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Small-scale structures formed during progressive shortening and subsequent collapse in the Navia–Alto Sil slate belt (Hercynian fold belt, NW Spain)

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Abstract—A prominent unit of the Hercynian orogen in north-western Spain is the Navia–Alto Sil slate belt, which is formed predominantly by Llanvirn–Caradocian slates (lower–upper Ordovician). From a structural point of view, the belt forms an infolded syncline between two uplifted areas, the Narcea Antiform and the Mondoñedo fold nappe. Both uplifted areas are hangingwall antiforms. The thrusts below these structures ramp downwards towards the hinterland and flatten towards the foreland. The first deformation events were controlled by low-angle shears, which at the cover level produced recumbent and asymmetric folds associated with a slaty cleavage in the west, and the detachment of the Cantabrian zone in the frontal part of the orogen eastwards of the Narcea antiform. These structures were modified as deformation progressed, and two generations of steep-dipping crenulation cleavages were locally formed. These crenulations occur in belts separated by others in which the slaty cleavage remains undisturbed. The youngest structures are flat-lying crenulations, small chevron folds and kink bands which develop where the slaty cleavage has not been previously crenulated. The flat-lying small-scale structures end, in general, against the bands with vertical crenulations, although in some cases they cross the boundary. The alternation of belts with vertical and horizontal crenulations is found in all scales, from the kilometre to the microscopic scale. The flat-lying structures indicate near vertical shortening, and together with a few W-dipping normal faults can be regarded as the result of orogenic collapse. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Narrow slate and schist belts bounded by or interlaced with more competent rock types are widespread in metamorphic zones of orogenic belts. Polyphase deformation, demonstrated by the successive generation of foliations and small-scale structures, is a normal feature in slate and schist belts (Williams, 1972; Dennis and Secor, 1987; Mosher and Berryhill, 1991; Burks and Mosher, 1996). The most obvious structure in these belts is a dominant foliation (schistosity or slaty cleavage) which can be coeval with the first-generation folds and thrusts, but which can also be superimposed upon older structures. In schist belts, schistosity can be strong enough to erase any previous structure. However, in slate belts structures older than the slaty cleavage can be more easily preserved. In general, later structures such as crenulations, minor chevron folds and kink bands overprint the main foliation, especially in slate belts due to the highly anisotropic character of slates.

The Hercynian orogenic belt of north-western Spain contains a well-developed slate belt (the Navia–Alto Sil slate belt), approximately 150 km long and 10–20 km wide, made up of Ordovician slates and bounded on both sides by Arenigian quartzites (Fig. 1). The aim of this paper is to evaluate the significance of small-scale structures in these slates for a reconstruction of the evolution of the orogen.

GEOLOGICAL SETTING

The Hercynian orogenic belt in north-western Spain describes an arc (the Asturian Arc) that is concave towards the east, and has structures facing towards its core. The structure and the evolution of the Asturian Arc, and the way in which the structures accommodate space problems, have been described in previous papers (Julivert and Arboleya, 1984a,b, 1986; Pérez-Estaú *et al.*, 1988) Palaeomagnetic studies have also been used to examine the development of the Asturian arc (Ries *et al.*, 1980; Perroud, 1983, 1985; Bonhommet *et al.*, 1981; Hirt *et al.*, 1992; Parés *et al.*, 1994). The arc curves through 180° in its core (Cantabrian zone) where the structures show a very complex pattern. However, further to the west the arc is quite regular, and folds can be followed over long distances.

A cross-section parallel to the arc axial trace (Fig. 1) shows a gradient of increasing strain, metamorphism and plutonism from east to west. In the east, the frontal part of the orogen (i.e. Cantabrian zone) is characterized by thin-skinned tectonics, with a fold and thrust belt in the detached Palaeozoic sequence. The basal detachment surface, placed in the upper part of the lower Cambrian (Julivert, 1971; Julivert and Arboleya, 1984a), has been recognized by deep-crustal reflection profiling as a highly reflective band at 5–6 s (Pérez-Estaún *et al.*, 1993). This surface, which remains remarkably flat below the Cantabrian zone, ramps

