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Ile de Groix: retrogression and structural developments in an extensional régime

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Abstract

The Paleozoic metamorphic rocks of Ile de Groix, France, record a retrogressive metamorphism from eclogite facies through blueschist to greenschist facies, produced during progressive uplift and exhumation, and accompanied throughout by high extensional strain. Extension was accompanied by formation of a generally flat-lying foliation, the result of either pure shear or conjugate simple shearing, with top to the northwest and southeast shear senses equally important. The foliation is either wrapped around pods of relatively competent and/or higher grade rock, elongate in the direction of stretching, or folded on axes parallel to the stretching direction; these structures represent the effects of the intermediate strain axis which transiently and locally fluctuated between being one of extension or shortening. Large-scale open folds of foliation may represent a wrapping of foliation about two giant pods which define the entire island. We suggest the so-called lawsonite pseudomorphs might possibly be altered calcium-bearing plagioclase which indicates a simpler path of retrogression than would lawsonite. The plate tectonic setting of Groix might be solved by applying the concept of suspect tectonostratigraphic terranes to Gondwanan France and Iberia, and invoking large-scale displacements. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The eclogite–blueschist–greenschist facies rocks of Ile de Groix, NW France, have attracted much attention, not only because areas of Paleozoic blueschist are relatively rare, but because they may possibly provide important clues to the plate tectonic setting of the time. Bernard-Griffiths et al. (1986), on the basis of geochemical data, suggested the rocks represent metavolcanic material of oceanic island origin mixed with quartz-rich sediments derived from a nearby continent. They give the age of volcanism and sedimentation as approximately 500 Ma. Audren et al. (1993) suggested the volcanics formed in an intracontinental rift environment, but, as Ballèvre et al. (1998) point out, the quartz-rich rocks may be meta-cherts rather than continentally derived sediment, and the occurrence of the Mn-rich mineral piemontite within the possible meta-chert is more consistent with an oceanic environment. Ballèvre et al. (1998) interpret the rocks as the remnants of a Paleozoic accretionary prism.

According to Triboulet (1991) and Audren and Triboulet (1993), the metamorphism was the result of a prograde anticlockwise P–T path to pressures of at least 1.0 Gpa and 400°C (anticlockwise and clockwise refer to P–T paths on graphs with pressure plotted increasing upwards). This was followed by a clockwise P–T path through the greenschist facies with temperatures reaching 600°C. However, in Audren et al. (1993), purely clockwise P–T–t paths are proposed, some reaching nearly 700°C at approximately 0.7 GPa, but this work is confused by the fact that these conditions are generally thought to be those of the amphibolite facies, and diagnostic minerals for this facies are not recorded; confusion is compounded by their use of the word amphibolite in an unconventional manner for any amphibole-bearing rock. Their data are not consistent with the following P–T determinations (Fig.

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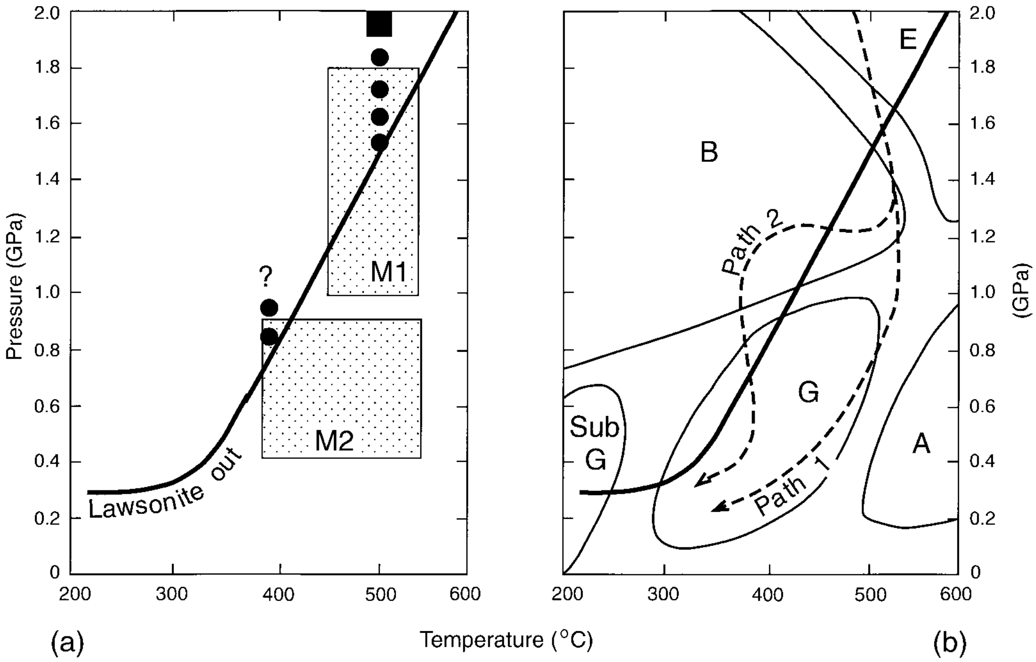

Fig. 1. (a) P–T determinations for Groix rocks by Barrientos (1992), the dotted squares, Bosse et al. (1998), the filled circles, and Müller et al. (1995), the filled square. The lawsonite out curve is from Nitsch (1972). (b) Sub-G, G, A, B, and E refer to subgreenschist, greenschist, amphibolite, blueschist and eclogite facies, as given in Bucher and Frey (1994), the lawsonite curve is from Nitsch (1972), as in (a), and two possible P–T paths for the exhumation of Groix rocks are shown by the dashed lines, and are discussed in the text.

1a): 1.0–1.8 GPa at 450–550°C for the blueschists, and 0.4–0.9 GPa at 400–550°C for the greenschists (Barrientos, 1992, her M1 and M2, respectively); pressures of at least 2.0 GPa at 500°C and retrogressive zoning in micas and garnet in the mica schists (Müller et al., 1995); 1.5–2.0 GPa and $T = 500°\text{C}$ for zoned garnets in eastern parts of Groix, and $P > 0.8$ GPa (imprecise data) and $T = 400°\text{C}$ in western areas (Bosse et al., 1998). These latest data are consistent with the zonal schemes established by Triboulet (1974) and Carpenter (1976), both of whom reported a higher pressure metamorphism in the east of the island. All these workers envisage the rocks in the east and west to be at different structural levels, and Bosse et al. (1998), for example, propose a tectonic boundary (a zone of intense shearing such as a thrust) between the east and west in order to explain the differences in temperature.

The pressures and temperatures reported by Müller et al. (1995) and Bosse et al. (1998) make it clear that the original volcanics and sediments of Groix were subducted to very great depths. The ensuing exhumation, according to Peucat (1986), was rapid, during which time greenschist facies mineral assemblages overprint the higher pressure mineralogy, sometimes more-or-less completely, sometimes incipiently or not at all.

Peucat and Cogné (1977) and Peucat (1986) report mica schist whole-rock isochrons which give a maximum age for blueschist facies metamorphism of 421 ± 7 and 422 ± 16 Ma, respectively; zircons provide a 399 ± 12 Ma minimum age. As noted above, Peucat suggests the greenschist facies metamorphism was superimposed during rapid uplift. Later Hercynian events on the nearby French mainland, around 300–320 Ma ago, were accompanied by significant tectonism and production of granitic rocks, but Peucat suggests the only effects on Groix were a partial resetting of K–Ar systems in phengites (which give intermediate dates between 400 and 320 Ma), and a complete resetting of glaucophane K–Ar systems, dated at 320 Ma; barroisites and paragonites were reset but continued to lose argon until 273–295 Ma ago. Peucat (1986) was uncertain which structural feature on Groix this resetting might be correlated with, but suggested either the D2 or D3 of previous workers. The principal geochronological data are given on Fig. 2; further work by M. Ballèvre and V. Bosse at Rennes is in progress.

