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Incipient strain partitioning in a slate belt: Evidence from the early Variscan Monts d'Arrée slate belt (Brittany, France)

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Abstract

Partitioning of strain is a fundamental process during mountain building. It commonly causes a compartmentalisation of a bulk regional strain into deformational domains with contrasting strain characteristics and largely oriented parallel to the orogenic grain. The Monts d'Arrée slate belt (Brittany, France) offers an opportunity to study strain partitioning in a slate belt deformed in an overall transpressional regime. The slate belt consists of highly deformed, low-grade, siliciclastic metasediments of upper Silurian to lower Devonian age. The deformation occurred during an early Variscan nappe stacking event ('Bretonian phase'). An extensive structural analysis has demonstrated that the slate belt reflects the initial stages of strain partitioning. The slate belt primarily reflects coaxial, contraction-dominated deformation. It resulted in NW-verging folding and a pervasive cleavage development, giving rise to a pronounced mechanical anisotropy. During the later stages of deformation, incipient strain partitioning lead to the development of punctuated strain heterogeneities, consistently reflecting dextral, belt-parallel, strike-slip strain. These structures are not organised in networks or domains. Incipient strain partitioning in the Monts d'Arrée slate belt did not reach the stage of compartmentalisation by the formation of an interlinked discontinuity network or wrench-dominated deformational domains.

Keywords: Contraction; Kinematic analysis; Simple shear; Slate belt; Strain partitioning; Transpression; Variscan

1. Introduction

Deformation zones in the middle to upper crust commonly show a very complex architecture, primarily because of the wide range of ways in which strain is accommodated during mountain building processes in continental crust. In recent years, it has become evident that complex structural patterns observed in deformation zones do not comply with simple two-dimensional simple-shear models and should be interpreted in a more realistic way, considering three-dimensional, non-coaxial non-plane strain (cf. Holdsworth et al., 1998 and references therein). Such three-dimensional, non-coaxial non-plane strain commonly shows a high degree of strain heterogeneity, reflecting strain partitioning. Strain partitioning gives rise to compartmentalisation of the bulk regional strain (cf. Jones and Tanner, 1995), developing deformational domains with contrasting strain characteristics, and enabling to maintain strain compatibility within different crustal levels (cf. Jones et al., 2005). Examples show that within transpression zones this kinematic partitioning is expressed by the development of contraction- and wrench-dominated domains, each with a particular spatial and temporal relationship between structural features (e.g. Holdsworth et al., 2002a,b; Tavarnelli et al., 2004; Clegg and Holdsworth, 2005).

In middle- to upper-crustal levels such deformation zones commonly develop in siliciclastic, predominantly argillaceous, metasedimentary series. The resulting slate belts commonly show a pronounced mechanical anisotropy, materialised by a pervasive, steeply dipping slaty cleavage. Many of such belts are commonly interpreted as crustal transcurrent shear zones.

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In recent work, however, the significance of coaxial shortening and pure shear has been recognised in most cases (e.g. Passchier et al., 1997; Robertson and Smith, 1999; Solar and Brown, 2001).

In this paper we focus on the Monts d'Arrée slate belt (MASB), which is situated in the Central Armorican terrane (CAT) in Brittany (France) (Fig. 1a). The MASB is a high-strain domain within the CAT, reflecting an early Variscan orogenic event ('Bretonian phase') related to the oblique convergence and collision of the Léon microcontinent with the northern margin of the Armorica microcontinent (cf. Faure et al., 2005). The excellent exposure of the MASB offers a unique opportunity to evaluate the way slate belts accommodate non-coaxial non-plane strain in a transpressional regime. An extensive structural analysis has revealed the predominance of a coaxial contraction-dominated deformation, expressed by NW-verging folding and a pervasive cleavage development. Subsequent deformation is expressed by punctuated strain heterogeneities, consistently reflecting dextral, belt-parallel, strike-slip strain. The MASB reflects the initial stages of strain partitioning in a slate belt, not reaching the stage of compartmentalisation in deformational domains or an interlinked network of shear zones.

2. Geological setting

The Central Armorican terrane (CAT) represents a part of the perigondwanan microcontinent Armorica, rifted off the northern margins of Gondwana during early Ordovician times. The remains of a similar perigondwanan microcontinent are located north of the CAT in the Léon domain (Fig. 1a). The CAT consists of a nearly continuous sedimentary sequence ranging in age from Arenig to Namurian (Guillocheau and Rolet, 1982). This sequence is deposited on top of

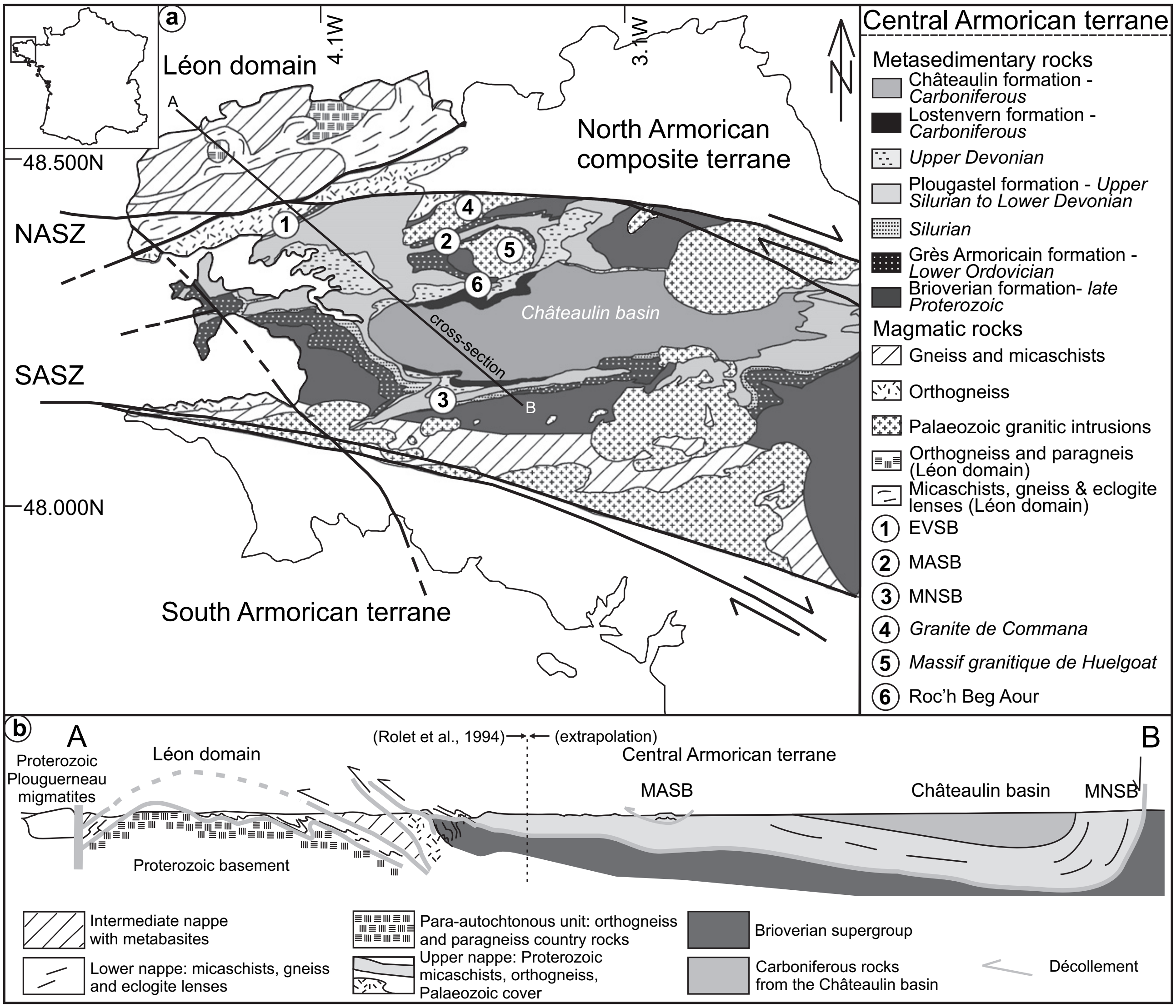

Fig. 1. (a) Tectonic setting of the Central Armorican terrane (CAT) in western Brittany (after Le Corre et al., 1991), showing the slate belts, (1) Elorn Valley slate belt (EVSB), (2) Monts d'Arrée slate belt (MASB), (3) Montagnes Noires slate belt (MNSB), the granitic intrusions of (4) Commana, and (5) Huelgoat, and the outcrops (6) Roc'h Beg Aour. (b) Tentative structural section across the Léon domain and the Central Armorican terrane, omitting Late Palaeozoic granitoid intrusions (after Rolet et al., 1994; Faure et al., 2005; van Noorden, 2007). NASZ, North Armorican shear zone; SASZ, South Armorican shear zone.

