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Tectonic history of the Hercynian Armorican Shear belt (Brittany, France)

C. Gumiaux ^{a,*}, D. Gapais ^a, J.P. Brun ^a, J. Chantaine ^b, G. Ruffet ^a

^a *Géosciences Rennes, UMR 6118 CNRS, Université de Rennes 1, 35042 Rennes cedex, France*

^b *Bureau de Recherche Géologique et Minière-CDG/MA, 3, avenue Claude Guillemin, BP 6009, Orléans cedex 2, France*

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Abstract

The Hercynian Armorican belt is made of different tectonic domains separated by large-scale shear zones. One of these domains, Central Brittany, was deformed by regional pervasive dextral strike-slip during Carboniferous times. This paper examines implications that the restoration of ductile strain within Central Brittany has on the deformation history along its boundaries and within adjacent domains. Data used for the analysis include surface structural features and recent deep seismic data. A good consistency is observed between model implications and available geological and structural data. Results lead to a reappraisal of the Carboniferous history of the Armorican belt, including relationships between tectonics, plutonism and basin development. They further emphasize the usefulness of restoration for integrated tectonic analysis of crustal-scale deformation zones.

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Keywords: Regional scale strike slip; Deformation restoration; Fault reactivation; Hercynian belt; Armorican Massif, France

1. Introduction

Crustal deformation generally combines distributed strain and strain localization along shear zones or faults. The Hercynian belt of Western Europe is marked by the development of large-scale shear zones, especially within the Ibero-Armorican syntaxis [1–3] (Fig. 1). Strike-slip components along these zones are often important (of the order of 100 km) and may be associated with substantial pervasive strains within adjacent domains (e.g. [4, 5]).

Three major shear zones occur within the Hercynian belt of Brittany. These are, from North to South, the North Armorican Shear Zone (NASZ), and the northern and southern branches of the South Armorican Shear Zone (SASZ) (Fig. 1a). These zones strike E-W to NW-SE, have dextral strike-slip components, and separate crustal blocks with contrasting tectonic and metamorphic histories (Fig. 1a) (see

[6]). Central Brittany is bounded by the NASZ and by the northern branch of the SASZ. The Montagnes Noires Shear Zone (MNSZ) (Fig. 1b) separates two sub-domains with distinct structural history, here called Western and Eastern Central Brittany. Eastern Central Brittany shows an overall continuous deformation of Carboniferous age, without major discontinuities [6]. In this area, most structures appear compatible with bulk pervasive plane strain in the horizontal plane, associated with regional dextral shearing [4, 7]. A geostatistical analysis of cleavage trajectories has shown that the associated deformation could be modelled as regional, rather homogeneous, dextral simple shear along an ESE-WNW direction [8].

The restoration of simple shear throughout Eastern Central Brittany outlines and quantifies compatibility problems that can be expected along domain boundaries due to their rotation during regional shearing. The present paper

* Corresponding author: Vrije Universiteit, Tectonics department, Faculty of Earth and Life Sciences, de Boelelaan 1085, 1081 HV Amsterdam, the Netherlands. Tel. 31 20 444 98 05.

E-mail address: charles.gumiaux@falw.vu.nl

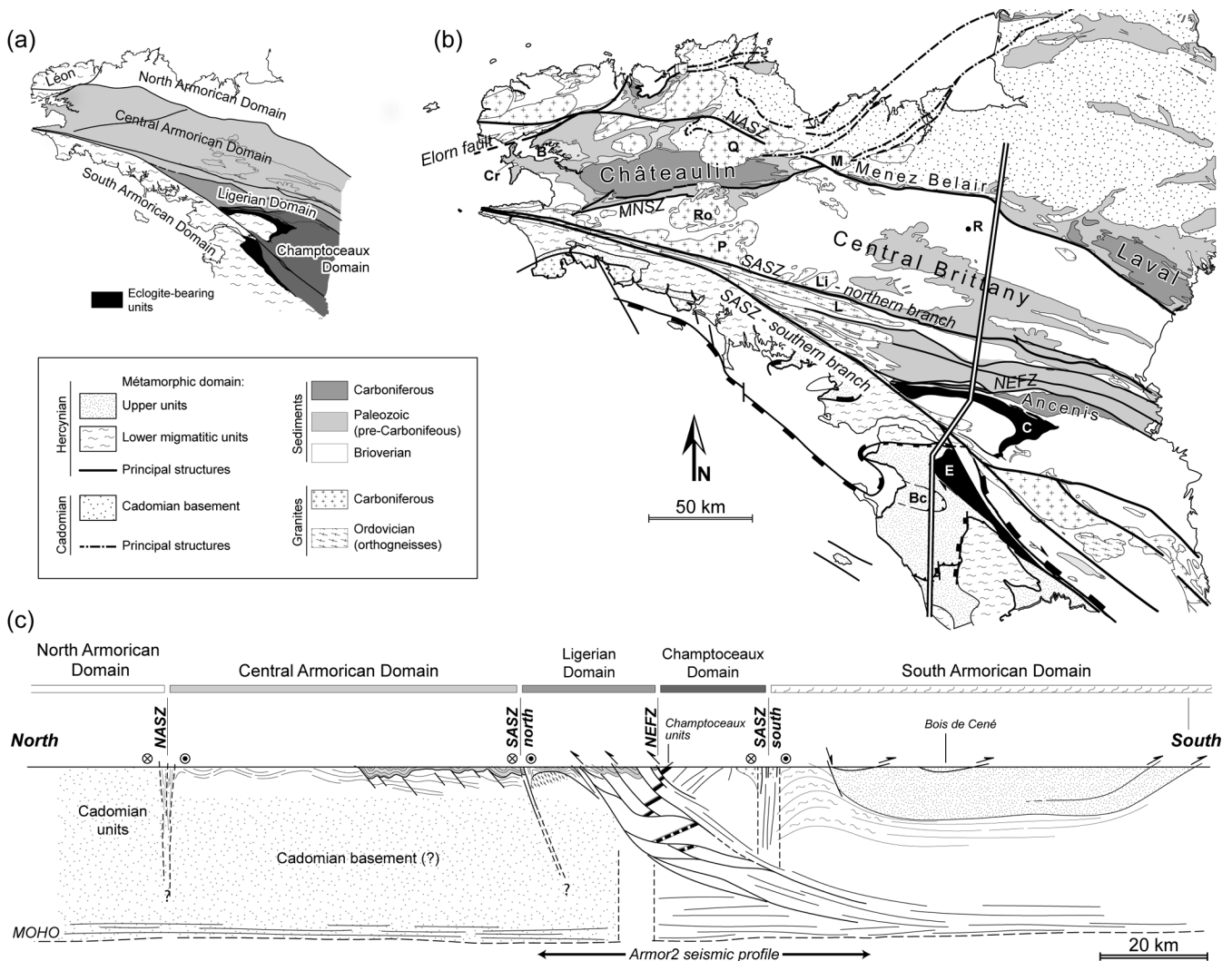


Fig. 1 (a) Main different domains forming the Armorican Massif. (b) Structural map showing main features across the Central Armorican Domain and adjacent areas. Modified after [31]. R, Rennes town; B, Brest town; Bc, Bois de Cené; C, Champtoceaux; Cr, Crozon peninsula; E, Essarts; Ro, Rostrenen granite; P, Pontivy granite; Li, Lizio granite; Q, Quintin granite; M, Montcontour granite; L, Lanvaux orthogneiss; SASZ, South Armorican Shear Zone; NASZ, North Armorican Shear Zone; MNSZ, Montagnes Noires Shear Zone; NEFZ, Nort-sur-Erdre Fault Zone. Double line locates cross-section of (c). (c) Crustal-scale geological section across the Armorican Massif; modified after [16] in its central part. Location is shown on (b).

describes and discusses kinematic implications of boundary rotations around the restored area. The analysis emphasizes that restoration may provide strong and constructive constraints for the tectonic analysis of regional ductile deformation. In the studied area, it provides a tectonic model that integrates most local structural features that were previously analysed separately, which locally led to erroneous, poorly constrained or missing interpretations.

2. Eastern Central Brittany

2.1. Tectonic setting

The Hercynian belt of Brittany can be divided into different domains separated by regional-scale fault zones.

North of the NASZ, the North Armorican Domain is mainly made of Cadomian (Proterozoic) basement, with an overall rigid or brittle behaviour during the Hercynian orogeny (see [9]).

South of the SASZ, the South Armorican Domain is part of the internal zones of the belt. It is marked by early Devonian to Carboniferous crustal thickening [2, 10–12] that led to regional extensional deformations during upper Carboniferous times [13,14]. Extension induced in particular the exhumation of lower-crustal migmatite units below detachment zones and along the SASZ [13] (Fig. 1b, c). Highest grade metamorphic rocks in South Brittany are eclogite-bearing units that mark the northern boundary of the South Armorican Domain (Fig. 1a), and outline a major suture zone of the belt [15, 16]. A segment of this zone is presently located just north of the southern branch of the SASZ, within the Champtoceaux Domain (Fig. 1).

The southern edge of Central Brittany is defined by the northern branch of the SASZ (Fig. 1). To the South, between the two branches of the SASZ, the Ligerian and Champ-toceaux Domains are separated by the EW-striking Nort-sur-Erdre fault zone (NEFZ). The Ligerian and Central Armorican Domains are both made of sedimentary rocks of late Proterozoic to Palaeozoic age and deformed during Carboniferous times. They are affected by low grade metamorphism, which emphasizes that these domains suffered only limited thickening during the Hercynian collision [4, 6].

To the West, the MNSZ separates Eastern Central Brittany from the Carboniferous Châteaulin basin that characterizes western Central Brittany (Fig. 1b).

2.2. Pre-Hercynian history

The oldest sediments deposited in Central Brittany consist in a thick detrital rhythmic series of late Proterozoic (Brioverian) to Cambrian age (Fig. 1b) [17–19].

The Lower Ordovician is marked by a regional extensional event accompanied by an important magmatism [20]. Then, and up to the Lower Devonian, a continuous sequence of marine sediments deposited. Regional-scale variations in associated deposition environment reflect bulk eustatic variations [21]. Sediments younger than mid-Devonian appear less continuous and localized within domains bounding Eastern Central Brittany (e.g. Laval-Menez-Belair area, Brest area, or Ligerian Domain) (Fig. 1b). During the Carboniferous, sedimentation became restricted to isolated basins located along fault zones that bound Central Brittany (Châteaulin, Laval and Ancenis basins, Fig. 1b).

2.3. Finite strain

Deformation is basically continuous throughout the entire Eastern Central Brittany [4,8]. The upright folds that affect the sediments have horizontal and EW striking axes (Fig. 1b, c). The first order fold wavelength is controlled at regional scale by the thickest competent unit of the sedimentary sequence, the lower Ordovician Armorican sandstone. An associated sub-vertical axial-plane cleavage is observed within phyllosilicate-rich rocks throughout the entire area. The regional cleavage bears a sub-horizontal mineral lineation, parallel to fold axes (see [4]).