Groix schists are *LS* tectonites with a strong mineral stretching lineation that trends generally NNW–SSE or NW–SE (Quinquis and Choukroune, 1981), and a foliation that is interpreted as having been flat-lying but which is now rippled on the kilometre scale by what are described as open upright late folds (Fig. 3). Quinquis and Choukroune (1981) and Cannat (1985) used asymmetric quartz *c*-axes patterns and asymmetric pressure shadows around garnets as shear-sense

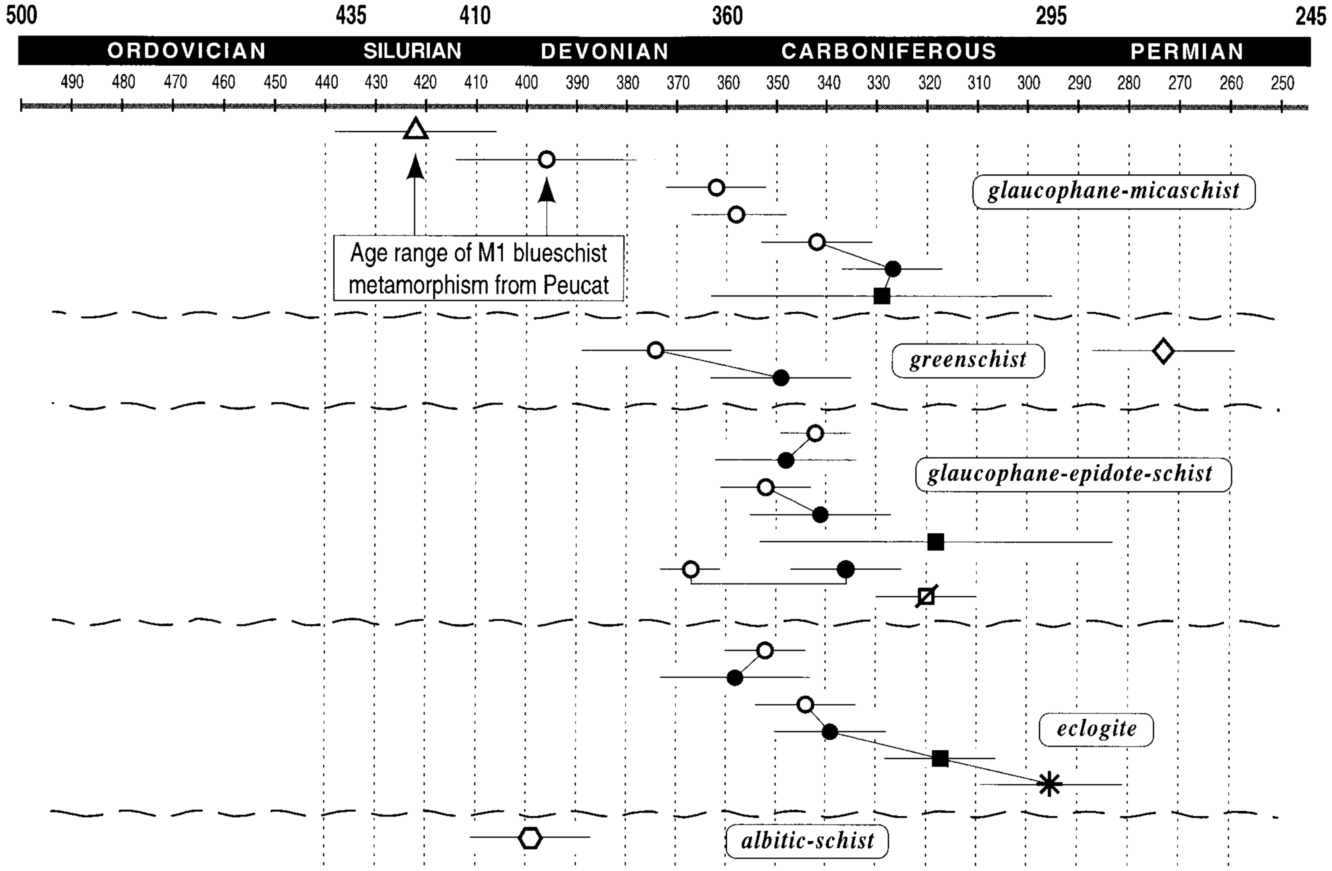

Fig. 2. Published radiometric dates for Groix rocks. Errors are shown by the horizontal bars. Data joined by tie lines are for the same specimen. Triangle, whole rock Rb–Sr isochron; open circle Rb–Sr phengite; filled circle K–Ar phengite; filled square K–Ar glaucophane; diamond K–Ar paragonite; crossed square Ar–Ar glaucophane; star K–Ar barroisite; hexagon U–Pb zircon. The glaucophane mica-schist data are from Peucat (1986), Peucat and Cogné (1977), and Carpenter and Civetta (1976); the greenschist data are from Hunziker (in Peucat, 1986) and Peucat (1986); the glaucophane–epidote schist data are from Hunziker (in Peucat, 1986), Peucat (1986), Carpenter and Civetta (1976), and Maluski (1977); the eclogite data are from Hunziker (in Peucat, 1986), Peucat (1986), and Carpenter and Civetta (1976); the zircon U–Pb date is from Peucat (1986).

indicators, and they recorded a dominant sense of shear of top towards the northwest with the mineral stretching lineation parallel to the trace of the movement direction. They also recorded reversals of shear sense, and these were explained by Cannat (1985) as possibly representing flow régime heterogeneities due to strong rheological contrasts between eclogitic rocks and quartzites, for example.

Synmetamorphic folds on the centimetre or metre scale with axes more-or-less parallel to the stretching lineation are very common and conspicuous, and some are sheath folds, the result of extreme strain (Quinquis et al., 1978). The foliation, lineation and small-scale folds developed during D1 according to Quinquis and Choukroune (1981), who interpreted small deviations in the trends of fold axes and lineations as the result of rotations during the formation of sheath folds. Other workers (e.g. Cannat, 1985) have subdivided the synmetamorphic deformation into D1 (blueschist facies) and D2 (greenschist facies), and interpreted some of the slight variations in trends as due to variations in movement direction with time. The late open folds (D2 of Quinquis and Choukroune, 1981, or D3 of Cannat, 1985) have axes more-or-less parallel to the dominant mineral stretching lineation.

All recent workers have been in agreement that the foliation, the mineral stretching lineation, and centimetre–metre scale folds relate to a more-or-less continuous and complex shear deformation that accompanied the blueschist facies metamorphism and the transition to the greenschist facies.

The tectonic setting of Groix remains problematical. Cogné (1977) proposed that the blueschists underwent metamorphism in a northwards dipping subduction zone to form a metamorphic belt paired with the mainland chain of granitoids. However, the dominantly top to the northwest sense of shear reported by Quinquis and Choukroune (1981) did not support this idea, so they suggested instead that the blueschists represent obduction of the Groix rocks onto the continent

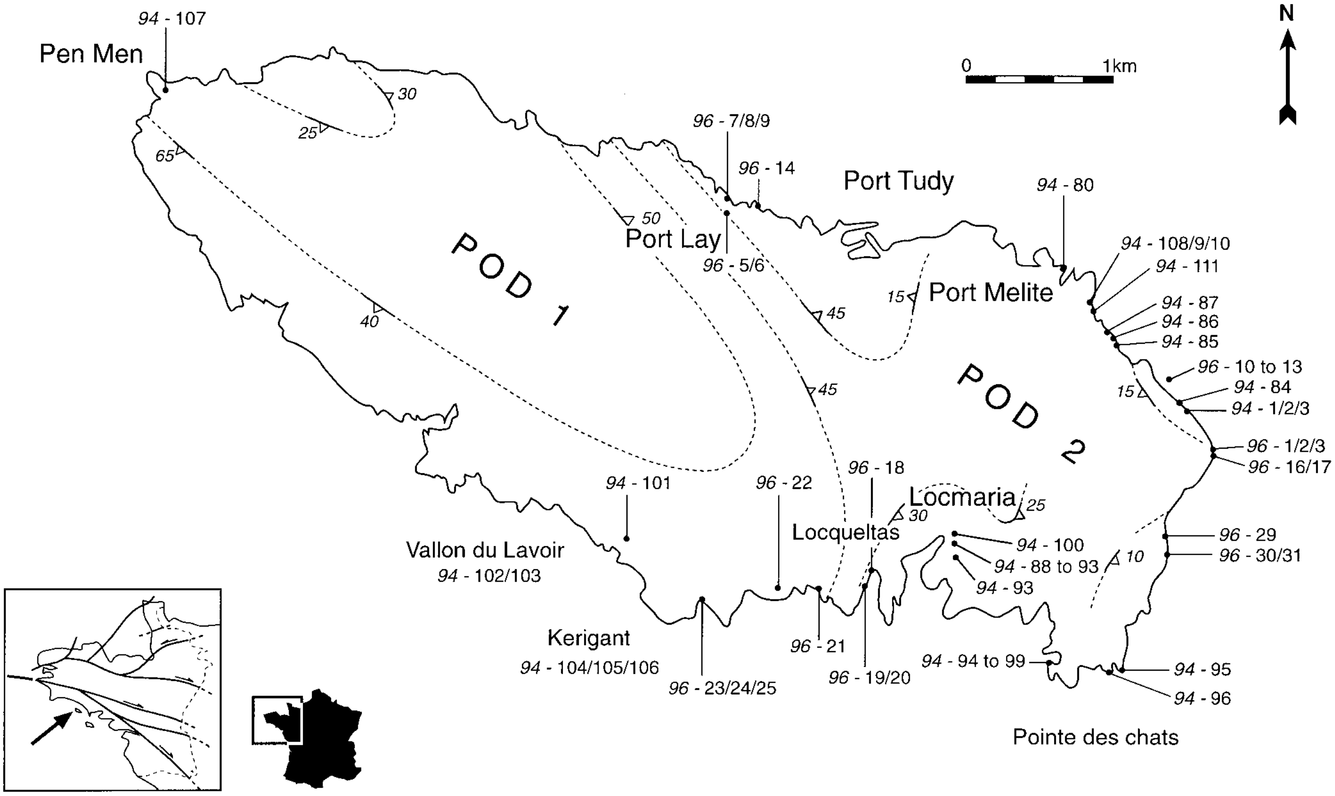

Fig. 3. Map of Ile de Groix showing the location of specimens collected. The form lines and strike and dip data are from fig. 3 of Quinquis and Choukroune (1981). The two 'pods' noted on the map are discussed in this paper in Section 3.3, and the boundary between them runs from Locmaria to Port Tudy.

to the north, perhaps preceded by some subduction. In either of these models, the proposition has been that the blueschist facies structures developed during a collisional event.

