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Late Precambrian thrust and wrench zones in northern Brittany (France)

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Abstract—Brioverian units of northern Brittany (Armorican massif, France) were deformed and metamorphosed during a late Precambrian tectonic episode: the Cadomian orogeny. Kinematic study (strain and displacement) in the St Cast–St Brieuc area shows that this tectonic episode was characterized by the obduction of a back-arc basin over a continental margin around 580–590 Ma ago. Strain-pattern analysis reveals a constant interaction between SSW-directed imbricated thrust zones and ductile sinistral wrench zones trending N 50°E. The arcuate pattern of Cadomian structures in this area results from such an interaction. Thickening as a result of the thrusts induced migmatization and the development of a high temperature belt around 540 Ma in the St Malo–Guingamp area.

INTRODUCTION

THIS paper is devoted to the analysis of late Precambrian structures in northern Brittany (France). Structures, ductile deformation and metamorphism are related to the Cadomian orogeny in this area. An internal part of this block was studied in the area between St Brieuc and St Malo (Fig. 1). We identify zones of intense strain through an analysis of strain gradients. Geometry of structures and strain analysis show that the kinematics of the system can be related to the interaction of imbricate thrusts and wrench shear zones. This tectonic episode corresponds to the closure of a back-arc basin along a frontal and a lateral ramp around 580–590 Ma ago. The implications for the regional tectonics of this Cadomian block and its influence on the Variscan structures are discussed: in particular, the vergence of a possible subduction zone and the possibility of oblique convergence during the Cadomian.

GEOLOGICAL SETTING

The Cadomian domain of northern Brittany (Fig. 1) is bounded to the west by the Palaeozoic sedimentary plutonic and metamorphic complex of Leon (Chauris 1972, Balé & Brun 1986). This complex was previously considered to include some units of Precambrian metamorphic rocks (Cabanis 1976). Recent studies by Balé & Brun (1986) have shown that the Leon region

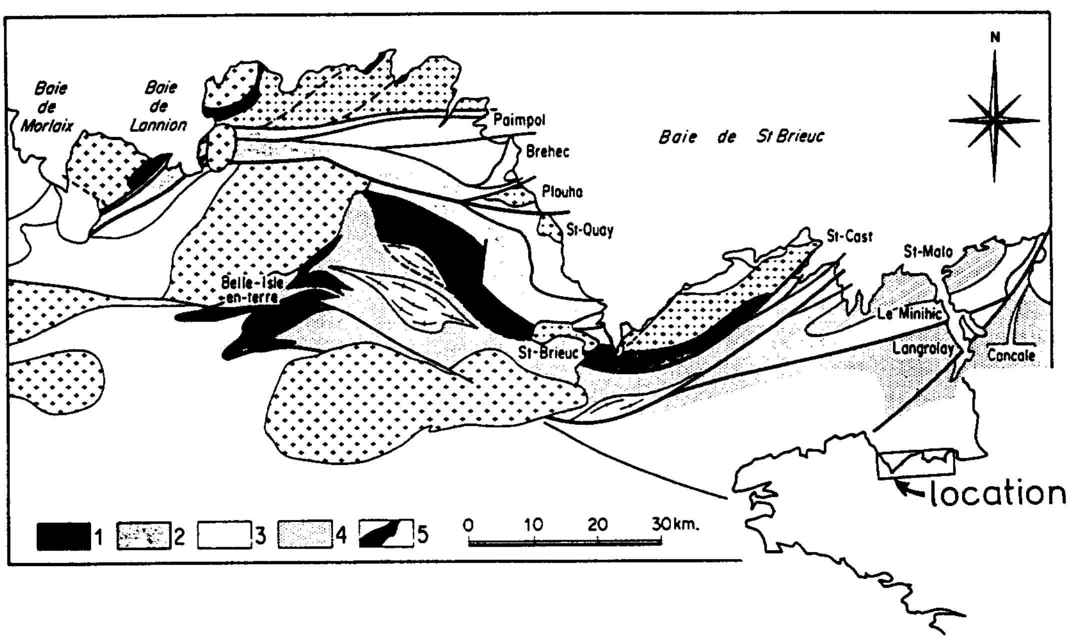

Fig. 1. Lithological and structural map of the Cadomian domain of northern Brittany. 1, Yffiniac metagabbro; 2, Lanvollon amphibolite and Tregor volcanics; 3, Binic metasediments; 4, Lamballe and St Malo metasediments and migmatites; 5, Icartian basement (~2000 Ma).

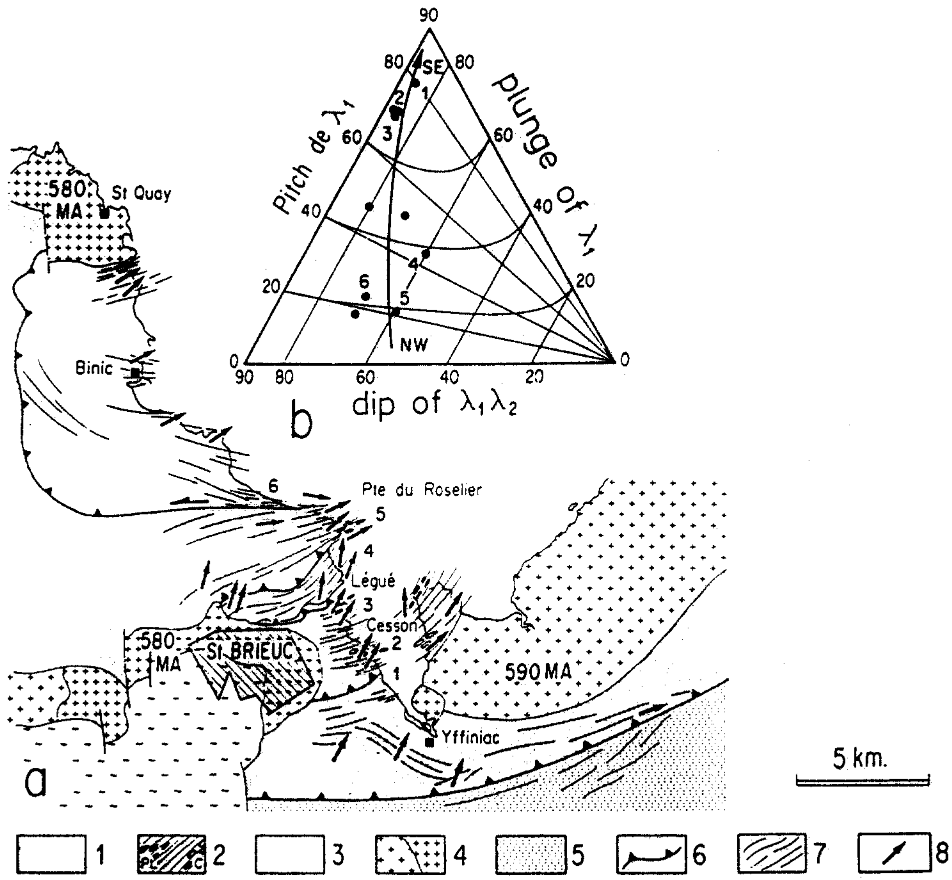

Fig. 2.(a) Geological and structural map. 1, Yffiniac metagabbro; 2, Lanvollon metavolcanics with pillow-lavas (PL) and conglomerates (C); 3, Binic and Légué metasediments; 4, dioritic and granodioritic intrusions; 5, Lamballe schist; 6, thrust faults; 7, cleavage trajectories; 8, stretching lineations. (b) Diagram showing from NW to SE the relative evolution of the $\lambda_1\lambda_2$ plane dip (foliation) and the pitch or plunge of the λ_1 direction (stretching direction). Numbers refer to stations quoted in (a).

would correspond to the eastern part of a large block of the Variscan collision belt of southern Brittany displaced to the north-east along a strike-slip shear zone during Devonian times. To the east, the Cadomian domain disappears underneath the Mesozoic series of the Paris Basin. To the south, it is covered by the Palaeozoic series of Central Brittany, and delineated by the North Armorican shear zone (Hirbec 1979, Watts & Williams 1979). For the purpose of the present paper, we define three main units in the western part of this Cadomian domain (Figs. 1 and 2).

The Tregor volcanic and plutonic belt is the north western unit of the domain. It is composed of (a) a granite and granodiorite batholith dated at 614^{+17}_{-10} Ma U–Pb on zircons (Graviou & Auvray 1985) and (b) a band of spilites and keratophyres of late Precambrian age (Auvray 1979) constituting a calc-alkaline complex of deep origin, which incorporates remnants of an old basement (Icartian in age, ~2000 Ma; Vidal *et al.* 1981). This volcanic and plutonic belt is considered to represent an island arc of Cadomian age above a SE-dipping subduction zone (Auvray 1979).

The St Brieuc metamorphic thrust belt (Balé & Brun 1983) consists of two types of amphibolites respectively derived from gabbro and basalt, and of metasedimentary gneiss and micaschist. This sequence of sediments, volcanics and gabbros is interpreted to represent back-arc oceanic crust (Balé & Brun 1983, Rabu *et al.* 1983). The thrust sheets were intruded during and after emplacement by gabbro, diorite and granodioritic plutons dated between 580 and 590 Ma (Vidal *et al.* 1972). The metagabbros have been recently dated at 602 ± 7 Ma (U–Pb on zircons, Peucat 1982, Guerrot 1985).