To the southwest of Rennes township (Fig. 1b), strain estimates have been made using pebble shapes within deformed conglomerates [22]. The intermediate principal strain axis is vertical, with a mean length around one, which indicates an overall plane strain in the horizontal plane [22,8]. The principal stretch direction deduced from strain analysis is sub-horizontal, parallel to the mineral lineation [4]. Folds that affect the Armorican sandstone are of limited amplitude and their overall envelope is sub-horizontal at regional scale [23]. All these features emphasize that variations in vertical stretch are negligible throughout Eastern Central Brittany.

2.4. Deformation regime

The overall plane strain in the horizontal plane is associated with dextral shearing deformation [4]. This is suggested by folds that are arranged in en échelon patterns. At smaller scale, dextral ductile shearing is indicated by asymmetric quartz fabrics [4, 24]. The elliptical shape of the syn-kinematic leucogranite intrusions to the North of the northern branch of the SASZ (e.g. Pontivy and Lizio granites, Fig. 1b) also indicates dextral shearing [25]. A detailed analysis of pluton geometries further showed that their shape is compatible with regional-scale simple shear [26].

Finite strain data available to the southwest of the Rennes township [22] have been used to remove pervasive strains within this portion of Central Brittany [7]. The result of the restoration is compatible with dextral simple shear. It further indicates that the shearing direction in the studied area was N125° (present-day reference frame).

The applicability of the simple shear model of Percevault and Cobbold [7] to the whole Central Brittany has been recently examined using a geostatistical analysis of cleavage orientation data available throughout the region [8]. The analysis showed that the regional cleavage trend was rather homogeneous within the whole Central Brittany, with a N095–N100 mean strike, statistically different from that within adjacent domains [8]. Computed cleavage trajectories have regular shapes, with moderate variations in mean orientation outlining ESE striking bands (Fig. 2a). The cleavage pattern is compatible with regional N125° dextral simple shear, internal band-shaped variations reflecting minor shear strain gradients. At regional-scale, the mean angle between cleavage and bulk shear direction is 26°, which yields a mean shear strain γ of about 1.5 [8].

Several syn-kinematic granite intrusions within Eastern Central Brittany (Pontivy, Lizio, and Bignan granites) yielded Rb/Sr whole rock ages around 345–335 Ma [27], which provides a minimum time range for the shearing deformation, from latest Tournaisian to early Viséan.

2.5. Result of strain restoration

Ductile strain within Central Brittany has been removed by applying a sinistral simple shear, parallel to a N125° direction (precisely N123°). Minor shear strain gradients computed from local variations of the angle between the mean regional shear direction and the cleavage strike have been taken into account in the restoration [8].

The restoration model has been further constrained by the occurrence of variations in amounts of horizontal displacement along the NASZ where several syntectonic Carboniferous granites have emplaced (see [6] and references therein) (Fig. 1b). To the West, granites show intense dextral wrenching with well-developed mylonites [28, 29]. Horizontal displacements recorded by plutons decrease eastward, between Quintin and Montcontour intrusions (Q and M, respectively, on Fig. 1b). Furthermore, the geological

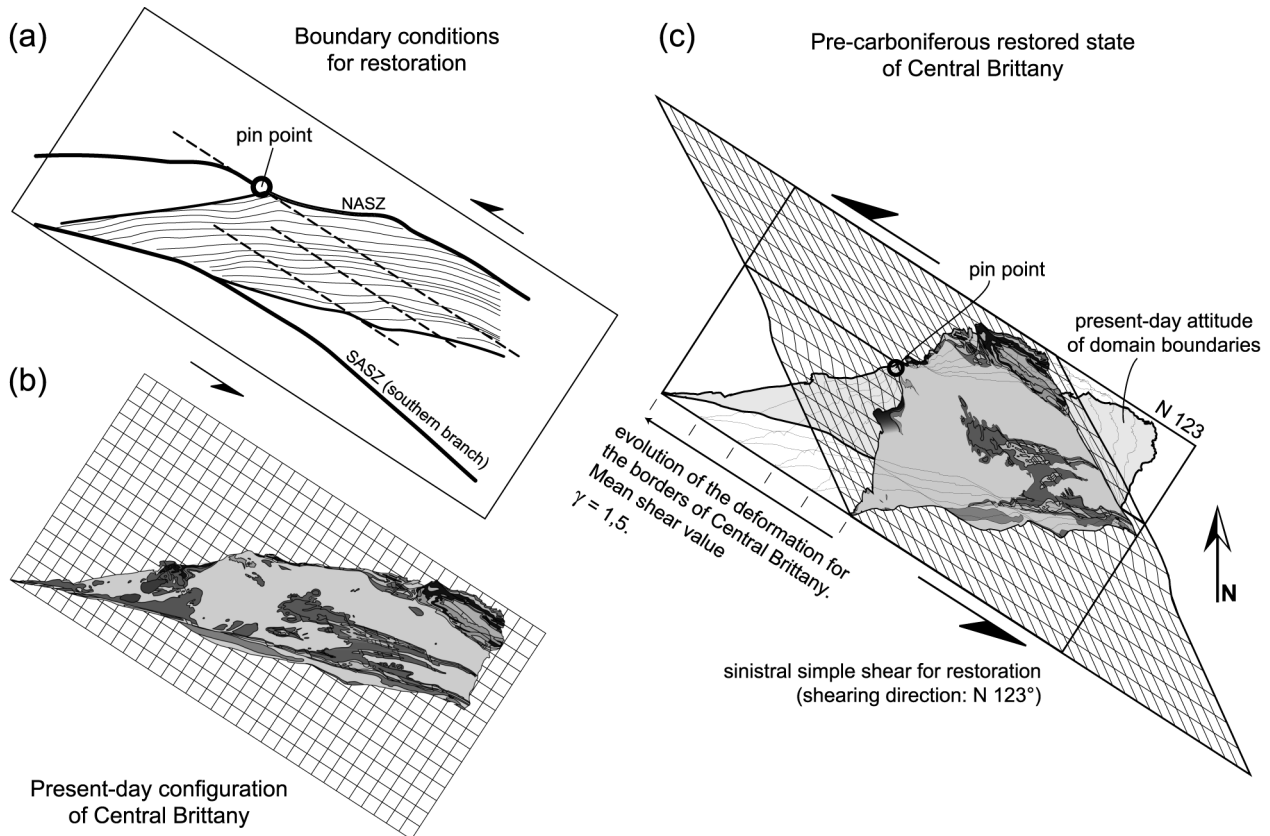


Fig. 2 Model of simple shear inversion within eastern Central Brittany, based on a geostatistical analysis of cleavage directions throughout the domain [8]. (a) Boundary conditions used for the restoration. Computed cleavage trajectories are shown for eastern Central Brittany. WNW-ESE striking bands marked by slightly different mean cleavage orientation are outlined by dashed lines (b) Present-day configuration of the geological contours, extracted from the 1/1,000,000 geological map of France [31]. (c) Restored state after strain removal by sinistral simple shear.

map shows that the strike-slip motion along the NASZ becomes close to zero in the Montcontour area where NE trending pre-Hercynian (Cadomian) structures are not significantly affected by Hercynian E-W dextral strike-slip (Fig. 1b) [30]. Consistently, the trace of the NASZ is interrupted in this area on the 1/1,000,000 geological map (Fig. 1b) [31]. For the restoration, a pin point has therefore been imposed in the Montcontour area (Fig. 2a).

Fig. 2b and 2c show images of present-day and restored states of Central Brittany, respectively. A main outcome of the restoration is that, because domain boundaries are oblique with respect to the regional shear direction, they undergo rotations and overlaps between Central Brittany and adjacent domains occur (Fig. 2c). These impose that horizontal displacements localized along fault zones have to combine with scissor-type motions along domain boundaries. Neither localized horizontal displacements, nor bulk rigid rotations of domains can be quantitatively constrained by the restoration model of distributed deformations. During progressive shearing, due to the change in angle between domain boundaries and shear direction, kinematics along them is expected to change with time.

In the followings, we develop a compared analysis of geological data and kinematic implications of the restoration along the different boundaries of Central Brittany.

3. The Montagnes Noires Shear Zone and the Châteaulin Carboniferous basin

3.1. Geology

Western Central Brittany, in the Châteaulin basin area, shows the most complete sedimentary sequence, from Brioverian detrital deposits to Viséan continental sediments (b2k to h2, Fig. 3a). This area is bounded to the South by the MNSZ and to the North by the Elorn fault zone and segments of the NASZ (Fig. 3b).

The MNSZ is a linear structure that cuts across the entire Central Armorican Domain, from the Douarnenez orthogneiss along the SASZ, to the Montcontour granite along the NASZ (Fig. 1 and 3). It consists in several faults striking N080° and affecting sediments up to Devonian in age. The area South of the MNSZ (Pontivy-Rostrenen area, Fig. 3 and 1) is marked by large surfaces of granitic rocks, whereas further East granites disappear progressively under the sedimentary series [23]. In addition, the area shows specific relatively high-grade metamorphic conditions [32, 33] that can reach kyanite and staurolite stability fields [33, 34]. These features suggest that this area shows a deeper erosion level than other parts of Central Brittany.

