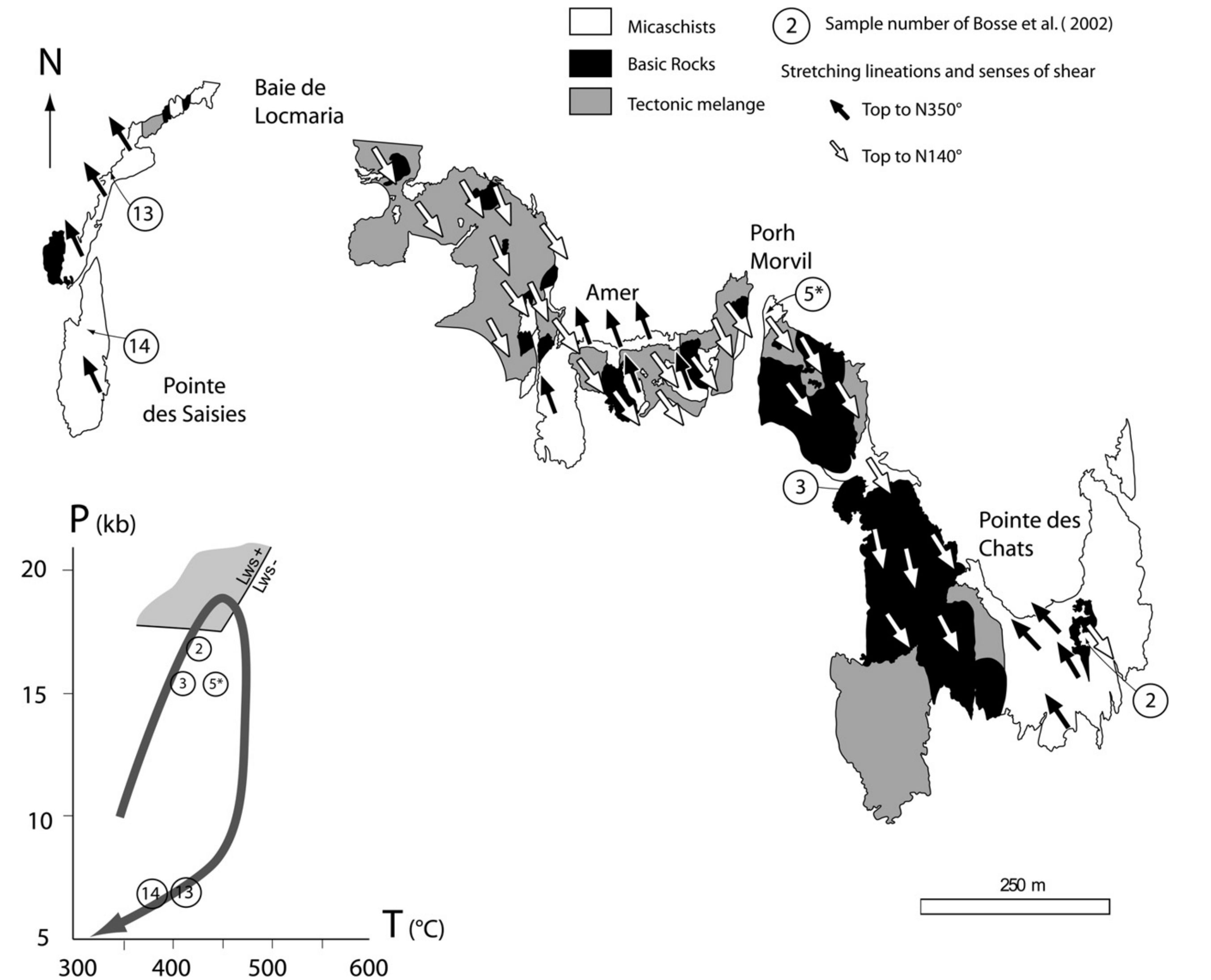

Fig. 10. A map-scale of the relationship between the senses of shear (see Fig. 6) and metamorphism in the southeastern part of the island. Numbers in circles refer to samples analysed by Bosse et al. (2002). The insert shows the position of these samples on the PT path calculated by Ballèvre et al. (2003).