Neoproterozoic, Brioverian metasediments, representing the erosional product of the Cadomian basement (Cogné, 1974; Le Corre et al., 1991; Autran et al., 1994; Chantraine et al., 2001). This Neoproterozoic, crystalline basement primarily crops out north of the North Armorican shear zone (NASZ) in the North Armorican composite terrane (NACT) (Fig. 1a).

Two major periods of deposition can be distinguished in the CAT (Guillocheau and Rolet, 1982). During the first period, from the Arenig until the late Famennian, the sedimentary record reflects the development of an unstable platform. The *Grès Armoricain* formation, a white, predominantly arenitic sequence, forms the base of this Ordovician transgression. The start of the second depositional period is marked by dynamic deposits (e.g. olistostromes, turbidites), associated with an increased tectonic activity in the CAT, during the 'Bretonian phase' (Rolet, 1982; Darboux, 1991; Le Gall et al., 1992; Gumiaux, 2003). This resulted in the development of the fault-bounded Châteaulin basin (Rolet and Thonon, 1979; Guillocheau and Rolet, 1982), consisting of Tournaisian to Viseo-Namurian volcanosedimentary and terrigeneous deposits.

The CAT is bounded to the south by the South Armorican shear zone (SASZ), a major terrane boundary (Autran et al., 1994) separating the CAT from the South Armorican terrane (SAT) (Fig. 1a). The latter consists of Neoproterozoic crystalline rocks, and is characterised by an Acadian deformation history (Le Corre et al., 1991; Autran et al., 1994).

The geodynamic history of the CAT is primarily related to the late Devonian to early Carboniferous closure of the Rheic Ocean and the related oblique docking of the Léon domain. This early Variscan, 'Bretonian', orogenic event leads to major top-to-the-NW overthrusting and nappe stacking and a significant crustal thickening of the central Armorican crust (Rolet et al., 1994; Faure et al., 2005; van Noorden, 2007) (Fig. 1b). Subsequently, middle to late Carboniferous, intracontinental deformation resulted in significant wrenching (e.g. Gapais and Le Corre, 1980; Jégouzo, 1980) and syn-orogenic collapse (Faure et al., 2005).

A typical feature in the western part of the CAT is the presence of three ENE-trending belts, the Elorn Valley, the Monts d'Arrée and the Montagnes Noires (Darboux et al., 1977; Le Corre et al., 1991) (Fig. 1a), commonly interpreted as dextral transcurrent shear zones in between the NASZ and the SASZ (Darboux and Le Gall, 1988; Darboux, 1991).

The Monts d'Arrée is a linear mountain chain, 30 km long and 2.5 km wide. The geomorphology is characterised by a flat plateau, at an altitude of 300 m above sea level, on top of which individual outcrop areas (e.g. Roc'h Trévézel) are exposed. These outcrops provide an excellent, three-dimensional exposure of the internal architecture of the Monts d'Arrée slate belt (MASB).[1] Furthermore, the exposures display a particular spatial distribution, i.e. the individual outcrop areas are organised in an en-echelon pattern (Figs. 2 and 4a).

The MASB is composed of the upper Silurian to lower Devonian Plougastel formation (Fig. 2), reflecting a proximal turbiditic facies. It consists of a typical multilayer sequence of white to grey sandstones and dark pelites. Deformation in the MASB occurred in low-grade metamorphic conditions (Darboux, 1981; Darboux and Le Gall, 1988) and shows a high degree of strain (up to 60% shortening) compared to the underlying *Grès Armoricain* formation. A major décollement is assumed on top of which a top-to-the-NW shear caused the deformation in the MASB (Fig. 3a) (van Noorden, 2007). This deformation took place prior to the granitic intrusions (*Granite de Commana*, *Massif granitique de Huelgoat* – Figs. 1a and 2 – Castaing et al., 1987b), causing an andalusite porphyroblastesis during the latest, wrench-dominated, stages of the deformation history (Hanmer et al., 1982; Darboux, 1991). The intrusion of the Huelgoat granite, furthermore, caused an overall doming of the *Grès Armoricain* formation (Fig. 3b). The Huelgoat granite has a radiometric age of 336 ± 13 Ma (Peucat et al., 1979), clearly demonstrating that the main deformation in the MASB can be fitted into the overall thrusting and nappe stacking during the 'Bretonian' orogenic event (Fig. 1b) (cf. Faure et al., 2005).

3. Strain in the Monts d'Arrée slate belt

3.1. Overall structural architecture

The overall structural architecture of the MASB displays a first-order fold train contained in a subhorizontal to moderately N-dipping envelope, largely parallel to the interface with the underlying Ordovician sequence (Figs. 3 and 5). Folding occurred cogenetic with respect to a steeply dipping, pervasive axial planar cleavage. The first-order folds, primarily defined by the envelope of higher-order, outcrop-scale folds, can be followed along the entire grain of the belt, from outcrop area to outcrop area. This suggests that the first-order fold train shows a high degree of cylindricity, excluding any significant lateral displacements between outcrop areas as may be suggested by the en-echelon pattern of individual outcrop areas (Fig. 4a). The structural polarity observed in the MASB, as exemplified by bedding/cleavage relationship, is always concordant with the observed stratigraphical polarity, i.e. all antiforms and synforms are anticlines and synclines, respectively. This infers only one single phase of folding.

In the northeasternmost section of the MASB (Roc'h Ar Feunteun; Figs. 2 and 4b, c), the broad, first-order 'Ar Feunteun synform' (Fig. 5, AFS) occurs, possibly followed to the north by a broad first-order antiform (Fig. 5, Roc'h Ar Feunteun 1 and 2). Towards the Roc'h Tredudon outcrop area (Figs. 2 and 4), we are able to follow the first-order fold-hinge-line trajectories of the 'Ar Feunteun synform' (Fig. 4b, c), with a N-dipping envelope in the southernmost outcrops (Fig. 5, Roc'h Tredudon). Slightly further to the north, we observe a fold sequence with a rather more steeply N-dipping envelope, indicative of the first-order, slightly N-verging 'Tredudon antiform' (Fig. 5,

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[1] MASB is used to describe the slate belt with its internal Variscan architecture. Monts d'Arrée is used for the description of the linear mountain chain and its morphological characteristics. The MASB is not confined to the Monts d'Arrée, as proven on outcrops south of the Monts d'Arrée and south of the *Massif granitique de Huelgoat* (e.g. Roc'h Beg Aour; Fig. 1a) (van Noorden, 2007).