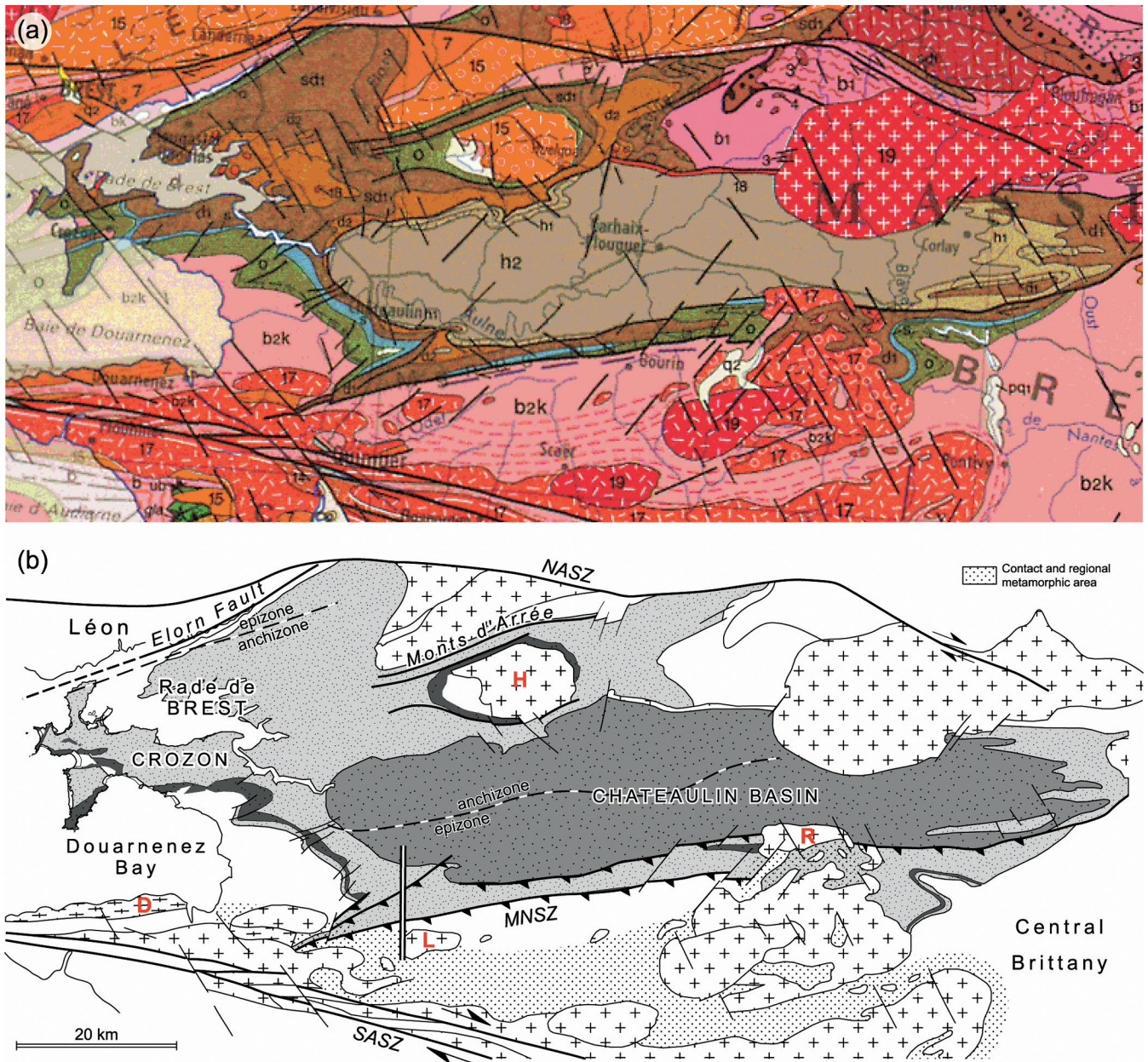


Fig. 3 (a) Close up of the 1/1,000,000 geological map of France on the Montagnes Noires and Châteaulin basin areas (geological captions in Chantaine *et al.* [31]). (b) Structural map showing main features of the area; drawing patterns same as on Fig. 1b. D, Douarnenez orthogneiss; H, Huelgouat granite; L, landulal granite; M, Montcontour granite; Ro, Rostrenen granite. Metamorphic isogrades are drawn from Paradis [39] and Darboux [37]. Double line across the MNSZ locates cross-section of Fig. 5.

Since the earliest Carboniferous, the history of the Châteaulin basin differs from adjacent areas. At this time, the basin is marked by (1) a shift of the depocenter from NW to SE [35], and (2) a strong increase in basin subsidence [21]. Thus, a thick shallow marine homogeneous sequence of early Tournaisian age is preserved in the northern part of the basin [35, 36]. This series contains olistoliths and debris flows that indicate the occurrence of substantial slopes along the northern boundary of the basin [35]. During the Tournaisian, sedimentation covered approximately the present-day basin surface. Debris flows and polygenic conglomerates still attest to the occurrence of proximate

reliefs [35]. The sedimentary history of the basin ends during the late Viséan to early Namurian, with the deposition of a thick turbiditic sequence that covers presently the main part of the basin, down to its southernmost part along the MNSZ.

The infill of the Châteaulin basin is asymmetric, with oldest sequences restricted to the northern part, and Tournaisian to lower Viséan series in direct contact with the MNSZ to the South [37]. Sedimentation depths increase from North to South, in particular for sediments of Viséan age, with lateral changes from debris flows along the northern boundary to dark shales along the MNSZ [37].

The area North of the Châteaulin basin (Brest and Crozon areas, Fig. 3b) is mainly composed of Ordovician to Devonian sediments unconformably deposited on the Brioverian sequence (Douarnenez Bay, Fig. 3a, b). To the North is the Léon Domain characterized by high-grade metamorphic rocks, including eclogites, and showing strong similarities with those found in the South Brittany Domain [38]. Balé and Brun [38] have proposed that this domain was translated from the South to its present position by dextral strike-slip along the Elorn fault (Fig. 3b) during Devonian times, prior to the development of the Châteaulin basin. During the Carboniferous, the Léon Domain is mainly affected by shearing along ductile shear zones, including the dextral NASZ, and by intrusions of syn-kinematic plutons [28].

Throughout the sedimentary domain North of the MNSZ, the Hercynian metamorphism increases from anchizone in the central part of the Châteaulin basin to epizone toward North and South bounding fault zones, the Elorn fault and the MNSZ, respectively (Fig. 3b) [37, 39].

3.2. Implications of the restoration

The western boundary of the restored Eastern Central Brittany corresponds to the MNSZ (Fig. 2b). There, the restoration induces an important triangular gap between Central Brittany and the Châteaulin basin (Fig. 2c). The change from restored to deformed states shows a relative clockwise rotation of the Montagnes Noires zone with a rotation axis located at the pin point of the Montcontour area (Fig. 4). From these, we infer scissor-type northward thrusting along the southern edge of the Châteaulin Basin. According to the change in attitude of this boundary with respect to the infinitesimal principal shortening during progressive simple shear, the MNSZ should have first been marked by sinistral wrenching, then thrusting, combined with dextral strike-slip in the latest evolution stages (Fig. 4). Because of the occurrence of the pin point at the northeastern tip of the MNSZ, strike-slip components should have remained limited.

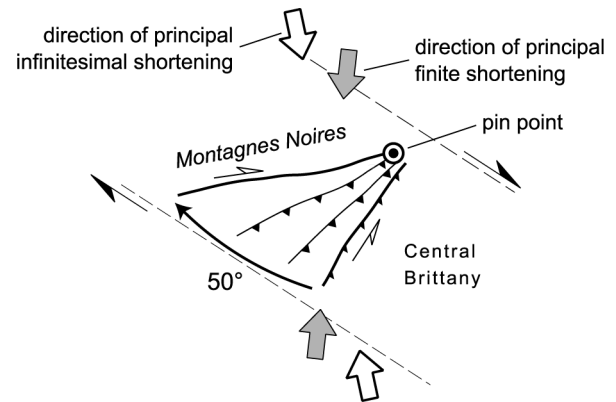


Fig. 4 Sketch showing structural changes during simple shear restoration at the western boundary of eastern Central Brittany.

In its restored state, the MNSZ strikes NNE, at low angle to the main Cadomian shear zones observed in the adjacent North Armorican Domain (Fig. 1b). There, major Cadomian fault zones join the pin point and the MNSZ in the Montcontour area (Fig. 1b).

The restoration model thus suggests that the MNSZ is an inherited Cadomian basement discontinuity on which scissor-type thrust zones developed during Hercynian reactivation and clockwise rotation.

3.3. Comparison with structural data

In the field, the MNSZ dips southward (Fig. 5) and is generally steep [33]. Around this shear zone, the regional foliation is sub-vertical and strikes N080°, parallel to the zone [32, 33]. Based on structural data at various scales, Darboux and Le Gall [33] have argued that the MNSZ was a dextral transpressive shear zone. Recently, Plusquellec *et al.* [40] have documented northward thrusting along the western part of the MNSZ, where Brioverian metasediments are thrust over Palaeozoic sediments. Furthermore, the regional foliation is affected by asymmetric folds with sub-vertical axes and consistent with dextral strike-slip along the MNSZ during the late stages of progressive deformation [33].

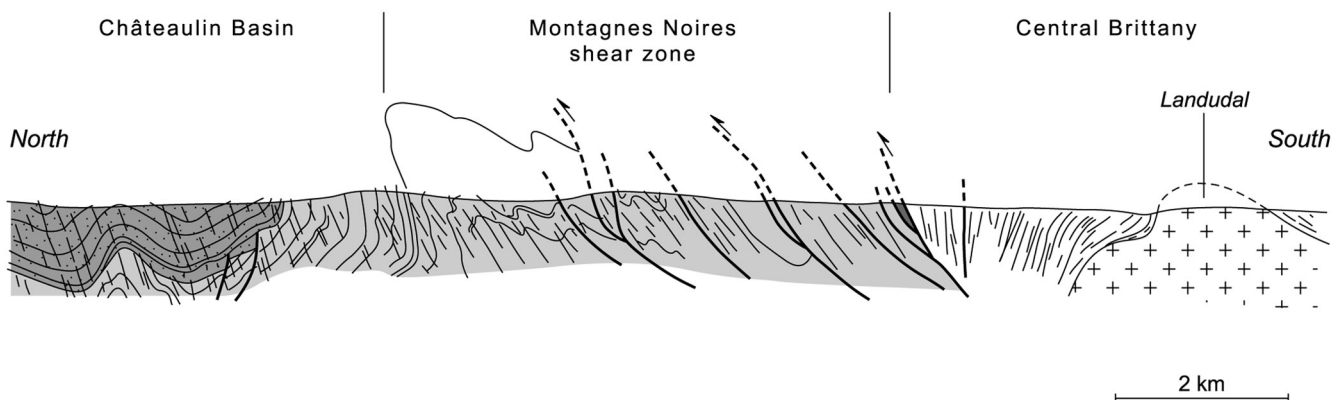


Fig. 5 Geological section across the MNSZ (modified after Plusquellec *et al.* [40]). Location is shown on Fig. 3. Drawing patterns same as on Fig. 1b.

Both the Châteaulin basin and the northern Crozon areas show evidence of N-S compression [33, 37, 40].

Folds within sediments of the Châteaulin basin have generally N080° sub-horizontal axes. Their north vergency and the development of thrusts along some reverse limbs indicate top-to-the north motions (Fig. 5). Folding is associated with a southward-dipping axial plane cleavage, bearing a stretching lineation with a generally strong southward pitch. These features are mainly observed in the southern part of the basin. Toward the centre of the basin, the decrease in metamorphic grade is accompanied by a change from slaty cleavage to fracture cleavage.

North of the Châteaulin basin, structures strike about N070°, parallel to the Elorn fault zone that marks the southern edge of the Léon Domain. N070°-striking folds occur through-

out the whole area. They are particularly well exposed in the Crozon Peninsula (Fig. 3b), where structures at various scales are typical of a thin-skinned fold-and-thrust belt (Fig. 6). Some NNE striking sinistral thrust-wrench faults contribute to accommodate the N160°-directed shortening (Fig. 6a, b). Thrusts appear to develop preferentially along short reverse limbs of folds. Locally, fault patterns suggest flat and ramp geometries, with décollements located along weak sedimentary layers (Fig. 6c). Fold asymmetry and fault geometry indicate both northward and southward thrusting (Fig. 6b, c), but top-to-the-South asymmetries dominate at regional scale [37]. Late dextral strike-slip movements occurred along N060–N070 striking faults [41]. Further east, along the N075°-striking Monts d'Arrée shear zone [37] (Fig. 3b), localized dextral strike-slip reworks an earlier flat-lying cleavage.