In this paper we provide a new analysis of the structures and mineral fabrics of Groix. In particular, we report that shear senses are equally as commonly top to the southeast as top to the northwest, and we record the fact that the structures are related to retrogressive rather than progressive metamorphism. We show that the fundamentally flat-lying foliation and horizontally disposed stretching lineation indicate extension and thinning during uplift. Furthermore we record observations of quartz *c*-axes fabrics in relation to some of the small-scale folds to show they are not sheath folds but originate with their axes parallel to the extension direction in response to shortening along the intermediate strain axis. We discuss the important role of the intermediate strain axis in causing conspicuous modifications to the flat-lying foliation as it was variously either slightly extended or shortened.

2. The retrogressive sequence on Groix

The highest grade rocks exposed on Groix are eclogites containing variable amounts of garnet and omphacitic pyroxene. The pyroxene is typically elongate (Fig. 4a, b), often strongly so, parallel to the general stretching lineation found throughout the island, implying the pyroxene fabrics developed during a period of substantial strain. Some oriented glaucophane is enclosed by garnet and pyroxene, and is probably contemporaneous with the eclogitic minerals, but more generally the rock textures and fabrics indicate that glaucophane continued to develop and evolve after the omphacitic pyroxene. Thus, on the thin section scale, glaucophane is wrapped around pyroxene, and oriented glaucophane forms in pyroxene pressure shadows (Fig. 4a); in the field, more highly strained blueschists can be seen wrapped around pods of pyroxene-rich rock. Such pods are elongate in the general direction of the stretching lineation defined by both pyroxene and glaucophane. Although glaucophane is wrapped around pyroxene, the direct product of pyroxene retrogression is usually crossite (and/or barroisite or actinolite) rather than glaucophane. The interpretation that the pyroxene–glaucophane–crossite textures and fabrics are a response to retrogression is consistent with the fact that eclogite facies mica schists display only retrogressive zoning in micas and garnet (Müller et al., 1995). Evidence for progressive meta-

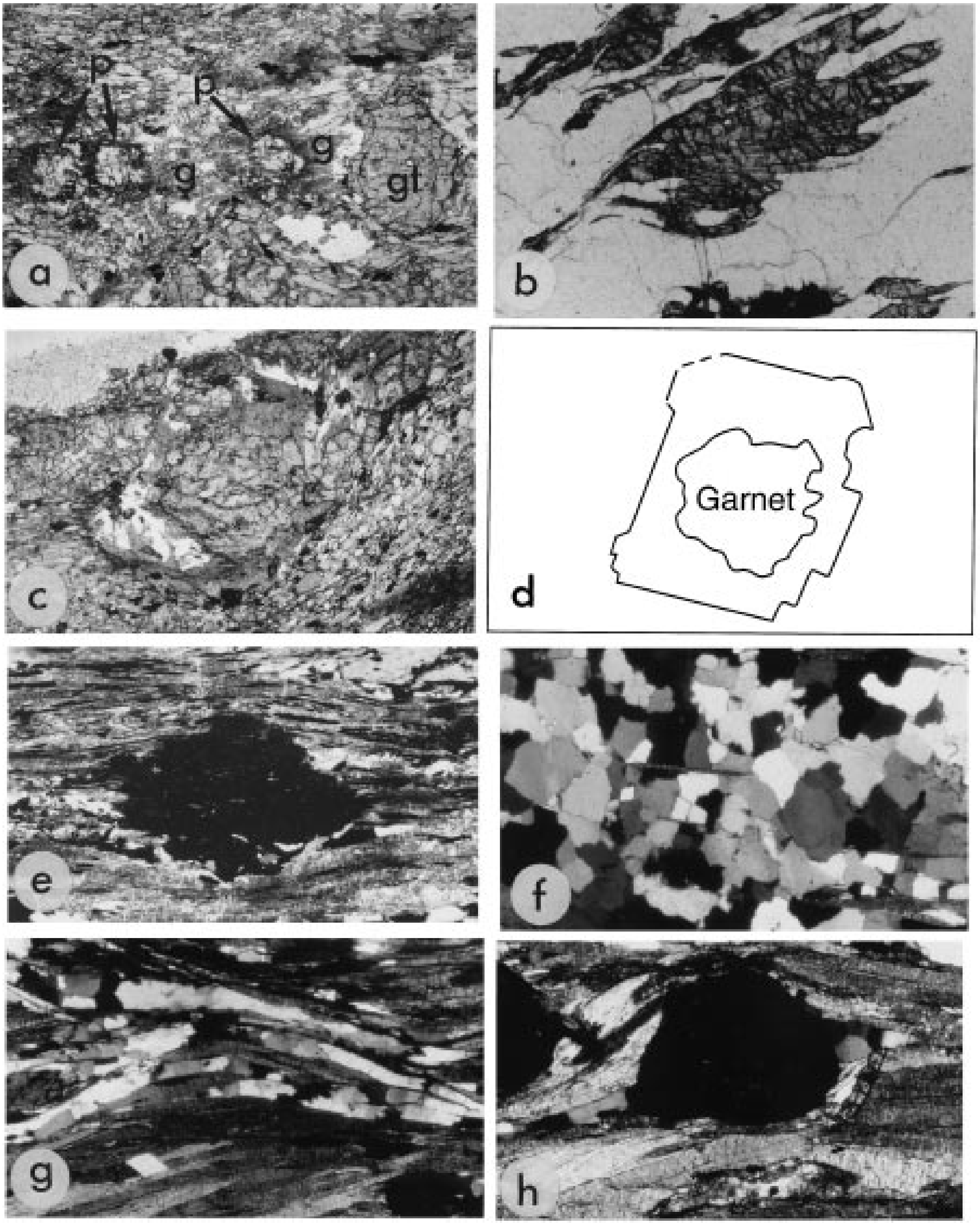

Fig. 4. (a) Three relics of a single elongate omphacitic pyroxene (p) to the left of the garnet (gt). The pyroxene extends further out of the field of view and is a prism 4.5 mm long. The pyroxene, grown in the shadow of the garnet, is partially replaced by symplectitic green amphibole. Both the garnet and the pyroxene fragments have developed pressure shadows with glaucophane (g), and subsequently dark barroisitic amphibole. Immediately on the left of the garnet is white mica, and on the immediate right hand side of the garnet, in the shadow, is biotite, then white mica, then glaucophane. Specimen 9486, cut parallel to lineation. (b) Cluster of elongate pyroxene crystals, set in quartz, and deformed by extensional shearing. The most sheared parts of the pyroxene are retrogressed to amphibole. The overall form of the deformed pyroxene clusters is similar to mica fish. Same thin section as (a). (c) 'Lawsonite' pseudomorph which encloses a large garnet (d is a key to this picture). The 'lawsonite' is replaced by chlorite, albite, and epidote. The host schist is mainly glaucophane and epidote. Specimen 9630 cut perpendicular to lineation. (d) Drawing to show the positions of the rhomb-shaped 'lawsonite', and the enclosed garnet in (c). (e) Rhomb-shaped albite porphyroblast (in extinction) in white mica-rich layer within a grey quartzite. Specimen 94105 cut parallel to lineation. (f) Typical mosaic of quartz with serrated grain boundaries due to dynamic recrystallisation. The quartz has a very strong lattice preferred orientation, and indicates a sense of shear which in this view is sinistral. Specimen 94100 cut parallel to lineation. (g) Thin layers of quartz along conjugate anastomosing shears in mica schist. The layers are one grain thick, and the quartz *c*-axes indicate dextral shear on the right of the view, and sinistral shear in the lower-central left of the view. Specimen 9493 cut parallel to lineation. (h) Asymmetric pressure shadow about garnet (in extinction) with quartz layer and white mica stepping up from left to right. Specimen 9487 cut parallel to lineation. Lengths of fields of view measure 4 mm for (a), (c), (d), (e), (f), and (g), and 3.1 mm for (b) and (h). Specimen locations are given on Fig. 3.

morphism in Groix rocks may possibly exist in the zoning of garnets in the eclogites, and in the inclusions within such garnets, but such evidence has yet to be described.