The high temperature belt, which is the southernmost unit of the domain, consists of micaschist, paragneiss and migmatite. Anatectic granites of the St Malo migmatitic dome (Brun 1977, Brun & Martin 1978, 1979) have been dated at 541 ± 5 Ma (Peucat 1982, 1986, U–Pb on zircons).

THE IMBRICATE THRUST BELT OF THE BAIE DE ST BRIEUC

Lithology and stratigraphy of units

Three metamorphic units imbricated by thrust faults may be recognized in the Baie de St Brieuc, namely the Binic and Légué metasediments, the Lanvollon amphibolite and the Yffiniac meta-gabbro. This whole pile of imbricated units is thrusted over the Lamballe schists and siliceous cherts (Fig. 2a) (Balé & Brun 1983). The main petrographic characters of these formations are briefly described from the top to the base of the thrust system.

The Binic and Légué metasediments are detrital formations which contain lenses of calc-silicate rock. The pelites and sandstones which constitute the turbidite sequences exhibit evidence of volcanic origin (Jeannette 1972, Rabu *et al.* 1983). At Binic, the metamorphism is at low grade except in the vicinity of the St Quay–Portrieux pluton where the sediments are affected by contact metamorphism. An analysis of the metamorphic paragenesis indicates a maximum pressure of 300–400 MPa at the site of emplacement (Fabries *et al.* 1985). This indicates a maximum thickness of 15 km of the sediments. Preferred orientation and dynamic growth of minerals in the zone of contact metamorphism indicates the syntectonic character of this event. In the Légué band (Fig. 2a), the metamorphism is at medium grade and characterized by the following mineral association: quartz + muscovite + garnet + biotite + chlorite. The Binic sediments were previously considered to be the uppermost formation of the Brioverian lying unconformably on the Lanvollon amphibolites (Jeannette & Cogné 1968). Balé & Brun (1983) and Rabu *et al.* (1983) have demonstrated a common deformation history for the two formations and refuted the evidence for a stratiraphic unconformity.

The Lanvollon amphibolite is a thick unit of fine-grained amphibolite which displays highly deformed pillow-lava structure, and which contains locally a few sedimentary layers of arkose and greywacke, and thin bands of acid volcanics. A polygenic conglomerate (Cesson) is present at the base of the pile. Metamorphism is at medium grade. The typical mineral association is blue–green amphibole + plagioclase + chlorite + quartz. U–Pb dating of granite pebbles from the Cesson conglomerate gives an age of 656 ± 5 Ma (Guerrot 1985, U–Pb on zircons). Note that the Lanvollon amphibolite was previously considered to represent the lower Brioverian lying unconformably on the Pentevrian basement (Cogné 1959, Cogné & Wright 1980).

The Yffiniac metagabbro is a thick unit of coarse-grained amphibolite derived from gabbro, in which original gabbroic textures can be observed locally in undeformed pods. The metamorphism is medium to high grade. Garnet amphibolite, pyroxenite and serpentinite are locally enclosed in this unit. The whole unit was previously considered to be the basement to the Brioverian series and was attributed to the Pentevrian (Cogné 1959). On the basis of petrological and structural similarities with the Belle-Isle-en-Terre basic formations (Hirbec 1979) dated at 602 $^{+4}_{-1}$ Ma (Peucat *et al.* 1981, U–Pb on zircons), Balé & Brun (1983) predicted a 600 Ma age for the Yffiniac gabbros. This has been recently confirmed by a U–Pb dating on zircon giving an age of 602 ± 7 Ma (Guerrot 1985).

Structures, deformation and strain

The emplacement and imbrication of thrust sheets in the Baie de St Brieuc is associated with a ductile deformation of the three units that increases in intensity from the north to the south.

Principal strain trajectories were constructed from measurements of the stretching lineation (λ_1 axis) and foliation ($\lambda_1\lambda_2$ plane). The stretching lineation is well developed in the Légué metasediments, in the amphibolite and in the metagabbro. It is defined by the preferred orientation of hornblende crystals and stretched aggregates of plagioclase in the amphibolites and by elongated quartz–feldspar aggregates in the Légué metasediments.

There is only one foliation at the scale of the thrust system. It generally parallels the layering of the amphibolites or the stratification of the metasediments except in the flat lying Binic metasediments, where it dips more steeply than the stratification. The strike lines of the foliation planes ($\lambda_1\lambda_2$) have been constructed at the scale of the thrust system (Fig. 2a). We note that the strike lines parallel the lithological boundaries.

If we divide the surveyed area in two domains, the λ_1 lineations display two characteristic directions at the scale of the surveyed area. In the southern domain, they are steeply plunging towards the NE. In the northern domain, they are shallow plunging towards the NNE. The change of orientation of λ_1 is observed in a narrow zone corresponding to the contact between the Légué metasediment and the Pointe du Roselier amphibolite (Fig. 2a). Nevertheless the relative evolution of the λ_1 plunge and λ_1 λ_2 dip is progressive from the south to the north. This is seen on the triangular diagram (Fig. 2b) whose axes are λ_1 plunge, λ_1 pitch and λ_1 λ_2 dip. Points plotted on the diagram show a continuous variation from thrusting type relationships to situations intermediate between thrusting and wrenching. Note that most of the area is characterized by intermediate type situations.

The analysis of principal strain trajectories confirms the interpretation in terms of a single phase of penetrative deformation (Balé & Brun 1983, Rabu *et al.* 1983) which is in contradiction with the previously prevailing polyphase model (Cogné & Wright 1980). Some variations in direction are related to local plutonic intrusions (e.g. St Quay Portrieux) or contacts between contrasted lithologic units. In the contact metamorphism zone around the St Quay Portrieux pluton, there is a local gradient of finite strain. The Binic metasediments display upright concentric folds with the axial planar cleavage striking 080°. Fold hinge lines plunge at 50° toward the NE, parallel to the stretching lineation. The interlimb angle of folds progressively decreases toward the contact of the pluton, and the cleavage, which grades into a metamorphic foliation, is itself folded in the immediate vicinity of the contact. Rabu *et al.* (1983) and Balé & Brun (1986) have listed the criteria that indicate the syntectonic character of the pluton emplacement: vertical foliation parallel to the diorite–country rock contact, and strong deformation and preferred orientation of metamorphic porphyroblasts in the fold limbs contrasting with low strain and misorientation in the hinges.

The metasediments of the Légué unit display all the characteristics of the Binic metasediments. In particular, the two units contain the same type of calc-silicate layers, which have never been observed in the Lamballe sediments. Two types of occurrences of these calc-silicates are frequent: cm-thick lenses, and thin layers strongly deformed and isoclinally folded, with hinges preserved and limbs attenuated by stretching. An additional character of the Légué unit never observed elsewhere is the presence of 1–10 m scale open folds that deform the foliation with axes parallel to the stretching lineation and mean axial plane orthogonal to the foliation. The undulation in the map contours of this unit (Fig. 2a) is attributed to the same deformation event at the map scale. We do not interpret this post-foliation folding as a distinct later phase of deformation. The Légué unit is enclosed between two thick units of amphibolites in which the post-foliation folds have not developed. It will be seen later that the strain ellipsoid in the Légué unit is of constriction type. Therefore, it is suggested that this late folding could be induced in the incompetent unit of sediments by differential movements between the two thick and irregularly shaped units of amphibolites.

The coarse-grained amphibolites of the Yffiniac unit are heterogeneously deformed. Near the contacts with the Lamballe sediments to the south and with Lanvollon amphibolites to the north they are strongly foliated and lineated. In the central part of the unit the deformation is localized in conjugate shear zones delimiting nearly undeformed blocks of gabbro. The shear zones have sharp boundaries indicating high strain gradients. The mean spatial attitude of stretching lineations and foliation is similar in the shear zones and in the boundaries of the Yffiniac unit. This indicates a coherent but heterogeneous bulk strain field for this unit.

Finite strain ellipsoid estimation

Estimates of the finite strain ellipsoid have been obtained from different types of strain markers, respectively pillow-lavas and volcanic vesicles in the fine-grained amphibolites and conglomerate clasts in metasediments. The methods of strain assessment depend on the nature of the strain markers and the intensity of finite strain.

In the Cesson conglomerate, which is located at the base of the Lanvollon amphibolites, two lithological types can be distinguished. The lower level is characterized by large pebbles and boulders locally more than 1 m in diameter. Most of the pebbles are granodiorite and the others are granite with globular quartz grains. The upper level is polygenic (granodiorite, quartzite, schist, aplite, granite) and contains smaller pebbles about 10 cm in diameter. The matrix is generally of arkosic composition and sometimes amphibolitic. Large blocks were collected on the outcrop and sawed parallel to the three principal planes of the strain ellipsoid.