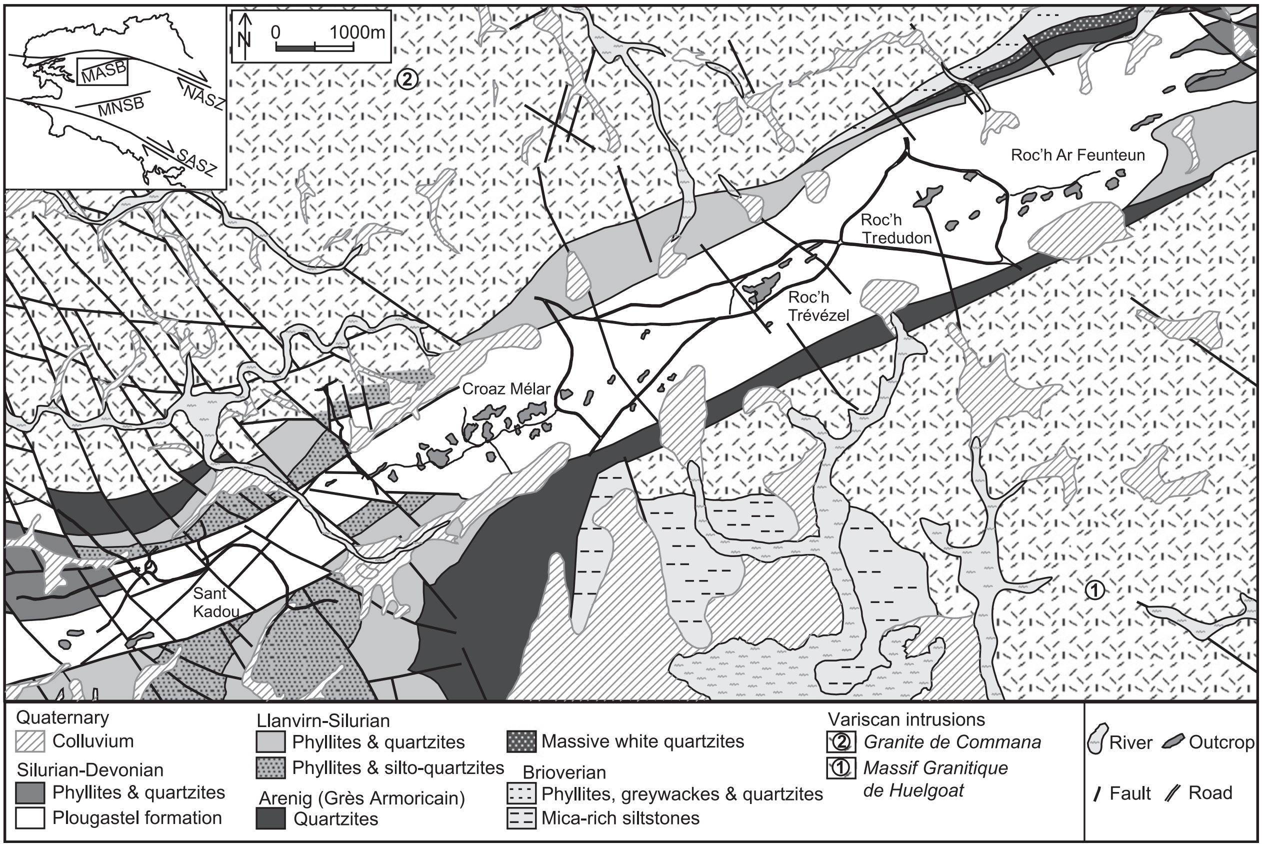

Fig. 2. Geological map of the Monts d'Arrée with the location of outcrops. Inset shows the Monts d'Arrée slate belt (MASB) and Montagnes Noires slate belt (MNSB) in between the North Armorican and South Armorican shear zones (NASZ and SASZ, respectively). (Map after Castaing et al., 1987a).

TDA). This first-order antiform may be the western continuation of the antiform inferred at Roc'h Ar Feunteun. In the northernmost outcrops another, sharp, first-order antiform can be observed, which is NE-plunging and NW-verging.

The central part of the MASB is formed by the Roc'h Trévézel (Figs. 2 and 4). In the southern outcrops, a moderately N-dipping fold envelope can be inferred (Fig. 5, Roc'h Trévézel 1), which may represent the northern limb of the

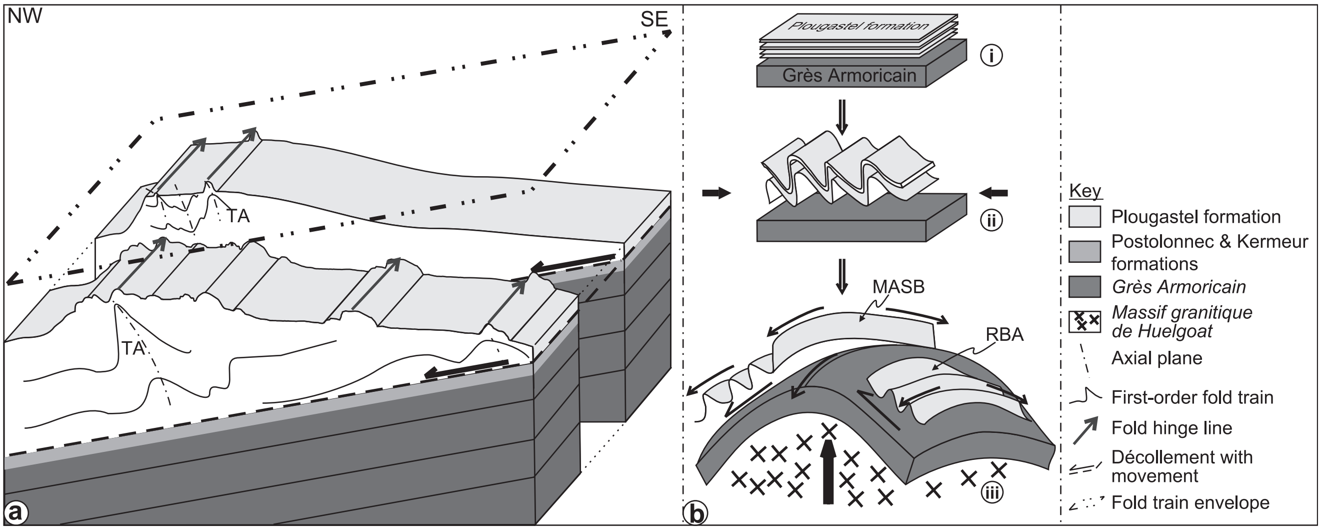

Fig. 3. (a) Three-dimensional sketch of the décollement model on top of the Ordovician sequence. The Trévézel antiform (TA) can be continued along strike, throughout various outcrops. The internal architecture remains a constantly N-verging fold train with SE-dipping axial planar cleavage and a subhorizontal to moderately N-dipping envelope (dashed line). (b) Conceptual model of the development of the Monts d'Arrée slate belt (MASB) with (i) the initial stage prior to deformation; (ii) the development of regional contraction-dominated domains on top of the décollement due to a NNW–SE orientated compression; and (iii) the situation after doming, due to the intrusion of the granitic intrusions. RBA, Roc'h Beg Aour.

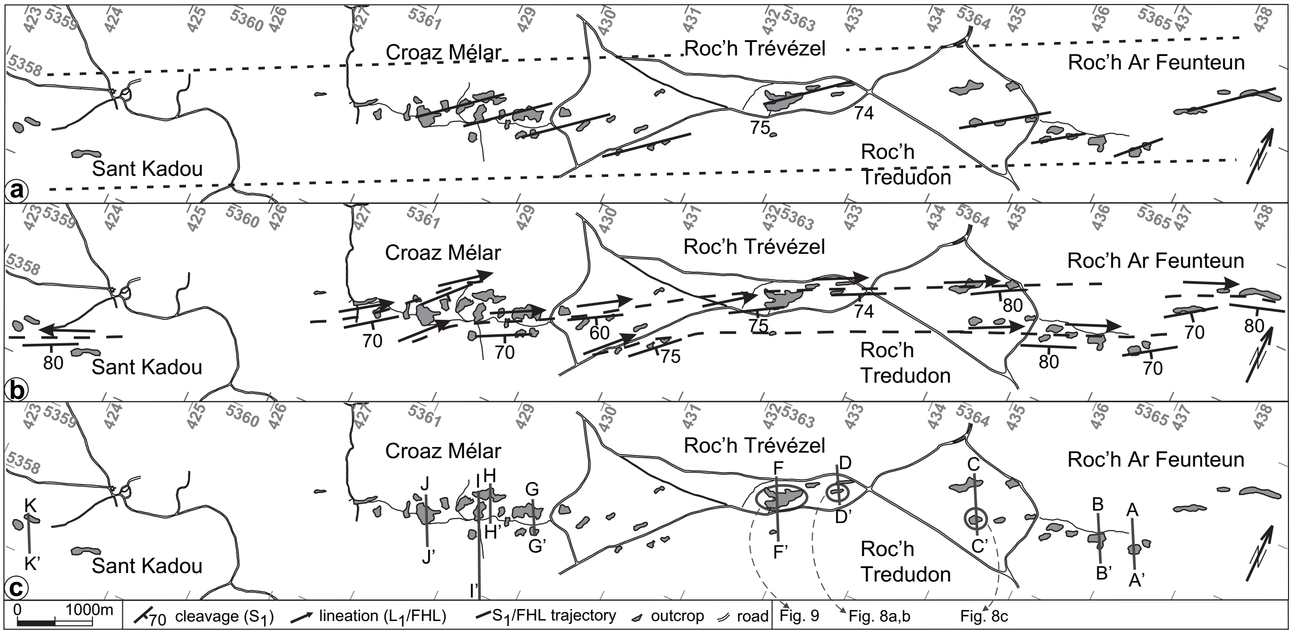

Fig. 4. Maps of the Monts d'Arrée slate belt (MASB) showing (a) the en-echelon pattern of individual outcrop areas (continuous black line) and the boundaries of the belt (dashed black line); (b) main fold hinge lines (FHL), main cleavages, and fold hinge lines and cleavage trajectories; (c) locations of the cross-sections (Fig. 5) and the locations of Figs. 8 and 9.

western continuation of the 'Tredudon antiform'. The outcrops in the northern parts of the Roc'h Trévézel outcrop area expose the N-verging, rather sharp first-order 'Trévézel antiform' (Fig. 5, TA), and the first-order 'Trévézel synform' (Fig. 5, TS). The northern limb of the 'Trévézel antiform' is commonly overturned, as evidenced by the bedding/cleavage relationship, and is characterised by a step-fold sequence and high degree of internal disharmony (Fig. 5, Roc'h Trévézel 1).