In turn, the blueschists, which crop out much more widely than the eclogites, are often partially retrogressed to assemblages which typically include albite, chlorite, barroisite, and tremolite–actinolite. Again, where blueschists and greenschists occur in outcrop together, one can see that the blueschists form pods, elongate parallel to the stretching lineation, and wrapped around by more highly strained greenschist.

From these data it seems clear that the Groix rocks, as a whole, represent a retrogression from eclogite facies, through blueschist facies, to greenschist facies, and this has been recognised by a number of previous workers. Sometimes the retrogressive minerals lack a fabric, indicating a lack of local strain, as for example in the retrogression of a competent pod. However, what is not clearly recognised in the previous literature is that structures such as foliation, folds, and stretching lineations formed during the retrogression rather than the preceding increase in pressure. As described below, the complete retrogressive sequence is characterised by the principal minerals crystallising and/or recrystallising during strain to form foliations, stretching lineations and pressure shadows with orientations in common and which can be most easily related to extension and exhumation. The significance of this is that it is not possible to discuss the principal structures and metamorphism of Groix in terms of subduction, even though it is clear from the *P–T* determinations of Müller et al. (1995) and Ballèvre et al. (1998) that the rocks must previously have been subducted.

The Groix retrogression is similar to that described from other exhumed eclogitic-blueschist complexes, as for example documented for the Cycladic massif in the Aegean Sea by Avigad (1993). As already noted for Groix by Barrientos and Selverstone (1993), such retrogressive paths imply the ingress of water-rich fluids and it is likely that the accompanying exothermic reactions would have had an important influence on the precise shape of the *P–T* path. The fluids would have facilitated deformation, and it is not surprising, therefore, that relic pods of higher pressure rock are wrapped around by more strained retrogressed material.

2.1. The 'lawsonite' pseudomorphs — were they really lawsonite?

Well known on Groix are conspicuous rhombic-shaped pseudomorphs which Barrois (1883) suggested were after andalusite, but which were later ascribed to lawsonite by Cogné et al. (1966) and Felix and Fransolet (1972). The crystals are large, up to several centimetres across, and are altered to diverse mixtures of white micas, albite, quartz, chlorite, and epidote family minerals. Felix and Fransolet (1972) have shown the rhombic shapes to be characterised by angles of 64° ± 2° and 115° ± 2°.

The pseudomorphs usually occur in rocks otherwise dominated by epidote–blueschist facies minerals, and there is a general consensus that they are relatively late in the host rock's deformational history, overgrowing the fabric as seen in trails of epidote and glaucophane. The inclusion of some very large garnets as well as glaucophane is consistent with them being part of the retrogressive sequence (Fig. 4c, d), and although the glaucophane foliation is sometimes wrapped around them, there is no evidence of significant relative rotation between internal and external foliations.

There is no relic of the original mineral, and thus there will always be some doubt as to what it was. The possibility of a calcium-bearing plagioclase, rather than lawsonite, was briefly considered by Felix and Fransolet (1972), because the shapes are those expected for (010) plates of plagioclase. Indeed, good examples of rhombic shaped (010) plates of albite in glaucophanite from New Caledonia, very reminiscent of the Groix pseudomorphs, are illustrated by Clarke et al. (1997, fig. 3d), and rhombic shaped albite crystals are also found on Groix (Fig. 4e). Felix and Fransolet (1972) rejected the idea of calcium-bearing plagioclase on the ground that such plagioclase is not considered stable in the blueschist facies.

We wish to re-evaluate the possibility of the pseudomorphs being derived from calcium-bearing plagioclase such as oligoclase or andesine. The discussion is important in the context of this paper because very different *P–T–t* paths and exhumation histories may be implied.

The eclogite, blueschist, greenschist, and amphibolite facies all more or less meet at pressure–temperature conditions of around 1.0–1.1 GPa and 500–600°C (Fig. 1b; Bucher and Frey, 1994). Evans (1990) describes facies in this *P–T* region as lacking plagioclase other than albite, and he puts an albite–epidote–amphibolite facies between the amphibolite facies and the eclogite or blueschist facies. However, in contrast, Goldsmith (1982) recorded the formation of plagioclase with compositions between An10 and An40 at these pressures and temperatures, and Bucher and Frey (1994, p. 296) report the formation of oligoclase in association with barroisite during the retrogressive transition from eclogite to blueschist and greenschist facies. It would seem, therefore, that calcium-bearing plagioclase may be stable in the *P–T* region of the eclogite–blueschist–amphibolite–greenschist facies join, despite the albite–epidote–amphibolite facies proposed by Evans (1990). In this context, it is worth noting that an albite–epidote–amphibolite facies has sometimes been advocated at lower pressures between the greenschist and amphibolite facies, but it has generally been abandoned because albite is normally accompanied in the transition from greenschist to amphibolite facies by more calcic plagioclase, a relationship controlled by the peristerite solvus. By definition, the eclogite facies does not contain plagioclase, and calcium-bearing sodic-plagioclase breaks down in the greenschist facies. Therefore, if the Groix rocks did produce calcium-bearing plagioclase during retrogression it is likely to have been within the higher temperature blueschist facies near or at the region transitional to the amphibolite facies. A possible *P–T–t* path is shown in Fig. 1(b) as path 1. In such a scenario, the plagioclase might represent a thermal climax, reminding us of the fact that Barrois (1883) first suggested a thermal overprint with andalusite. Subsequent alteration to albite and/or mica and/or epidote represents retrogression through the greenschist facies, a retrogression that singled out the plagioclase. Such alteration products are fundamentally the same as the familiar ‘saussurite’.

If, on the other hand, the crystals were lawsonite, a more complex *P–T–t* path is indicated. Lawsonite break-down curves have distinctly positive slopes on a *P–T* diagram, with lawsonite stable on the lower *T*, higher *P* side (Fig. 1). Its relatively late development within the blueschist facies would therefore require an increase in *P* and/or a very sharp isobaric (or nearly isobaric) decline in *T*, followed by a more or less isothermal decrease in *P* (Fig. 1b — path 2). This would be contrary to an expected exhumation path, where *T* would not normally drop markedly until the rocks were very close to the surface. Such paths would require either an extraordinary thickening of the rock mass above Groix during exhumation, or for Groix rocks to have been thrust over relatively cold rock during exhumation. There is no evidence for thrusting during exhumation, which would in any case seem unlikely in an extensional environment. It is conceivable, however, that during gravitational collapse of a thickened continent, large rock masses might locally have overridden otherwise extending and thinning zones, thus locally increasing pressure.

There is yet another alternative to consider, that the pseudomorphs represent lawsonite that was so late that it postdates a path through the greenschist facies. However, this is inconsistent with the observation that the glaucophane foliation is sometimes wrapped around the pseudomorphs, and implausible because such large crystals would not be expected at such low temperatures. Not only that, but their subsequent alteration would require a later reheating into the greenschist facies.

Regardless as to whether the pseudomorphs represent lawsonite or plagioclase, the alteration products represent retrogression into the greenschist facies, and a lack of equilibrium with the blueschist host. If the pseudomorphs were lawsonite, they were differentially retrogressed leaving the host blueschist almost unchanged. At first sight, the complete alteration of lawsonite seems easily explained because its breakdown causes a release of copious water. However, the products of retrogression contain significantly less water than any original lawsonite, and it is a problem, therefore, to explain why the excess water did not promote a more general retrogression of the host rock. If the pseudomorphs were plagioclase, the retrogression requires water to be introduced into the system, but in such a situation the lack of host-rock retrogression can be explained simply in terms of a preferential alteration of the plagioclase. Again, the alteration products are not in equilibrium with the host rock.

To summarise, we believe the idea that the pseudomorphs were plagioclase, although it cannot be proved, is worthy of serious consideration. Although the idea of lawsonite pseudomorphs seems to be favoured by their occurrence in blueschists, their relatively late development requires a complex exhumation history. The total alteration of lawsonite could easily have been catalysed by the release of water during alteration, but given the mobility of elements indicated by the alteration products, which are clearly metasomatic, it is not easy to understand why the host rock was not retrogressed also. The literature indicates that calcium-bearing plagioclase may form on retrogression from eclogite through the blueschist facies, and the simpler *P–T–t* path implied is more in line with the normal expectations of exhumation. In either case, the alteration was selective, and the products are out of equilibrium with the host rock. The selective alteration of plagioclase due to a limited ingress of water leaves it easier to explain the lack of host rock retrogression.