Two types of pebbles were disregarded for strain measurement: respectively those of schist, which had high initial ratios due to their planar original fabric, and those of aplite, which were almost undeformed due to their strong ductility contrast with the matrix. Axial ratios (R_f) and orientations (ϕ) of granodiorite and quartzite pebbles were measured on several sections parallel to $\lambda_1\lambda_2$ and $\lambda_2\lambda_3$. Those kinds of pebbles that have a small ductility contrast with the matrix (slight cleavage refraction) slightly underestimate the intensity of strain undergone by the matrix. Measurements are treated according to the R_f/ϕ method (Dunnet 1969). This is justified by the non-spherical shape of pebbles before deformation. Results are reported in Table 1 (C1 and C2). The shape parameter ($K = (\lambda_1/\lambda_2 - 1)/(\lambda_2/\lambda_3 - 1)$, Flinn 1962) of the strain ellipsoid indicates constriction-type strain not far away from plane strain ($1 < K < 3$). The same method was applied to the quartz-filled volcanic vesicles in the Roselier amphibolites. The deformation of such an assemblage is equivalent to that of quartz pebbles in an amphibolitic matrix; and results may be directly compared with those obtained in conglomerates. Plots of R_f/ϕ values on Dunnet (1969) charts show the initial ratios did not exceed 2. This initial ellipticity is surely due to the compaction of pillow-lavas following the volcanic event. Measurement made on the three principal planes in the samples give an excellent correlation for the strain ratios

Table 1. Strain measurements in St Brieuc Bay

Sites	Nature of rocks	Strain markers	Method of strain measurement	λ_1/λ_2 (a)	λ_2/λ_3 (b)	K	r
Cesson C1	(Arkose) Conglomerate	Pebbles	Dunnet (R_f/ϕ)	3.6	2.1	2.36	4.70
Cesson C2	(Arkose) Conglomerate	Pebbles	Dunnet ($R_f\phi$)	3	2.1	1.82	4.10
Roselier RO_1	Amphibolite	Vesicles (quartz)	Dunnet (R_f/ϕ)	2.6	1.5	3.2	3.1
Roselier RO_2	Amphibolite	Vesicles (quartz)	Dunnet (R_f/ϕ)	2.4	1.5	2.8	2.9
Pte de Cesson	Amphibolite	Pillow-lavas	Ramsay	5	4	1.3	8
Yffiniac	Gabbro	Mineral relicts	Dunnet (R_f/ϕ)	2	2.1	0.91	3.1

($\lambda_1/\lambda_3 = \lambda_1/\lambda_2 \times \lambda_2/\lambda_3$) and quasi-isotropic initial distribution of the strain markers. Results (Table 1) give a constriction type strain ellipsoid (K = 2.8 and 3.2). The strain intensity (r parameter, $r = \lambda_1/\lambda_2 + \lambda_2/\lambda_3 - 1$) is lower than in the conglomerates.

Strongly deformed pillow-lavas occur in the upper part of the Cesson series near the contact with the metasediments of the Légué series. Because of high axial ratio of the pillows (up to 20 : 1 in the $\lambda_1\lambda_3$ plane) the measurements were performed directly on the outcrop. The fluctuation or variation in angle was negligible so the strain ratio was obtained by calculating the slope of the least-squares line between the long and short axis of pillows (Ramsay 1967). Because pillow-lavas constitute a closely packed assemblage, the volume of matrix is negligible. Therefore strain measurements obtained from deformed pillows characterize the whole rock strain. Here again the shape parameter of the strain ellipsoid ($1 < K < 3$) indicates plane to slightly constrictive strains (Table 1). Strain intensities are high. The comparison with previous values obtained by the R_f/ϕ method must be handled with care due to the viscosity contrast in conglomerates and vesicular volcanics. Nevertheless because r values are twice those measured in the conglomerates it is indisputable that the strain intensity is higher at the top of the Cesson series.

As quoted before, the Yffiniac amphibolite is heterogeneously deformed. Strain measurements obtained locally are not representative for the whole mass. However, it was interesting to have an indication of the strain ellipsoid shape in the unit. A measurement was achieved on low strained blocks of gabbros occurring between the conjugate shear zones. Strain markers used for the measurement were pseudomorph pods after minerals or patches of minerals (probably pyroxene). The R_f/ϕ method gives a value K = 0.91 (near plane strain, see Table 1). The results obtained at the different sites are plotted on a Flinn (1962) diagram. Note the concentration of points near the plane strain line (K = 1) with a tendency for scattering in the constriction field (Fig. 7).

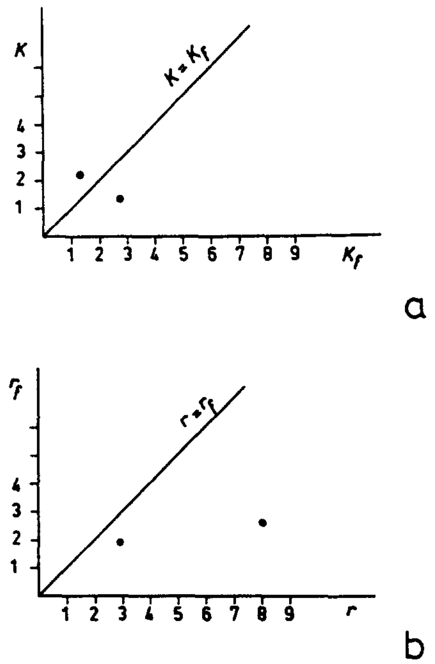

Fig. 3. Comparison between strain ellipsoid parameters and amphibolite fabric parameters: (a) K and K_f, (b) r and r_f.

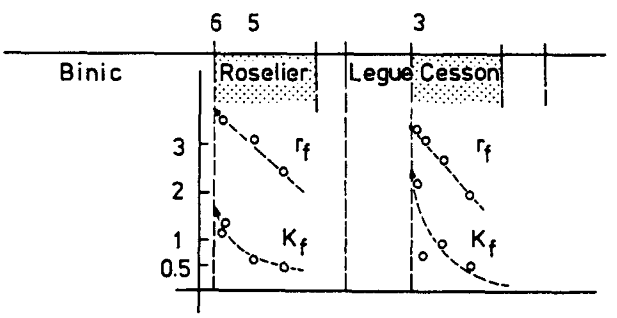

Fig. 4. Variations in fabric ellipsoid parameters from Binic to Sesson.

Fabric ellipsoid

The preferred orientation of [110] axes of blue–green amphiboles has been determined in the fine-grained amphibolites by texture goniometry. A fabric ellipsoid is computed according to the method described by Gapais & Brun (1981) which gives a K_f shape parameter and a r_f intensity parameter. It has been shown (Gapais & Brun 1981) that K_f is a good approximation of the K value of the strain ellipsoid even if the r_f underestimates the r value of strain intensity (Fig. 3). Nine sites have been sampled and treated along the two available natural sections of fine-grained amphibolite along the coast (Figs. 4, 5 and 7; Table 2). Along the two sections K_f and r_f values increase towards the top of amphibolite units, indicating a correlation between fabric and strain. It is acknowledged that the amphibolite fabric is not only a

Table 2. Fabric ellipsoid in deformed amphibolites

Sites	λ_1/λ_2	λ_2/λ_3	K_f	r_f
C2	1.31	1.61	0.51	1.92
$L6_a$	1.82	1.85	0.96	2.67
$L6_b$	1.82	2.28	0.64	3.10
GT3	2.04	1.47	2.22	2.51
M2	1.74	2.32	0.56	3.06
R0	1.45	1.94	0.47	2.39
R32	1.53	1.39	1.37	1.92
R1	2.41	2.07	1.33	3.48
H4	2.24	1.44	2.82	2.68