Further southwest, the N-verging 'Trévézel antiform' and 'Tredudon antiform' can be identified within the Croaz Mélar outcrop area (Figs. 2 and 4; Fig. 5, Croaz Mélar 1 and 2). North of the 'Trévézel antiform', a N-verging fold train with a moderately N-dipping overall envelope and a steeply SE-dipping, axial planar cleavage (Fig. 6b,c) can be observed (Fig. 5, Croaz Mélar 2 and 3). From south to north, this first-order fold train outlines the 'Croaz Mélar antiform 1' (CMA1), the 'Croaz Mélar synform' (CMS) and the 'Croaz Mélar antiform 2' (CMA2). To the south the moderately NW-dipping interface with the Ordovician sequence can be inferred (Fig. 5, Croaz Mélar 2b).

Outcrops in the most southwestern section of the MASB are marked by a W-plunging first-order fold train (Fig. 6c) that most probably forms the western continuation of the northernmost fold train in the Croaz Mélar outcrop area. In the Sant Kadou outcrop area (Figs. 2 and 4), a step-fold sequence occurs within a moderately N-dipping envelope (Fig. 5, Sant Kadou).

It is clear that the orientation of the regional fold train is oblique with respect to the rather abrupt boundaries of the mountain chain, suggesting that the linear morphology of the Monts d'Arrée is to a large extent unrelated to its internal architecture.

3.2. Shortening structures

The internal deformation of the multilayer sequence is characterised by higher-order folding, commonly developed in quartzitic layers of all thicknesses. The majority of the individual higher-order folds can be described as class 1B folds but commonly also as class 1C folds, as defined by Ramsay (1967). We infer that the amount of homogeneous shortening, as evidenced by individual fold geometries is in the order of 50–60%. Higher-order folds have a clear disharmonic occurrence, since they die out rapidly in transverse sections, while in longitudinal sections they are rather continuous, as indicated by the regularity and continuity of the bedding/cleavage intersection (Figs. 6 and 7a), consistently parallel to the fold hinge lines. Open, upright higher-order folds commonly occur within the hinge zone of first-order synforms (e.g. 'Ar Feunteun synform'), displaying a cuspate–lobate morphology, with open antiforms and sharp synforms. Predominantly phyllitic sequences are characterised by a chevron-type folding.

The main tectonic foliation is a pervasive, steeply dipping cleavage, largely axial planar with respect to the first-order folds and with a generally constant attitude (Figs. 6 and 7b). This cleavage is only occasionally deformed by: (1) kink band development (Fig. 7c) or (2) late folding (Fig. 8d).

Linear features, such as the bedding/cleavage intersection lineation (Fig. 6b) and kink axes are parallel to the mean ENE-plunging fold hinge line of the first-order fold train (Fig. 6c). In outcrops and in samples on various scales, the bedding/cleavage intersection lineation is the most prominent linear feature. There is no clear evidence for a pervasive stretching lineation, on outcrop-scale or on microscale.

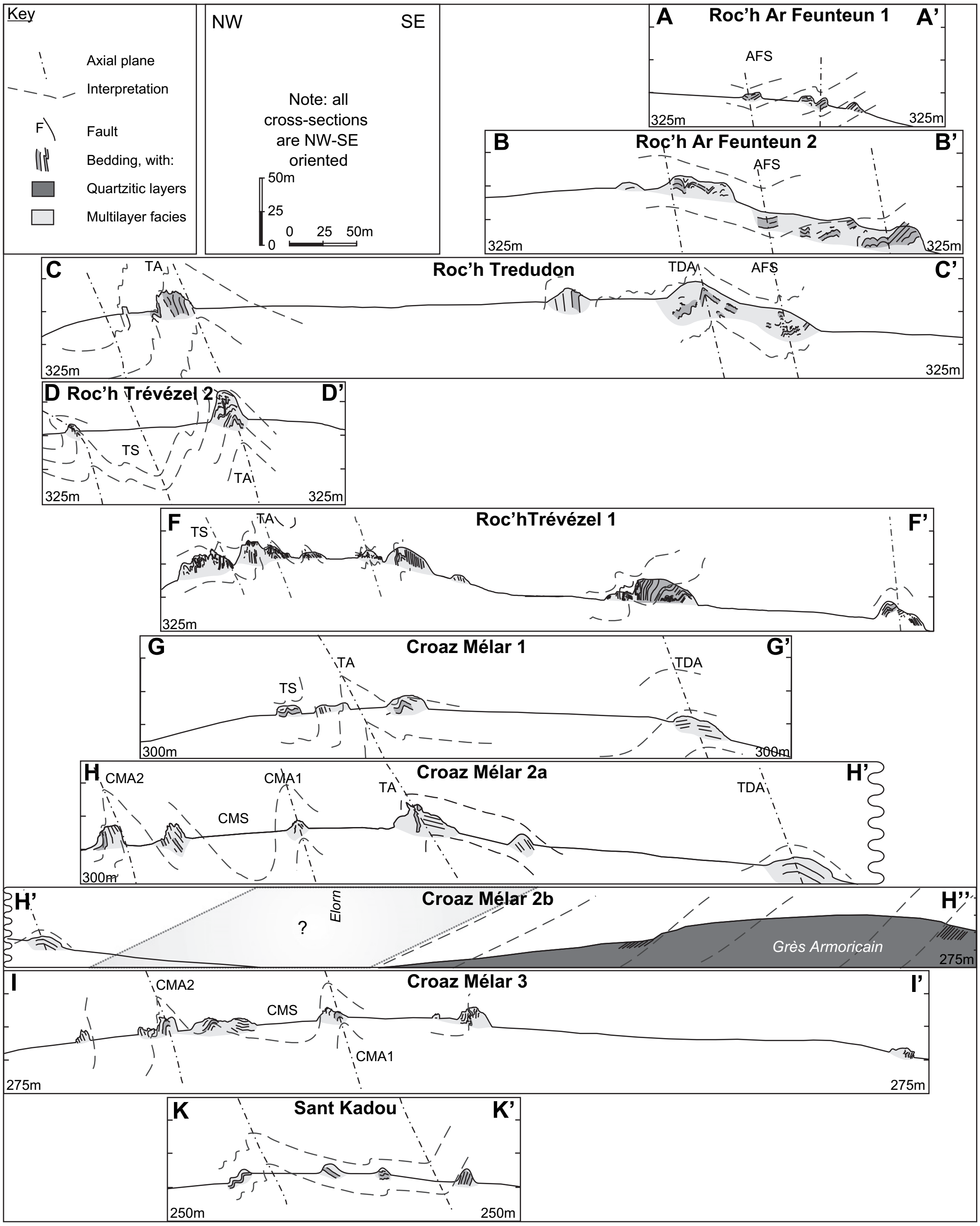

Fig. 5. Schematic cross-sections of the outcrop domains in the Monts d'Arrée slate belt (MASB), with (A–A') Roc'h Ar Feunteun 1, (B–B') Roc'h Ar Feunteun 2, (C–C') Roc'h Tredudon, (D–D') Roc'h Trévézel 2, (F–F') Roc'h Trévézel 1, (G–G') Croaz Mélar 1, (H–H') Croaz Mélar 2a and b, (I–I') Croaz Mélar 3, and (K–K') Sant Kadou. See Fig. 4c for the location of the cross-section lines. The cross-sections show a fold train with subhorizontal to weakly N-dipping envelope. AFS, Ar Feunteun synform; CMA1, Croaz Mélar antiform 1; CMA2, Croaz Mélar antiform 2; CMS, Croaz Mélar synform; TA, Trévézel antiform; TDA, Tredudon antiform; TS, Trévézel synform. Note: all cross-sections are NW–SE orientated.

