BSGF - Earth Sciences Bulletin 2020, 191, 6
© J. Aller *et al.*, Published by EDP Sciences 2020
https://doi.org/10.1051/bsgf/2020003

BSGF
Earth Sciences Bulletin
Available online at:
www.bsgf.fr

OPEN ACCESS

On the development of kink-bands: A case study in the Westasturian-Leonese Zone (Variscan belt, NW Spain)

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Received: 26 March 2019 / Accepted: 15 January 2020

Abstract – A field analysis of kink bands developed in slates from three areas (Grandas, Boal and Luarca areas) of the Westasturian-Leonese Zone (Iberian Variscan belt) is presented. The analysis of the main parameters that characterize the geometry of the studied kink bands shows that those of the Grandas and Luarca areas exhibit a different evolution than those of the Boal area. In this latter area, the interlimb angle of the kink bands has lower values than those developed in the former areas and it involves rotation of the foliation inside and outside the band. In the areas with higher bulk shortening associated with the development of kink bands, chevron folds formed by juxtaposition of kink bands. Slip between folia and their rotation was probably the dominant mechanism in the formation of the kink bands, as deduced from the different values of the angle between the kink plane and the foliation inside (ϕ_K) and outside (ϕ) the band, and the occurrence of fractures along the kink planes and small steps between folia cross-cutting these fractures planes. The fractures along the kink planes prevented subsequent hinge migration. Geometrical analysis of kink bands formed by slip between folia and their rotation provides an estimation of the changes in area and thickness, and the strain inside the kink band. For angles of folia rotation $\psi < 50°$, the ratio between the strain ellipse axes is < 3 inside the band; this ratio is almost independent of the orientation of the kink planes with respect to the foliation outside the band (angle ϕ).

Keywords: kink bands / chevron folds / kinematical modeling / strain / cleavage / variscan belt

Résumé – Sur le développment des kink-bands : un exemple dans le Zone Asturoccidentale-léonaise (chaîne varisque ibérique, nord-ouest de l'Espagne). Dans ce travail, on présente une analyse sur le terrain des kink-bands développées dans les schistes de trois zones (Grandas, Boal et Luarca) de la Zone Asturoccidentale-léonaise (chaîne varisque ibérique). L'analyse des principaux paramètres caractérisant la géométrie des kink-bands étudiées montre que ceux des régions de Grandas et de Luarca présentent une évolution différente de ceux de la région de Boal. Dans cette dernière zone, l'angle d'ouverture des kink-bands a des valeurs inférieures à ceux développées dans les premières zones et ceci implique une rotation de la foliation à l'intérieur et à l'extérieur de la bande. Dans les zones où le raccourcissement est plus élevé, des plis en chevron se forment par juxtaposition de kink-bands. Le glissement entre feuilles et leur rotation était probablement le mécanisme dominant dans la formation des kink-bands, comme on peut le déduire des différentes valeurs de l'angle entre le plan de kink et la schistosité à l'intérieur (ϕ_K) et à l'extérieur (ϕ) de la bande, et de l'apparition de fractures tout au long des plans de kink et de petites marches entre les feuilles qui se croissent avec ces plans de fracture. Les fractures tout au long des plans de kink ont empêché la migration ultérieure de la charnière. L'analyse géométrique des kink-bands formées par glissement entre les feuilles et leur rotation permet d'estimer la variation de l'area et l'épaisseur, et la déformation à l'intérieur du kink-band. Pour les angles ψ de rotation de folia $< 50°$, le ratio entre les axes de l'ellipse de déformation est < 3 à l'intérieur de la bande ; ce ratio est presque indépendant de l'orientation des kink-bands par rapport à la foliation à l'extérieur de la bande (angle ϕ).