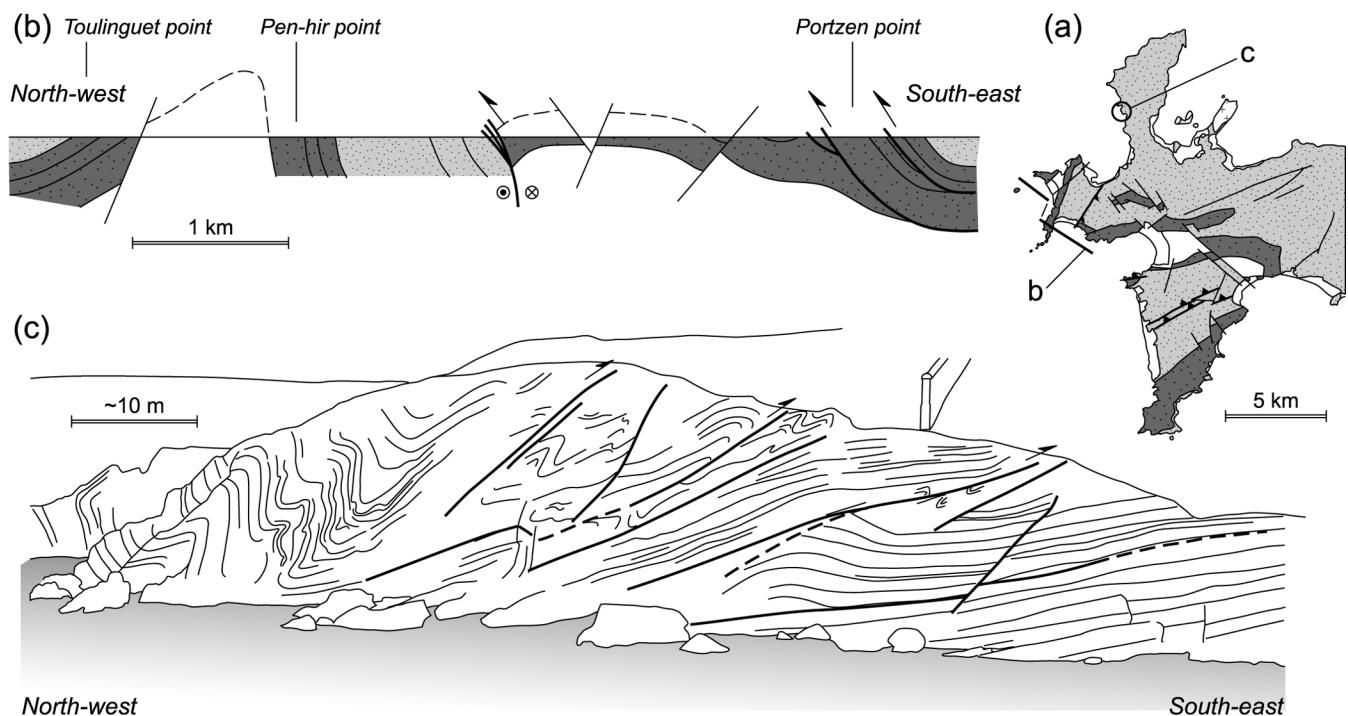


Fig. 6 Examples of compressive structures observed in the Crozon Peninsula (a) (drawing patterns same as on Fig. 1b). (b) geological cross-section; modified after Darboux [37], located on (a). (c) Sketch of outcrop illustrating thin-skinned geometries in Palaeozoic sedimentary rocks (Fort de la Fraternité, Roscanvel; located on (a)).

Thus, deformation throughout the Châteaulin basin and the Crozon area is mainly compressive, and is related to transpressive motions along the inherited Cadomian MNSZ.

To the South of the MNSZ, the western corner of Eastern Central Brittany appears as an uplifted and eroded hanging wall. It is worth noting that the shape of the zone of granite-rich and particularly high-grade metamorphism in this part of Central Brittany (Fig. 1b) matches that of the triangular domain located between the initial and final positions of the MNSZ (Fig. 4). To the North, the asymmetric Carboniferous basin that thickens and deepens towards the South appears as a compressive ramp basin developed at the footwall of the MNSZ (Fig. 7). Also consistent with the restoration model,

dextral strike-slip components along and North of the MNSZ appear to be relatively late and localized with respect to thrusting components. On the other hand, no evidence of early sinistral components, as predicted by the model, has been documented.

Granitic intrusions in NW Brittany provide some time constraints for the deformation of the area. The Huelgoat granite (Fig. 3b) yielded a Rb/Sr whole rock age of about 340 Ma [42], comparable to ages obtained on syn-kinematic granites of the southern edge of Central Brittany. Pebbles of granite and hornfels that may be derived from the Huelgoat intrusion [42] are found within neighbouring conglomerates that have been attributed to the Upper Tournaisian by Guill-

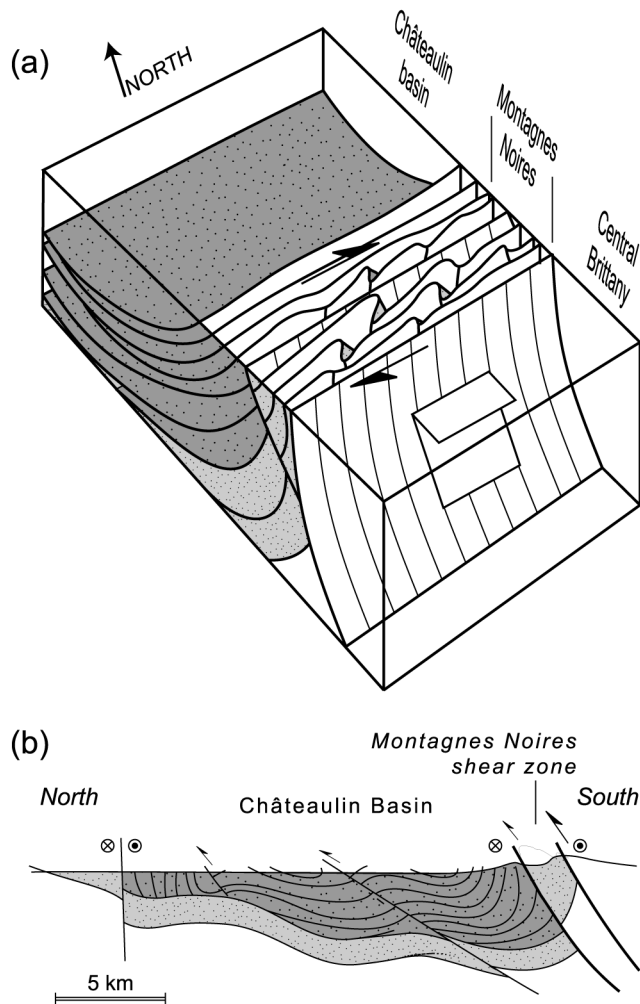


Fig. 7 Block diagram and schematic cross-section illustrating relationships between the MNSZ and the Châteaulin basin. Modified after Darboux [37].

ocheau and Rolet [35]. If so, this would attest to significant erosion at this time along the northern edge of the basin. One facies of the composite Rostrenen intrusion, which cuts across the MNSZ, has yielded a U-Pb zircon age around 315–325 Ma [43]. The Carboniferous sedimentation within the Châteaulin basin ranges between Tournaisian and earliest Namurian. This, compared with available granite ages, emphasizes that the Châteaulin basin is a compressive basin developed during regional dextral shearing.

4. The North Armorican Shear Zone

4.1. Geology

The northern boundary of Central Brittany is defined by the continuation of the NASZ, east from the Montcontour granite (Fig. 1). Since the end of the Cadomian, this northern edge of Central Brittany constituted a major boundary between a northern basement domain and a southern domain

of regional-scale sedimentation (see [44]). It comprises two distinct segments. To the West, the N100° striking Menez-Belair segment is sharp and well defined (Fig. 8). To the East, the shear zone splits in different branches, one corresponding to the southern edge of the Carboniferous Laval basin, that strikes N120° to N125° (Fig. 8).

The Menez-Belair segment corresponds to a narrow band mainly made of Palaeozoic sediments quenched between Brioverian rocks (Fig. 8). Within the Menez-Belair, different band-shaped or lens-shaped units are separated by an anastomosed fault array. The age of Palaeozoic sediments involved in the deformation zone ranges from Arenig (Armorican sandstone) to early Carboniferous. Carboniferous sediments are localized along a small segment of the NASZ (Fig. 8b). They are marked by strong lateral facies variations, include volcanic rocks, and are strongly immature [45]. North of the Menez-Belair, Cadomian granitic intrusions mark the end of the ductile deformation [46]. This part of the North Armorican Domain mainly behaved as a brittle block during the Hercynian.

To the East, the Laval basin is bounded by faults (Fig. 8). Pre-Carboniferous Palaeozoic sediments on northern and southern sides of the basin display contrasting depositional environments, up to Lower Devonian times [47]. This feature emphasizes the inherited nature of this eastern part of the Northern boundary of Central Brittany. After a period of no sedimentation during the Devonian, three main development stages of the Laval basin have been recognized [47]. The Tournaisian is marked by detrital sedimentation, with evidence of local reworking of deposits within inter-bedded conglomerates. Then, basin subsidence became asymmetric, increasing in the southern part. During early to mid Visean times, a stable carbonate platform developed to the North of the basin; whereas strong lateral variations of bathymetry are recorded to the South. During the late Visean and the earliest Namurian, reworking of older deposits is recorded in detrital sediments, conglomerates and debris-flows. During the whole basin history, sediments attest to strong and rapid small-scale lateral variations of depositional environment and subsidence, which suggests local changes in vertical displacements.

4.2. Implications of the restoration

Because of the different angles they make with respect to the bulk simple shear direction, the two segments of the northern edge of Eastern Central Brittany behave differently during restoration (Fig. 9).

In the Menez-Belair area, the deformation between restored and deformed states is imaged by a clockwise rotation of about 40° of the Central Brittany edge around the Montcontour pin point (Fig. 2 and 9). This indicates that substantial shortening occurred across the Menez-Belair zone.