the north and northeast (Ballevre et al., 1987), as clearly imaged by deep seismics (Bitri et al., 2003). At the lithosphere scale, *P*-wave tomography (Judenherc et al., 2003; Gumiaux et al., 2004) has provided evidence for the existence of a northeast-dipping slab remnant below central Brittany. The evidence for a first event of southeastward shearing contemporaneous with HP metamorphism in the Ile de Groix at 358–366 Ma (Bosse et al., 2002) can be interpreted as a result of thrusting within a northward dipping subduction zone (Figs. 11 and 12a). As already stated, the northwestward shearing was previously interpreted as a northward directed thrusting, synchronous with HP metamorphism, but antithetic to a northward dipping subduction (Quinquis and Choukroune, 1981; Cannat, 1985; Fig. 11b). Our study shows that this northwestward shearing is synchronous with retrogressive metamorphic conditions dated at 345–353 Ma (Bosse et al., 2005). As there is no evidence of any major south-dipping thrust to the north of the Ile de Groix and because all units dip northward at a regional-scale, there is no other alternative than to relate this second shearing event to a normal sense detachment dipping northward (Figs. 11c and 12). However, due to the late hercynian extension (Gapais et al., 1993; Cagnard et al., 2004), this early detachment which has accommodated the exhumation of HP units does not outcrop onland (see cross section of Fig. 1b). At the present day level of erosion, the migmatitic core complex of the Morbihan Gulf, controlled by a southwestward dipping detachment, emplaced between the South Armorican Shear Zone and the Ile de Groix (Fig. 1a, b). To some extent, this situation can be compared to the Cyclades, in the Aegean, where the exhumation of HP rocks that are accommodated by an extensional detachment is rapidly followed by the development of a high temperature core complex. The existence of an extensional detachment located on top of the HP units that dips in the same direction as the subduction and brings HP rocks back to the surface in a flat-lying position over a broad area would suggest that, like in the Aegean, exhumation was driven by slab rollback (Brun and Faccenna, 2008).

7.2. Significance of opposite senses of shear in high pressure rocks

The Ile de Groix is not the only example of opposite senses of shear in HP rocks. It is especially relevant to recall the example of HP rocks that belong to the Briançonnais units in the western Alps (Ganne et al., 2006). In this recent orogenic domain, where thrust

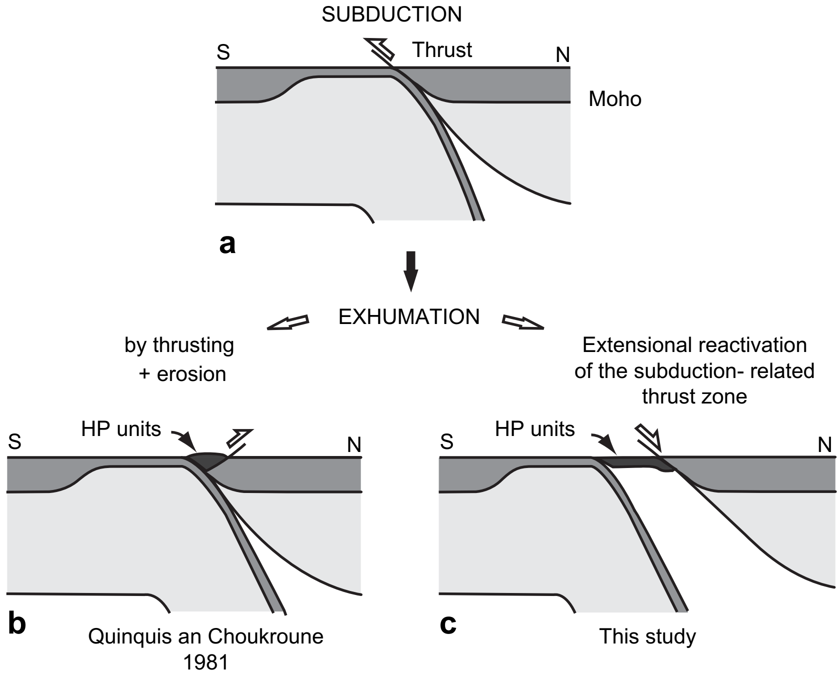

Fig. 11. Sketch summarizing the subduction-exhumation cycle of the Ile de Groix blueschists. a. Northward dipping subduction. Models of exhumation where the northwest sense of shear is interpreted as related to northward thrusting (modified after Quinquis and Choukroune, 1981) (b) or to northward dipping extensional detachment (this work) (c).

units trend north-south, HP rocks display two shear senses: dominantly top to the west in the west and top to the east in the east. Both westward and eastward senses of shear are observed in the same proportion in the transition zone. As Ganne et al. (2006) interpret the two senses of shear as synchronous, they attribute the westward shearing to westward thrusting and eastward shearing to a coeval eastward dipping detachment. Consequently, they propose that the two senses of shear represent the lower and upper parts of a corner flow within a so-called subduction channel. This dynamic interpretation would be acceptable only if the hypothesis concerning the synchronism of the two senses of shear is demonstrated.