On balance, we believe the evidence fits plagioclase better than lawsonite, but the case is surely not closed. A solution is important if we are to understand the tectonic setting for the exhumation of Groix rocks.

3. New observations and synthesis of Groix structures and fabrics

3.1. Shear senses: top-to-the-NW or top-to-the-SE?

Previous workers have recorded a dominant shear sense of top towards the northwest, but reversals of shear sense have also been noted, and Cannat (1985), for example, observed 4 out of 19 specimens with a top-to-the-SE movement direction. For this study we investigated shear senses by examination of 57 oriented specimens using quartz fabric asymmetries, pressure shadows, extensional shears, and other indicators such

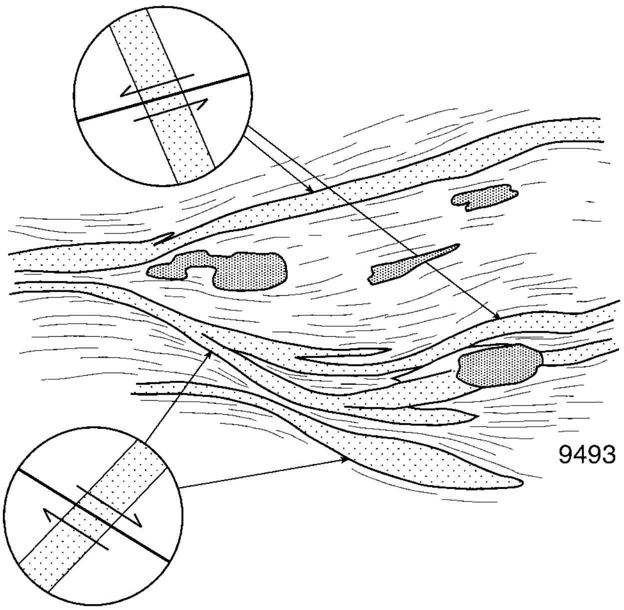

Fig. 5. Drawing from a thin section cut parallel to lineation to illustrate the changes in asymmetry of quartz *c*-axes fabric in relation to anastomosing extensional shears, as discussed in the text. The location of specimen 9493 is given on Fig. 3. The view is approximately 6 mm long. Light stipple is quartz, heavy stipple, chloritoid, and fine lines, mica.

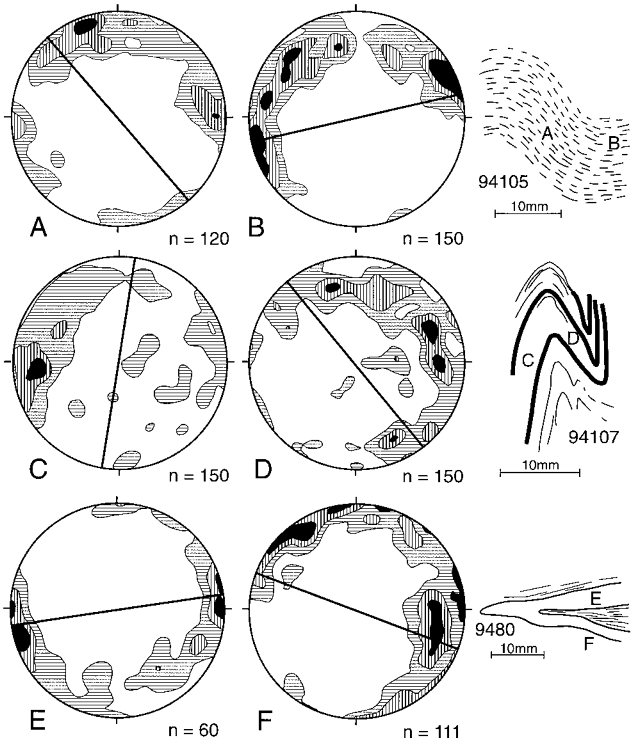

Fig. 6. Equal area lower hemisphere projections showing the orientation of quartz *c*-axes for the limbs of three folds. For each of the projections the lineation is vertical and plots at the centre. The folds are drawn as seen in thin sections cut perpendicular to the lineation. The quartz *c*-axes orientations, measured on fold limbs, A, B, C, D, E, and F, in the drawings, are represented in the projections A, B, C, D, E, and F, respectively, and the orientations of the limbs are given by the great circles. The oblique single girdles of quartz *c*-axes, rotated during folding by angles of 65°, 130°, and 153°, reverse the apparent sense of shear where the fold is relatively tight. Specimen 94105 is a quartzite with trains of opaque minerals, and 94107 and 9480 are mica schists with quartz-rich layers. Locations are given on Fig. 3. The number of quartz grains measured is given by '*n*' for each projection. Contours in A are at 1, 3, and 5% per 1% area (maximum 7.1%), in B, 1, 2.3, and 3.6% per 1% area (maximum 5.1%), in C, 1, 2.8, and 4.6% per 1% area (maximum 6.4%), in D, 1, 1.9, and 2.8% per 1% area (maximum 3.8%), in E, 1, 4, and 7% per 1% area (maximum 10.1%), in F, 1, 2.2, and 3.5% per 1% area (maximum 5.1%).

as *CS* structures and late folds. Observations were made in *XZ* sections (parallel to lineation and perpendicular to foliation), and the most commonly observable and reliable shear-sense indicators are quartz fabrics, pressure shadows, and extensional shears.

Asymmetric quartz *c*-axis fabrics are illustrated in Figs. 5–7. Figs. 6 and 7 represent the same data in different orientations, Fig. 6 with the lineation vertical, Fig. 7 with lineation horizontal and E–W. Typically the *c*-axes form an oblique girdle at a high angle to the foliation intersecting it in the intermediate strain axis, *Y*. Such oblique girdles have been observed on Groix by previous workers (e.g. Cannat, 1985), and are well known as shear-sense indicators (Jessel, 1988). The oblique girdles are observable without the aid of the universal stage from birefringence and the orientations of fast and slow directions, and with the use of the sensitive tint plate, the asymmetries of quartz *c*-axes fabrics, and hence shear senses, are easily determined. Thus, using sections cut parallel to the stretching lineation and perpendicular to the foliation, if the slow direction of the tint plate is SW–NE, and if the foliation is rotated into the E–W orientation with the microscope stage, a dextral shear sense is indicated if the bulk of the quartz changes from first order grey and white interference colours to second order blue, a sinistral shear sense if the interference colours change mainly to first order yellows.

Although Groix quartz *c*-axes fabrics are commonly asymmetric, giving clear indications of shear sense, quartz grain shapes generally lack the oblique shapes common in many mylonitic rocks (Lister and Snoke, 1984). This is largely due to dynamic recrystallisation, as witnessed by serrated boundaries (Fig. 4f). In very mica-rich rocks, thin quartz foliae are often only one grain thick, and these grains may be very elongate (Fig. 4g), but it is difficult to judge whether this is a direct result of plastic deformation or the pinning of grain boundaries by closely spaced sheet-silicates.

An asymmetric pressure shadow is illustrated in Fig. 4(h). Pressure shadows are consistently elongate in the direction of the stretching lineation, and as with σ-porphyroclast systems, pressure shadows that step up