In contrast, the margins of the Laval basin are sub-parallel to the regional shear direction. Consequently, they are not

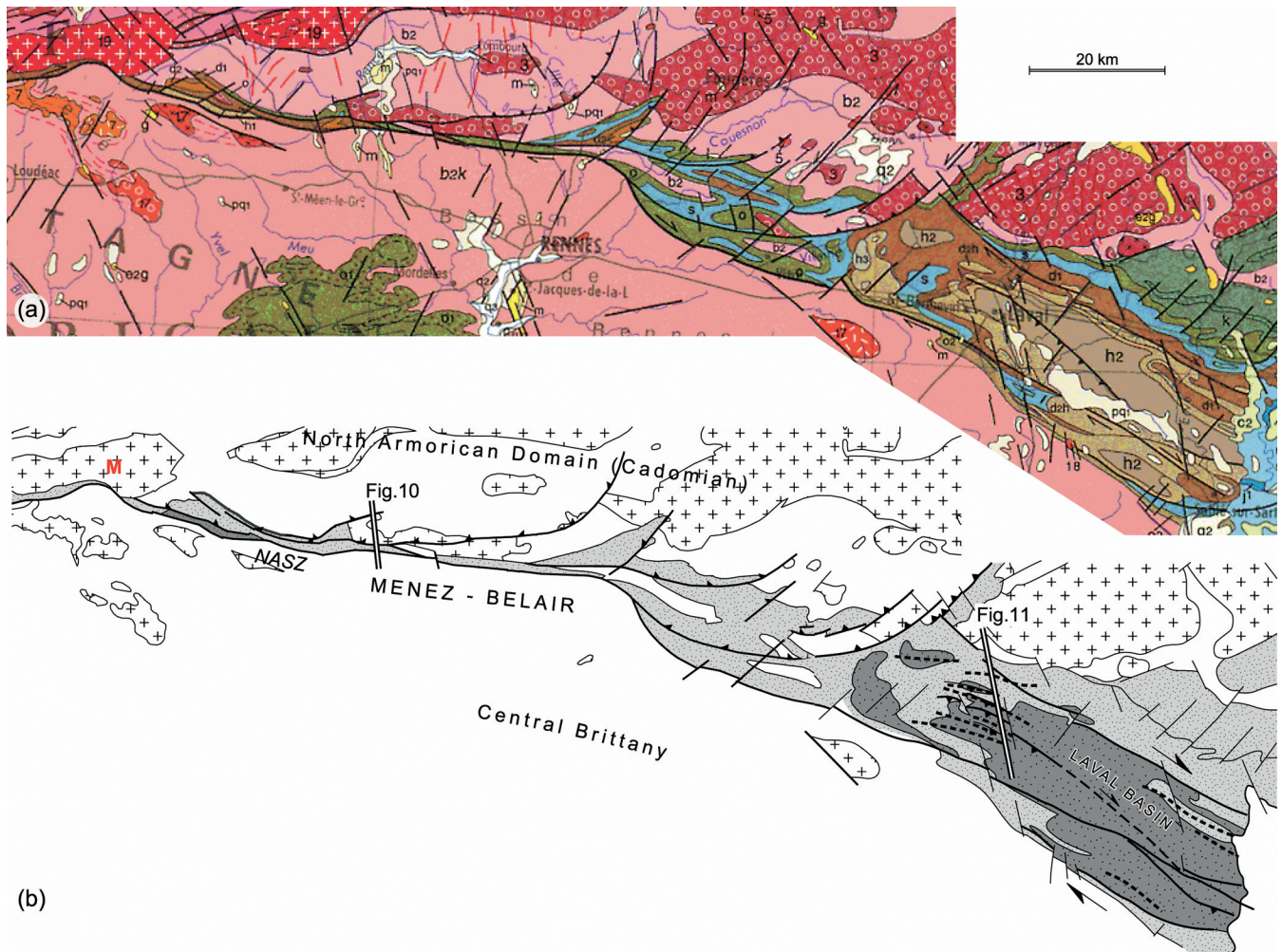


Fig. 8 (a) Close up of the 1/1,000,000 geological map of France on the northern boundary of eastern Central Brittany (after Chantraine *et al.* [31]). (b) Structural map showing main features of the area; drawing patterns same as on Fig. 1b. M, Montcontour granite. Fold axes (dashed lines) are from Houlgatte *et al.* [47]. Double lines locate cross-sections of Fig. 10 and 11.

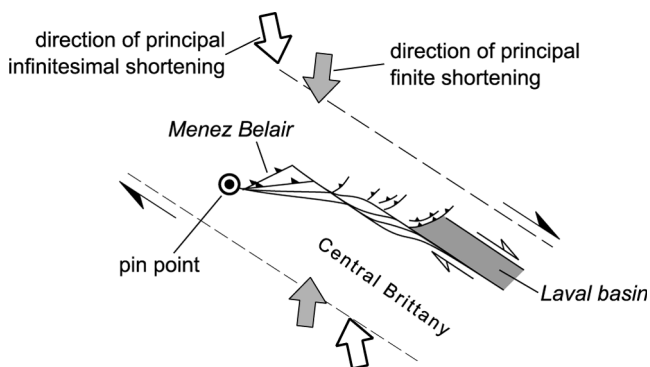


Fig. 9 Sketch showing structural changes during simple shear restoration at the northern boundary of eastern Central Brittany.

strongly modified by the restoration and are good candidates for shear localization during Carboniferous deformation.

The junction between the two segments behaves as a hinge zone during restoration, with strong differential rotations on both sides (Fig. 2c and 9). In such zone, one can expect that the northern brittle Cadomian Domain might

have suffered complex block rotations, with associated strong local variations of shortening directions.

4.3. Comparison with structural data

The Menez-Belair units define fault-bounded syncline structures aligned between the North Armorian Domain and Central Brittany (Fig. 8) [45, 48, 49]. Consistent Carboniferous kinematics, with overall NNW-ESE principal shortening, is observed within the NASZ and adjacent rocks from Central Brittany [45, 49]. Units strike N100°-N110°. The bedding generally dips to the north and becomes sub-vertical along the northern side of the shear zone (Fig. 10) [45]. The south-verging asymmetry is also observed at outcrop-scale, especially within pre-Carboniferous sediments where folds and a steeply north-dipping cleavage are observed. In these units, folds with sub-vertical and curved axes deform the previous north-dipping cleavage, and their asymmetry indicates dextral strike-slip components [45]. Carboniferous sediments only show this late stage of shear-

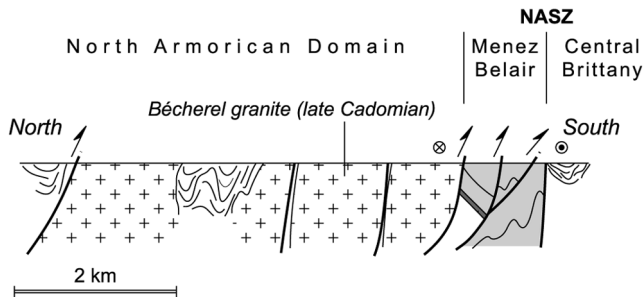


Fig. 10 Geological cross-section in the Menez-Belair area, modified after Paris [48]. Location is shown on Fig. 8. Drawing patterns same as on Fig. 1b.

ing deformation. This might be due to a complete transposition of the earlier fabrics [45]. It may also indicate that most of the south-verging deformation predates the deposition of Carboniferous sediments. In any case, the strain pattern along this part of the NASZ reflects dextral transpressive motions, with an increase of the strike-slip component with time. Along the NASZ, quartz grain shape and lattice fabrics within quartzite mylonites indicate flattening strains ($K < 0.2$) [50], a feature generally expected in transpressive contexts (e.g. [51, 52]).

In the Laval basin, Carboniferous and older sediments show similar structural patterns [47]. The overall geometry is that of north-verging open folds, with local faults having thrust components (Fig. 11). The amount of shortening reflected by folds remains moderate, of the order of 20%. At regional scale, Carboniferous sediments do not show any age gradient across the basin, and folds display an overall sub-horizontal envelope (Fig. 8a and 11), which contrasts strongly with patterns observed in the Châteaulin Basin.

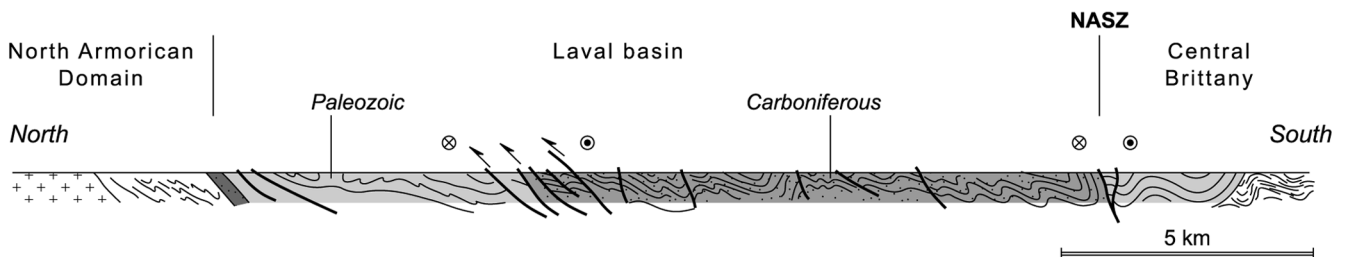


Fig. 11 Geological cross-section in the Laval basin area, modified after Houlgatte *et al.* [47]. Location is shown on Fig. 8. Drawing patterns same as on Fig. 1b.

5. The Plouguenast metamorphic dome

5.1. Geology

The Plouguenast metamorphic massif crops out to the northwest of Eastern Central Brittany, just South of the Montcontour pin-point, at the junction between the MNSZ and the NASZ (Fig. 12). It is a dome-shaped structure comprising high-grade micaschists and paragneisses, with locally metatexites [53]. Its central part is occupied by the St

Moreover, thrusting of old sediments over significantly younger ones is not observed, which indicates that movements along south dipping thrusts remained limited (Fig. 11). On the other hand, strike-slip may have occurred along these faults. However, geological boundaries mainly outline the folds, and do not show large offsets along NW striking faults (Fig. 8). Localized strike-slip components within the basin must therefore be limited, and mainly concentrated along basin boundaries (Fig. 8a).

The junction between the Menez-Belair segment and the Laval Basin is marked by several NE striking thrusts, oblique to the NASZ (Fig. 8). Thrusts often bring Palaeozoic synclines over Cadomian rocks. This suggests either post-fold thrust localization along syncline limbs [49], or reactivation of pre-existing normal faults. The NE faults strike would be consistent with the NW direction inferred for the lower Ordovician extensional event [20]. In map view, most of these faults present a curved trace that merge southward in the Menez-Belair segment (Fig. 8). This feature underlines that strong local variations of shortening directions occur in this particular hinge zone.

The structural pattern of the NASZ remains relatively poorly documented. However, available data are consistent with strains predicted by the restoration model. Main consistencies are (1) the transpressive character of the Menez-Belair segment, with a progressive evolution from dominant compression to dominant strike-slip, (2) a limited shortening across the Laval basin that strikes at low angle to the bulk shear direction within Central Brittany, and (3) the concentration of compressive faults observed around the hinge junction zone between the two segments of the NASZ.

Gouéno leucogranite and by a foliated granodiorite (Plouguenast orthogneiss), with local amphibolite bodies.