The internal deformation of the multilayer sequence of the Plougastel formation is strongly controlled by the inherent anisotropy related to its lithostratigraphical composition and the original sediment architecture. Examples include abundant sedimentary features, such as load casts (Fig. 7d), ripple marks, worm borings, and isolated sand lenses, significant lateral thickness variations, as well as small-scale, non-cylindrical folds, showing typical strongly curved fold hinge lines. In coastal outcrops (Fig. 1a), where weakly deformed, non-metamorphosed rocks of the Plougastel formation are exposed, the small-scale, non-cylindrical folds are interpreted as the result of a synsedimentary, soft-sediment deformation (Bradshaw, 1963; Renouf, 1965). Typically, quartzitic layers are very discontinuous and highly variable in thickness in transverse sections

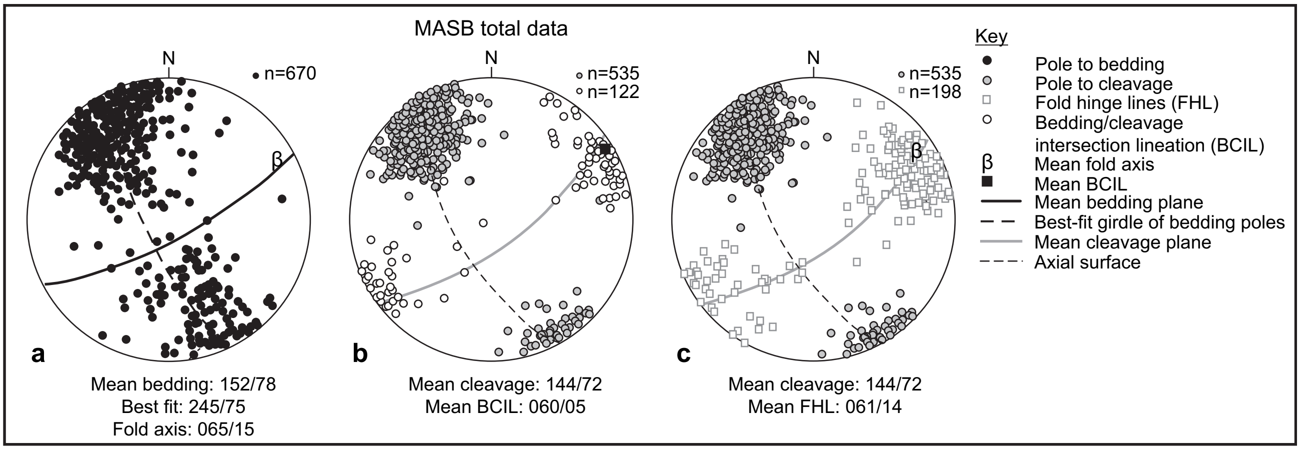

Fig. 6. Structural orientation data of the Monts d'Arrée slate belt (MASB): (a) poles to bedding with best-fit great circle (dashed line), mean bedding (continuous line) and regional fold axis (β); (b) poles to cleavage and bedding/cleavage intersection lineation (BCIL) with mean BCIL (■), mean cleavage plane (continuous grey line) and axial surface (dashed line) and (c) poles to cleavage and fold hinge lines (FHL), with mean FHL (β), mean cleavage plane (continuous grey line) and axial surface (dashed line).

(strike-perpendicular) sections. Within quartzitic layers, thickening occurs in the hinge zone of folds, whereas thinning occurs on the limbs (Fig. 7e). Thinning has resulted in boudinage or even in completely pinching out of layers. Boudinaged quartzitic layers are commonly associated with massive quartz veins. The internal deformation is, moreover, characterised by the particular deformation behaviour of the quartzitic layers. They seemingly played no part in controlling the overall deformation, but were deformed in a very viscous manner (Fig. 7f).

3.3. The top-to-the-NW shear structures

Throughout the MASB, a spatial variation in strain intensity is observed that can be linked with a top-to-the-NW shearing. This variation is particularly exemplified at different levels in the hinge zone of first-order antiforms. It is possible to distinguish four different stages, in which these first-order antiforms underwent a variable amount of deformation. The first stage is represented by an upright, tight antiform (Fig. 8a), with a subvertical axial plane. This type of deformation is the most common type in the outcrops. With increasing strain, the first type of deformation gradually changed into a more overturned antiform (Fig. 8b), as represented by higher-order isoclinal folds. These isoclinal folds typically show a slightly curved axial plane. The next stage of increasing strain intensity is represented by antiforms with a clear, even more curved axial plane (Fig. 8c). Higher-order folds sometimes show strongly deformed axial planes, clearly the effect of a

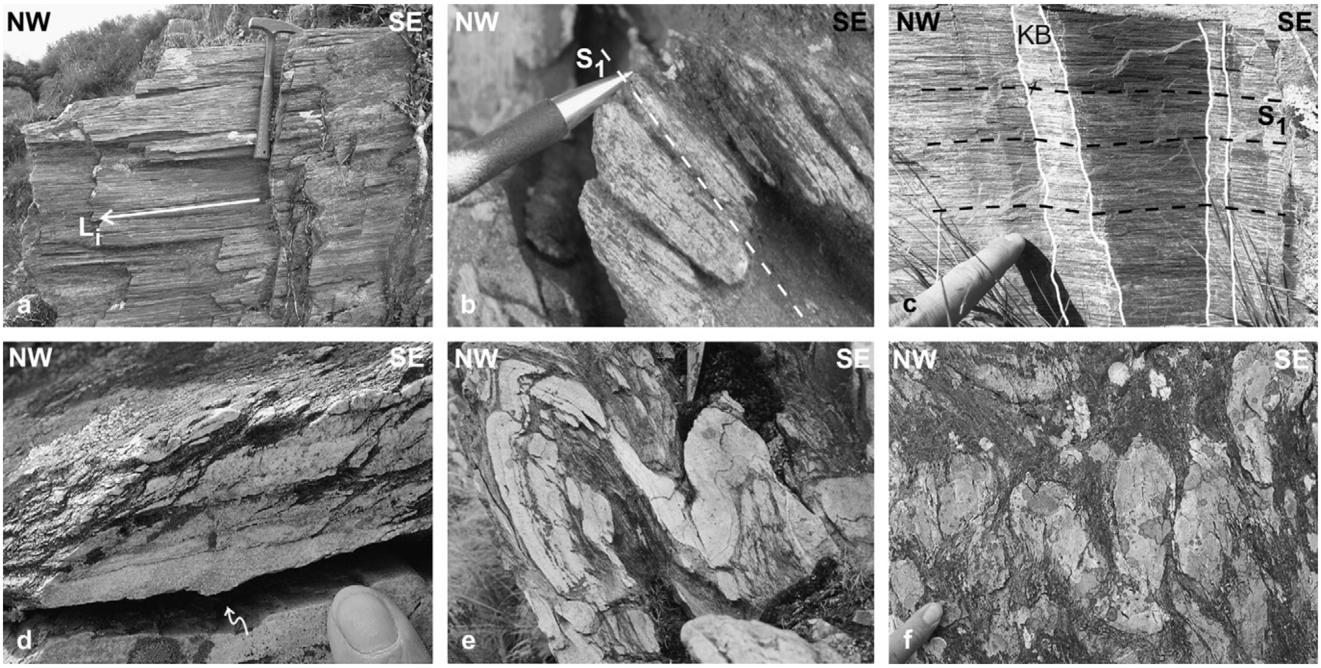

Fig. 7. (a) Pronounced bedding/cleavage intersection lineation. (b) Axial planar cleavage. (c) Kink band developed in the phyllitic series, which has deformed the cleavage. (d) Example of load casts. (e) Typical disharmonic fold with thinned fold limbs and thickened fold hinge. (f) Intensely deformed, viscous quartzitic layer.