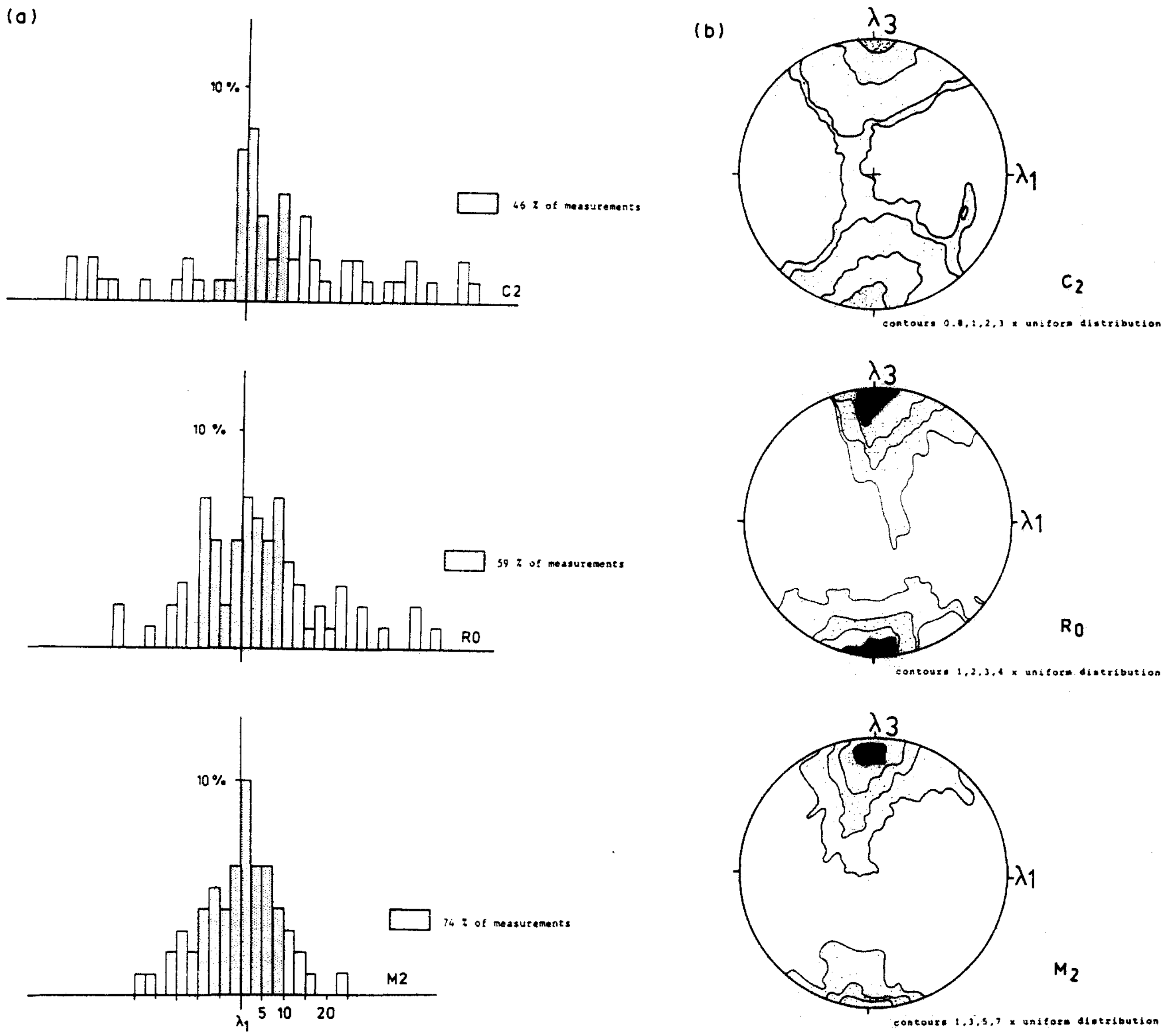

Fig. 5. Representation of a fabric intensity gradient in three amphibolite samples. (a) Frequency histograms of amphibole long-axis orientations using optical microscopy. (b) Pole figures of [110] axes of amphiboles using texture goniometry.

function of finite strain and depends on other parameters such as initial fabric, physical mechanisms of deformation, grain size, relative proportions of amphiboles, quartz and plagioclase. Anomalies have been detected which can be explained by some of these parameters. So, a few sampled levels with low percentage of amphiboles were characterized by a strong r_f decrease although K_f remained unchanged.

The analysis of strain and fabric ellipsoid give common important results.

(1) The bulk finite strain is not far away from plane strain ($1.4 < K < 0.7$) (Fig. 7).

(2) The finite strain ellipsoid is displaced toward the constriction field when the pitch of λ_1 in the $\lambda_1\lambda_2$ plane decreases. Strike-slip attitudes of the stretching lineation give the most constrictive strains, whereas thrust type attitudes correspond to nearly plane strain (Fig. 6).

(3) As a mean the strain intensity increases from north to south (Figs. 7 and 8).

(4) Local gradients of strain intensity are associated with contacts between the three lithological units (Figs. 4, 7 and 8).

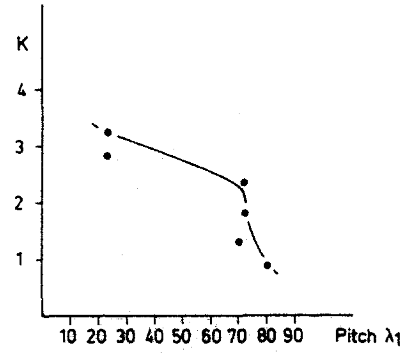

Fig. 6. Diagram showing the relation between v_1 pitch and K parameters.

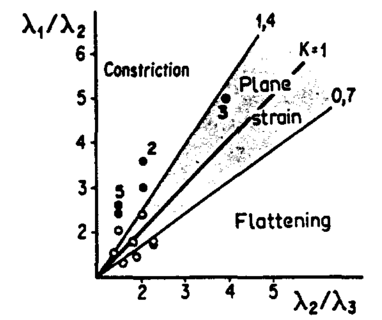

Fig. 7. Geometrical characteristics of finite strain ellipsoids (black dots) and fabric ellipsoids of amphibolites (open circles) between Cesson and Binic Formations. Numbers refer to stations quoted in Fig. 2(a).

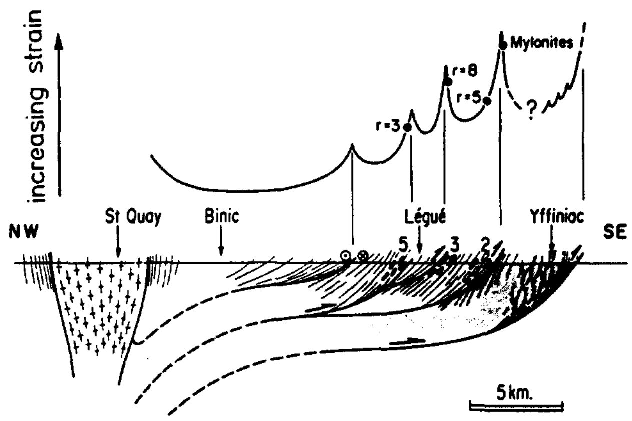

Fig. 8. Interpretative cross-section of the Bay of St Brieuc between St Quay and Yffiniac. The curve shows qualitatively the evolution of strain intensity. The parameter $r = \lambda_1/\lambda_2 + \lambda_2/\lambda_3 - 1$) is indicated for three of the stations quoted in Fig. 2(a).

Finite shear components

Evidence for non-coaxial deformation are not very numerous. They are mainly C' type shear bands (Berthé *et al.* 1979a,b) porphyroclast rotation and asymmetry of minor folds. They all indicate a shear sense top to the SW or WSW. Strain intensity gradients associated with lithological contacts are compatible with this interpretation and show that the discontinuities between the units are zones of intense shear.

Spatial variation of principal axes of finite strain

The main contact between Yffiniac metagabbro and the Lamballe Formation (Fig. 17) shows an arcuate pattern at the scale of the map. This arcuate pattern is related to a kinematic evolution of strain (see Discussion). The position of principal axes changes along the contact: in particular, stretching lineation λ_1 becomes horizontal on a subvertical $\lambda_1\lambda_2$ plane toward the NE (Fig. 17a). Shear criteria are always constant in sense. It is possible to follow this progressive evolution to the St Cast area. A detailed study has been undertaken in this area because of the outcrop of complete sections perpendicular to the structures (Fig. 9).

THE SINISTRAL WRENCH SHEAR ZONE OF ST CAST

The lithologic units constituting the St Cast shear zone are bounded to the northwest by the Plevenon diorite and the southeast by the St Malo migmatites (Jeannette 1972, Brown 1978). They mainly consist of para- and orthogneiss and micaschist (Fig. 9). At the Pointe de St Cast there is a distinctive rock known as the "Roche St

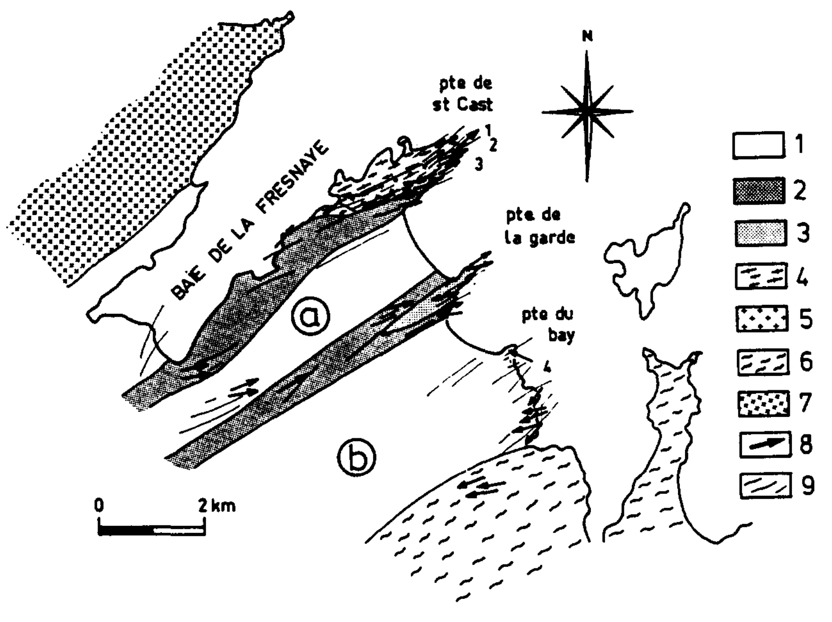

Fig. 9. Geological and structural map of the St Cast area. 1, Lamballe schist; 2, gneiss; 3, orthogneiss and paragneiss mylonites; 4, granodiorite; 5, syntectonic leucogranite; 6, migmatites; 7, Coëtmieux–Fort-la-Latte diorite; 8, stretching lineation; 9, foliation trajectories.

Cast". It is an orthogneiss derived from a leucogranite, which is very strongly deformed. Micaschist and gneiss from the Point de la Garde are derived from two types of sediments. The first type is dark and rich in fine-grained plagioclase, and contains calc-silicate layers and volcanic quartz grains. They are fairly comparable with Binic and Légué metasediments. The second type is more pelitic and contains phtanitic layers that are believed to be typical of the Lamballe series (Cogné & Wright 1980). The two types of metasediments are interlayered. This situation seems to us to result from a strong tectonic imbrication during the deformation. This point will be discussed later.