Mots clés : kink-bands / plis en chevron / modélisation cinématique / déformation / schistosité / chaîne varisque

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1 Introduction

Kink bands are strongly asymmetric angular or subangular folds, whose geometry is that of a monoclinal step (Fig. 1). Although they have been described in diverse lithologies, kink bands typically develop in laminated materials (mainly shale, slates or schist) with a previous well-marked anisotropy (usually slaty cleavage or schistosity). The bands are usually the short limb of the fold; in fact, the term "kink band" refers strictly to the band, while "kink fold" refers to the whole fold. However, the term "kink band" has been generalized to refer indistinctly to the band or to the whole fold. Most authors admit that the kink bands are late structures in the orogenic evolution (e.g. Ramsay, 1962; Anderson, 1964, Anderson, 19691969; Sharma and Bhola, 2005; Misra and Burg, 2012). Anderson (1964) defined two angles, α and β, for the geometrical analysis of kink bands; these angles were named ϕ and ϕ_K, respectively, by Paterson and Weiss (1966), which is the terminology used here (Fig. 1). The rotation angle of the folia ψ with respect to their initial orientation is also considered here in the analysis; when there is no rotation outside the kink band, $\psi = 180° - \phi_K - \phi$.

Kink bands can be reproduced experimentally fairly easily, both in rocks (Paterson and Weiss, 1962, 1966; Donath, 1964, 1968, 1969; Anderson, 1974) and in other materials, e.g. in stacks of cards (Weiss, 1969; Gay and Weiss, 1974; Pulgar, 1980; Hunt *et al.*, 2000; Wadee *et al.*, 2004), plasticine (Cobbold *et al.*, 1971; Price and Cosgrove, 1990), rubber layers (Honea and Johnson, 1976; Ramberg and Johnson, 1976; Reches and Johnson, 1976) or layers of lead separated by layers of wax-impregnated cloth (Stewart and Alvarez, 1991). The observations and data provided by theoretical, experimental and field studies of kink bands have given rise to several interpretations of their evolution, which have been a source of controversy as yet unresolved. Different kinematical mechanisms proposed for the evolution of kink bands are as follows:

- slip between folia and their rotation (e.g. Donath, 1969; Bhattacharya, 1977; Sharma and Bhola, 2005; Dunham *et al.*, 2011). This involves an evolution of the kink bands by rotation of the folia, whose length remains constant; the orientation of the kink planes also remains constant (cf. rotation shear, Bastida *et al.*, 2018). The hinges are linked to the same material points during the process, which involves slip along the folia inside the band, and a change in thickness of the kink band, the band thickness being maximum when $\phi_K = 90°$ and equal to the initial thickness when $\phi_K = \phi$ (no finite area change). The evolution of the kink band ceases when this equality is reached;
- hinge migration (Paterson and Weiss, 1966; Weiss, 1969). This involves a first stage with the generation of a small core or a very thin kink band oblique to the foliation. This core evolves as its boundaries migrate, giving rise to an increase in the thickness of the band without a change in the orientation of the folia inside it. The equality $\phi_K = \phi$ is maintained during the kinking, so that the orientation of the kink planes does not change, although their position changes. The evolution of kink bands by this mechanism can give rise to chevron folds that will first appear in the band intersections. Subsequently, the widening of the bands by hinge migration can result in the kink bands being replaced by chevron folds;

Fig. 1. Sinistral kink band with indication of some parameters used in the analysis of structures of this type; *KP*, kink planes (near Grandas de Salime, Asturias, Spain).

- rotation of the kink planes combined with band widening (Rondeel, 1969a, 1969b; Weiss, 1980; Stewart and Alvarez, 1991). Unlike the previous mechanisms, this implies a shift in the orientation of the band as the deformation progresses. According to Weiss (1980), this mechanism is dominant when the rotation angle of the folia ($\psi = 180° - \phi_K - \phi$) is less than 60°, while when this angle exceeds 60°, the mechanism of hinge migration becomes dominant;
- simple shear (Johnson, 1956; Ramsay, 1962; Dewey, 1965). This involves rotation and longitudinal strain of the folia inside the band. In this case, the structure can be considered as a ductile fault. This mechanism involves that the kink planes form an angle $< 45°$ with the direction of the maximum compressive stress (σ_1). Nonetheless, in most cases this angle is $> 45°$; hence, this mechanism is generally not accepted.