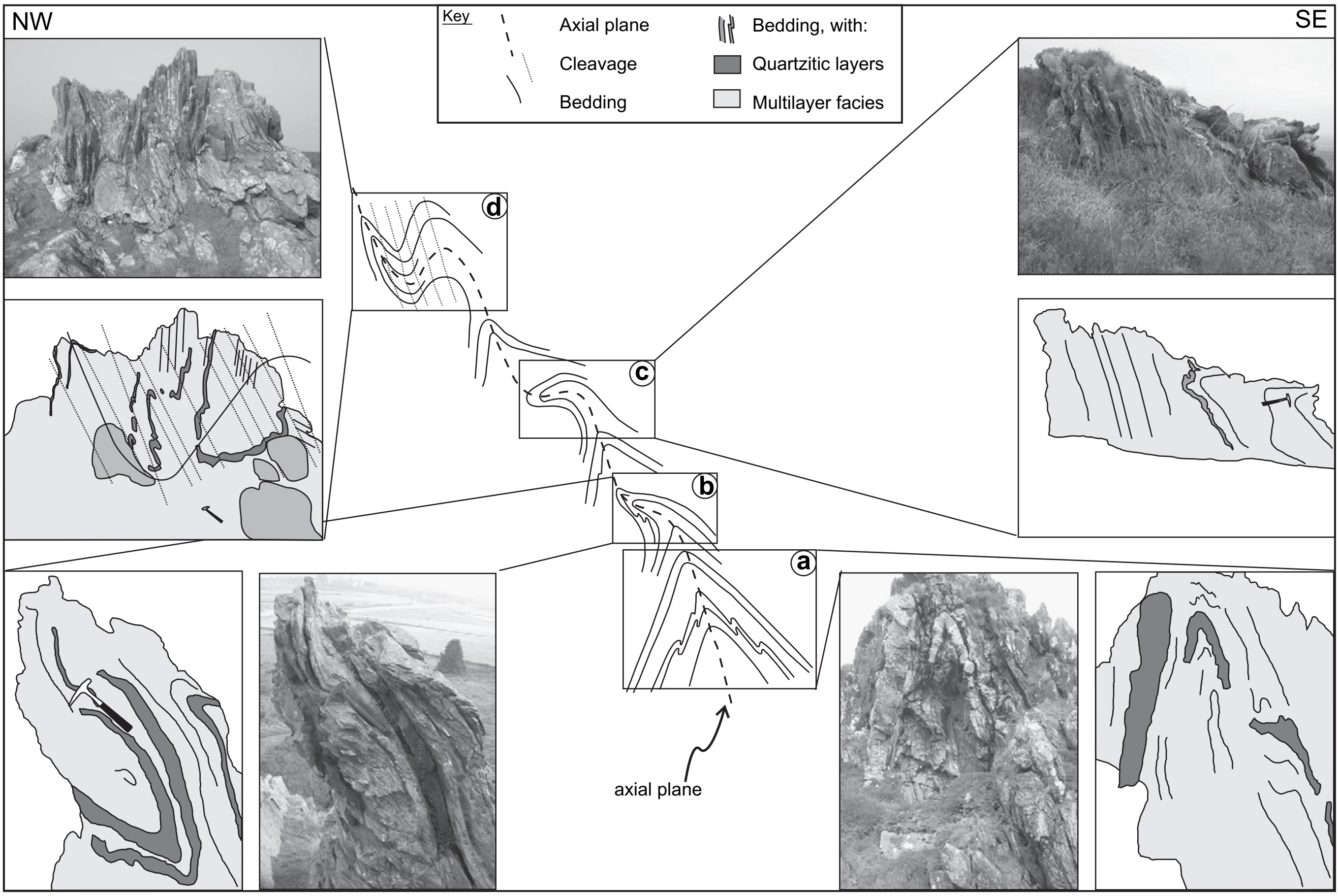

Fig. 8. Sketches and photographs of the spatial variation in strain intensity, which is exemplified at different levels in the hinge zone of a large-scale antiform: (a) upright, sharp to isoclinal antiform; (b) more overturned antiform; (c) intensively deformed antiform and (d) completely overturned and refolded antiform with secondary cleavage.

low-angle, top-to-the-NW shearing. The last stage shows a completely overturned antiform, with a folded axial plane, and the possible development of a secondary foliation (Fig. 8d).

3.4. Strike-slip structures

Strike-slip structures occur very punctuated in the MASB. They are non-pervasive throughout the entire MASB, both in cross-section (Fig. 9), in plan view, and at all scales. Furthermore, they are not organised in a network or domains, but appear to be rather randomly distributed, and are commonly associated with quartz veins. They all systematically indicate the same dextral sense of shear.

Extensional shear bands (ESB) (Fig. 10a) occur in phyllitic series, having deformed cleavage-parallel quartz veins. They have a subvertical attitude and are approximately ENE-trending. In cross-sectional view the penetration of the ESBs is limited (Fig. 10b). They commonly occur in the S-dipping, northern limb of first-order antiforms. The ESBs seem to be kinematically linked with small-scale, higher-order, asymmetric, drag folds (cf. Twiss and Moores, 1992) with strongly curved fold hinge lines, and could be related to sheared limbs of higher-order folds. These small-scale, higher-order, drag folds show a typical W-plunge (Fig. 10c). Characteristically, they are non-cylindrical, asymmetric and disharmonic. In the Roc'h Tredudon outcrop area (Fig. 4), geometrically similar small-scale, higher-order folds occur in the direct vicinity of massive quartz veins. In the Roc'h Ar Feunteun outcrop area (Fig. 4), non-cylindrical, higher-order folds occur on a larger-scale (Fig. 10d). These curvilinear folds show variable strain intensity, including sheath fold-like morphology, and display a step-like fold hinge to the east.

The punctuated strike-slip deformation is furthermore expressed by a large-scale sheath fold (Fig. 10e) in the N-dipping, southern limb of a large-scale, first-order, and synform. This sheath fold affects a thick quartzitic layer. Its orientation is consistent with a dextral sense of shear. In front of this sheath fold, there is evidence of a related distortion of the axial planes of higher-order folds (Fig. 11). Similar distortions have been observed elsewhere, suggesting the occurrence of sheath folds is more common in the MASB.

3.5. Veins

The rocks in the MASB are, furthermore, characterised by the abundant presence of veins. The veins predominantly

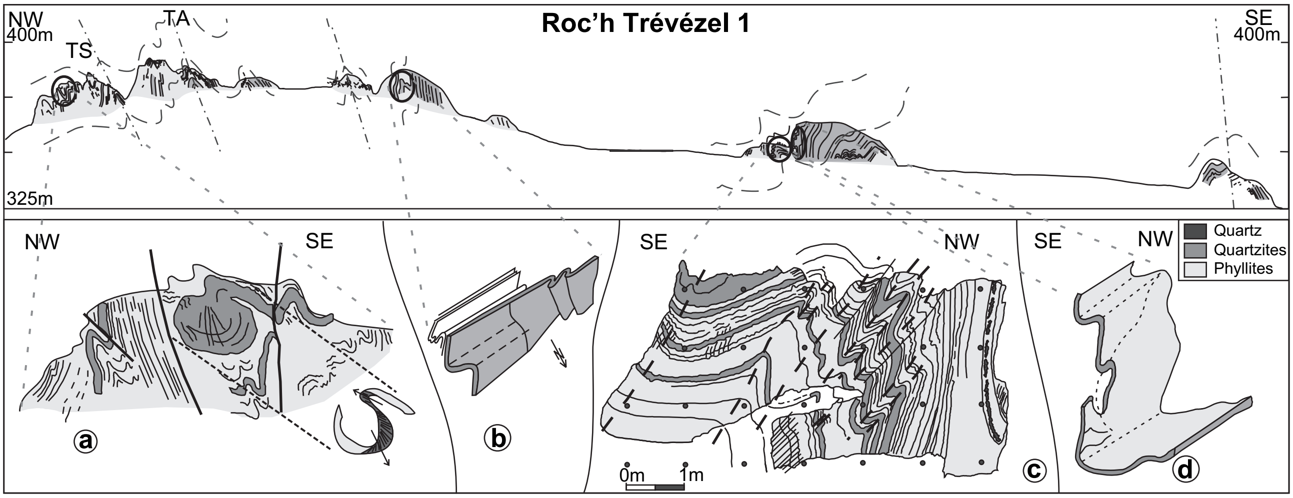

Fig. 9. Schematic cross-section, which shows the non-pervasive occurrence of wrench-related deformation, and an example of commonly observed contraction-related deformation. Sketch (a) shows the occurrence of a single massive quartzitic layer with both E- and W-plunging fold hinge lines; (b) exemplifies the observed shifts in plunge of fold hinge lines, from overall subhorizontal to intensively steeply plunging; (c) is an example of common contraction-related deformation and (d) shows a schematic representation of the large-scale sheath fold. Note that sketch (c) and (d) are SE–NW orientated while sketch (a) and (b) and the cross-section are NW–SE orientated.

consist of quartz. In addition to quartz, chlorite and muscovite have been recognised by conventional microscopy. Quartz veins occur parallel, oblique or perpendicular to bedding and cleavage. Seven types of pre-, syn-, and post-folding/cleavage veins can be recognised (Fig. 12) (van Noorden, 2007). Pre-, and syn-folding/cleavage veins are the most common types of veins, and are characterised by their localised occurrence, and are relatively small-scaled. Massive, post-folding/cleavage veins are generally NS-trending. They have a blocky character. It is apparent that veining was a continuous process occurring throughout the entire progressive deformation history.