The study made by Saunier [53] has shown that metamorphic isogrades tend to define concentric surfaces around the Plouguenast dome (Fig. 12). From dome boundaries to dome centre, an increase in temperature from about 300–400°C to about 650°C at pressures lower than 500–600 MPa is recorded by the successive development of biotite, andalusite and sillimanite (Fig. 12b). A progressive transition is observed between the external biotite-bearing Brioverian

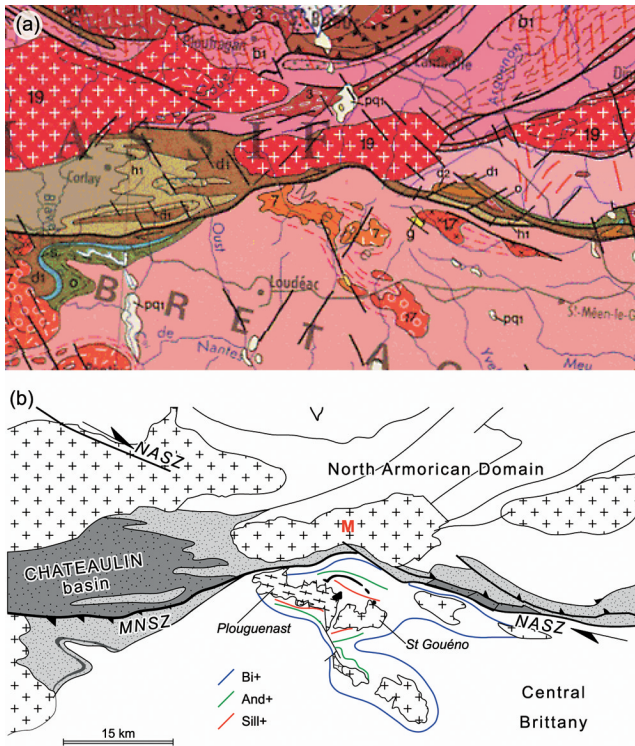


Fig. 12 (a) Close up of the 1/1,000,000 geological map of France on the Plouguenast area (after Chantaine *et al.* [31]). (b) Structural map showing main features of the area. Drawing patterns same as on Fig. 1b. M, Montcontour granite. Metamorphic isograds are from Saunier [53].

metasediments and the low-grade Brioverian country-rocks typical of those found throughout Central Brittany. In the core of the dome, garnet-kyanite assemblages of unknown age are locally preserved within paragneisses, giving a minimum P-T estimate around 700 MPa and 680°C. Retrogressive metamorphic assemblages reflect a decompression of the order of 300 MPa for a cooling of about 100–150°C [53]. According to Saunier [53], the St. Gouéno leucogranite crystallised at pressures higher than 300–400 MPa, which is compatible with the metamorphic evolution observed within country-rocks. The retrograde evolution of these high grade metamorphic rocks has been interpreted as a result of progressive exhumation and dome formation [53]. This metamorphic dome is a peculiar geological feature of Central Brittany where low grade metamorphism dominates.

5.2. Implications of the restoration

Restoration imposes rotations of the western and northern edges of Central Brittany (Fig. 2b, c and 13). Between restored and deformed states, the clockwise rotation of the western boundary is about 50°; whereas it is about 30° for the northern boundary. This is imaged by an increase in the angle between the two boundaries during shearing. Consequently, the restoration model suggests that a local E-W extensional context should have occurred just south of the Montcontour pin-point during shearing of Eastern Central Brittany (Fig. 13).

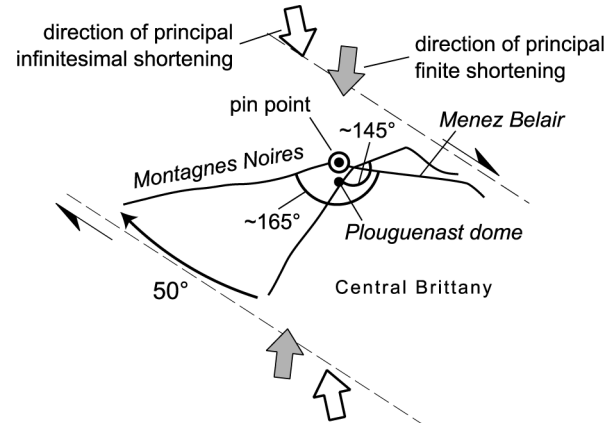


Fig. 13 Sketch showing structural changes during simple shear restoration in the Plouguenast area.

5.3. Comparison with structural data

The Plouguenast dome is elongate in the NW direction (Fig. 12). According to Saunier [53], associated foliations strike E-W to NW-SE, with decreasing dips inwards. Stretching lineations are about E-W, with variable moderate plunges. Associated dextral shear criteria (shear bands and asymmetric quartz fabrics) are observed within the orthogneiss [53]. In the surrounding Brioverian rocks, cleavage attitudes suggest wrapping around the dome structure.

Thus, the overall structural pattern indicates that both dome formation and regional dextral shearing are coeval. Furthermore, the overall geometry of the metamorphic dome is consistent with the local EW extension predicted by the restoration. On the other hand, Saunier [53] provided a Rb/Sr whole rock age of 457 ± 23 Ma for the St. Gouéno leucogranite. In order to better constrain the timing of metamorphism, new geochronological analyses using the $^{40}\text{Ar}/^{39}\text{Ar}$ method have been made on both the orthogneiss and the leucogranite. Results are described in detail in Appendix 1. For the St Gouéno leucogranite, $^{40}\text{Ar}/^{39}\text{Ar}$ ages on muscovites and biotites range between about 341 Ma and 322 Ma, suggesting a slow cooling and (or) a long deformation and recrystallisation history. Concerning the orthogneiss, muscovites yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of about 330 Ma, suggesting that its cooling was coeval with that of the leucogranite.

As the St Gouéno intrusion crystallised at depth (higher than 300–400 MPa) [53], the span in Ar/Ar ages could reflect combined cooling and syntectonic recrystallisation during exhumation. Syn-shearing leucogranites of Central Brittany yield a comparable age range, between 335 and 345 Ma. Thus, the restoration that implies a local extensional site in the Plouguenast area during regional Carboniferous shearing appears supported by geochronological data.

orthogneiss presents petrographic variations that suggest that its elongate shape, in map view, may result from the coalescence of aligned intrusions. The intrusion may be correlated with the extensive calc-alkaline magmatism associated with Ordovician extension. At least since the Ordovician, the Palaeozoic sedimentary history south of the northern branch differs significantly from that observed in Central Brittany [57–59]. These features emphasize that the northern branch of the SASZ developed along a major inherited discontinuity.

Ages of sediments within the Ligerian and Champtoceaux Domains, between the two branches of the SASZ, are poorly constrained. However, there is evidence for sedimentation up to Carboniferous times, in the Ancenis basin, and also probably in the St Georges-sur-Loire basin. In the southern part of the latter basin, sediments include olistoliths of various composition and age, youngest being reported to mid-Devonian [60]. Interbedded volcanic rocks have yielded Rb/Sr whole rock ages of 350 ± 13 Ma [58, 61].

To the South, the Champtoceaux Domain comprises a stack of units, including eclogites, showing intense ductile deformation that accumulated during late Devonian burial and early Carboniferous exhumation [11]. Exhumation of the eclogites occurred in the footwall of a major normal fault zone. After exhumation, the whole structure has been deformed by a large-scale E-W striking fold (Fig. 14) with a steeply eastward plunging axis. In the hanging wall of the normal fault, the Ancenis basin contains a very low-grade sedimentary sequence of Carboniferous age. To the East, this basin has an E-W elongate shape along the NEFZ (Fig. 14b). To the West, it is quenched between the NEFZ and the northern border of the Champtoceaux units (Fig. 14b).

6.2. Implications of the restoration

From restored to deformed state, the southern boundary of Eastern Central Brittany undergoes a clockwise rotation of about 15° (Fig. 15). Because this edge is long, its rotation may have induced significant along-strike variations of the amount of associated thrust motion. Furthermore, because the southern edge of Central Brittany remains at a large angle to the infinitesimal principal shortening direction during shearing (Fig. 15), thrusting must have accompanied regional shearing in the area and in southern domains.

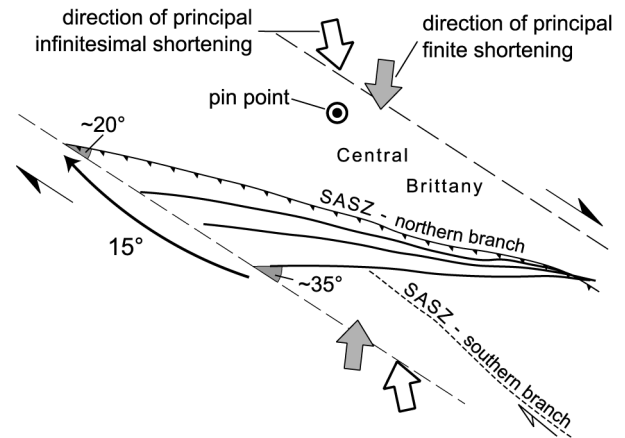


Fig. 15 Sketch showing structural changes during simple shear restoration of the southern border of eastern Central Brittany.

6.3. Comparison with structural data

Along the northern branch of the SASZ, sediments are affected by upright to north-verging folds (Fig. 16) [23, 54, 62]. The associated steep cleavage bears a sub-horizontal and E-W trending stretching lineation. Many works have shown that this deformation was associated with dextral strike-slip [24, 25, 54, 62–65]. Along the northern branch, north of the Lanvaux orthogneiss, S-C fabrics within syntectonic granites strike $N100^\circ$, parallel to the trace of the shear zone [25, 63].

South of the Lanvaux orthogneiss, there is widespread evidence for shearing along a $N120$ – $N130$ direction, parallel to the central part of the southern branch of the SASZ (Fig. 14b). Shearing is shown by (1) asymmetric quartz fabrics in the westernmost part of the St. Georges-sur-Loire unit [4] and in the Angers area [62], (2) S-C fabrics throughout the Allaire granite, and (3) local sigmoidal shapes of contacts between the different tectonic units (Fig. 14b). Evidence of strike-slip is mainly concentrated at the vicinity of the two branches of the SASZ, especially where the two branches merge (Fig. 14a). In contrast, the Ligerian Domain located between the two branches of the SASZ shows evidence of northward thrusting. Thus, the St. Georges-sur-Loire unit is thrust over the Lanvaux area [59, 60]. More generally, the different units are separated by south dipping

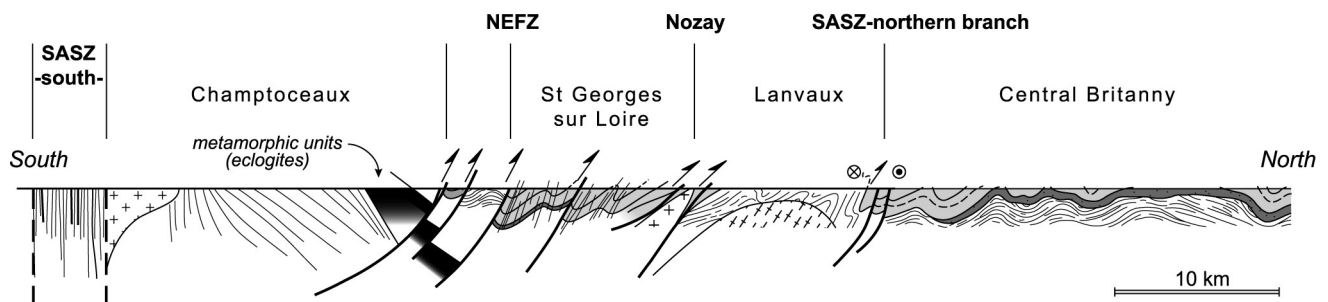


Fig. 16 Cross-section in the Champtoceaux area and southern part of eastern Central Brittany (modified from [23], [59], and [16]). Drawing patterns same as on Fig. 1b. Location is shown on Fig. 14.

thrusts (Fig. 16). Within units, folds are verging to the North, with a south dipping N100–N110 striking cleavage [59, 60]. Consistently, the mean direction of the stretching lineations, which is N090° to N100° in the Lanvaux area, changes to about NS in the St. Georges-sur-Loire and surrounding areas [59, 62].