Each of these mechanisms should result in a characteristic deformation history, and a number of criteria have been described to discriminate between them. The inequality between the angles ϕ and ϕ_K, which is found in most cases, and the corresponding volume change, have been used as a criterion to discard the hinge-migration mechanism (e.g. Dewey, 1969; Bhattacharya, 1977; Sharma and Bhola, 2005) and to infer rotation of the foliation (Anderson, 1964; Ramsay, 1967). Stewart and Alvarez (1991) have criticized this view, because in general they find that $\phi \neq \phi_K$ in their experiments with cards, in which the existence of a widening of the kink bands during their development is shown. However, this interpretation should be taken with caution, since in at least one of their experiments (Fig. 9 of these authors), there is a strong rotation of folia within the bands while the hinge migrates. The coexistence of kink bands and chevron folds formed from the intersection of conjugate kink bands has been interpreted by these authors as evidence of the hinge-migration mechanism. Likewise, the coexistence of small cores of kink bands and more developed bands suggests a mechanism of band

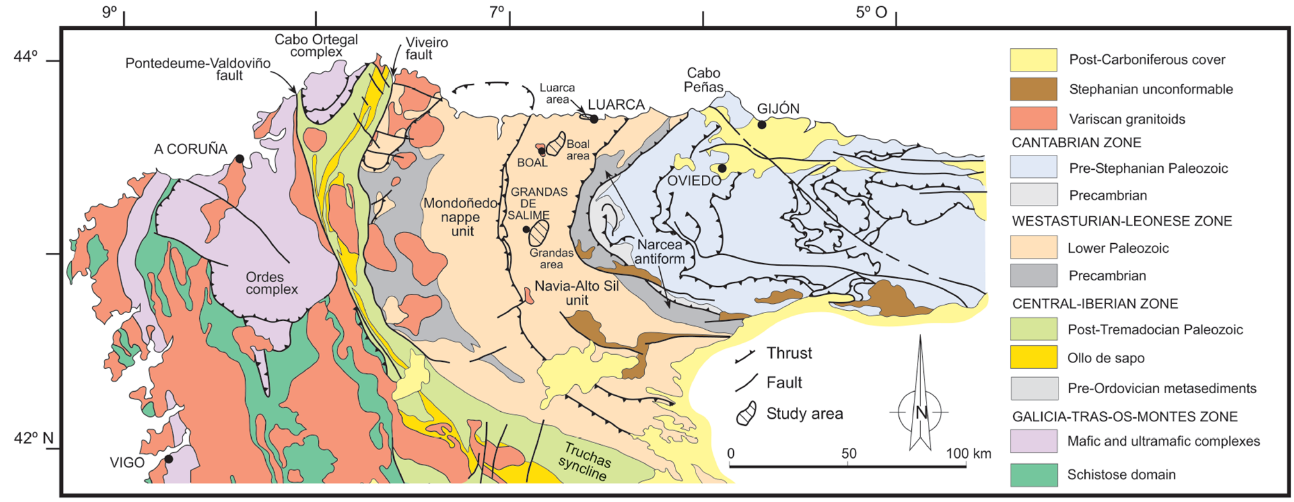

Fig. 2. Geological map of the Veriscan belt in NW Spain with the location of the three studied areas in the Navia-Alto Sil slate belt.

widening. The model with a combination of hinge migration and kink plane rotation involves the existence in an outcrop of kink planes with different orientations that depend on the degree of evolution.

The aim of this study is to contribute to the knowledge of the mechanisms that lead to the development of compressional kink bands by analyzing the excellent examples that occur in three areas located in the Westernasturian-Leonese Zone (Iberian Variscan belt) (Fig. 2). In addition, a geometrical analysis is carried out in order to explain the properties of the deformation involved in the formation of these structures.

2 Kink bands in the Navia-Alto Sil slate belt (Westernasturian-Leonese Zone)

2.1 Geological setting

The Westernasturian-Leonese Zone is one of major zones of the Iberian Variscan Belt in NW Iberia (Fig. 2). It mainly consists of a thick lower Paleozoic succession, mostly siliciclastic with the exception of a lower-middle Cambrian carbonate formation, and represents the hinterland of the orogen in the transition zone to the foreland fold and thrust belt (Cantabrian Zone) located to the east, in the core of the arc described by the general trend of the structures (Ibero-Armorican Arc). The orogenic metamorphic grade increases westward up to the amphibolite facies and granitoid outcrops occupy a large area in the western part of the zone. The structure of this zone resulted from three phases of deformation (Marcos, 1973). The first deformation phase (D_1) gave rise to foreland-verging folds (F_1) with associated axial planar cleavage (S_1) and sub-horizontal hinges. The second phase (D_2) gave rise to thrusts and shear zones with abundant minor structures (F_2 and S_2), and the third phase (D_3) gave rise to upright open folds (F_3) with associated crenulation cleavage (S_3), being F_3 folds almost homoaxial with F_1 folds. Post D_3 structures are represented by sub-horizontal kink bands and normal faults.