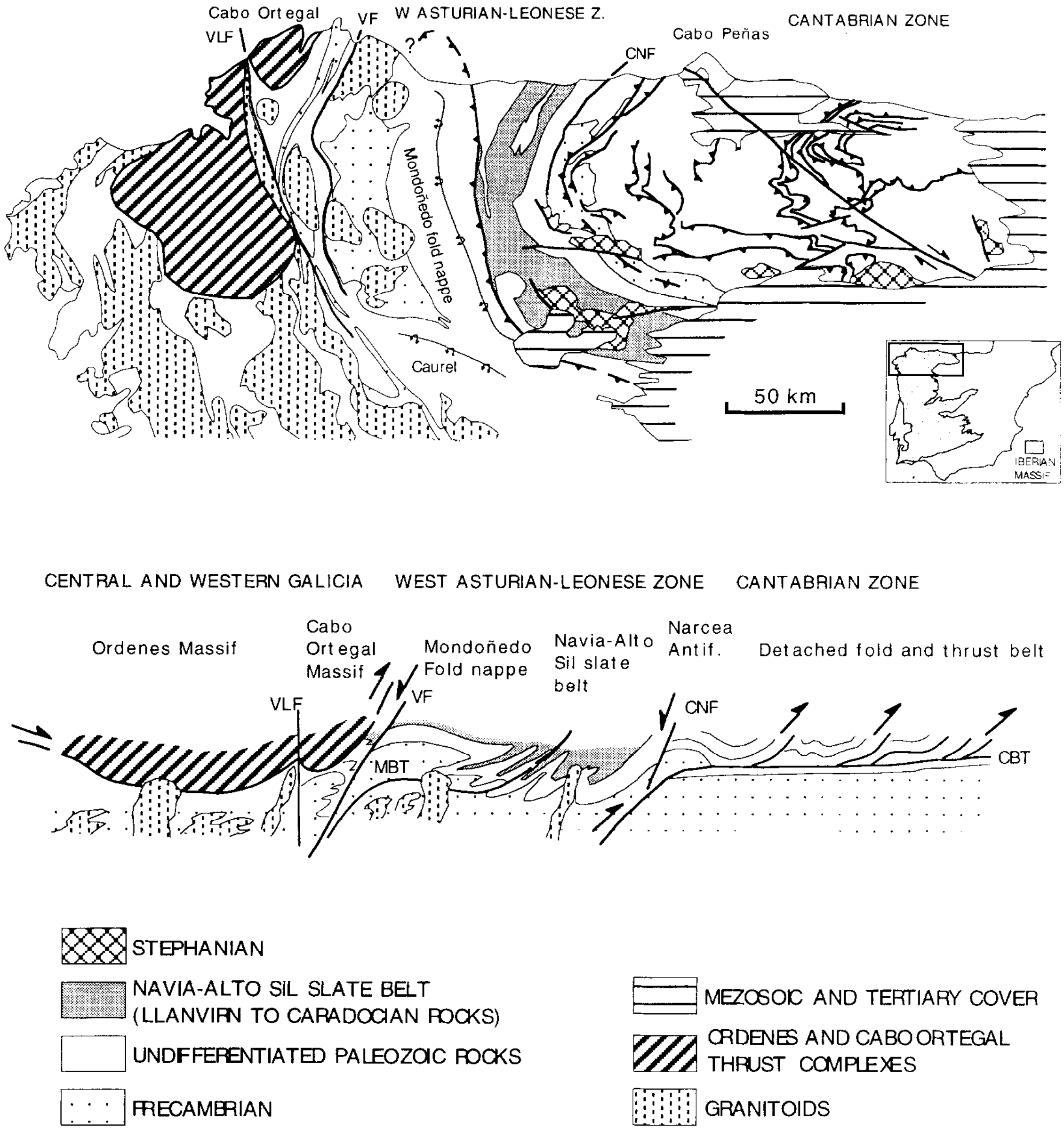

Fig. 1. Geological sketch and schematic cross-section of the Hercynian fold belt in the northwestern part of the Iberian Peninsula. VLF, Valdoviño Fault; VF, Vivero Fault; CNF, Cangas del Narcea Fault; MBT, Mondoñedo basal thrust; CBT, Cantabrian basal thrust.

downwards towards the hinterland, deep into the crust, accommodating the cover shortening of the Cantabrian zone at lower crustal levels. This structure brings up Precambrian rocks to crop out along the so-called Narcea Antiform, which extends with a curved trace from the Cantabrian coast to the Duero Tertiary basin (Fig. 1).

Further west, folds are the most prominent structures of the arc, and Precambrian rocks are involved in the largest folds. Granitoids become more abundant, and west of the Mondoñedo nappe they form most of the outcrops. Finally, the highest tectonic unit is a large overriding plate formed by displaced terranes, the remnants of which form the klippen of Cabo Ortegal, Ordenes, Morais and Bragança in Galicia and northern Portugal. This highest unit is made up of metabasic and ultrabasic rocks and also of deep crustal rocks. The meaning of the rock associations found in these klippen and the age of the events recorded in them is still in dispute (Arenas *et al.*, 1988; Gil-Ibarguchi *et al.*, 1990; Peucat *et al.*, 1990); however, it is generally accepted that they represent the suture zone of a collisional orogenic belt.

Thus, the orogen, considered as a whole, shows an anatomy common to many other orogenic belts: the Galicia–northern Portugal klippen forming the hinterland, followed by a thick-skinned domain with the Precambrian involved in the Mondoñedo recumbent fold and Narcea Antiform, and finally the frontal thin-skinned fold and thrust belt of the Cantabrian zone.

Late faulting, related to the Stephanian basins, has allowed the preservation of Stephanian sediments in

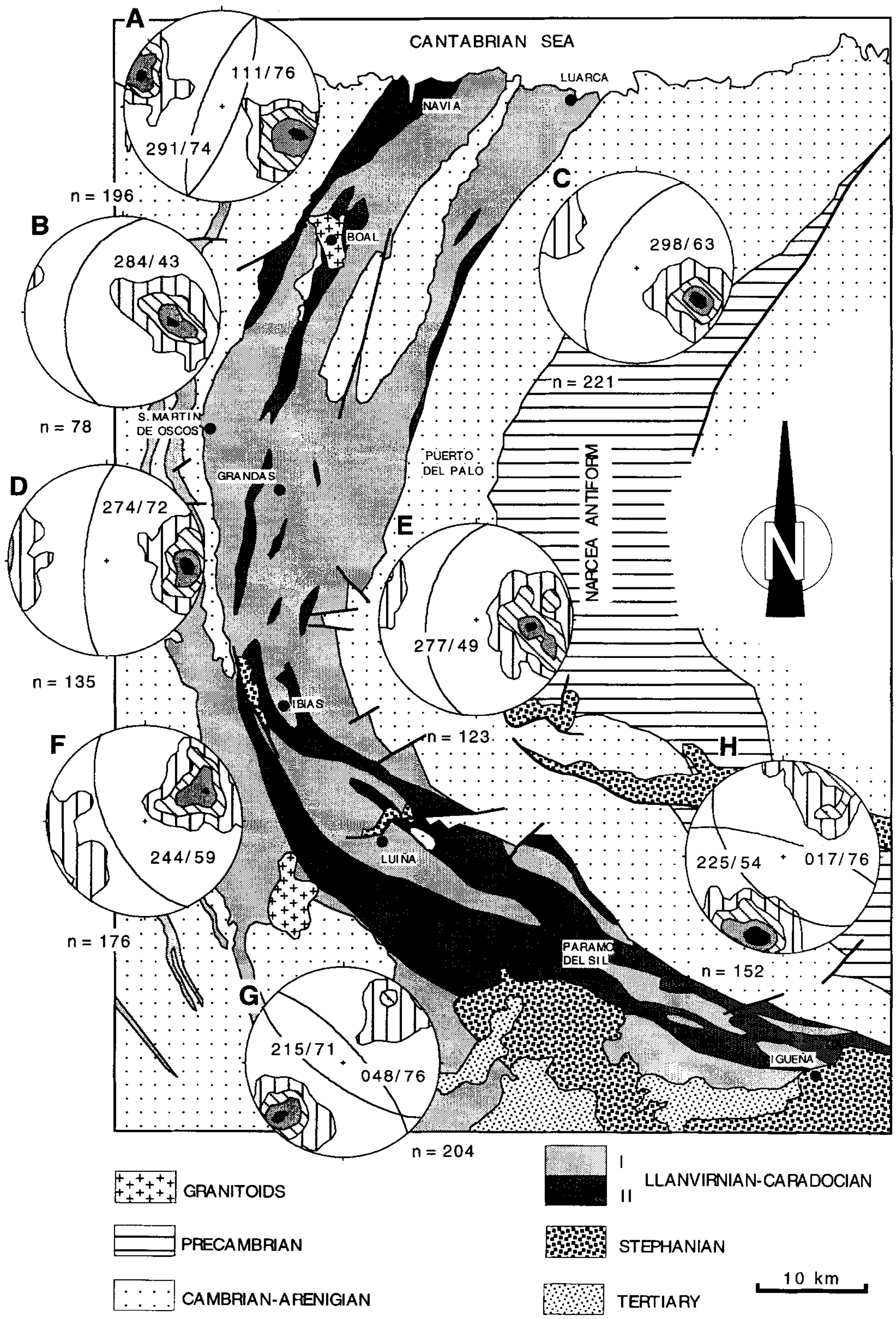

Fig. 2. Slaty cleavage (S_1) distribution along the Navia–Alto Sil slate belt. All stereoplots are poles to slaty cleavage, equal-area, uniform distribution and lower-hemisphere projection (in brackets maximum pole concentrations). (a) Area between Navia and San Martín de Oscos (8.9%). (b) Area between San Martín de Oscos and Grandas (9.4%). (c) Area between Luarca and northwestern Puerto del Palo (15.3%). (d) Area between Grandas and Ibias (11.3%). (e) Area between northwestern and southwestern Puerto del Palo (7.8%). (f) area between Ibias and Luiña (9.4%). (g) Area between Luiña and Paramo del Sil (11.2%). (h) Area between Paramo del Sil and Igueña (8.2%). I and II: S_1 dipping towards (I) or away from (II) convexity of arc.

some small areas, that are resting unconformably on older rocks. The most noticeable faults however, such as the Valdoviño, Vivero and Cangas del Narcea (or Allande) faults, do not have Stephanian sediments preserved on their downthrown blocks. The first of these faults has a strike-slip component, and the remainder are W-dipping normal faults.