All these units were metamorphosed in the amphibolite facies. Biotite and garnet are stable in the foliation surfaces. Locally sillimanite is present and metatexites (Menhert 1968) are developed and show an incipient partial melting, especially at St Cast harbour and Pointe de la Garde. All rock types are strongly deformed.

Strain analysis

A northern domain (a on Fig. 9) is characterized by a nearly vertical foliation plane ($\lambda_1\lambda_2$) striking 050–060°, bearing a strong stretching lineation (λ_1) especially well marked in gneisses (Fig. 14). In the micaschists, which have a $L < S$ type fabric (Flinn 1965), the lineation is outlined by quartz–feldspar aggregates. In this zone, the pitch of λ_1 in the $\lambda_1\lambda_2$ plane is never greater than 30°. In the southern domain, the foliation is locally crenulated and deformed by open folds. The stretching lineation whose low pitch and strike are constant over most of the domain deviates locally around folds (Fig. 9).

A plot of λ_1 pitch against $\lambda_1\lambda_2$ dip (Fig. 10) demonstrates the dominant strike-slip character of the whole shear zone. Only a few points fall in the intermediate field between strike-slip and thrust shears.

Markers suitable for strain analysis were found at only a few sites. A qualitative interpretation was made using the symmetry of L–S fabrics or tectonites (Flinn 1965). Figure 11 illustrates the variations of L–S fabrics across the shear zone from the Baie de la Fresnaye to the Plage des Quatre-Veaux. Most of the zone is characterized by L–S fabrics. The Pointe de St Cast and Pointe de la Garde outcrops display a strong lineation ($L > S$ fabric) and the southern domain defined before (Fig. 9) a strong foliation ($S > L$ fabric).

At St Cast, strain measurements were performed using micaceous xenoliths in orthogneisses. For two sites, long and short axes of the xenoliths were directly measured on the outcrop in the foliation plane ($\lambda_1\lambda_2$) and in a plane perpendicular to the stretching lineation ($\lambda_2\lambda_3$). The strain ratio was obtained by plotting long axes vs short axes and computing the slope of the best-fit straight line (least-squares method). For a third site, the fluctuation in orientation of xenoliths was too high in the $\lambda_2\lambda_3$ plane for this method to be used. Samples were cut and measured in the laboratory. Strain ratios were com-

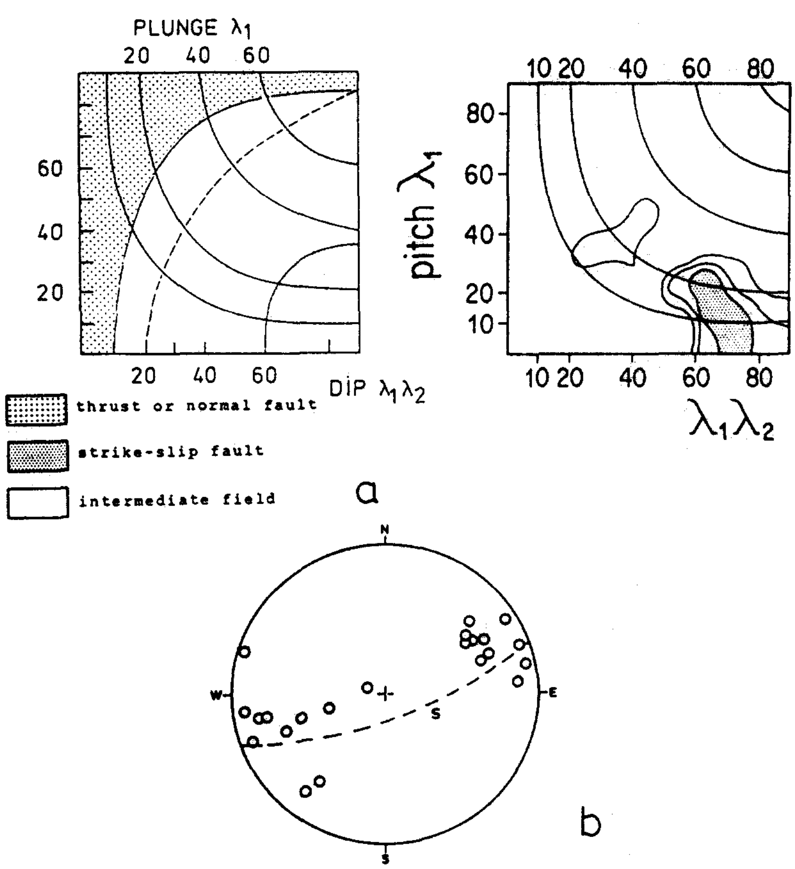

Fig. 10.(a) Diagram showing the statistical attitude of λ_1 on $\lambda_1\lambda_2$ plane. (b) Stereo plot of stretching lineation (λ_1). S represents the average λ_1 plane.

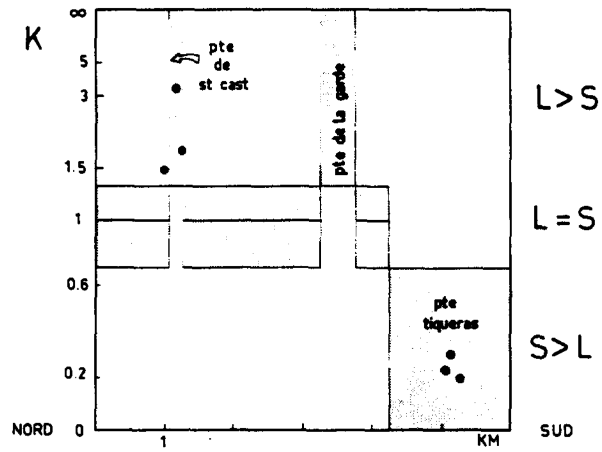

Fig. 11. Qualitative shape parameters of strain ellipsoid using the Flinn tectonite scheme along a N–S cross-section through the St Cast shear zone (black dot represents the quantitative measurements).

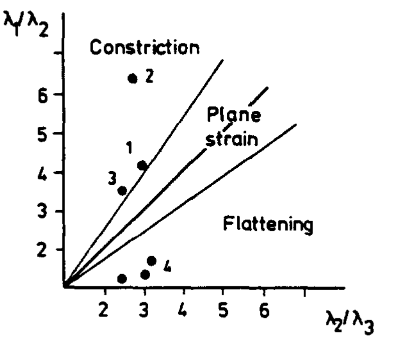

Fig. 12. Flinn diagram showing quantitative measurements of strain ellipsoid.

puted using the R_f/ϕ method. Results are plotted on a Flinn diagram (Fig. 12) and reported on Table 3. For two sites, the K parameter (1.71 and 1.5) indicates nearly plane strain or slightly constrictive ellipsoids. The third site sampled in a mylonitic shear zone gives a highest K value (3.18) and a strong strain intensity ($r = 8.1$) that is certainly underestimated, the extremities of the long axes of xenoliths being difficult to locate precisely in ultramylonites.

In the southern domain, the strain ellipsoid shape was estimated from deformed veins using the minimum strain ellipsoid method of Talbot (1970). Because veins appeared during the deformation, the strain parameters K and r obtained by this method are certainly not representative of the whole strain undergone by the rocks. They should represent a late finite strain increment. Results are plotted on a Flinn diagram (Fig. 12) and reported in Table 3. K values range between 0.2 and 0.3 indicating flattening type strain ellipsoids. r values are low (between 1.5 and 2.5). Even if these strain intensity amounts do not represent the bulk finite strain, it is striking that the strain intensity in this area is lower than in the northern domain. This conclusion is corroborated by examination of mesoscopic fabrics.

In conclusion, the finite strain across the shear zone is characterized by an increase in the mean strain intensity from south to north, with two local zones of high strain (Pointe de la Garde and Pointe de St Cast). Strain is nearly plane, except in the south where the strain is of flattening type, and in the zones of very intense strain where the strain becomes slightly constrictional (Fig. 13).

Finite shear components

Evidence for non-coaxial deformation is abundant. All criteria indicate a bulk sinistral finite shear component striking 040°.