The kink bands are well developed in a slate belt formed by the Luarca Slates (Middle Ordovician) in the oriental part of the Westernasturian-Leonese Zone (Navia-Alto Sil Unit; Marcos, 1973), in the chlorite metamorphic zone. These kink bands were studied in this slate belt by several authors (Matte, 1968, 1969; Marcos, 1973; Pulgar, 1980; Julivert and Soldevila, 1998). According to them, they have subhorizontal kink planes, they deform the slaty cleavage (S_1) that presented high dip angles, and they are the last structures to form; conjugate kink bands are rare. The mechanisms that formed these structures are not well known. Within this slate belt, we consider three areas for this study (Fig. 2): the area close to Boal (Boal area), the area between Berducedo and Grandas de Salime (Grandas area), and the sector of the Cantabrian coast near Luarca (Luarca area). The dip direction of the slaty cleavage is to the west or northwest in general and the angle ranges between 30° and 90°, with a modal interval of between 60° and 70°. The dispersion of values is higher in the Boal area. The Luarca area contains a lower number of kink bands than the other two, so the volume of data it provides is not suitable for a comparative analysis with the other areas. However, the three areas are nearby and their stratigraphic, structural and metamorphic features are similar, being in the Luarca area where the evolution of the kink bands with respect to other structures has been best explained (Fig. 3). Therefore, the Luarca area, which is very well exposed, provides valuable information for the interpretation of the formation mechanisms of kink bands, in this slate belt of the Westernasturian-Leonese zone.

A thorough analysis of kink bands requires considering the physical conditions that enabled their development. The analysis of quartz veins that occur in the Luarca area can provide insights into the understanding of these conditions. These veins formed at early stages of the development of the third regional deformation phase and were subsequntly folded during this phase (Pérez-Alonso *et al.*, 2016). At the same time, an associated axial planar crenulation cleavage developed on the S_1. Therefore, these veins formed in the deformational event prior to the development of the kink bands. In order to know the conditions of formation of these veins, Pérez-Alonso *et al.* (2016) combined the chlorite geothermometers of Cathelineau (1988), and Kranidiotis and MacLean (1987), the thermobarometry of Titanium-in-quartz, and the study of fluid inclusions in quartz. These authors

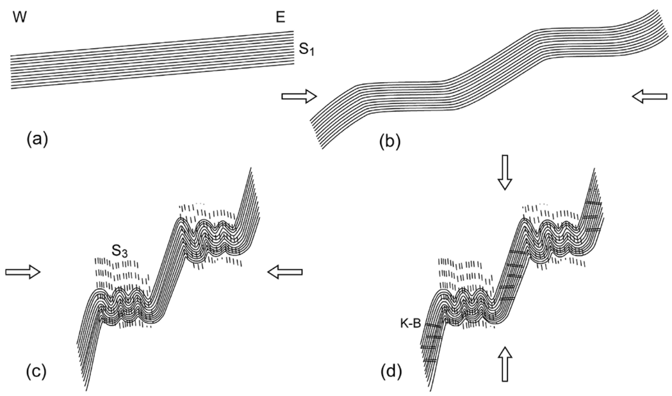

Fig. 3. Evolutionary outline of the structure in the Luarca area. (a) Attitude of the cleavage S_1 after the first deformation phase; (b) development of major folds during the third deformation phase with subhorizontal limbs and steeper limbs; (c) tightening of the third phase folds with development of minor folds and S_3 cleavage in the subhorizontal limbs; (d) development of kink bands on strongly inclined limbs. After Bastida *et al.* (2010).

distinguished between two types of inclusions: primary aqueous-carbonic fluid inclusions (type I), and secondary aqueous fluid inclusions (type II). The latter form fluid inclusion planes in transgranular microcracks that crosscut the quartz grains; these microcracks were the result of a fracturing event following the plastic deformation of quartz due to the third deformation phase. Pérez-Alonso *et al.* (2016) conclude that the temperature of the veins forming fluid was between 350 and 375 °C and the fluid pressure fluctuated between 220 MPa (lithostatic pressure) and 75 MPa (infralithostic pressure). The type II inclusions were entrapped at temperatures between 140 and 251 °C, and at a hydrostatic pressure < 2 MPa. Like the kink bands, the microcracks that affect the veins were generated after the third phase of deformation and, although kink bands and microcracks cannot be directly correlated, the latter indicate a decrease in temperature after the third deformation phase. This conclusion can also be applied to the areas of Boal and Grandas.