THE NAVIA–ALTO SIL SLATE BELT

The western limb of the Narcea Antiform is formed by a 4000 m thick siliciclastic sequence that ranges from Early Cambrian to Arenigian in age, with only a thin carbonate level at the lower–middle Cambrian boundary. This sequence is overlain by 1000 m of black slates (Luarca Formation, Llanvirnian–Llandeilian), overlain in turn by Llandeilian?–Caradocian turbidites (Agüeira Formation) (Matte, 1969; Marcos, 1973). The Luarca and Agüeira formations form a curved slate belt that is parallel to the trace of the Narcea Antiform. The eastern boundary of this belt is quite regular as it coincides with the western limb of the Narcea Antiform. The western boundary is more irregular (Fig. 2). The belt itself is affected by several folds as outlined by outcrops of the Arenigian quartzites. The Luarca Formation is made up of typical roofing slates, displaying a well-developed slaty cleavage. As they are practically without interlayered competent beds, bedding or intersection lineations are rarely observed. The Agüeira Formation is made up of a rhythmic sequence of metapelites, silts and fine-grained sandstones with well-preserved bedding. However, metapelites are abundant enough to permit the formation of the same microstructures as found in the Luarca Slates, although less well developed.

As is usual in slate belts, deformation is polyphase. The deformation phases traditionally defined for the low- to high-grade metamorphic parts of the Hercynian chain in north-western Spain are: (1) a first phase responsible for the generation of folds with an axial plane slaty cleavage (S_1), (2) a second phase producing a strong flat-lying crenulation cleavage (S_2), related to low-angle shear zones, (3) a third phase producing variable, but often steeply dipping crenulation cleavage (S_3), locally with a strong tectonic banding, and (4) a late phase of kink-bands. The crenulation cleavage S_2 has only been described in the high-grade metamorphic zones, and has not been found in the Navia–Alto Sil slate belt. Although generally accepted and incorporated into most of the papers dealing with the area (Julivert and Martínez, 1987; Pérez-Estaún *et al.*, 1991), field data suggest that the tectonic model is an oversimplification and for this reason a different approach will be presented in this paper.

SMALL-SCALE STRUCTURES IN THE SLATE BELT

The structures recognized by the authors in the Navia–Alto Sil slate belt are: (1) a dominant slaty cleavage (S_1), (2) one (S_{tb}) or two (S_{tb1} and S_{tb2}) steeply dipping crenulation cleavages, depending on the observation area, that define well-developed tectonic banding, (3) an oblique crenulation cleavage (S_{ob}) commonly present in the phyllosilicate-rich microlithons of S_{tb} or S_{tb2}, (4) a flat-lying crenulation cleavage (S_{cr}); (5) chevron folds (S_{ch}); and (6) kink bands (S_k).

Slaty cleavage (S_1)

Slaty cleavage is pervasive throughout the Navia–Alto Sil slate belt. It completely erases bedding in the Luarca Slates, but not in the Agüeira Formation, where cleavage can be absent in the coarse-grained layers. The cleavage trace follows the Asturian Arc quite regularly, with only some inflections around the noses of the quartzite folds inside the belt. The slaty cleavage is axial planar in first-generation folds, which face towards the core of the arc. The cleavage dip direction changes along the strike from dominantly NW and W in the northern and middle part of the arc, to NE and N in its southern part (Fig. 2). This change follows the dip variation of the western limb of the Narcea Antiform, which changes from normal to overturned, from north to south, due to the formation of the Narcea antiformal stack and to later back-folding. There are also variations across the strike of the belt, such as smaller areas in which S_1 shows an opposite dip with respect to its general attitude. Changes across the strike do not represent post-S_1 folds. These changes are due to cleavage inflections around hinges of quartzite folds or to a progressive dip variation, especially where the general dip is high. The only exception is in the Luarca area, where S_{tb} is well developed. In this area the folds affecting S_1 are always asymmetric folds that have very reduced short limbs, and with the fold-enveloping surfaces plunging west.

Crenulation cleavage with a strong tectonic banding (S_{tb})

A strong crenulation cleavage (S_{tb}) overprints S_1 in some areas. The crenulations are asymmetrical with pressure-solution driven quartz migration, leading to a strong tectonic banding or pressure-solution striping. This crenulation cleavage is well developed in the northern part of the slate belt, in the Luarca area. It is well exposed in cliffs along the coast, particularly in Punta Percebera to the northwest of Luarca (Marcos, 1973). It decreases progressively towards the south, and is very uncommon south of the Puerto del Palo (Fig. 3). For this reason, the description of this struc-