Shear bands. These are well developed in gneisses. In the northern domain and especially at the Pointe de la Garde and the Pointe de St Cast, *C–S* structures and *C′* shear bands (Berthé *et al.* 1979a,b) are well developed. At the Pointe de St Cast, the Roche St Cast (gneissose leucogranite) displays very clear sinistral *C–S* structures in which the *C* shear bands are cm spaced. The regularity of the *C–S* fabric gives a very homogeneous aspect to the rock (Fig. 14). At the scale of the outcrop, the angle between *C* and *S* is always lower than 20°. When *C* and *S* planes are near parallel *C′* shear bands start to develop, finite strain passes from plane strain to constriction, and the stretching lineation becomes stronger (Figs. 12 and 13). The transition is relatively sharp and a progressive

Table 3. Strain measurements in St Cast Area

Sites	Nature of rocks	Strain markers	Method of strain measurement	λ_1/λ_2 (a)	λ_2/λ_3 (b)	K	r
Port Jacquet 3	Granodiorite	Xenoliths	Ramsay	3.57	2.5	1.71	5.07
Pte de St Cast 1	Granodiorite	Xenoliths	Ramsay	4	3	1.5	6
Pte de St Cast 2	Granite	Xenoliths	Dunnet (R_f/ϕ)	6.4	2.7	3.18	8.1
Pte de Tiqueras 4	Micaschists	Quartz veins	Talbot	1.25	1.90	0.26	2.20
Pte de Tiqueras 4	Micaschists	Quartz veins	Talbot	1.32	2.10	0.3	2.42
Pte de Tiqueras 4	Micaschists	Quartz veins	Talbot	1.09	1.47	0.2	1.56

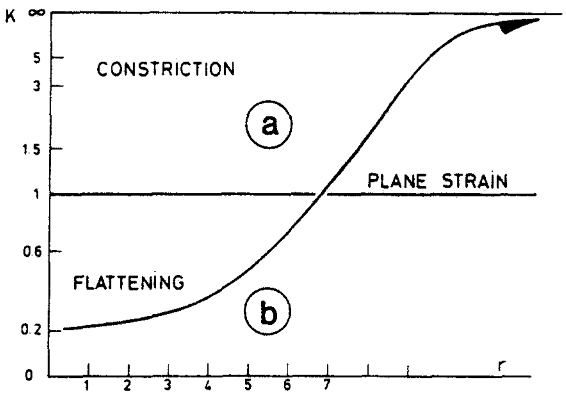

Fig. 13. Plot of K v r in the St Cast area.

decrease of the C–S angle is not observed. The strain pattern in the country rocks apparently contrasts with the pattern in the deformed intrusion. The deformation of the country rocks, which are made of orthogneisses derived from granodiorite material, is heterogeneous at the scale of the outcrops. Anastomosing conjugate shear zones delineate low-strained lenticular blocks. Sinistral shear zones striking 040–050° are more numerous than dextral shear zones. The two sets of shear zones are compatible with a bulk sinistral wrench shear interfering with the emplacement of the Roche St Cast, and do not result from two superposed deformations (Gapais *et al.* in press, Gapais & Balé in preparation). The bulk foliation plane is constant in orientation and parallel to the foliation in the Roche St Cast.

The Point de la Garde gneisses are the most intensely strained rocks of the section. C and S planes are parallel and C' shear bands are locally well developed (Fig. 14) and indicate a sinistral wrenching component. In some places there are conjugate shear bands indicating a dextral shear. Here again finite strain is slightly constrictional and the stretching lineation is very strong. In the southern domain (Fig. 9), shear bands are less numerous than in the northern domain. The contact with the St Malo migmatites to the south is characterized by a late dextral sense and a narrow shear zone. This deformation, which affects the migmatites themselves, is later than 540 Ma (age of the anatectic granite; Peucat 1982). We relate dextral kink bands and en échelon veins in the micaschists of the southern domain to this event.

Other shear criteria have been observed at the sample and outcrop scales or in thin section: rotation of quartz veins, rotation of porphyroclasts, asymmetric pressure shadows around feldspars and asymmetric quartz fabrics (Fig. 15).

Quartz fabrics. An analysis of quartz fabrics in a quartzite sample from the Pointe de la Garde has been performed using a texture goniometer. Figure 15 shows preferred orientations of [1014] (which gives a good indication of the preferred orientations of the c axis; Gapais 1979) and [a] axes in the $\lambda_1\lambda_3$ plane. The asymmetry of fabric diagrams indicates the non-coaxial character of the deformation and confirms the sinistral wrenching component deduced from mesoscopic shear

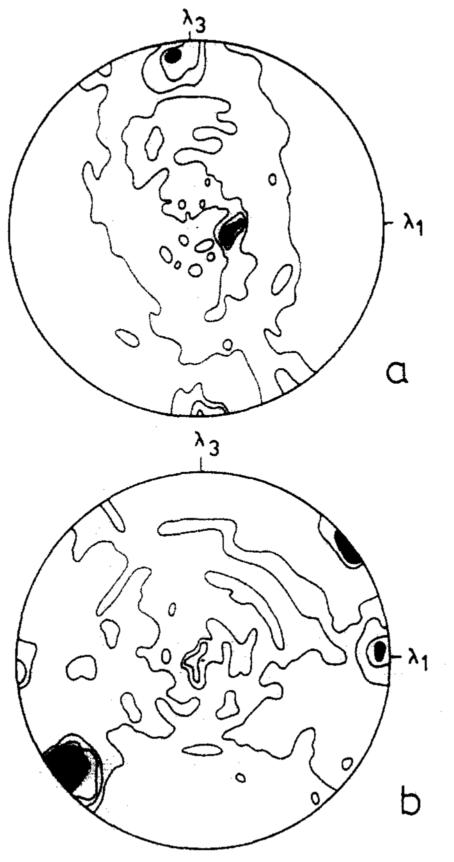

Fig. 15. Pole figure of quartz fabric. (a) [1014] axes. (b) [a] axes. Note the sinistral asymmetry of the pole figure (Pte de la Garde).

criteria. The statistical orientation of the [1014] axes shows concentrations parallel with the λ_2 and λ_3 strain axes indicating both prismatic and basal slip. The lack of [a] axis concentrations on λ_3 tend to prove the predominance of basal slip. From the finite strain point of view, these types of quartz fabric result from plane strain type ellipsoid (Gapais & Cobbold in press).

Folds. Most of the observed folds are of metre scale. They are compatible with the bulk sinistral wrenching. In the northern domain, fold axes are parallel to the stretching lineation (Fig. 16). At the Pointe de la Garde,

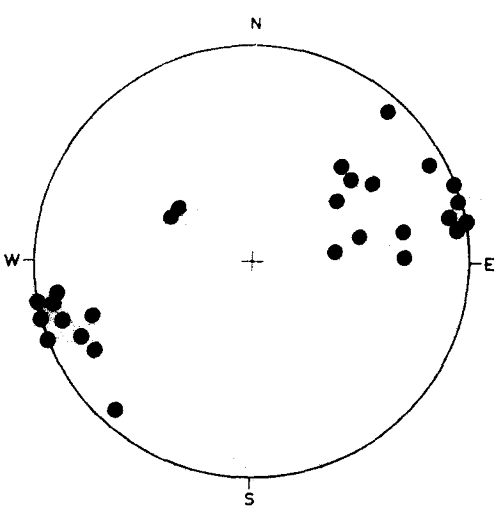

Fig. 16. Stereoplot of fold axes in the St Cast area.