In the Cycladic blueschists in Greece, the problem of opposite senses of shear has also been considered. On the islands of Syros and Sifnos, both Rosenbaum et al. (2002) and Bond et al. (2007) argue that opposite senses of shear are contemporaneous and result from pure shear during blueschist exhumation. On the contrary, in this study the analysis of shear criteria at the island-scale indicates that shearing in *H–P* conditions is dominantly top-to-northeast (Trotet et al., 2001). The apparent discrepancy between these two conclusions demonstrates that kinematic analysis is strongly scale-dependant. In fact, strain can be co-axial at a small-scale within a system that is sheared in a uniform sense at a larger scale. In other words, these conclusions are not mutually exclusive.

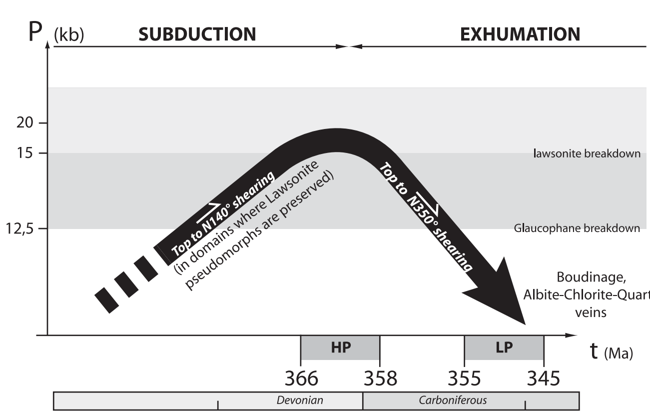

Fig. 12. Summary of the pressure–time evolution of the Ile de Groix blueschists at $T = 450\,^{\circ}C$.

Regardless of the opinion that one might have about the particular examples above, they illustrate the problem of interpretation opposite shear senses in HP rocks, especially if conclusions are to be drawn at the crust and lithosphere scales.

8. Conclusions

From a regional geological point of view, it is shown that the Ile de Groix blueschists have preserved the kinematic record of both subduction and exhumation as a function of lithology. Shear criteria synchronous with prograde HP and retrograde greenschist metamorphism are directed to the southeast and northwest, respectively. Both shearing deformations lead to intense finite strains as demonstrated by the occurrence of sheath folds and the general orientation of tight fold axes parallel to the stretching lineation. Well conserved lozange shaped lawsonite pseudomorphs occur only in rocks showing only a top-to-southeast sense of shear. In rocks affected by a top-to-northwest shear, the lawsonite pseudomorph shape is destroyed by intense stretching. The pseudomorphs cannot be identified anymore as their constituting minerals are similar to those of the matrix. In the frame of the hercynian belt of southern Brittany, the southeast directed shear is attributed to thrusting related to a northward dipping subduction and the northwest directed shear to an exhumation controlled by a northward dipping extensional detachment.

From a methodological point of view, this study illustrates that deciphering between burial-subduction and the exhumation of HP metamorphic rocks requires not only the analysis of timing and chronology of shear criteria development but also the consideration of their spatial distribution, their relation to lithology and metamorphism and their setting within the regional-scale structures. In addition, the presence of lawsonite pseudomorphs is especially interesting in this perspective because, as illustrated in the Ile de Groix, rocks where they are conserved have not been deformed during exhumation.

Acknowledgements

We would like to thank our Géosciences Rennes collegues and particularly M. Ballèvre for discussions at various stages of this work and Pavel Pitra for providing the thin section photograph of lawsonite pseudomorphs. Great thanks are also due to the master students Marianne Boix, Nathan Cogné, Aurélia Kerdraon and Irene Mannino for their participation in the field mapping. Thanks to Ian Alsop and Florian Fusseis for very constructive reviews.

References

Alsop, G.I., Carreras, J., 2007. The structural evolution of sheath folds: a case study from Cap de Creus. Journal of Structural Geology 29, 1915–1930.

Alsop, G.I., Holdworth, R.E., McCaffrey, K.J.W., 2007. Scale invariant sheath folds in salt, sediments and shear zones. Journal of Structural Geology 29, 1585–1604.

Ballevre, M., Kienast, J.R., Paquette, J.-L., 1987. The eclogitic metamorphism of the Hercynian Champtoceaux nappe (Armorican Massif). Comptes Rendus de l'Académie des Sciences Paris 305 (2), 127–131.

Ballèvre, M., Pitra, P., Bohn, M., 2003. Lawsonite growth in the epidote blueshists from the ile de groix (armorican massif, France): a potential geobarometer. Journal of Metamorphic Geology 21, 723–735.