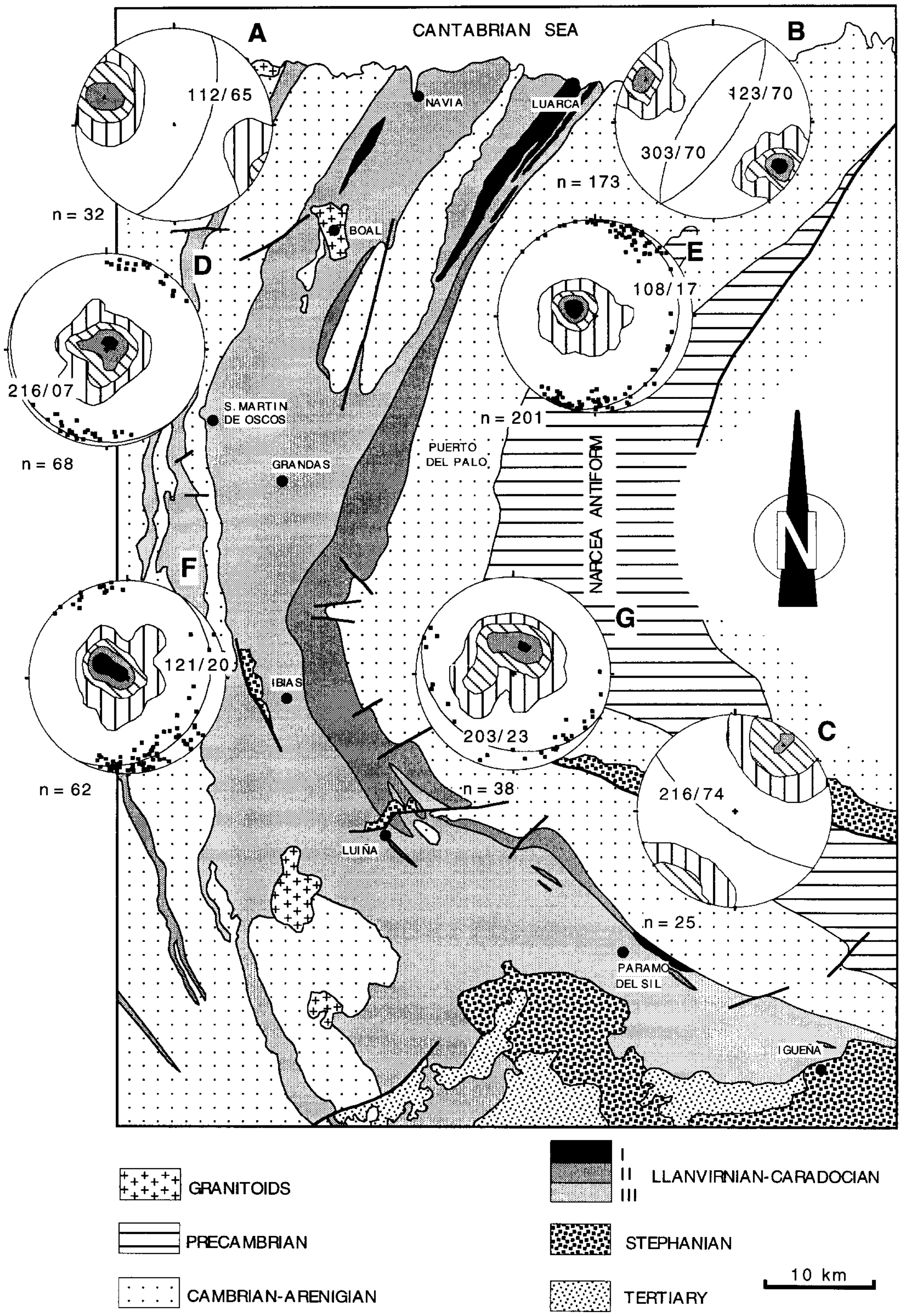

Fig. 3. Steeply dipping crenulations, with a strong tectonic banding (S_{tb}), chevron folds and flat-lying crenulations (S_{ch} and S_{cr}) along the Navia–Alto Sil slate belt. (a)–(c) Stereoplots of S_{tb}; (d)–(g) Stereoplots of S_{cr} and S_{ch}. Contours are poles to tectonic banding or crenulation cleavage and chevron axial planes; equal-area, uniform distribution and lower-hemisphere projection. For areas with chevron folds, black squares represent chevron and crenulation hinges. (In brackets are the maximum pole concentrations.) (a) Area between Navia and Boal (8.6%). (b) and (e) Area between Luarca and Puerto del Palo (S_{tb} = 12.4%, $S_{cr}+S_{ch}$ = 21.6%). (c) Area north-east of Paramo del Sil (6.6%). (d) Area between Boal and San Martín de Oscos (11.1%). (f) Area between Puerto del Palo and Ibias (12.3%). (g) Area between Ibias and Paramo del Sil (7.3%). I—areas with steeply-dipping crenulation cleavage (S_{tb}); II—areas with dominant flat-lying chevrons; III—areas with kink bands or without significant minor structures other than S_1.

ture will focus on the Luarca area. This crenulation has been called S_3 in previous papers dealing with western Asturias and Galicia, but its importance has been overestimated because, commonly, any crenulation has indiscriminately been assigned to S_3.

The distribution of S_{tb} is very heterogeneous. It is usually concentrated in belts separated by others in which S_1 is undisturbed. This distribution is very clear in the Luarca area (Pulgar, 1980), where these belts are found on a decametre to centimetre scale. The overall structure corresponds to a system of folds affecting S_1, where the long western limbs preserve S_1, while the hinges and the short, eastern, limbs develop a crenulation cleavage. The first-order folds have their long limbs dipping towards the W and the same applies to the enveloping surface. It is uncommon to find eastern limbs of folds with undisturbed S_1 on a metre scale, although it occurs at decimetre to microscopic scales. The crenulation cleavage and associated fold axial planes are close to vertical and the intersection lineation and associated fold axes are close to horizontal. Both seem to follow the Asturian Arc, as far as paucity of data in its southern limb permit a conclusion to be reached.

At the microscopic scale, quartz is concentrated either in limbs at high angles to the crenulation surfaces or in fold hinges. Platy minerals in quartz-poor limbs lie at very small angles to the crenulation surfaces. In this way well-defined microlithons, visible at different scales, are generated. Quartz-poor limbs at the microscopic scale can be situated both towards the convex (west) and the concave (east) side of the Asturian Arc, although the first are more common as commonly the crenulation shows a staircase arrangement with the enveloping surface dipping W.

In most localities S_{tb} appears as a single, coarse tectonic banding, but locally two generations of steeply dipping crenulations are observed, which are labelled S_{tb1} and S_{tb2}. In these localities, coarse steeply dipping deformation bands (S_{tb2}) intersect a previous crenulation (S_{tb1}), also with pressure-solution striping. These two crenulations are considered to be the result of the same progressive deformation, which has produced one simple crenulation (S_{tb}) in other localities. The second crenulation (S_{tb2}) forms quartz-rich bands, about 0.5–1.5 cm wide, although smaller crenulations parallel to the wider S_{tb2} bands also exist. These kinds of structures are best developed 20 km southwest of Luarca, not far from the contact between the Luarca Slates and the Arenigian quartzite. At this locality all transitions have been observed from asymmetrical folds deforming S_{tb1}, whose short limbs define more or less a band, to bands with a strong quartz concentration where S_{tb1} is only preserved as relics inside the band (Fig. 4). In the latter case there is a very strong contrast between bands formed exclusively by phyllosilicates, from which all quartz has been removed, and quartz-rich bands. Besides the disseminated quartz grains, there is a series of gashes filled with quartz in these bands. These gashes do not cross-cut the S_{tb1} microlithons. Instead, there has been an opening up of the microlithons, producing a dilatation along the band, and across the S_{tb1} layering.

During the generation of S_{tb2} bands, S_{tb1} acted mechanically as a planar anisotropy, because of the contrast between quartz-rich and quartz-poor bands. Vertical crenulations deforming S_{tb1}, which may represent also an S_{tb2} crenulation, also exist near Otur (locality of Marcos, 1973, plate 60).

A peculiarity observed at the microscopic scale is the common occurrence of a crenulation (S_{ob}, Fig. 4) at 30–60° to S_{tb} or S_{tb2}, affecting only the quartz-poor microlithons.

Flat-lying crenulation cleavage (S_{cr}) and chevron folds (S_{ch})

More or less gently dipping crenulation cleavages are found throughout the studied area. Many of them are associated with kink bands and will be described later. However, a widespread crenulation cleavage grading progressively to centimetre scale chevron folds is found along the eastern part of the slate belt, near the contact with the Arenigian quartzites, and also along the western boundary of one of the quartzite anticlines inside the belt, southeast of Boal. In these areas, besides S_1, flat crenulations and chevron folds are the predominant or even the only microstructures present. Both kinds of structures are not present where S_{tb} is well developed. Crenulations and small chevrons are subhorizontal and have coincident pole concentrations. For this reason, and because a gradation between them is often observed, they are interpreted as equivalent. The attitude of the crenulation and chevron planes does not vary along the arc (Fig. 3). The lineation (crenulation lineation and chevron axes) follows the arc, as a consequence of the arcuate trace of the slaty cleavage.