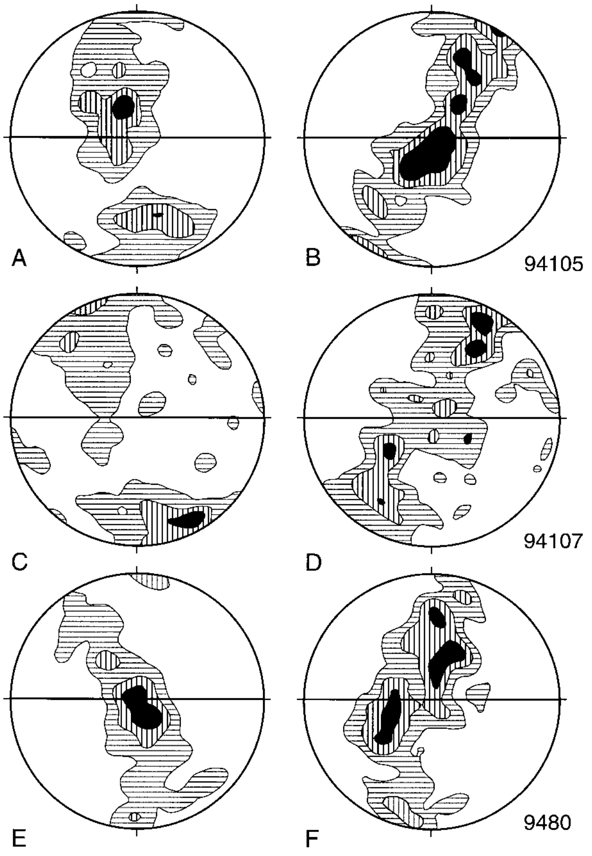

Fig. 7. Rotated equal area lower hemisphere projections, derived from Fig. 6, showing the orientation of quartz *c*-axes for the limbs A to F of the three Fig. 6 folds. Unlike Fig. 6, this figure has the lineation in the standard horizontal E–W orientation, and fold limbs represented by the E–W great circles. The limbs of each fold are presented in orientations as if the folds were perfectly isoclinal. The purposes of the figure are (i), to show clearly the asymmetry of the quartz fabric, and (ii) to show how, in principle, folding which effects a passive rotation of quartz *c*-axes fabrics produces apparent reversals of shear sense. A, C, and E suggest sinistral shear, in the orientation plotted, B, D, and F suggest dextral shear. The number of grains represented, and the contour intervals are exactly the same as for Fig. 6.

from right to left indicate sinistral shear, those that step up left to right, dextral shear.

Examples of extensional shears are shown in Figs. 4(b), (g) and 8(a), (b). In all cases they intersect in the intermediate strain axis, *Y*, perpendicular to the penetrative stretching lineation, and they usually intersect the foliation at low to moderate angles. The sense of shear is seen in the bending and displacement of the foliation, and in the vast majority of cases, the associated deformation was entirely ductile. Rarely, however, such shears are accompanied by brittle deformation (Fig. 8b).

A summary of our observations is given in Table 1. Most importantly, it can be seen that the number of observations indicating top-to-the-NW shear are exactly balanced by the number indicating top-to-the-SE shear. Also of importance is that a number of specimens display no particular asymmetry (possibly due to pure shear), and that others display clear evidence for both senses of shear. The latter is most obvious in the case of extensional shears which frequently occur in conjugate pairs, often in anastomosing arrays (Figs. 4g and 8a), but it is also the case for some pressure shadow patterns and quartz fabrics. For example, in seven specimens, the quartz fabrics display both senses of shear, often in connection with low-angle anastomosing extensional shears (Figs. 4g and 5). The change of asymmetry is real, not just a function of rotation of a pre-existing fabric by the undulating foliation, because the opposing asymmetries are still obvious even when each part of the undulating foliation is placed E–W under the microscope (see the above description of technique).

In terms of the timing of shearing, there is clear evidence from the relationship of key minerals to shear-sense indicators that strain was taking place somewhere in the Groix rocks throughout the eclogite, blueschist, and greenschist facies, and possibly sub-greenschist facies, as in the case of brittle deformation associated with extensional shears (Fig. 8b). In some cases, the evidence is that a particular feature formed completely within one facies, as for example in the case of pressure shadows around garnet entirely filled with elongate glaucophane crystals, but in others, formation of a particular feature spanned two or more facies. Some pressure shadows, for example, are zoned

Table 1
Shear-sense data from 57 oriented specimens (Note: some specimens contain no quartz, pressure shadows, extensional shears or other possible indicators of shear sense)

Shear-sense indicator	Top to NW	Top to SE	Top to both NW and SE	Possibly both or neither[a]
Quartz *c*-axes fabrics	10	8	7	8
Pressure shadows	7	16	7	9
Extensional shears	10	6	20	–
Other indicators	8	5	3	–
Totals	35	35	37	17

[a] Includes (a), cases of quartz fabrics where it is unclear whether the fabric relates to a pure shear or a combination of opposing shear senses and (b), cases where the pressure shadows are more-or-less symmetrical.

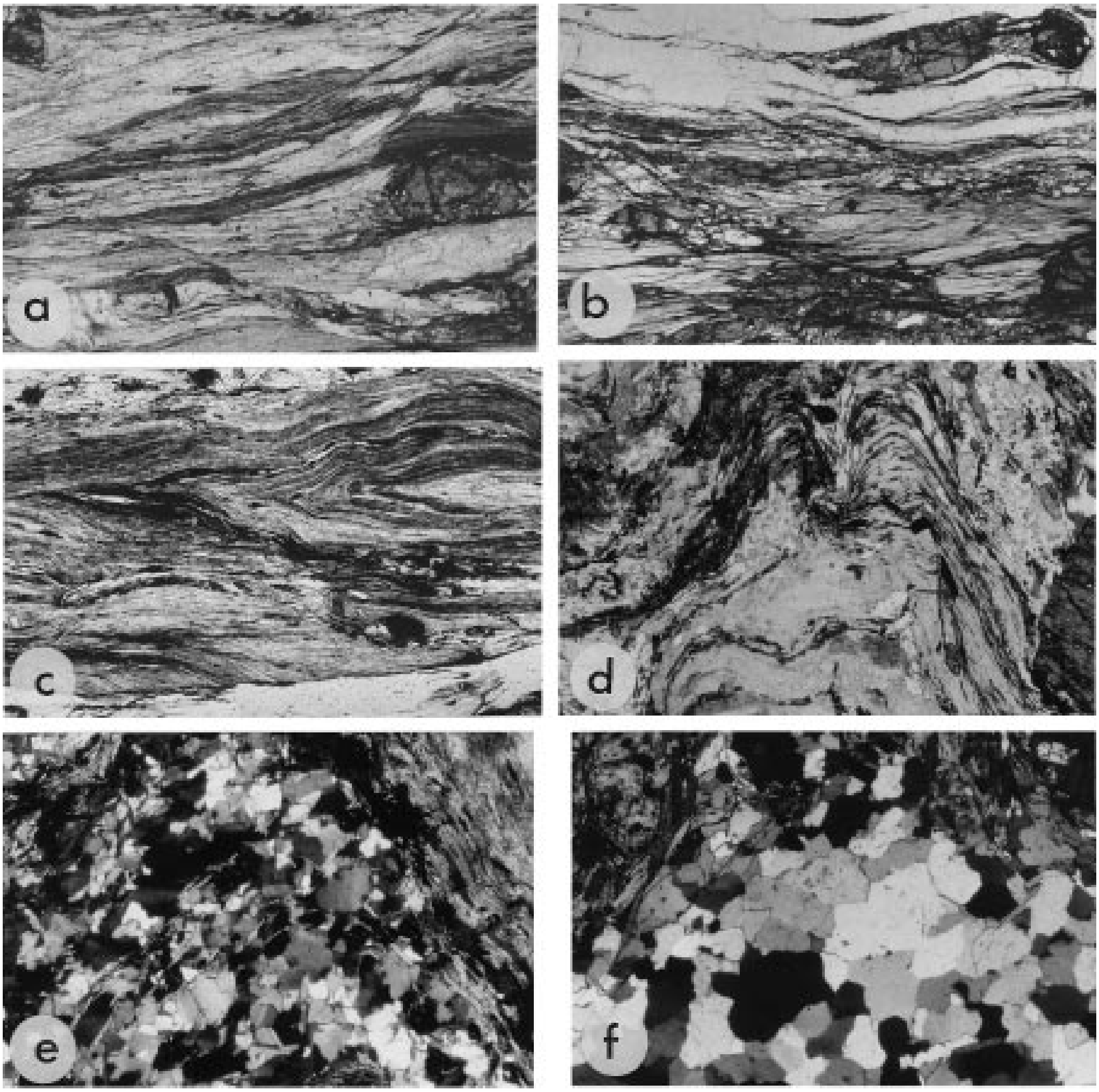

Fig. 8. (a) Curved, anastomosing extensional shears. The crystal on the right is garnet; thin layers of quartz are near the bottom of the view; most of the schist is white mica. Specimen 94109 cut parallel to lineation. (b) Extensional shears along which there has been brittle deformation, most conspicuously in albite and glaucophane. The view shows, at top, a quartz layer with a glaucophane and garnet crystal (top right) set in it. The necked zone between them is filled with broken albite. The lower part of the view is made dominantly of white mica with broken crystals of glaucophane and albite set in it. Specimen 9487 cut parallel to lineation. (c) Isoclinal folds with axes parallel to the lineation in schist made dominantly of white mica and opaque material. Specimen 94108 cut perpendicular to lineation. (d) Relatively open folds with axes parallel to the lineation in schist made dominantly of white mica, albite, epidote, glaucophane, opaques, and garnet (bottom right). Specimen 9483 cut perpendicular to lineation. (e) and (f) View of quartz mosaics in the hinges of folds which illustrate a bulk rotation of the quartz *c*-axes fabric (see text and Figs. 6 and 7). Both photos show the hinge as if it were an upright antiformal structure. Specimens 94107 (e) and 94100 (f), both cut perpendicular to lineation. Lengths of fields of view measure 4 mm for (a), (b), (c), (d), (e), and (f). Specimen locations are given on Fig. 3.