Bernard-Griffiths, J., Carpenter, M.S.N., Peucat, J.J., Jahn, B.M., 1986. Geochemical and isotopic characteristics of blueschist facies rocks from the ile de groix, armorican massif (northwest France). Lithos 19, 235–253.

Bitri, A., Ballevre, M., Brun, J.P., Chantraine, J., Gapais, D., Guennoc, P., Gumiaux, C., Truffert, C., 2003. Imagerie sismique de la zone de collision Hercynienne dans le Sud-Est du Massif Armoricain (Projet Armor 2/Programme Géofrance 3D). Comptes Rendus Géoscience Paris 335, 969–979.

Bond, C., Bulter, R.W.H., Dixon, J.E., 2007. Co-axial Horizontal Stretching Within Extending Orogens: The Exhumation of HP Rocks on Syros (Cyclades) Revisited. In: Geological Society of London, Special Publication, vol. 272, pp. 203–222.

Bosse, V., Ballèvre, M., Vidal, O., 2002. Ductile thrusting recorded by the garnet isograd from blueschists-facies metapelites of the Île de groix, armorican massif, France. Journal of Petrology 43, 485–510.

Bosse, V., Féraud, G., Ballèvre, M., Peucat, J., Corsini, M., 2005. Rb-sr and 40ar/39ar ages in blueschists from the Île de groix (armorican massif, France): implication for closure mechanisms in isotopic systems. Chemical Geology 220, 21–45.

Boudier, F., Nicolas, A., 1976. Interprétations nouvelles des relations entre tetonique et métamorphisme dans l'île de groix. bretagne. Bulletin de la Société géologique de France 7 (XVIII), 135–144.

Brun, J.P., Burg, J.P., 1982. Combined thrusting and wrenching in the Ibero-Armorican arc: a corner effect during continental collision. Earth and Planetary Science Letters 61 (2), 319–332.

Brun, J.P., Faccenna, C., 2008. Exhumation of high-pressure rocks driven by slab rollback. Earth and Planetary Science Letters 272 (1–2), 1–7.

Brun, J.P., Merle, O., 1988. Experiments on folding in spreading gliding nappes. Tectonophysics 145 (1/2), 129–139.

Cagnard, F., Gapais, D., Brun, J.P., Gumiaux, C., Van Den Driessche, J., 2004. Late pervasive crustal-scale extension in the south Armorican Hercynian belt (Vendée, France). Journal of Structural Geology 26, 435–449.

Cannat, M., 1985. Quartz microstructures and fabrics in the island of Groix (Brittany, France). Journal of Structural Geology 7, 555–562.

Carpenter, M.S.N., 1976. Petrogenetic Study Of The Glaucophane Schists and Associated Rocks from the Ile De Groix. University of Oxford, Brittany, France.

Chopin, C., 2003. Ultrahigh-pressure metamorphism: tracing continental crust into the mantle. Earth and Planetary Science Letters 212 (1–2), 1–14.

Cobbold, P.R., Quinquis, H., 1980. Development of sheath folds in shear regime in "shear zones in rocks". Journal of Structural Geology 2.

Cogné, J., 1954. L'île deGroix (Morbihan) (feuille ile de Groix au 50.000e). Bulletin du Service de la Carte Géologique de France 239, 41–50.

Cogné, J., 1960. Schistes cristallins et granites en bretagne méridionale: le domaine de l'anticlinal de Cornouaille, Rennes.

Felix, C., 1972. Etude structuro-minéralogique des pseudomorphes de présumée Lawsonite des glaucophanoschistes de l'île de Groix (Bretagne-France): considération sur la possibilité d'une paragénèse à Glaucophane -Lawsonite. Annales de la Société Geologique de Belgique 95, 345–391.

Felix, C., Fransolet, A.M., 1972. Pseudomorphes à épidote s.l., paragonite, muscovite s.l., chlorite, albite.,de porphyroblastes de lawsonite (?) dans les glaucophanites de l'île de groix (bretagne – France). Annales de la Société Geologique de Belgique 95, 323–334.

Ganne, J., Marquer, D., Rosenbaum, G., Bertrand, J.M., Fudral, S., 2006. Partitioning of deformation within a subduction channel during exhumation of high-pressure rocks: a case study from the western alps. Journal of Structural Geology, 1193–1207.

Gapais, D., Lagarde, J.L., Le Corre, C., Audren, C., Jegouzo, P., Casas Sainz, A., Van den driessche, J., 1993. The Quiberon shear zone: evidence for Carboniferous extension in the Variscan belt of South Brittany (France). Comptes Rendus de l'Académie des Sciences 316 (8), 1123–1129.