Kink bands (S_k)

Kink bands exist in all areas where S_1 has not been disturbed by the crenulation cleavages S_{tb}, S_{cr} and S_{ch}. They are ubiquitous in the central and northern part of the arc, and much less numerous in the southern part. Most kinks are subhorizontal, and their attitude does not show significant changes along the arc. The kink axes follow the arc, as a consequence of the arcuate trace of S_1. A comparatively small number of kinks are steep dipping, most of them with the kink planes transverse to the general strike of the belt. These kinks will be referred to as S_{kt}. In the following description clockwise and counterclockwise are taken as looking at the kink from the southern to the northern part of the arc.

Conjugate kink bands are exceptional, in general only one set being developed. Most kink bands are counterclockwise. Clockwise kinks occur in general in separate areas, not coexisting with counterclockwise ones (Fig. 5). Normally there is a good correlation between sense of kink rotation and attitude of S_1. Where S_1 dips west kinks are counterclockwise, and where it dips east kinks are clockwise.

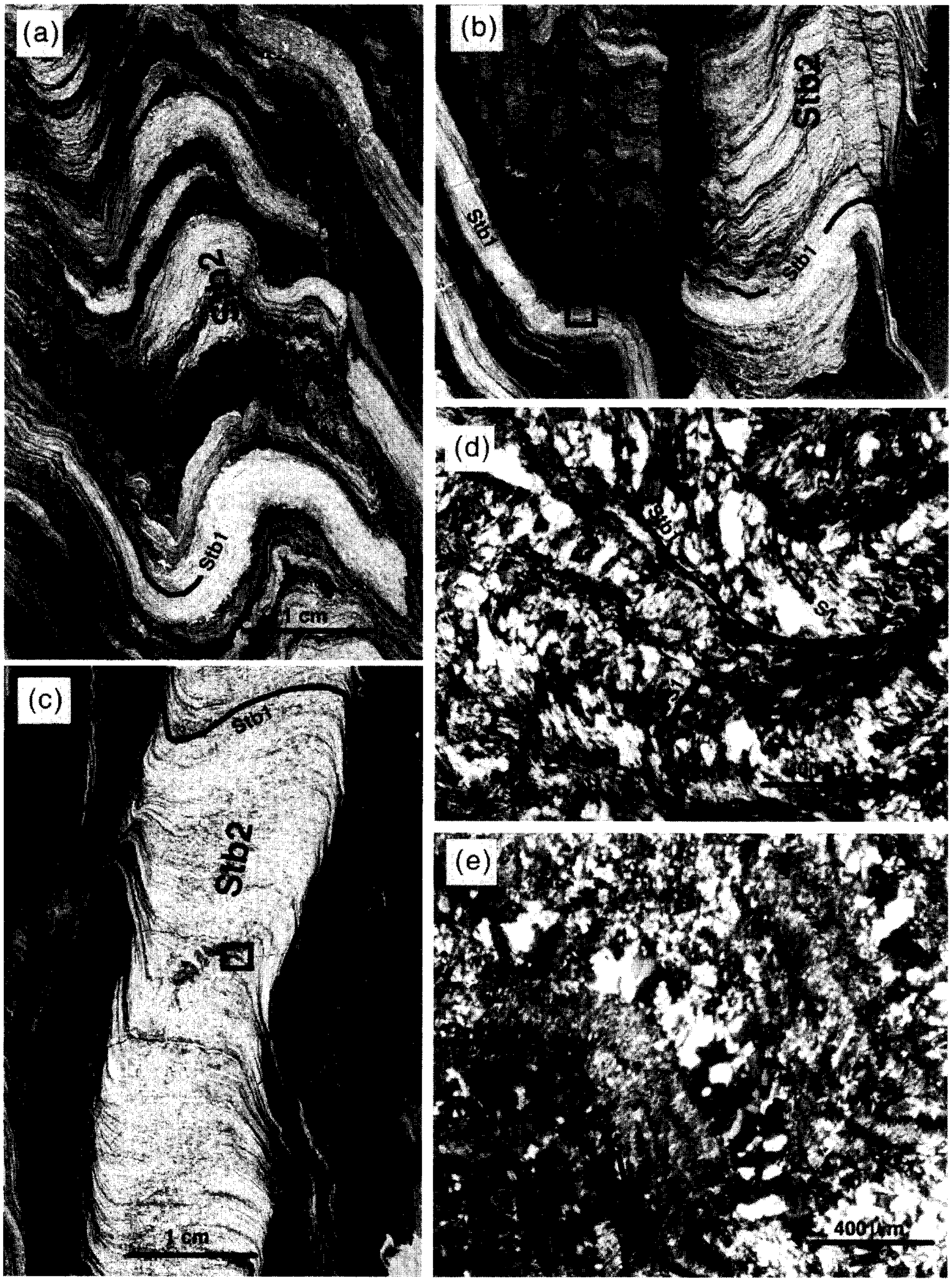

Fig. 4. Three stages in the progressive development of an S_{tb2} band. (a) S_{tb1} bands folded, with the generation of S_{tb2} crenulations and the initiation of a larger S_{tb2} band along the short limb of an asymmetric fold. (b) More advanced stage, with a wide S_{tb2} well-differentiated band. (c) Final stage, with a fully developed S_{tb2} wide band. (d) and (e) Enlarged parts of (b) and (c). (a)–(c) PPL, (d) and (e) XPL. (West is to the left, locality 20 km south of Luarca.)