The interpretation of a recent deep seismic profile across the Ligerian and Champtoceaux Domains [16] has outlined the occurrence of a crustal-scale south dipping thrust system, major thrusts being correlated with the WNW striking contacts between mapped units (compare Fig. 1 and 14). The thrust system cuts across the north-dipping eclogite-bearing units of the Champtoceaux anticline (Fig. 16). Along the seismic profile, the total amount of horizontal displacement has been estimated of the order of 25 km [16]. On map view, the thrust system merges within, or is cut by, the trace of the southern branch of the SASZ (Fig. 1b and 14b). In contrast, the SASZ merges at depth within the thrust system [16] (Fig. 1c). From these structural relationships, Bitri *et al.* [16] concluded that motions along the two structures were at least partly coeval. A 3D crustal-scale model from gravimetric and seismic data, has confirmed that the overall structure was non-cylindrical, thrusts becoming sub-vertical to the West where they merge into the SASZ [66]. The overall structure of the Ligerian and Champtoceaux Domains is therefore compatible with a progressive increase of the strike-slip component to the west, thrusts acting as scissor-type faults, with rotation axes located at their western tips, along the SASZ.

Granite intrusions provide some brackets for the age of the wrench-thrust deformation observed in the area.

The Vallet granite (Fig. 14), in the southern limb of the Champtoceaux syncline, is a good marker to constrain the onset of the post-exhumation history of this area. Its map shape shows the main granite body intrusive within metapelites (Fig. 14). To the NW, the main body connects with dyke-shaped bands, some of them cutting across the Champtoceaux metamorphic units as well as the overlying detachment (Fig. 14c). This geometry shows that the intrusion post-dates both the stacking and the exhumation of the Champtoceaux units. It further suggests that granite emplacement pre-dates the folding of the nappes. Indeed, the dykes can be interpreted as feeding conduits, which would mean that the Vallet granitic system has been tilted toward the southeast during folding. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of muscovites from the Vallet granite has yielded a plateau age of 336–337 Ma (Appendix 1), which gives a maximum age for the syn-shearing folding of the Champtoceaux units.

Syn-shearing granites along the southern branch of the SASZ (Allaire and Mortagne granites, Fig. 14b) have yielded Rb/Sr ages ranging from 310 to 330 Ma [27, 67]. $^{40}\text{Ar}/^{39}\text{Ar}$ ages between 312 and 305 Ma have been obtained on phyllosilicates from the Allaire massif (Ruffet, unpublished data). To the North, the small granite (St Lambert granite) that cuts across the trace of a fault parallel to the

northern branch of the SASZ, just southwest of Angers (Fig. 14b), has yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age on muscovites of 312 ± 3 Ma, which bounds the maximum age of shearing deformation in this area [60].

Thus, geochronological data suggest that most of the shearing within the Ligerian and Champtoceaux Domains took place between about 335 and 305 Ma. South of the SASZ, leucogranites are slightly younger, around 305–300 Ma [27]. These granites emplaced during late Carboniferous extension of the South Brittany Domain [13,14]. Their age is similar to that of ultramylonites that crop out along the SASZ (muscovite Ar/Ar ages, Ruffet, unpublished data), suggesting that localized ductile shearing still occurred along the SASZ while South Brittany underwent extension.

6.4. Restoration of the Ligerian and Champtoceaux Domains

The above discussion underlines that the northern branch of the SASZ constitutes a major structural boundary between Eastern Central Brittany, that underwent pervasive strike-slip, and the southern zone that underwent combined strike-slip and thrusting. Therefore, an attempt has been made to geometrically restore the Ligerian and Champtoceaux Domains between the northern and southern branches of the SASZ.

From restored to deformed states, boundary conditions are (1) westward decrease of thrusting motions along faults that merge within the southern branch of the SASZ, (2) thrusts that rotate clockwise, consistently with the regional dextral strike-slip component, and (3) amounts of thrusting on individual faults constrained by northward displacements estimated along the seismic profile (Fig. 1c) [16]. Results are shown on Fig. 17.

The restoration implies a decrease in the angle between the two branches of the SASZ of about 15°. This value is similar to the relative rotation predicted by the restoration of the bulk simple shear throughout Central Brittany for its southern boundary (compare Fig. 15 and 17). Accordingly, we infer that the model calculated for Central Brittany can be extended further South. Hence, we have restored the Champtoceaux anticline assuming a strike slip component with a γ value of 1.5 along a N123° direction, similar to that calculated for Central Brittany (Fig. 17). The result suggests a pre-shearing NW strike of the Champtoceaux units.

6.5. Segmentation of the southern branch of the SASZ

To the West, the southern branch of the SASZ joins the northern one, with an overall N105° trend. This segment of the shear zone is marked by Ordovician intrusions attributed to early Palaeozoic extension (e.g. Douarnenez trondjemite) [68] and underlying its inherited character. The southeastern part of the shear zone is marked by the eclogite-bearing

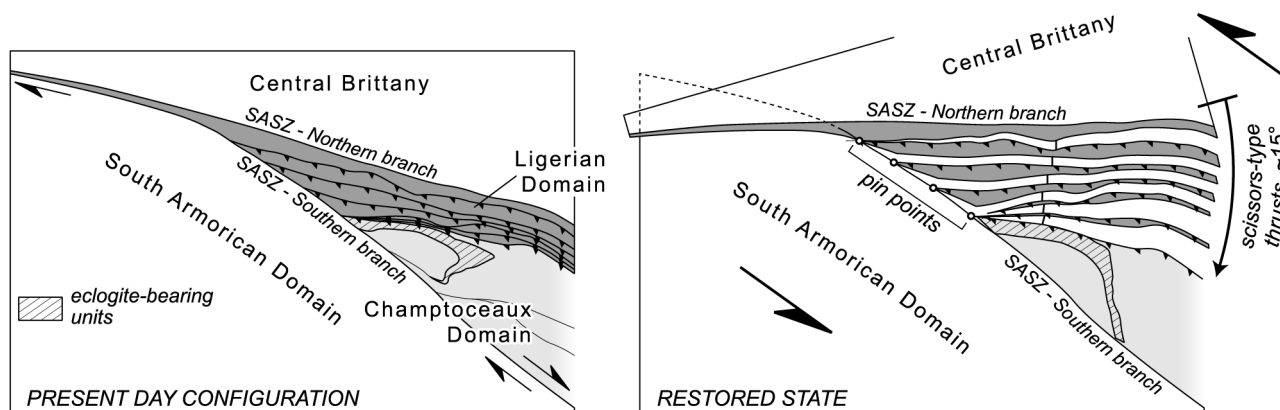


Fig. 17 Sketch illustrating the restoration of thrusting and regional-scale folding between the two branches of the SASZ. See text for further explanations.

Essarts unit (Fig. 1). This segment of the shear zone strikes about N130°, and splits into several zones toward the South-east (Fig. 1). Its direction is consistent with that of the Champtoceaux eclogites after restoration of the regional simple shear (Fig. 17). Eclogites being interpreted as the trace of a major suture zone (see [15]), this southeastern segment of the SASZ appears also as an inherited discontinuity. Between these two segments, the southern branch of the SASZ strikes N120°–N125°, parallel to the bulk simple shear direction affecting domains located North of it (Fig. 1). This segment clearly cuts across the suture zone. Moreover, thrusts within the Ligerian and Champtoceaux Domains merge within it. From these, we infer that this central segment of the southern branch of the SASZ is a rather recent feature resulting from regional-scale localization and southward migration of the dextral simple shear during Upper Carboniferous times.

7. Progressive deformation history, a summary

7.1. Early Carboniferous, onset of regional-scale simple shear (Fig. 18a)

In the Central Armorican Domain, regional-scale dextral shearing began during latest Devonian to earliest Carboniferous times. Deformation was continuous and pervasive across Eastern Central Brittany, with development of upright folds and associated sub-vertical cleavage.

To the West, the MNSZ was a NNE striking inherited Cadomian structure. During Carboniferous deformation, faults with a north-westward verging thrust component initiated along this discontinuity, with sedimentation localized in the foot-wall, a high increase of subsidence being observed in the lowermost Carboniferous sequences of the Châteaulin basin. Slightly later, two other local Carboniferous basins developed along the north-eastern and southern edges of the Central Armorican Domain, in Laval and Ancenis areas, respectively.

7.2. Middle Carboniferous, the main pervasive deformation of Central Brittany (Fig. 18b)

During the Viséan, the sedimentation was mainly restricted to the current outcropping surface of the Carboniferous basins. Syn-kinematic plutons emplaced to the South of Central Brittany, around 345–335 Ma. Their southern part is marked by mylonites reflecting dextral strike-slip motion localized along the northern branch of the SASZ. In the cartoon (Fig. 18b), we have applied about 40 km displacement along the northern branch of the SASZ, according to the offset of the Bignan granite estimated by Jégouzo and Rosselo [69].

In the northwestern part of Central Brittany, in the junction area between the MNSZ and the NASZ, onset of exhumation of the extensional Plouguenast metamorphic dome is attested by the Carboniferous age of the associated St-Gouéno leucogranite. To the South, the emplacement of the Vallet granite marks the transition between Lower Carboniferous exhumation of the Champtoceaux units and their folding during regional shearing.

7.3. Late Carboniferous, localization of the shearing deformation to the South (Fig. 18c)

No sediments younger than early Namurian are preserved in the Carboniferous basins. Moreover, the emplacement of the leucogranitic part of the Rostrenen massif along the MNSZ constrains the end of the deformation along this inherited structure around 320–315 Ma. Late activity of this zone is marked by an increase in the dextral shear component. During late Carboniferous times, regional-scale deformation decreased across Central Brittany and adjacent areas to the North and the West, and propagated southward. The Ligerian and Champtoceaux Domains were affected by a bulk transpressional regime expressed by (1) dextral strike-slip, largely localized along the SASZ and marked by leucogranite intrusions (Allaire, Vigneux and Mortagne leucogranites), and (2) crustal-scale northward thrusting whose geometry and kinematics are compatible with the regional-scale NW-SE oriented dextral simple-shear.