Gumiaux, C., Judenherc, S., Brun, J.P., Gapais, D., Granet, M., Poupinet, G., 2004. Restoration of lithosphere-scale wrenching from integrated structural and tomographic data (Hercynian belt of Western France). Geology 32, 333–336.

Iglesias, M., Brun, J.P., 1976. Signification des variations et anomalies de la déformation dans un segment de la chaîne hercynienne (les séries cristallographylliennes de la Vendée littorale). Bulletin de la Société Géologique de France 7, 1443–1452.

Jeannette, D., 1965. Etude tectonique de l'île de Groix (Morbihan), Rennes.

Jolivet, L., Faccenna, C., Goffé, B., Burov, E., Agard, P., 2003. Subduction tectonics and exhumation of high pressure metamorphic rocks in the Mediterranean orogens. American Journal of Science 303, 353–409.

Judenherc, S., Granet, M., Brun, J.P., Poupinet, G., 2003. The Hercynian collision in the Armorican Massif: evidence of different lithospheric domains inferred from tomography and anisotropy. Bulletin de la Société Géologique de France 174, 45–57.

Lacassin, R., Mattauer, M., 1985. Kilometre-scale sheath fold at Mattmark and implications for transport direction in the Alps. Nature 316, 739–742.

Lamouche, 1929. Etude tectonique de l'île de Groix. Bulletin de la Société de Sciences Naturelles de l'Ouest 4 (IX), 72–87.

Le Hebel, F., Vidal, O., Kienast, J.R., Gapais, D., 2002. Les "Porphyroïdes" de Bretagne méridionale: une unité de HP-BT dans ka chaîne Hercynienne. Comptes Rendus Géoscience Paris 334, 205–211.

Moore, J.C., Allwardt, A., 1980. Progressive deformation of a tertiary trench slope, Kodiak Islands, Alaska. Journal of Geophysical Research 82 (B9), 4741–4756.

Platt, J.P., 1993. Exhumation of high-pressure rocks: a review of concepts and processes. Terra Nova 5 (2), 119–133.

Quinquis, H., Audren, C., Brun, J.P., Cobbold, P.R., 1978. Intense progessive shear in the île de Groix blueschists and compatibility with subduction or obduction. Nature 273, 43–45.

Quinquis, H., Choukroune, P., 1981. Les schistes bleus de l'île de Groix dans la chaîne Hercynienne: implications cinématiques. Bulletin de la Société Géologique de France 7 (XXIII, no. 4), 409–418.

Quinquis, H., Cobbold, P.R., 1978. Etude de plis noncylindriques résultant d'un cisaillement simple. In: R.A.S.T, p. 327. Lyon.

Quinquis, H., 1980. Schistes bleus et déformation progressive: l'exemple de l'Île de Groix (Massif Armoricain). Université de Rennes 1.

Ring, U., Brandon, M.T., Willet, S.D., Lister, G., 1999. Exhumation Processes. In: Geological Society, London, Special Publication, vol. 154, pp. 1–27.

Rosenbaum, G., Avigad, D., Sánchez-Gómez, M., 2002. Coaxial flattening at deep levels of orogenic belts: evidence from blueschists and eclogites on Syros and Sifnos (Cyclades, Greece). Journal of Structural Geology 24 (9), 1457–1462.

Searle, M.P., Alsop, G.I., 2007. Eye-to-eye with a mega–sheath fold: a case study from Wadi Mayh, northern Oman Mountains. Geology 35 (11), 1043–1046.

Shelley, D., Bossière, G., 1999. Ile de groix: retrogression and structural developments in an extensional régime. Journal of Structural Geology 21, 1441–1455.

Stanek, K.P., Maresch, W.V., Grafe, F., Grevel, C.H., Baumann, A., 2006. Structure, tectonics and metamorphic development of the Sancti Spiritus Dome (Eastern Escambray massif, Central Cuba). Geologica Acta 4 (1–2), 151–170.

Triboulet, C., 1974. Les glaucophanites et roches associéesde l'île de Groix (Morbihan, France): étude minéralogique et pétrologique. Contributions to Mineralogy and Petrology 45, 65–90.

Triboulet, C., 1991. Etude geothermo-barométrique comparée des schistes bleus paléozoïques de l'ouest de la France (Ile de Groix, Bretagne méridionale et bois de Céné, Vendée). Comptes Rendus de l'Académie des Sciences 312 (10), 1163–1168.

Trotet, F., Jolivet, L., Vidal, O., 2001. Tectono-metamorphic evolution of Syros and Sifnos islands (Cyclades, Greece). Tectonophysics 338 (2), 179–206.