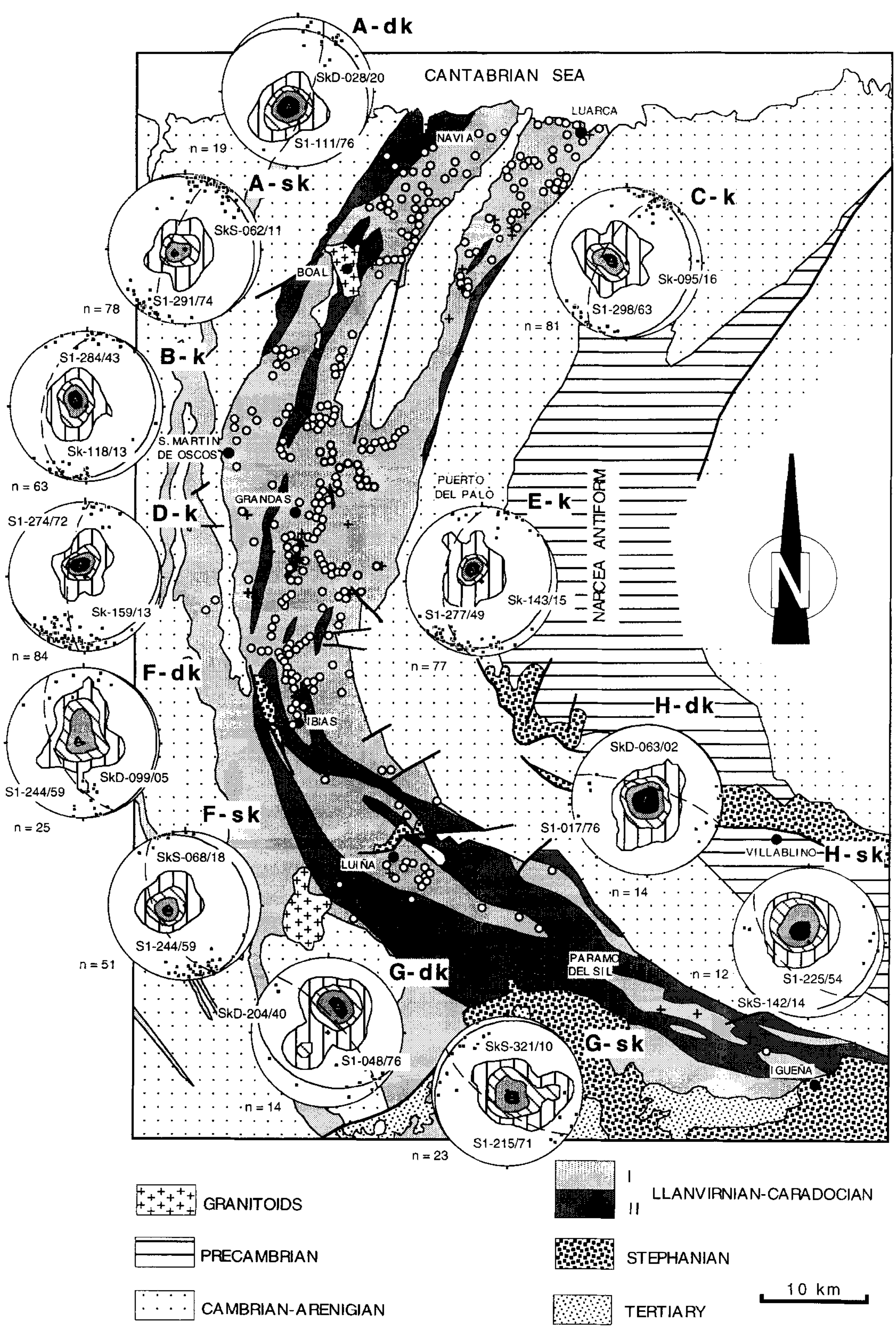

Fig. 5. Kink band distribution along the Navia–Alto Sil slate belt. All stereoplots are poles to kink planes (equal-area, uniform distribution and lower-hemisphere; in brackets are the maximum pole concentrations): dk – clockwise kinks; sk – counterclockwise kinks; k – areas with counterclockwise kinks, with a few, non-significant clockwise ones. Black squares are kink hinges. Dashed and solid great circles indicate main slaty cleavage and kink orientation, respectively. Counterclockwise kink bands coincide essentially with S_1 W-plunging areas and clockwise kink bands with S_1 E-plunging areas. The small number of data in the southern part of the belt reflects the scarcity of kink bands in this area. (a) Area between Navia and San Martín de Oscos (dk = 12.3%; sk = 17.7%). (b) Area between San Martín de Oscos and Grandas (k = 15.9%). (c) Area between Luarca and NW Puerto del Palo (k = 14.5%). (d) Area between Grandas and Ibias (k = 20.9%). (e) Area between northwestern and southwestern Puerto del Palo (k = 20.8%). (f) Area between Ibias and Luiña (dk = 7.3%; sk = 17.6%). (g) Area between Luiña and Paramo del Sil (dk = 7.7%; sk = 7.7%). (h) Area between Paramo del Sil and Igueña (dk = 8.6%; sk = 7.7%). I and II: S_1 dipping towards (I) or away from (II) convexity of arc. Open circles represent localities with predominant counterclockwise kink-bands, crosses represent localities with predominant clockwise ones.

In a comparatively small number of localities clockwise and counterclockwise kinks coexist. In a few cases they form typical conjugate arrays, commonly with a low angle between both sets. In a few localities the kink patterns are more complicated, probably indicating local stress conditions and/or deviation of the stress field relative to S_1 during kink generation. A narrowly spaced crenulation is frequently found inside the bands oblique to the kink surfaces, but it can also exist in the interspace between kink bands, as already reported by Matte (1969) in the same area, by Stubley (1990) in southeastern Australia, and experimentally obtained by Williams and Price (1990).

RECURRENCE OF STRUCTURES AT DIFFERENT SCALES

The existence of bands with vertical crenulations (S_{tb}, S_{tb1}, S_{tb2}) and other with horizontal crenulations, chevrons or kinks (S_{cr}, S_{ch}, S_k) is recurrent at all scales (Fig. 6). At the kilometre scale, vertical crenulations are concentrated next to the Ordovician quartzite of the western limb of the Narcea Antiform and in a few other places, while horizontal chevrons and kinks are widespread in the rest of the slate belt. At the metre to decametre scale, the best examples occur along the coastal cliffs to the northwest of Luarca. At the decimetre scale, the alternation of both kinds of bands can be observed in Otur. Finally, where tectonic banding is well developed, a differentiated crenulation cleavage (S_{ob}) can be often observed at the microscopic scale, which is bounded to the phyllosilicate-rich layers and which terminates against the quartz-rich ones.

AGE RELATIONSHIP BETWEEN MICROSTRUCTURES

The slaty cleavage S_1 is the first minor structure that was formed; it is the axial plane cleavage to the