(Fig. 4a), displaying all or part of the gradation from eclogite through blueschist to greenschist facies, usually represented in the shadows by any or all of pyroxene, glaucophane, green amphiboles, biotite and albite, the lowest pressure minerals occurring closest to the garnet. The zoned pressure shadows demonstrate that strain continued from the eclogite facies through to the greenschist facies, and there is no evidence of any significant change in strain pattern during the retrogressive sequence. Strain is, however, heterogeneously distributed, and some specimens strained at higher pressures were not strained during later incipient lower pressure metamorphism.

It is not always possible to determine the facies of metamorphism pertaining to a particular shear feature, and therefore it is difficult to present accurate data on

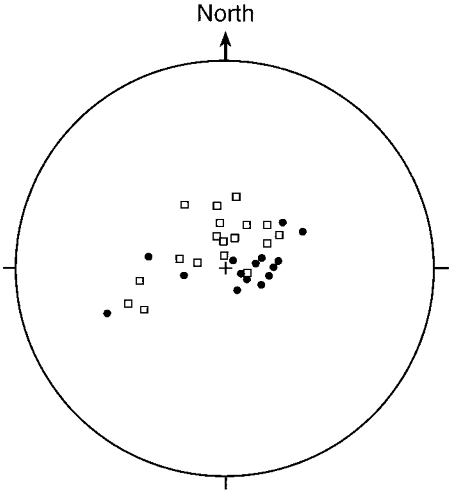

Fig. 9. Equal area lower hemisphere projection showing the orientation of poles to foliation, as measured in the field, for specimens (a), with shear sense dominantly top to NW — filled circles, and (b), with shear sense dominantly top to SE — open squares. For discussion, see the text.

the sense of shear for any one facies. Nevertheless, there is no suggestion in our observations that the opposing shear senses can be separated in time and associated with a particular metamorphic facies. This is particularly clear with anastomosing extensional shears (Figs. 4g and 8a) and the quartz fabrics associated with them (Fig. 5) where shearing with opposing senses was synchronous.

Previous workers on Groix have reported but not explained opposing shear senses, and they considered them departures from the norm, the norm consistently being reported as top to the northwest shearing. Similarly opposing shear senses have been noted elsewhere, and Garcia Celma (1982, figs. 6–8), for example, records opposing shear senses and quartz fabric asymmetries on either side of porphyroclasts and in association with extensional crenulations in the Cap de Creus quartz mylonites of Spain. In addition, domains with opposing fabric asymmetries are described parallel to foliation. Garcia Celma (1982) regards all these as a function of thin section scale heterogeneities and claims that the overall sense of shear becomes clear in zones of high strain. However, in contrast, we note that Lister and Price (1978, fig. 23) show that fabric asymmetries may be quite consistent, despite local heterogeneities.

In the case of Groix, our observations indicate that opposing shear senses are the norm; indeed, the two opposing directions are equally common. Given the fact that the foliation and stretching lineations are more-or-less horizontal, shearing in both directions is hardly surprising as it can be explained by conjugate shearing during extension and vertical thinning. Support for this is found in the orientation of foliation in specimens with either top-to-the-NW or top-to-the-SE shearing dominating. Hence top-to-the-SE shear foliations dip gently towards the southeastern quadrant compared to top-to-the-NW shear foliations which dip gently more towards the west-northwest, as shown in Fig. 9, and these data can be interpreted in terms of conjugate shear planes rotated as a result of ductile deformation almost into parallelism. The spread of data along great circles about axes in the NW–SE quadrant is commented on under 'pods', below.

Pure shear may also possibly have been effective in producing some of the thinning of the Groix rocks, and it may be represented by those specimens with more-or-less symmetrical fabrics. Combinations of conjugate non-coaxial shearing and pure shearing might be expected to be quite normal in extensional régimes, in contrast, for example with the expected single dominant sense of shear in a transpressional or thrusting régime.

3.2. The nature of the small-scale folds

Asymmetric pressure shadows, asymmetric quartz *c*-axes fabrics, and extensional shears are all most clearly visible in *XZ* sections of Groix schists, parallel to the lineation and perpendicular to foliation, and in these sections one can rarely observe folding. On the other hand, in sections perpendicular to both the foliation and lineation, the dominant feature usually visible is folding of the foliation or some pre-existing marker (Fig. 8c, d). This small-scale folding with axes parallel to the stretching direction is so common that 70% of our specimens show it. In detail, the folding varies so that some folds are isoclinal and have axial planes parallel to the general foliation (Fig. 8c) whereas others are more-or-less upright and buckle the main foliation (Fig. 8d). Vergence may be in either direction.

This folding appears to have developed under the conditions of any of the metamorphic facies. For example, in specimens displaying dominantly blueschist facies minerals, glaucophane often forms a stable mosaic of grains in layers that define the fold structures, and there is no doubt that the folds formed mainly during the blueschist facies metamorphism. Minerals typical of the greenschist facies such as albite, biotite and late chlorite often overprint blueschist folds, though late chlorite and biotite are sometimes slightly folded suggesting folding was continuous into the greenschist facies. Specimens dominantly of the greenschist facies display folds which are synchronous with or subsequent to the greenschist facies.

Sheath folds exist on Groix, as shown by Quinquis et al. (1978), and they may be recognised by circular or elliptical patterns of layering in sections perpendicular to the stretching direction or by observing the rarely exposed noses of the sheaths (Cobbold and

Quinquis, 1980). However, elliptical patterns are rarely seen in the field, and they are not seen in any of our specimens.

In four specimens (9480, 94100, 94105, 94107), the quartz *c*-axes fabric pattern has undergone a bulk rotation about the fold axis (two of the fold hinges are shown in Fig. 8e, f). The bulk rotation of the quartz is most convincingly seen as a sweeping of the dominant extinction pattern around some of these fold hinges, when viewed on the stage of an ordinary polarising microscope, but the rotation is also clearly discernible in the equal area projections (Fig. 6, for three specimens). The U-stage measurements have, of necessity, been made on relatively small areas of the thin sections (individual limbs), and are correspondingly few in number (between 60 and 150 grains); nevertheless, the rotations are clear. When the bulk rotation is greater than 90°, the effect is to reverse the apparent sense of shear. This effect is illustrated in Fig. 7 which represents the same data as Fig. 6, presented in the standard orientation with lineation horizontal and E–W, and with data re-oriented as if the folding were perfectly isoclinal. Clearly, what seems sinistral on one limb becomes dextral on the other.

It has already been noted that quartz grain shapes on Groix are not usually directly related to plastic deformation, but result from dynamic recrystallisation. This is so for quartz around these folds, and Fig. 8(e) and (f) illustrate mosaics of almost equidimensional grains, despite the bulk rotations recorded in the *c*-axes fabrics.

The phenomenon of bulk rotation of quartz fabrics around folds is one that Cannat (1985) searched for but did not find, and she concluded, therefore, that the folds she examined must be sheath folds, and that by the time the limbs had been rotated into parallelism with the stretching direction, *c*-axes fabrics on different limbs had been thoroughly overprinted. Similarly, for the Cap de Creus quartz mylonites, Carreras et al. (1977) noted that folds with axes parallel to the stretching lineation had the same fabric asymmetry on both limbs, indicating a thorough overprinting of any earlier quartz fabrics, confirming they are sheath folds. Interestingly, in the same area, Carreras et al. (1977) recorded bulk rotations of quartz fabrics about folds with axes at a high angle to the stretching direction.

In the case of Groix, the folding of *c*-axes patterns about axes parallel to the stretching lineation (Figs. 6 and 7), plus the general lack of elliptical fold patterns in *YZ* sections, indicates that many folds are not sheath folds, but nucleated with axes initially parallel to the stretching direction. This is to be expected if, during an approximately plane strain shearing, the intermediate strain axis (Y) becomes slightly constrictive, as discussed and described from a core-complex in California by Fletcher and Bartley (1994). Folds formed with this attitude at a relatively late stage are the ones most likely to preserve the rotation of earlier formed asymmetric quartz fabric patterns. On the other hand, folds formed with this attitude at an early stage of a non-coaxial deformation are likely to be overprinted by later penetrative fabrics, and to become isoclinal eventually, as the result of progressive strain and stretching along X; a lack of evidence for rotation in the quartz fabrics of a fold does not prove they are sheath folds.