2.2 Description of the structures

The studied kink bands are sinistral when viewed towards the north, with angles ϕ and ϕ_K presenting a great dispersion (Fig. 4a). Except in a few cases (2.16%), the two angles are not equal, with a slight majority of cases in which $\phi_K > \phi$ (50.35%), the cases in which $\phi_K < \phi$ (47.48%) being numerous in all three areas. A number of the points representative of kink bands of the Boal area coexist with those of the Grandas and Luarca areas in one sector of the diagram in Figure 4a. However, the points corresponding to the Boal area show dispersion towards lower ϕ and ϕ_K values; this tendency is not observed in the Grandas area. In general, the value of ϕ increases as the S_1 dip increases, with the occurrence of lower values of ϕ and S_1 dip more common in the Boal area than in the Grandas area (Fig. 4b).

The interlimb angle ($\phi + \phi_K$) of the kink bands presents different frequency distribution patterns in the two areas considered for comparison (Fig. 5). In the Grandas area, most of the interlimb angles range between 120° and 160°, with a mean value of 142.4, whereas the Boal area presents a greater dispersion of values without a well-defined modal interval. In addition, the latter area presents a much larger number of cases with angles ranging from 60° to 120°, these lower values corresponding to chevron or quasi-chevron folds. When the interlimb angle is related to other geometrical parameters of the kink bands, we observe that:

- in the Grandas area, the interlimb angle shows little variation between 120° and 160° and is independent of the ϕ value, whereas in the Boal area the larger the interlimb angle the larger the ϕ value (Fig. 6);
- the correlation of a larger interlimb angle for a larger ϕ_K occurs in both the Granda and Boal areas (Fig. 7), although the correlation is more noticeable in the latter, with larger interlimb angle variation from 80° to 160°. The value of ϕ_K exerts a stronger influence on the interlimb angle than does the value of ϕ in Grandas area.

In most cases, dilation within the kink band [100×(final area-initial area)/initial area] lies between a 20% increase and a 20% decrease (90% of the kink bands of the Grandas area and 76.5% of those of the Boal area are within that range).

The bands very commonly present fractures along one or both boundaries. In many cases, the fractures are sharp and well developed, whereas in others they have a subtler, discontinuous nature. The fractures can be planar or irregular, and sometimes they appear inside the band, generating thin bands juxtaposed to the major band. It is also possible to observe fractures outside the kink bands but parallel to them. Sometimes, small steps between folia inside the band are observed; they crosscut the fractures that limit the band and therefore, they developed after them.

It is common for the S_1 foliation to present a different appearance inside the band than outside it. S_1 is usually more marked and sometimes more open inside the band, but this is not always the case; exceptionally, the opposite may occur. In general, when the foliation appears open within the band, $\phi_K > \phi$. Secondary spaced foliation inside the bands and oblique to the kink planes has been observed in some localities near Berducedo; this foliation has also been observed by other authors (Matte, 1969; Marcos, 1973).

The folds sometimes present a geometry similar to that of chevron folds (Fig. 8). These folds occur through the development of adjacent kink bands in such a way that one limb is only a little longer than the other.

2.3 Interpretation and discussion

The kink bands in the slate belt have been interpreted as late Variscan structures caused by compressive stresses driven by gravitational body forces. This interpretation is based on the subhorizontal disposition of most of the kink bands, developed on pelitic rocks with steeply dipping S_1 (Matte, 1969; Pulgar, 1980; Julivert and Soldevila, 1998; Bastida *et al.*, 2010). The existence of a certain obliquity between the maximum compressive stress direction and S_1 has been put forward as