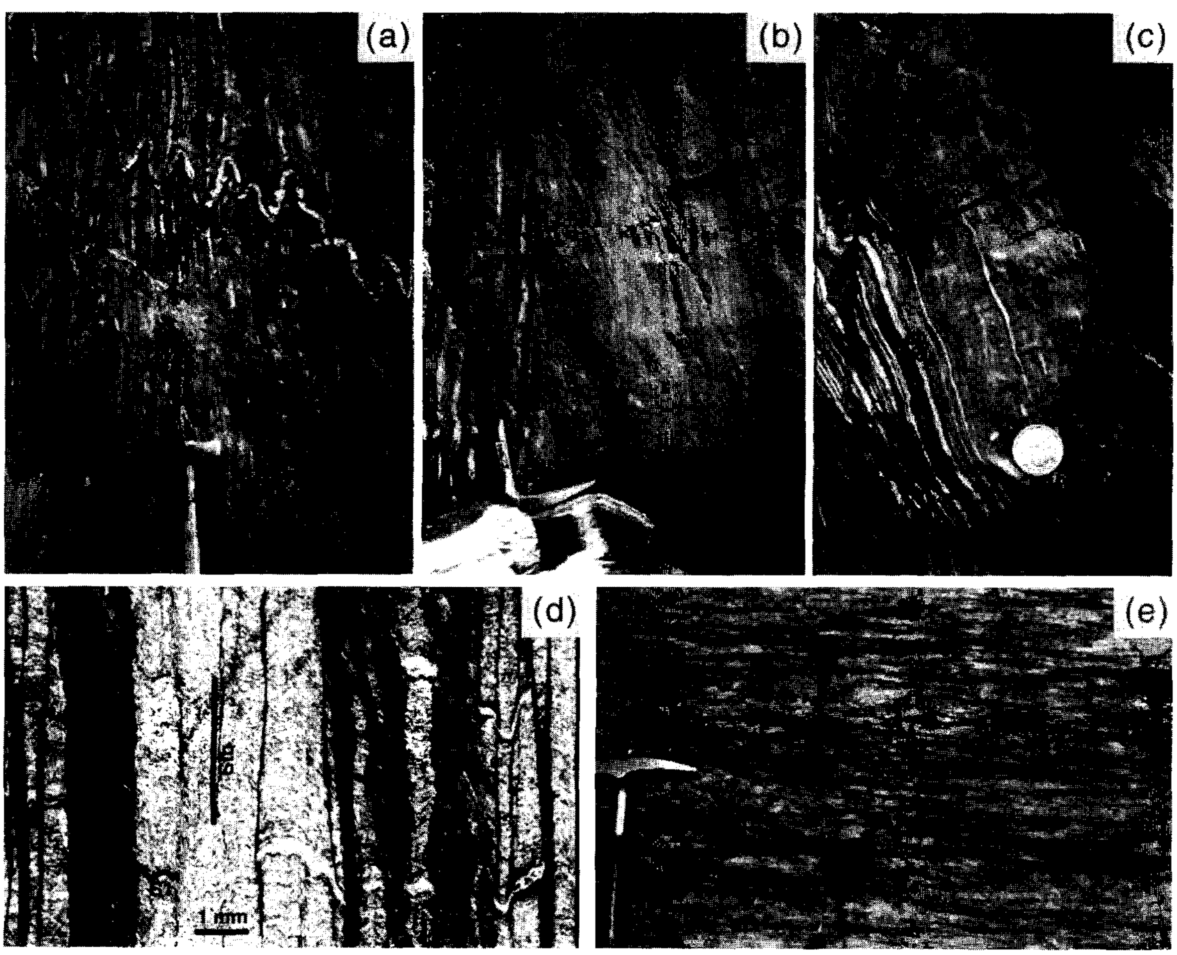

Fig. 6. (a) Vertical tectonic banding (S_{tb}) at Punta Percebera, with a quartz folded vein parallel to the slaty cleavage S_1. (b)–(d) Metre to microscopic scale alternation of vertical and flat-lying minor structures. (b) Metre scale, vertical tectonic banding (S_{tb}) on the left and steeply dipping S_1 with subhorizontal kink bands on the right (Punta Percebera). (c) Decimetre scale S_{tb1} and S_{tb2} steeply dipping bands and flat-lying kinks in between (near Otur, west of Luarca). (d) Microscopic scale S_{tb} bands and S_{ob} in the phyllosilicate-rich layers (near Piñeros, south of Luarca), PPL. (e) Horizontal crenulations on a vertical rockface (near Berducedo, west Puerto del Palo). In photographs (a)–(d), west is to the right; in photograph (e) north is to the right.

main folds in the area, which are E-facing folds at the kilometre scale. Excluding heterochronisms due to the progression of deformation from inner to outer parts of the belt, these folds have the same significance as the detached structures of the Cantabrian zone, both being the first structures to register in their respective domains the shortening across the belt.

The steep dipping crenulation cleavage, with a strong tectonic banding (S_{tb}), is younger than the slaty cleavage and older than the chevrons and kink bands. Kink bands are sometimes found affecting S_{tb}, although not very frequently because the tectonic banding is too coarse to be easily kinked. Where the two crenulations S_{tb1} and S_{tb2} cross-cut, both can be considered as the result of progressive deformation during the same tectonic event, with S_{tb2} slightly post-dating S_{tb1}.

Flat-lying crenulation cleavage (S_{cr}), chevrons (S_{ch}) and kink bands (S_k) show a complete coincidence both in the orientation of planes (Fig. 7) as in lineation directions. Furthermore, in many localities there exists a gradation from chevrons to kinks, and at the scale of the belt this gradual change can be observed going from east to west across the slate belt, particularly in the cross-section from Puerto del Palo to Grandas. Therefore, these kinds of structures are interpreted as equivalent. S_{kt} kinks are also late structures, probably related to small adjustments of the arc shape.

The small oblique crenulations S_{ob} are in general bounded to the quartz-poor microlithons, ending against the quartz-rich ones. As S_{ob} has been observed to cross microlithon boundaries in some thin sections, they are considered to be a late structure. In a few cases, however, some oblique crenulations curve at their ends and seem to nucleate on an S_{tb} or an S_{tb2} microlithon.

STRUCTURAL EVOLUTION: THE LOCATION OF THE NAVIA–ALTO SIL SLATE BELT IN THE OROGEN

East-facing structures and the formation of the first cleavages (S_1, S_{tb} and S_{tb2})

The northern Galicia thrust massifs with basic ultramafic rocks are generally accepted to represent a suture zone in a collisional orogen. In consequence, the structures shown in the cross-section of Fig. 1 were formed in a continental margin at the footwall of the suture.

The first deformation events were controlled by low-angle shears, which at the cover level gave way to a thin-skinned fold and thrust belt in the Cantabrian zone, and to recumbent or E-facing folds that are associated with a slaty cleavage in the West Asturian Leonese zone. At lower crustal levels the structure consists probably of an array of shear zones which concentrate in two main broad zones, below two hangingwall structures: the Narcea Antiform and the Mondoñedo fold nappe. The Navia–Alto Sil slate belt forms an infolded syncline area between both structures.

The Mondoñedo basal thrust has been claimed to crop out at several localities (Marcos, 1973; Bastida and Pulgar, 1978; Martínez-Catalán, 1985; Bastida *et al.*, 1986), and although some of the outcrops can be questioned, the existence of the thrust itself has to be accepted. A flat-lying crenulation cleavage, designated as S_2 in papers dealing with the Mondoñedo area, has been described in some localities and was interpreted as related to the basal Mondoñedo thrust. As this crenulation is not found in the slate belt studied here, it is not considered in this paper.

As deformation progressed, the old structures were modified. The structures in the Cantabrian zone evolved according to the thin-skinned domain model, and also by buckling with nucleation of folds where

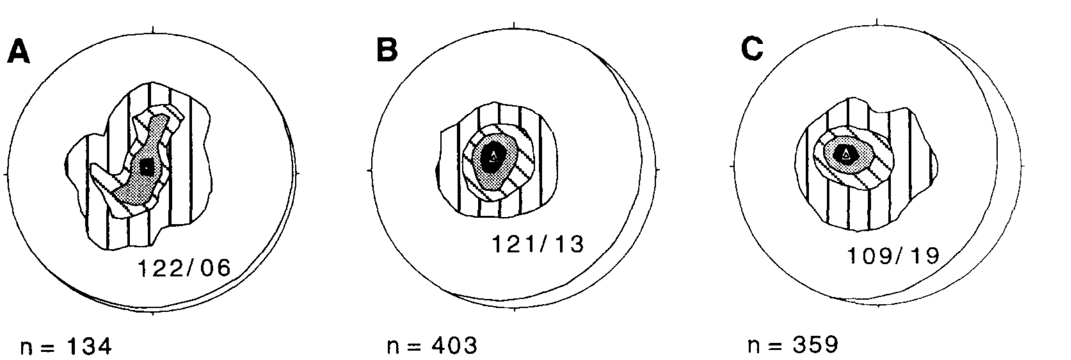

Fig. 7. Stereoplots of kink bands, chevrons and crenulations along the whole slate belt. (a) Clockwise kink bands (max. 7.5%). (b) Counterclockwise kink bands (max. 15.9%). (c) Flat crenulations and chevron folds (max. 15.1%). All stereoplots are equal-area, uniform distribution and lower-hemisphere projection.