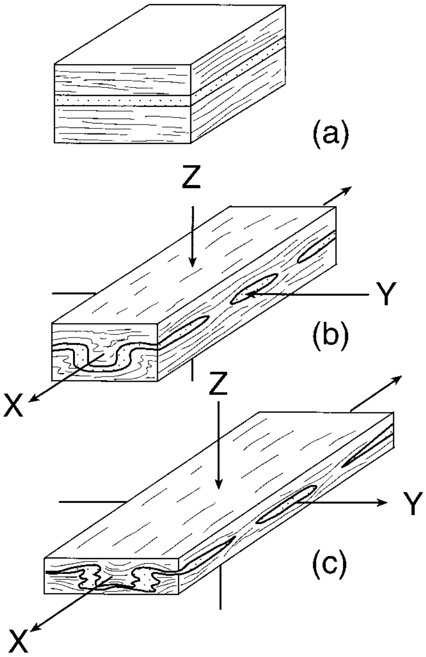

Fig. 10. Diagrams that illustrate how 'pods' of competent material may have developed: (a), single existing competent layer in a block of schist; (b), the competent layer is extended parallel to X, with boudinage, and shortened parallel to Z, the principal strain axes during deformation, but it is also buckled (box-folding) in response to transient shortening along the intermediate strain axis Y; (c), further shortening along Z, combined with extension along X and transient extension along the intermediate strain axis Y, results in folding and thickening of the competent layer where it is sub-parallel to the XZ plane, and thinning where it is sub-parallel to the XY plane. The overall strain from (a) to (c) is plane, so that the volume of the block and its dimension along the intermediate axis are the same in (a) and (c).

One can expect complex rotations to occur during a combination of shearing, sheath-folding, formation of folds related to σ_2, and boudinage, and it is not surprising that apparent movement directions, lineations and fold-axes are not always exactly parallel. It would be surprising if they were.

3.3. The pods

Discrete pods of relatively competent and/or higher grade rock are present, on all scales. They are elongate parallel to the stretching lineation, and cannot therefore be termed simple boudins which should be elongate at high angles to the stretching direction. Nevertheless, the thinning of pods towards their margins, the wrapping of foliation around them, and the precipitation of quartz and other minerals in their shadows, all bring to mind boudinage.

Internally, the pods often reveal earlier folding on axes parallel to their length, often with the folded layers steeper than the host schist which, wrapped around the pods, has a flatter foliation attitude. It is the folding in the pods that probably explains their general geometry. We suggest that the pods originate as competent units, 'thickened' in the vertical direction after folding on axes parallel to the stretching direction (Fig. 10) as a result of a transient shortening along the intermediate strain axis (as discussed in the preceding section of this paper). Such vertically oriented fold limbs, or a vertical layer that has been repeatedly folded, made of competent material, will thicken during subsequent shortening in the vertical direction, whereas the neighbouring horizontally disposed limbs will thin. They would therefore become a relatively rigid 'pod' parallel to the lineation around which the host schist would wrap as it underwent relatively high strain.

It is important to note that the typical way in which the host schist is wrapped around the pods, when viewed in the *YZ* section (Fig. 10c), indicates some extension along the intermediate strain axis. The fact that folds were produced in response to shortening along the intermediate axis suggests that the axis fluctuated in time and place from one of extension to one of shortening. Such fluctuations are probably a response to lithological heterogeneities. It may possibly be that the gross strain is actually plane, despite the conspicuous folding that catches the eye, and which would at first sight suggest a constrictional régime. Certainly the measured quartz *c*-axes fabrics suggest a more-or-less plane strain.

Whether or not the intermediate strain axis was one of shortening or extension, the effect was to rotate the otherwise flat-lying foliation about NW–SE axes, either by folding (shortening) or by wrapping around competent pods (extension). Such rotation of the foliation is seen in the plots of foliation in Fig. 9.

It is probably no coincidence that the late open folds of Quinquis and Choukroune (1981), their D2, and Cannat (1985), her D3, have axial trends that parallel the main stretching lineation. Small-scale late folds where axial planes are vertical are basically the same as those described here related to strain along the intermediate strain axis. The island scale open folds geometrically have much the same geometry as that of foliation which is wrapped around pods, and in essence it may be that these indicate two large pods, joined to form Ile de Groix. The boundary between the two possible pods runs from Locmaria to Port Tudy (Fig. 3), and it is not just foliation attitude that defines the pods, but the present shape and topography of the island.

4. The tectonic setting of Groix

The causes and mechanisms of exhumation of eclogite–blueschist facies rocks in complexes such as Groix are poorly understood, generally, and we do not have a magic solution here. In any case, the tectonic setting of exhumation is a secondary problem, the primary one being the reconstruction of the plate tectonic setting of Groix and neighbouring areas of NW France in the Paleozoic. Attempting such a reconstruction is beset with the following problems:

1. Groix is part of a South Armorican complex of fault-bound terranes with absolutely disparate geologies (Rolet, 1994). For instance, whilst the oceanic rocks of Groix indicate Silurian–Devonian subduction to depths of at least 70 km followed by exhumation to shallow depths, other parts of South Armorica such as the Ancenis Basin (Rolet, 1994, fig. 1) present a stable platform sequence of marine sediments ranging in age from the Ordovician into the Upper Devonian (Robardet et al., 1994).
2. Groix is just part of a broad region which extends through South Armorica into the Massif Central. Many parts of this region expose lower-middle Paleozoic oceanic volcanics, ophiolites, volcanic arcs, and high pressure metamorphism (Girardeau et al., 1986; Ledru et al., 1986; Ballèvre et al., 1987; Guiraud et al., 1987; Bodinier et al., 1988; Dubuisson et al., 1989), all of which have been explained as representing the lower-middle Paleozoic opening and closing of a South Armorican Ocean (Dubuisson et al., 1989). It is, however, difficult to reconcile this ocean with the platform sequence at Ancenis, for example.
3. It is also difficult to understand how such a South Armorican Ocean could open and close, with all the tectonism implied by areas such as Groix, whilst the immediately adjacent stable Paleozoic platform sequences of North Brittany and Southern France exhibit no significant signs of disturbance until the Middle Devonian or later (Robardet et al., 1994).
4. Other problems include (i), the fact that the Gondwanan Paleozoic platform sequence of North Brittany is proximal, the sequence of Southern France distal, yet their relative positions now with respect to Gondwana are the reverse of this (Robardet et al., 1994), and (ii), the fact that proximal Gondwanan sediments of North Brittany are immediately adjacent to the suture of the major

Rheic Ocean which closed during the Hercynian Orogeny.

We are presently trying to address these problems by an analysis of the greater French–Iberian Gondwana region in terms of the concept of suspect tectonostratigraphic terranes (Howell, 1995), and a paper discussing possible very large displacements is now in preparation.

5. Conclusions

1. The rocks of Groix record extensional strains with thinning vertical and stretching directions more-or-less horizontal in the NW–SE quadrant (in terms of present day coordinates). Shearing was either pure or on conjugate sets with both senses of shear equally important.
2. Bulk axes of strain in all Groix rocks, from the eclogite facies through blueschist to the greenschist facies, remained more-or-less parallel throughout the deformation.
3. The possibility that the well-known rhombic-shaped pseudomorphs are altered plagioclase, rather than lawsonite, deserves serious consideration. Calcium-bearing plagioclase is compatible with a simple *P–T–t* retrogressive metamorphism, whereas lawsonite would require a more complex *P–T–t* path.
4. Although sheath folds occur, there is no evidence that most of the conspicuous folds on Groix have that origin. The conspicuous folds are more likely to have formed in response to the intermediate strain axis being transiently or locally an axis of shortening, and they would have been initiated with axes parallel to the extension direction.
5. Pods of competent and/or relatively high grade material are parallel to the extension direction. They probably represent competent horizons, locally thickened by folding. The wrapping of foliation about them indicates that the intermediate strain axis was transiently or locally an axis of extension.
6. Fluctuations of the intermediate strain axis from one of shortening to one of extension suggests that the bulk strain may have been plane.
7. The so-called late, open, large-scale folds on Groix have the geometry of foliation wrapped around giant pods. It may be that Groix comprises two giant pods.
8. The highest pressures recorded for Groix rocks (ca. 2.0 GPa), and the presence of metasediments, require that the rocks were first subducted. The subducted material may have been part of an accretionary prism.
9. The Groix rocks are part of a large region of central France made up of oceanic volcanic rocks subjected to complex tectonic events and high pressure metamorphism in the Silurian–Devonian. It is unlikely that these events took place in the present geological context, mixed in with and sandwiched between areas of stable platform sediments of the same age. Work is in progress to address this problem by applying the ideas of suspect tectonostratigraphic terranes and invoking very large-scale displacements.

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