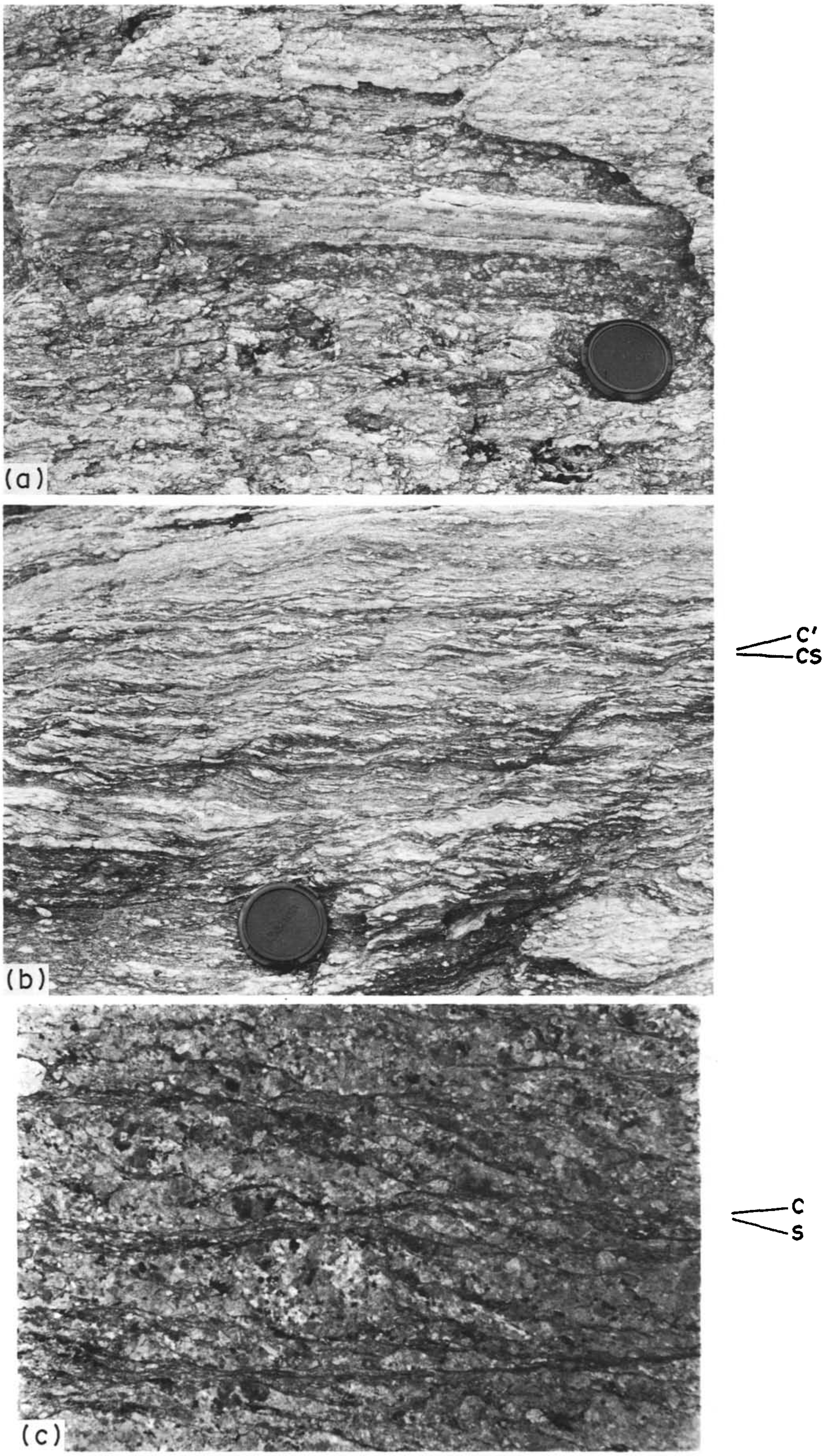

Fig. 14. (a) Quartz rods showing the strong horizontal stretching lineation at St Cast (Pte de la Garde): $\lambda_1\lambda_2$ plane. (b) Sinistral C' shear bands within mylonites at the Pte de la Garde: $\lambda_1\lambda_3$ plane. (c) Sinistral C–S type relation in the Rock St Cast.

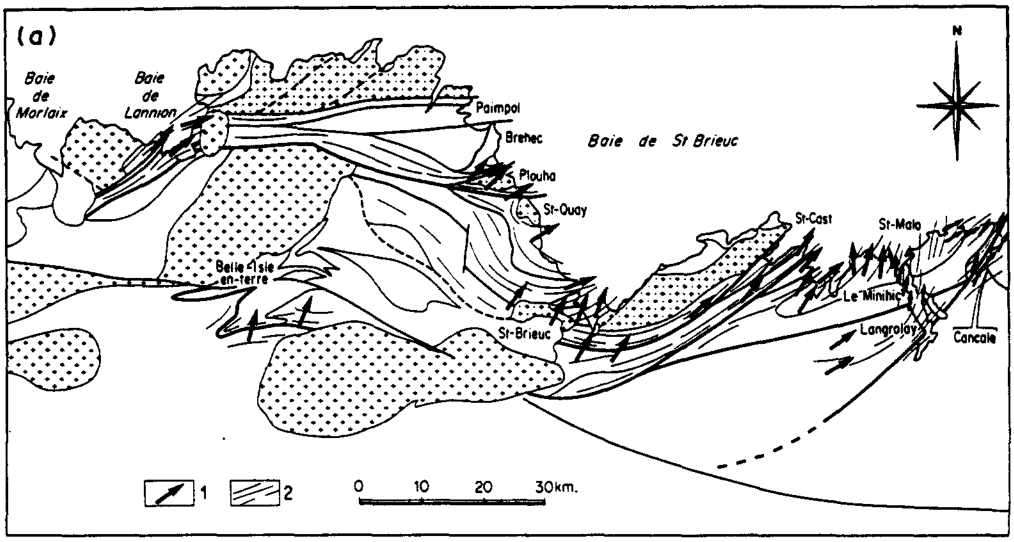

Fig. 17. (a) Map of Cadomian structures. 1, Stretching lineations; 2, foliation trajectories. (b) Cross-sections in the Cadomian Domain.

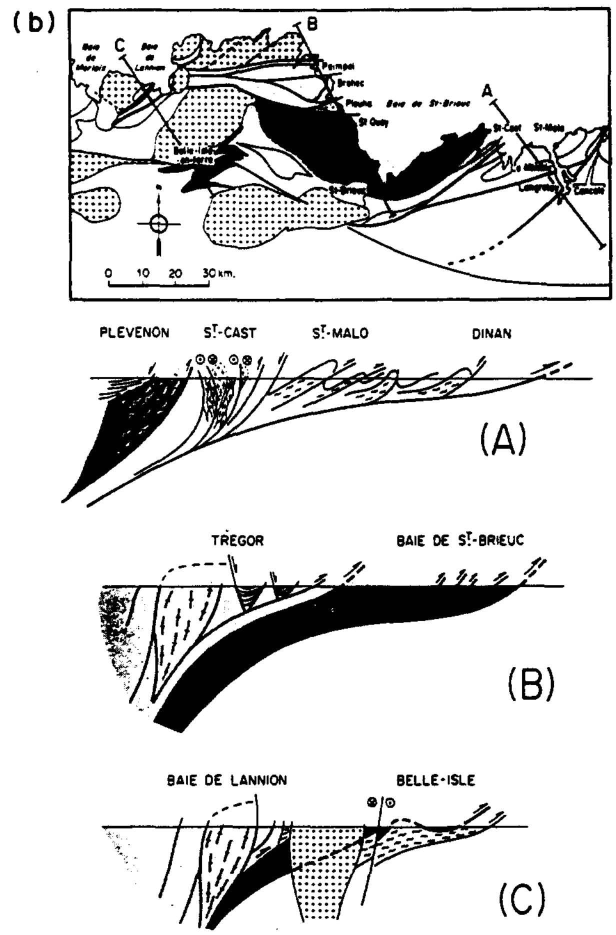

Fig. 17. (b)

sheath folds are marked by calc-silicate bands or quartz and quartz–feldspar veins. At the same place there are syntectonic folded dykes of granite. In the southern domain, folds that deform the foliation are more open and fold axes plunge steeply (Fig. 16).

In conclusion, the analysis of strain trajectories, finite strain ellipsoids and finite shear components demonstrate that the St Cast area is a large sinistral wrenching shear zone. The finite strain gradients inside the zone are associated with two zones of preferential movement at the Pointe de St Cast and the Pointe de la Garde. We note that they correspond to contacts between micaschist and gneiss.

DISCUSSION : A GENERAL MODEL FOR THE ST BRIEUC–ST CAST DEFORMATION

Strain gradients and principal strain trajectories have been used to delineate major surfaces of movement or zones of high strain at the regional scale. They are summarized in Fig. 17(a). The analysis of the finite shear component gives indications of the direction and sense of movement along these zones. The structural continuity which is observed from St Cast where sinistral strike-slip is dominant to St Brieuc where southwestward thrusting is dominant indicates (a) a curvature of the movement surfaces at the regional scale (Fig. 17a), and (b) the combined nature of thrust and strike-slip displacements in Cadomian tectonics (Fig. 19).

The map of movement zones when compared to the geological map (Fig. 1) helps to identify three types of zones. Firstly there are zones separating two domains with different lithologic assemblages. They are the main Cadomian thrust (MCT Fig. 17) which separates the Baie de St Brieuc series from the Lamballe sedimentary series, and the south Tregor thrust (STT, Balé in press) which separates the plutonic and volcanic (Auvray 1979) formation of the Trégor from the St Brieuc series. Second are thrusts and strike-slip faults that cut up-section in the Baie de St Brieuc series. Third are movement surfaces that follow lithologic contacts between Binic-Légué, Cesson-Roselier and Yffiniac units. We interpret two latter types of movement zones as the results of décollements within the St Brieuc thrust belt (Fig. 18, see also Fig. 8).

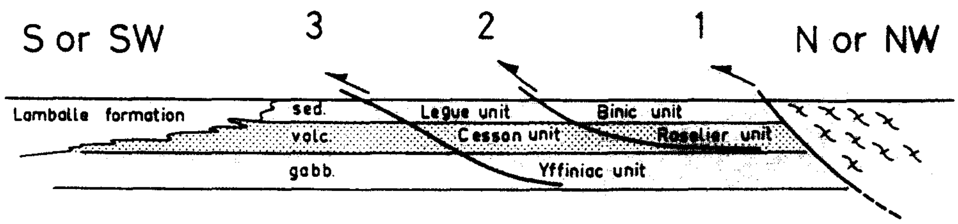

Fig. 18. Possible relation between thrusts and regional units.

Both structural data presented here and previous work (Balé & Brun 1983) and geochronological data (Vidal *et al.* 1981, Peucat 1982, 1986, Guerrot 1985) lead to a new geological history for the Cadomian orogeny in Northern Brittany.

Firstly, the existence of a Pentevrian basement (Cogné 1959) has not been confirmed. The oldest rocks known in the region are Icartian in age (Vidal *et al.* 1981) and only occur in the Tregor block. Between the STT and the MCT all ages range between 650 Ma (granite pebbles in the Cesson conglomerate, Guerrot 1985) and 580 Ma (diorites and granodiorites, Vidal *et al.* 1972, Auvray 1979). The three lithologic units of the Baie de St Brieuc thrust belt can be interpreted as a back-arc basin or volcanic arc (Balé & Brun 1983, Rabu *et al.* 1983). The lower unit of gabbro gives an age of crystallization of 602 ± 7 Ma (Guerrot 1985). Cesson conglomerate pebbles dated at 656 ± 5 Ma (Guerrot 1985) may themselves represent erosion products of volcanic arc.