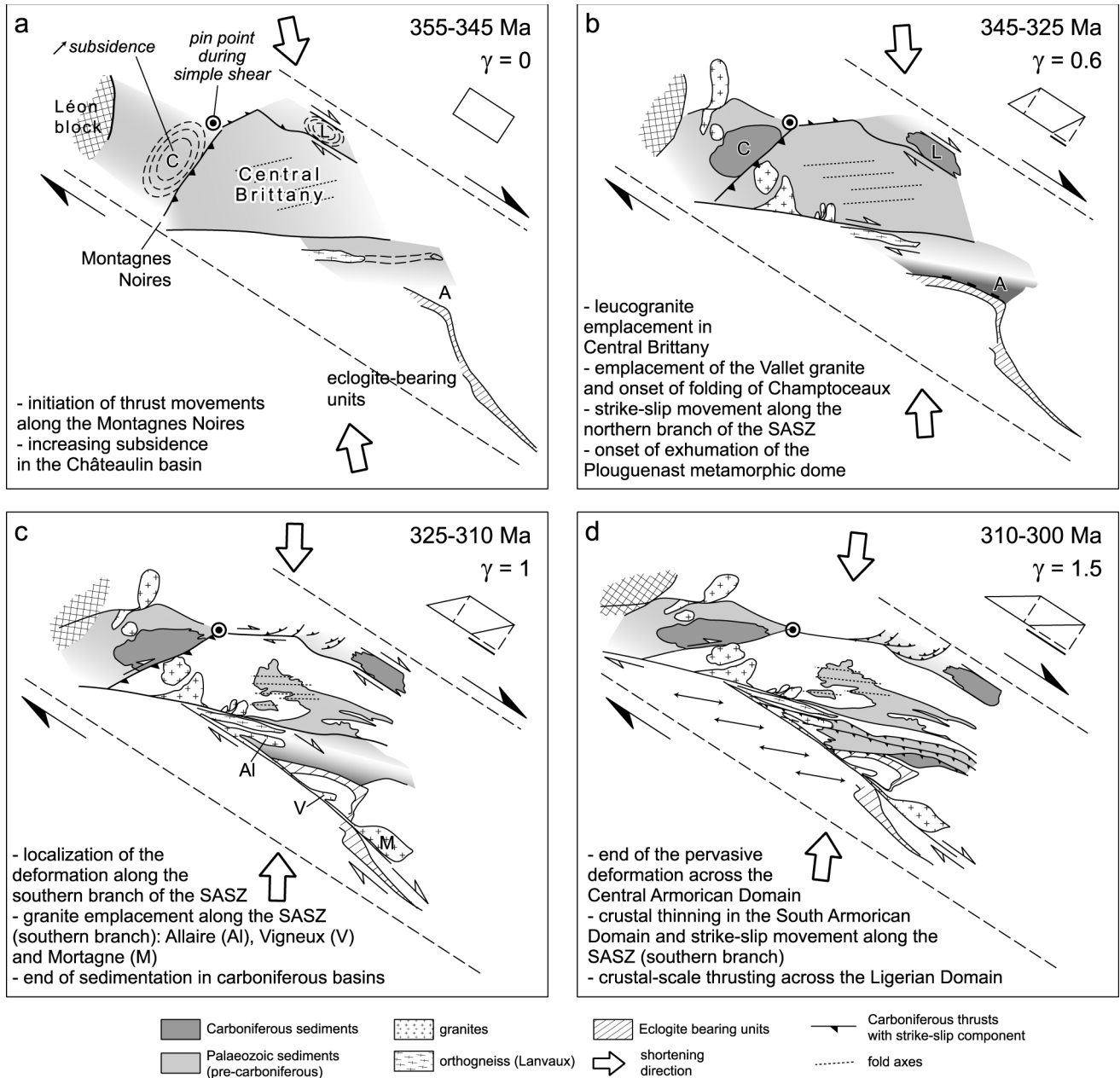


Fig. 18 Cartoon summarizing the Carboniferous evolution of shearing tectonics in Central Brittany and adjacent areas. See text for further explanations.

7.4. Latest Carboniferous, end of ductile deformation North of the SASZ (Fig. 18d)

At this time, rocks to the North and northeast of the southern branch of the SASZ all belong to the upper crust. Deformation of these domains seems to decrease around 310 Ma. Simple-shear was then restricted along the southern branch of the SASZ, where mylonites developed at about 300 Ma (Ruffet, unpublished data). During this period, the South Armorican Domain suffered crustal thinning marked by regional-scale WNW-ESE stretching [12, 13]. Thus, during the latest Carboniferous, the Southern branch of the SASZ appears as having acted as a transfer zone between a thinning domain to the South [13,14] and a stable crust to the North.

8. Conclusions

The present study has emphasized that a simple restoration model may provide a constructive basis for an integrated analysis of the ductile deformation within an orogenic belt. The example of the Central Brittany shear belt is of course particularly simple because the restored Hercynian strain is rather homogeneous, basically 2D, and steady with time. The model did not take into account poorly or not constrained relative displacements and rotations between the different domains. Nevertheless, it has provided new kinematic interpretations of several major structures, including the Carboniferous Châteaulin Basin, the Plouguenast gneiss dome, or relationships between strike-slip and thrusting that

affect the southern part of the study area. The restoration model, combined with chronological constraints, further allowed us to propose an integrated tectonic history during Carboniferous times. The restoration emphasized the first-order role of inherited crustal-scale structures on the development of the regional structural pattern. These in particular clearly controlled local basin development and emplacement of syn-kinematic intrusions. They further acted as zones of localized vertical movements between adjacent blocks.

Central Brittany belongs to the Ibero-Armorican arc. An attempt to extend the restoration model at a larger scale might provide strong constraints on the genesis and significance of this major feature of the Hercynian belt of Western Europe.

Acknowledgements

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Appendix: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

The $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiment on single grains was described by Ruffet *et al.* [70]. The grains extracted from the different samples were sieved in the range 300–600 μm . The irradiation flux was calculated using the Hb3gr amphibole (1072 Ma, [71]) as irradiation monitor.

All errors are quoted at the 1σ level and do not include the errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio and age of the monitor. The error on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio of the monitor is included in the calculation of the plateau age error bars.

The Plouguenast metamorphic dome

Two plutonic rocks from the Plouguenast area have been analysed, the St Gouëno leucogranite and the Plouguenast orthogneiss of granodioritic composition. Precise location of analysed samples are available on request.

The Saint-Gouëno leucogranite crops out in the middle of the metamorphic complex. 3 samples have been analyzed (Fig. A1). Two of them (98PL1 and 98 PL3) yielded plateau ages around 330 Ma and 325 Ma, respectively (Fig. A1). The third sample shows a more complex pattern, with a saddle-type shape (sample 98 PL2, Fig. A1). Apparent ages increase at low and high temperatures, up to values around 350 Ma, and a minimum apparent age of about 335 Ma is found at intermediate temperatures. The saddle shape could reflect long-lived crystallization history, due to slow cooling and/or long deformation history accompanied by mica recrystallisation. In such interpretation, the oldest age around 350 Ma could correspond to relict indicators of crystallisation of oldest micas, i.e. of the emplacement age at

depth within the dome. The gradual transition between 350 Ma and 325 Ma would thus reflect progressive exhumation of the metamorphic complex.

One sample from the Plouguenast orthogneiss has provided a plateau age around 330 Ma (Fig. A1), consistent with

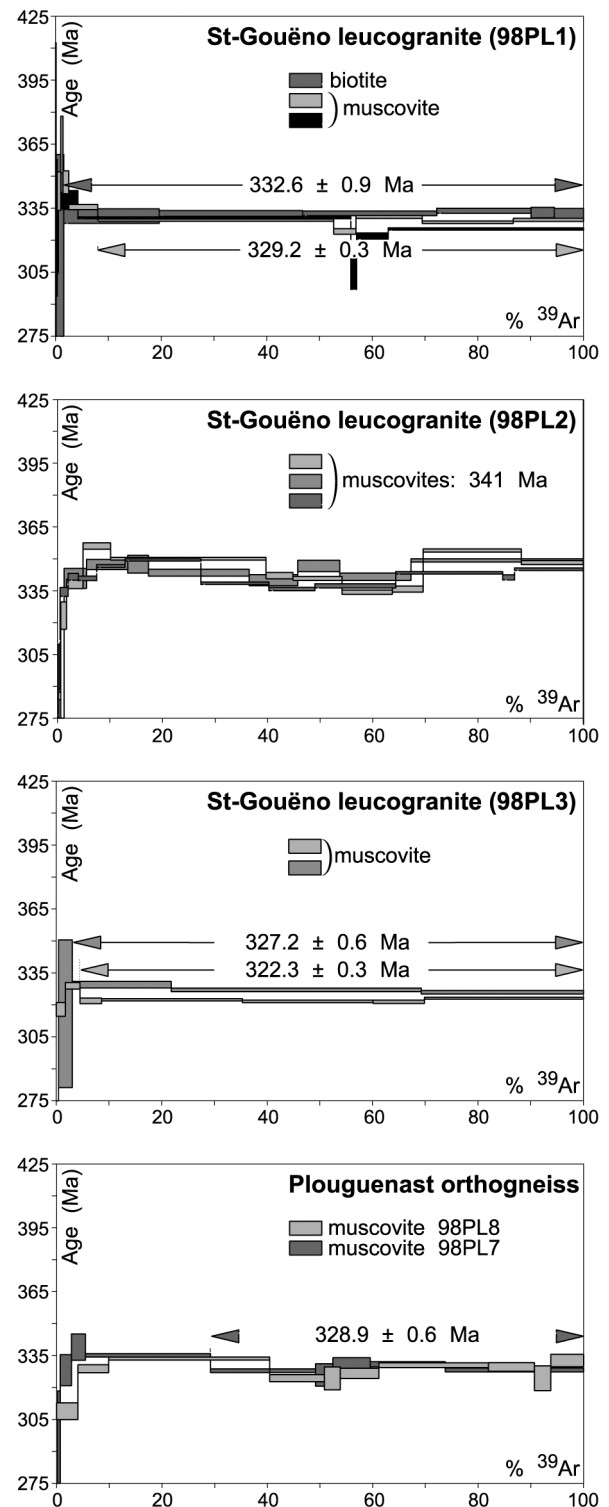


Fig. A1 Ar-Ar data from the Plouguenast dome (see Fig. 12 for location).

the youngest ages obtained in the leucogranite. This suggests that both rocks shared a common exhumation history.

The Vallet granite

This pluton from the Champtoceaux area emplaced within metapelites from the upper part of the metamorphic pile. Muscovites from two samples have been analysed and give quite consistent plateau ages around 335–337 Ma (Fig. A2). The regional metamorphism within the metapelites, which are overlain unconformably by low-grade Cambrian sediments, is of Proterozoic age [72]. Thus, country-rocks were in upper-crustal position during granite emplacement, and the age is interpreted as associated with pluton cooling.

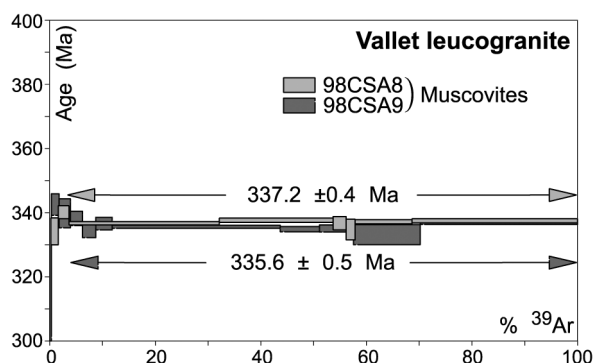


Fig. A2 Ar-Ar data from the Vallet leucogranite (see Fig. 14 for location).

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