4. Discussion

The overall structural architecture of the MASB is clearly the result of a coaxial contraction-dominated deformation, reflecting a largely NW–SE oriented shortening (Fig. 13). The upright, slightly NW-verging, highly cylindrical, first-order fold train and the cogenetic, axial planar,

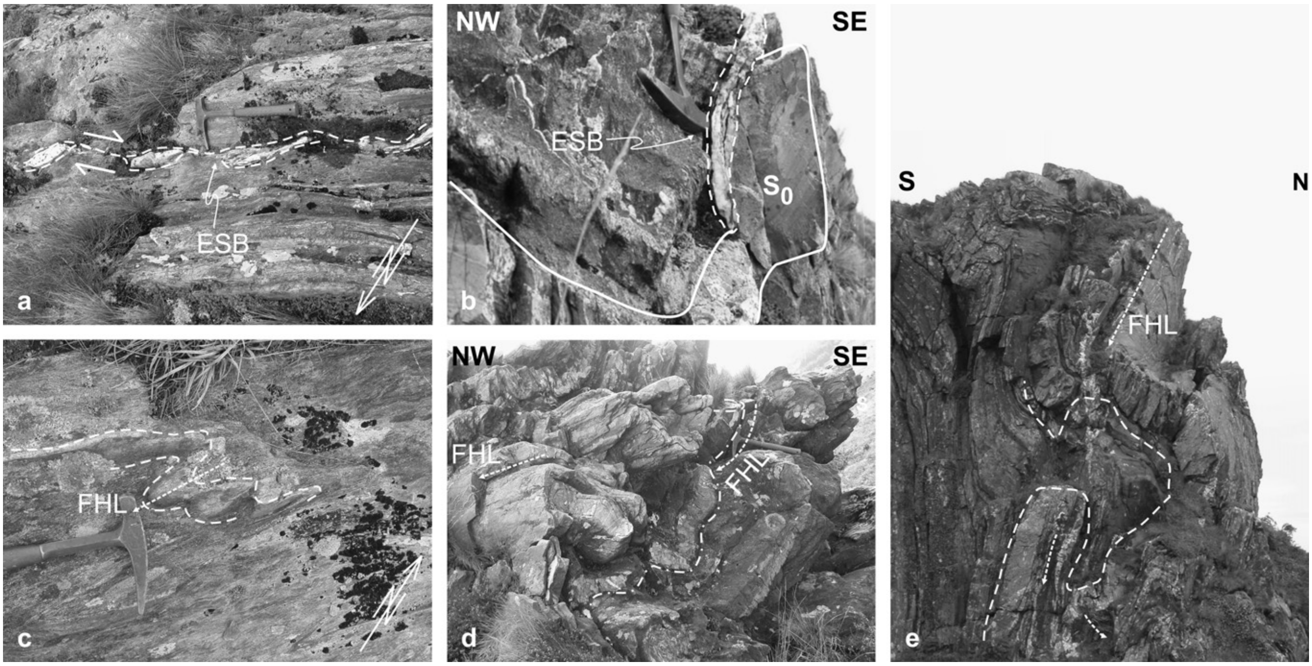

Fig. 10. (a) A dextral extensional shear band in plan view. (b) An isolated, localised extensional shear band in cross-section; indicated is bedding S_0. Note that the extent of the ESB is limited in depth. (c) A small-scale drag fold with a typical curved fold hinge line. (d) A strongly curvilinear fold hinge line in association with a subhorizontal plunging fold hinge line. (e) A large-scale sheath fold structure with curvilinear fold hinge lines (see Fig. 9d).

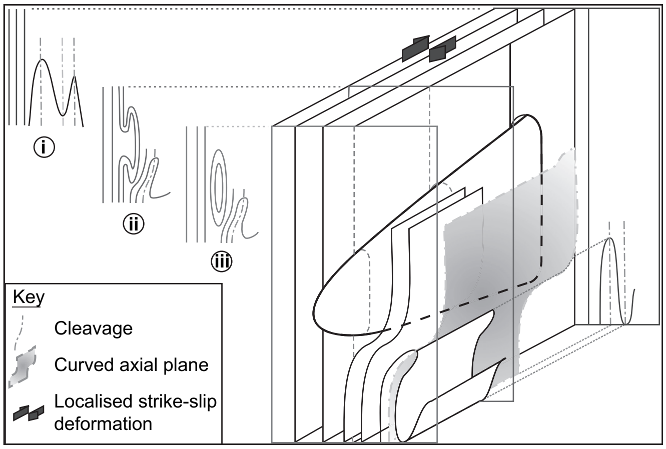

Fig. 11. Schematic diagram showing the relation between the large-scale sheath fold and distortion of the axial planes of higher-order folds. The axial plane of such higher-order folds is curved due the development of the sheath fold, but this curvature is only limited. This is exemplified by the three cross-sections (i–iii), showing different stages of related distortion.

pervasive cleavage development resulted in a significant shortening (50–60%) and subsequent up-dip, crustal thickening, on top of a décollement, thus maintaining the overall strain compatibility (cf. Jones et al., 2005). Strain compatibility is, moreover, maintained by the strong internal disharmony in the folded multilayer sequence of the Plougastel formation (cf. Hudleston, 1999; Jones et al., 2005), the bedding-parallel detachments during folding, and the localised break-down of the mechanical continuum by extensive, synkinematic, quartz veining (cf. Jones et al., 2005). The dominance of the coaxial strain accumulation (see also Law, 1986) allows to suggest that the strain recorded in the MASB largely reflects the bulk regional strain. A NW–SE oriented regional strain is in accordance with the top-to-the-NW overthrusting and nappe stacking, related to the oblique(?) convergence of the Léon domain with the CAT (Rolet et al., 1994; Faure et al., 2005; van Noorden, 2007) (Fig. 1b).

In the overall transpressional setting of the CAT, the steeply dipping mechanical anisotropy, induced by the pronounced subhorizontal shortening and inherited from the sedimentary prehistory of the Plougastel formation (e.g. Bradshaw, 1963; Renouf, 1965), created conditions to initiate strain partitioning during the later stages of deformation (e.g. Fossen and Tikoff, 1993; Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Kirkwood, 1995; Kirkwood et al., 1995; Tikoff and Greene, 1997; Dewey et al., 1998). In the MASB this strain partitioning resulted in punctuated strain heterogeneities, consistently reflecting a dextral strike-slip strain parallel to the overall structural grain (Fig. 13). These punctuated outcrop-scale strike-slip structures are rather randomly distributed and are definitively not organised in an interlinked network of discontinuities (faults, shear zones) (cf. Jones et al., 2005) or in wrench-dominated domains (e.g. Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Jones and Holdsworth, 1998; Lin et al., 1998; Holdsworth et al., 2002a,b). The observed strike-slip structures, such as extensional shear bands and associated small-scale folds with highly curved fold hinge lines, are common features in transpressional settings (e.g. Holdsworth et al., 2002a,b; Tavarnelli et al., 2004; Clegg and Holdsworth, 2005). Holdsworth et al. (2002b) pointed out that folds with highly curved fold hinge lines are unrelated to sheath fold development, primarily because the latter structures are typical for an intense, highly ductile deformation. The presence of the large-scale sheath fold in the MASB (Figs. 9d, 10e and 11) shows that such structures may also develop in low-grade metamorphic conditions. The highly ductile deformation of the quartzitic layers may be facilitated by the 'wet' deformation conditions, as indicated by the continuous veining throughout the entire deformation history (Fig. 12).

Strain partitioning in the MASB shows no compartmentalisation into deformational domains with contrasting strain characteristics, nor the presence of an interlinked network of discontinuities. In this respect the MASB can be considered as a high-strain, contraction-dominated, slate belt, in which the initial stages of strain partitioning has been preserved. This incipient strain partitioning is expressed by the rather randomly distributed and isolated occurrence of strain heterogeneities that consistently show the same non-coaxial strain component. A further development of wrench-dominated domains or an interlinked network of shear zones was, most probably, blocked because of an overall tilting, caused by the late-orogenic, Viséan (Peucat et al., 1979), intrusion of the Huelgoat granite (Fig. 3). Deformation subsequently shifted to the south, affecting the syn-orogenic deposits of the Châteaulin basin and the Montagnes Noires slate belt (Fig. 1). During the Late Carboniferous, the intracontinental deformation became progressively localised in the NASZ and SASZ (Fig. 1), reflecting to a large extent the wrench-dominated component of the bulk regional strain. This is, e.g. evidenced by the presence of sheared sedimentary rocks (up to Gzhelian) and plutons (e.g. Berthé et al., 1979) along the SASZ.