Syntectonic plutons (e.g. Coëtmieux–Fort-la-Latte dated at 593 ± 15 Ma, St Quay 584 ± 56 Ma) and the 587 ± 1 Ma date for the metamorphism of gabbros (Guerrot 1985) give the age of the thrusting in the Baie de St Brieuc (Fig. 19). Note the short time lapse between the age of gabbros (602 Ma Yffiniac and Belle-Isle-en-Terre) and the age of thrusting (590–580 Ma). This would be easily explained in terms of volcanic arc accretion.

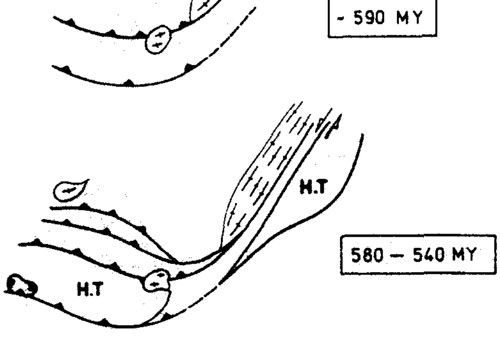

Fig. 19 Model of possible progressive development of arcuate structures in St Brieuc–St Malo area.

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REFERENCES

Auvray, B. 1979. Genèse et évolution de la croûte continentale dans le Nord du Massif Armoricain. Unpublished thèse d'Etat, University of Rennes.

Balé, P. In press. La tectonique cadomienne dans l'Est du Tregor. *Bull. B.R.G.M.*

Balé, P. & Brun, J.-P. 1983. Les chevauchements cadomiens de la Baie de St Brieuc. *C. r. hebd. Séanc. Acad. Sci., Paris* II, **297**, 359–362.

Balé, P. & Brun, J.-P. 1986. Les complexes métamorphiques du Léon (NW Bretagne): un segment du domaine éohercynien sud-armoricain translaté au Dévonien. *Bull. Soc. géol. Fr.*, 8 *Ser.*, II, 3, 471–477.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979a. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican Shear Zone. *J. Struct. Geol.* **1**, 31–42.

Berthé, D., Choukroune, P. & Gapais, D. 1979b. Orientations préférentielles du quartz et orthogneissification progressive en régime cisaillant: l'exemple du Cisaillement Sud-Armoricain. *Bull. Minéral.* **102**, 265–272.

Brown, M. 1978. The tectonic evolution of the Precambrian rocks of the St Malo region, Armorican Massif, France. *Precamb. Res.* **6**, 1–21.

Brun, J.-P. 1977. La zonation structurale des dômes gneissiques. Un exemple: le Massif de Saint-Malo (Massif Armoricain, France). *Can. J. Earth Sci.* **14**, 1697–1707.

Brun, J.-P. & Martin, H. 1978. Relations métamorphisme–déformation au cours de l'évolution d'un dôme migmatique: le Massif de St Malo (France). *Bull. Soc. géol. Fr.* XX, **1**, 91–101.

Brun, J.-P. & Martin, H. 1979. The St-Malo Migmatite Belt: a late Precambrian gneiss dome. A comment. *Precamb. Res.* **8**, 137–143.

Cabanis, B. 1976. Arguments en faveur d'un socle orthogneissique dans le Pays du Léon (Bretagne). *C. r. hebd. Séanc. Acad. Sci., Paris* **D282**, 263–266.

Chauris, L. 1972. *Légende de la Feuille au* 1/80 000 (3rd Edn). B.R.G.M., Brest.

Cogné, J. 1959. Données nouvelles sur l'Antécambrien dans l'Ouest de la France: Pentévrien et Briovérien en Baie de St Brieuc (Côtes du Nord). *Bull. Soc. géol. Fr.* 7 Ser., **1**, 112–118.

Cogné, J. & Wright, A. E. 1980. L'orogène cadomien. In: *Colloquium Géologie de l'Europe, 26th Congress Géol. Int.*, Paris, 29–55.

Dunnet, D. 1969. A technique of finite strain analysis using elliptical particles. *Tectonophysics* **7**, 117–136.

Fabries, J., Arnaud, G. & Conquéré, F. 1985. Paragenèse à biotite—cordiérite–antophyllite dans l'auréole métamorphique au Sud du pluton gabbro–dioritique de St Quay–Portrieux (Côtes du Nord). *Bull. Soc. géol. Fr.* 8 Ser., I, **3**, 435–440.

Flinn, D. 1962. On folding during three dimensional progressive deformation. *Q. Jl geol. Soc. Lond.* **118**, 385–433.

Flinn, D. 1965. On the symmetry principle and the deformation ellipsoid. *Geol. Mag.* **102**, 36–45.

Gapais, D. 1979. Orientations préférentielles de réseau et déformations naturelles. Applications aux quartzites (segment hercynien de Bretagne Centrale) et aux amphibolites (couverture des dômes gneissiques de Kuopio, Finlande). Unpublished thèse 3e Cycle, University of Rennes.

Gapais, D., Balé, P., Choukroune, P., Cobbold, P., Mahdjoub, Y. & Marquer, D. 1987. Bulk kinematics from shear zone patterns: some field examples. *J. Struct. Geol.* **9**, 635–646.

Gapais, D. & Brun, J.-P. 1981. A comparison of mineral grain fabrics and finite strain in amphibolites from Eastern Finland. *Can. J. Earth Sci.* **18**, **6**, 996–1003.

Gapais, D. & Cobbold, P. In press. Slip system domains 2: kinematic aspects of fabric development in polycrystalline aggregates. *Tectonophysics.*

Genestier, V. 1984. Pétrologie d'une intrusion calco-alcaline et de ses enclaves: le Massif cadomien de "Fort la Latte" (Bretagne Nord). Unpublished report DEA, University of Rennes.

Graviou, P. & Auvray B. 1985. Caractérisation pétrographique et géochimique des granitoïdes cadomiens du domain nord-armoricain: implications géodynamiques. *C. r. hebd. Séanc. Acad. Sci., Paris* 8 ser., II, **5**, 1315–1318.

Guerrot, C. 1985. Géochronologie et géochimie des roches basiques de la Baie de St Brieuc. Unpublished report DEA, University of Rennes.

Guerrot, C., Peucat, J. J. & Dupret, L. 1986. Age du Précambrien sédimentaire (Briovérien) dans le Massif Armoricain. Ile R.S.T., Clermont-Ferrand, 86.

Hirbec, Y. 1979. Le complexe basique de Belle-Ile-en-Terre (Côtes du Nord). Sa place dans l'evolution géodynamique du Nord du Massif Armoricain. Unpublished thèse 3e Cycle, University of Rennes.

Jeannette, D. & Cogné, J. 1968. Une discordance majeure au sein du Briovérien du Flanc Ouest de la Baie de St Brieuc. *C. r. hebd. Séanc. Acad. Sci. Paris* **226**, 2211–2214.

Jeannette, D. 1972. Analyse tectonique des formations précambriennes: Etude du NE de la Bretagne. *Sci. Géol. (Strasbourg)*, Mém. No. 36.

Menhert, K. R. 1968. *Migmatites and the Origin of Granite Rocks.* Elsevier, Amsterdam.

Peucat, J. J. 1982. Géochronologie des roches Métamorphiques (Rb/Sr et U/Pb). Exemples choisis du Groënland, en Laponie, dans le Massif Armoricain et en Grande Kabilie. Unpublished thèse Etat, Mém. S.G.M.B., University of Rennes.

Peucat, J. J. 1986. Behaviour of Rb–Sr whole rock and U–Pb zircon systems during partial melting as shown in migmatitic gneisses from the St Malo Massif, N. E. Brittany, France *J. geol. Soc. Lond.* **143**, 875–885.

Peucat, J. J., Hirbec, Y., Auvray, B., Cogné, J. & Cornichet, J. 1981. Late Proterozoic zircon age from a basic ultrabasic complex. A possible Cadomian orogenic complex in the Hercynian belt of Western Europe. *Geology* **9**, 169–173.

Rabu, D., Chauvel, J. J. & Chantraine, J. 1983. Nouvelles propositions pour la lithostratigraphie du Briovérien (Protérozoïque supérieur) et pour l'evolution géodynamique cadomienne en Baie de St Brieuc (Massif Armoricain). *Bull. Soc. géol. Fr.* 7 Ser., XXV, 4, 615–621.

Ramsay, J. 1967. *Folding and Fracturing of Rocks.* McGraw-Hill, New York.

Talbot, C. J. 1970. The minimum strain ellipsoid using deformed quartz veins. *Tectonophysics* **9**, 47–76.

Vidal, Ph., Auvray, B., Chauvet, J. F. & Cogné, J. 1972. L'âge radiométrique de la diorite de St Quay–Portrieux (Côtes du Nord). Ses conséquences sur le Briovérien de la Baie de St Brieuc. *C. r. hebd. Séanc. Acad. Sci., Paris* **D275** 1323–1326.

Vidal, Ph., Auvray, B., Charlot, R. & Cogné J. 1981. Precadomian relicts in the Armorican Massif: their age and role in the evolution of the Western and Central European Cadomian–Hercynian Belt. *Precamb. Res.* **14**, 1–20.

Watts, M. J. & Williams, G. P. 1979. Fault rocks as indicators of progressive shear deformation in the Guingamp region, Brittany. *J. Struct. Geol.* **1**, 323–332.