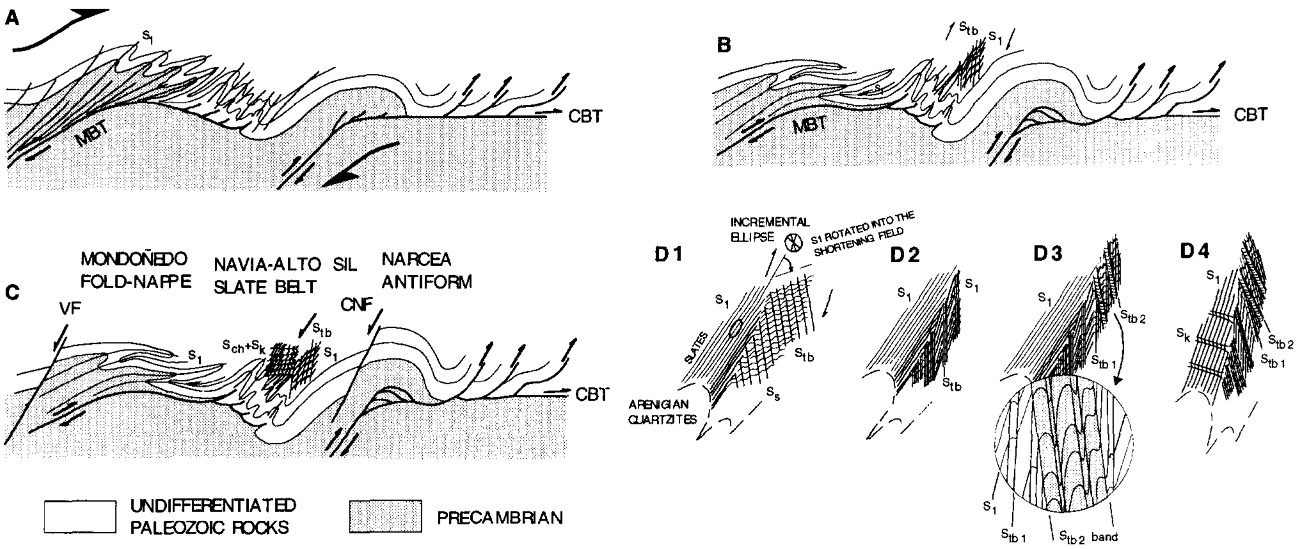

Fig. 8. Schematic presentation of the evolution of the Navia–Alto Sil slate belt. (a) Emplacement of the Mondoñedo fold nappe with formation of slaty cleavage (S_1), the Narcea antiform and the Cantabrian detached fold and thrust belt. (b) Local generation of crenulations with a strong tectonic banding (S_{tb} and other related crenulations). (c) Collapse and generation of flat-lying crenulations, chevrons and kink bands. MBT, Mondoñedo basal thrust. CBT, Cantabrian basal thrust; VF, Vivero Fault; CNF, Cangas de Narcea Fault. (d) Sketch showing the development of the minor structures. D1: S_1 is locally rotated into the shortening field, due to shearing. D2: a narrow zone with a foliation (S_{tb}) is formed. D3: a new foliation (S_{tb2}) is generated, probably due to deflections of S_{tb} induced by the underlying Arenigian quartzites. D4: formation of kink bands where S_1 has not been affected by later crenulations.

tectonic duplications existed. At the back end of the Cantabrian zone, the Narcea antiform developed in a similar way, as a progressively tightened antiformal stack. Recent papers have described a complicated succession of thrusts (Gutiérrez-Alonso, 1996). In the West Asturian–Leonese zone the deformation of the earlier structures was, in general, more gentle (Pulgar, 1980), but at the base of the Luarca Slates, near the contact with the underlying Arenigian quartzites, the slaty cleavage S_1 was folded, producing folds at several scales including crenulation cleavage (S_{tb}). The strip where these structures occur is narrow and can be interpreted as resulting from the rotation of S_1 into the shortening field due to the propagation of some deeper structure (Fig. 8). Where two crenulations (S_{tb1} and S_{tb2}) exist, both can be interpreted as having formed by successive refolding during the same progressive deformation. This can be due to deflections of S_{tb} produced by heterogeneities, which led the S_{tb} foliation to enter into the shortening field, as may happen inside some shear zones (Carreras *et al.*, 1977; Cobbold and Quinquis, 1980) or due to the successive generation of foliations in a shear zone as postulated by Mosher and Berryhill (1991). The first possibility, that is the external rotation of foliations within a constant strain field, seems the most likely. Outside the Navia–Alto Sil slate belt vertical crenulations also exist, but a map of the distribution of the different kinds of crenulations, chevrons and kinks is not available. Thus, the real importance of vertical crenulations is not known. Besides, in the Mondoñedo nappe S_1 is horizontal in wide areas and consequently vertical crenulations develop easily. The situation is quite different in the Navia–Alto Sil slate belt where a steeply dipping S_1 has to enter into the contraction field to give steeply dipping crenulations.

The later deformation events

The later structures occurring in the slate belt indicate a vertical shortening. The flat attitude of kink bands and the strong dip of S_1, coupled with the general occurrence of a single kink set clockwise or counterclockwise according to the dip direction of S_1, are indicative of nearly vertical shortening. The same argument applies to the flat-lying crenulations and chevrons, indicating a shortening in the S_1 dip direction. Therefore, gravity must be responsible for these structures (Matte, 1969). The gradual change, from east to west, from chevrons to kinks indicates a decreasing vertical shortening in this direction. The chevrons are predominant at the base of the Luarca Slates near the contact with the massive Arenigian quartzites, and grade into kink bands towards the west, which become progressively less abundant in this direction. In conclusion, where S_{tb} is not present, there has been a detachment near the Luarca Slates–Arenigian quartzite boundary, with collapse along a bedding fault, and microfolding of the Luarca Slates. These structures on the western limb of the Narcea Antiform have a similar significance to the Cangas del Narcea Fault, which can be considered as a drop fault related to the Narcea Antiform (Fig. 8c). The Vivero Fault, similarly placed with respect to the Mondoñedo culmination, is interpreted in a similar way (Pérez-Estaún *et al.*, 1991), just as some of the minor structures in both areas

(Matte, 1969; Martínez *et al.*, 1996). The abundance of chevrons and kink bands also decreases from north to south along the arc, while the Vivero and Cangas del Narcea faults vanish from north to south, both indicating a decrease of collapse in that direction.

With respect to S_{ob}, despite size differences the similarity of the relationships between horizontal and vertical or moderately dipping crenulations suggest that the processes at work for their generation are size-independent. The S_{ob} crenulation can be interpreted as being due to selective refolding of the quartz-poor microlimbs, formed by platy minerals and related to the same subvertical shortening which generated the chevron folds and kink bands.

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