5. Conclusions

The Monts d'Arrée slate belt resulted from an early Variscan, 'Bretonian', predominantly contraction-dominated deformation in an overall transpressional setting. The internal architecture displays a highly cylindrical, first-order fold train within a subhorizontal to moderately N-dipping envelope, and a pervasive axial planar, steeply SE-dipping, cleavage. Strike-slip structures (e.g. ESBs, drag folds) are randomly distributed and occur very localised. These strain heterogeneities, reflecting the wrench component of the transpressional strain, represent incipient strain partitioning within the slate belt.

Our work has demonstrated that an extensive and detailed field-based structural analysis of well-exposed three-dimensional outcrops is imperative to be able to assess the spatial, three-dimensional continuity of the structures, and to constrain the degree of strain partitioning in a transpressional setting

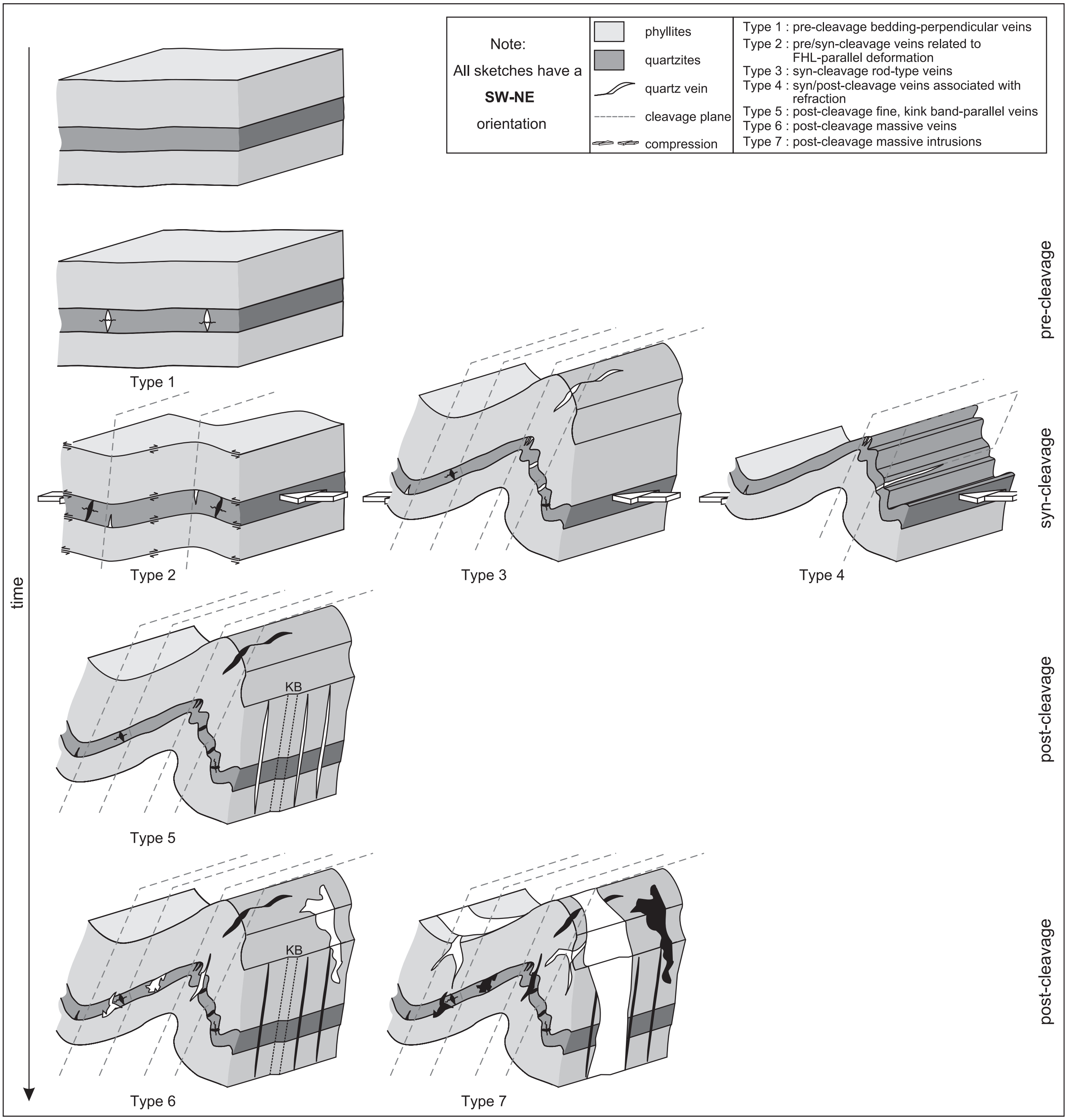

Fig. 12. Schematic paragenesis of seven different quartz vein generations. Based on cross-cutting relations of the veins with other structural features, seven main groups were identified: regular bedding-perpendicular quartz veins in quartzitic layers (type 1); quartz veins related to fold hinge line parallel deformation (type 2); quartz veins associated with the phyllitic sequence, the “rod-type” (type 3); regular quartz veins in quartzitic layers, associated with cleavage refraction (type 4); fine regular quartz veins (type 5); massive quartz veins associated with quartzitic layers (type 6); and massive quartz intrusions (type 7).

(cf. Jones et al., 2005). Only then any reliability with respect to the kinematics of the entire slate belt can be obtained. In this respect, the Monts d’Arrée slate belt offers an opportunity for a thorough investigation of the spatial variation across a wide range of scales, using geostatistical sampling in combination with digital field data acquisition, as suggested by Jones et al. (2005), but in a deformation zone in which the initial stages of strain partitioning is preserved.

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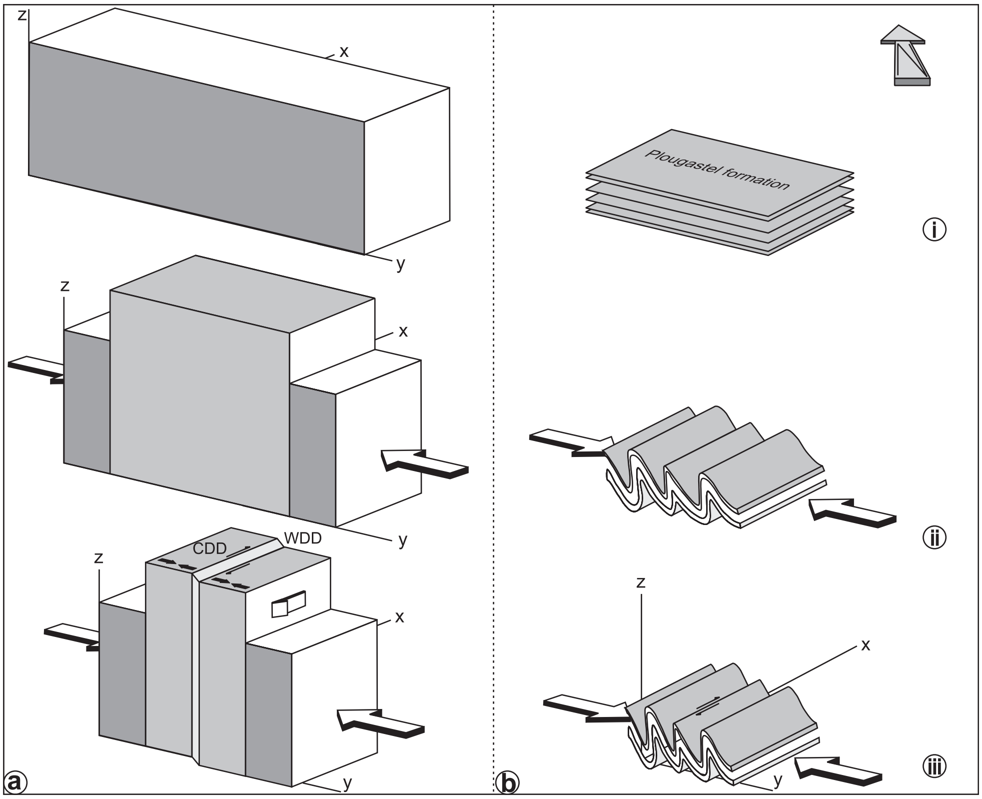

Fig. 13. Conceptual model of the development of partitioned, wrench-dominated domain in an overall pure shear dominated transpressional setting (after Holdsworth et al., 2002b; Jones et al., 2005) and its application to the MASB. (a) The evolution of transpression in block diagrams, through stages i–iii, with a dominant pure shear component in the y-z plane (stage i–iii), and a development of a wrench-dominated domain (WDD) within an overall contraction-dominated (CDD) setting. (b) The deformation of rocks of the Plougastel formation, through stages i–iii, by a contractional strain (folding and cleavage development), and incipient strain partitioning (dextral shear).

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