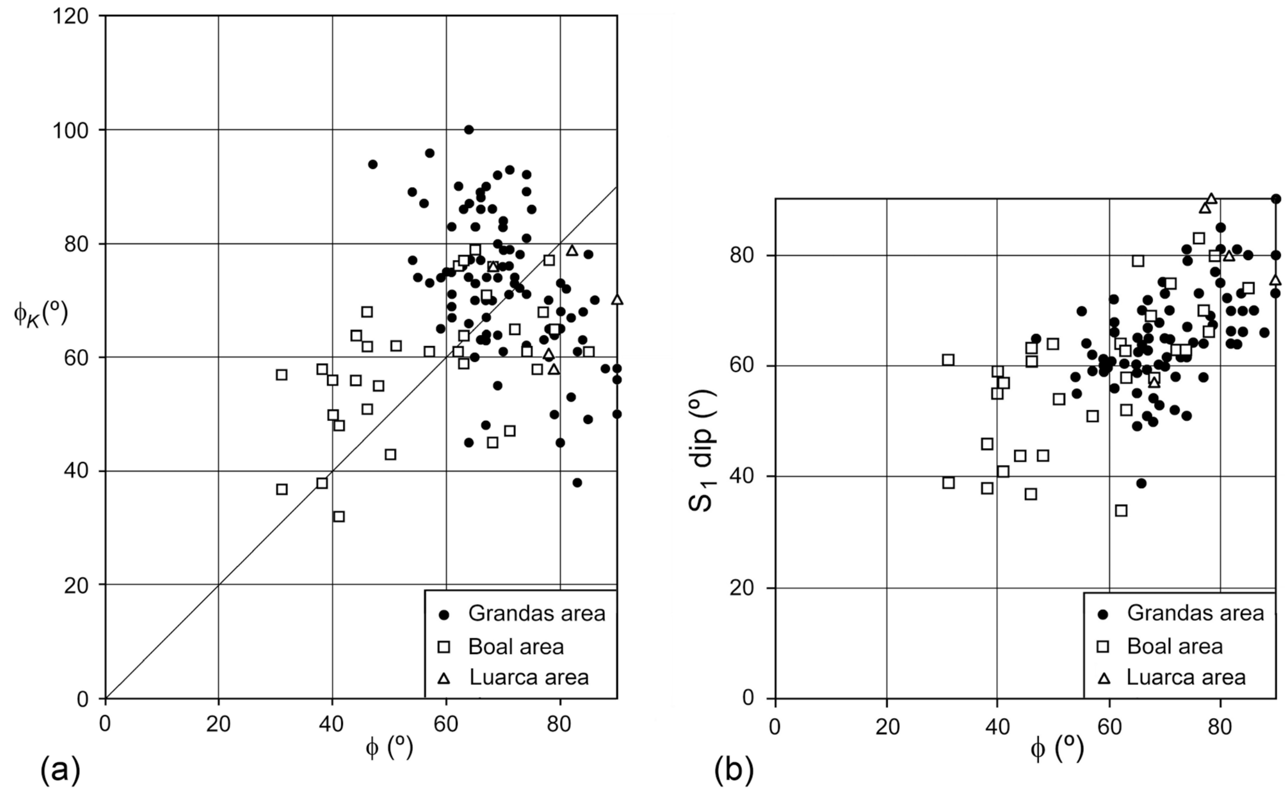

Fig. 4. ϕ_K against ϕ(a) and S_1 dip against ϕ (b) for the Grandas, Boal and Luarca areas.

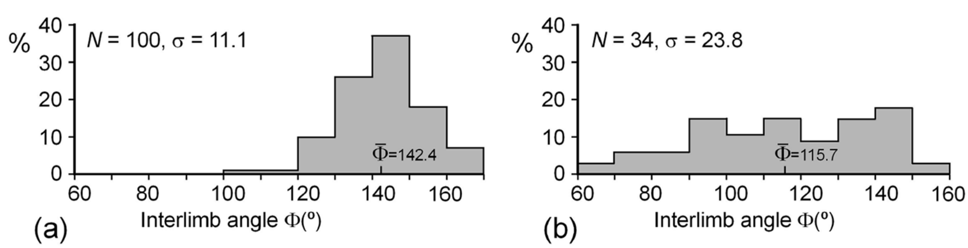

Fig. 5. Frequency histograms of the interlimb angle ($\phi + \phi_K$) for the Grandas area (a) and the Boal area (b).

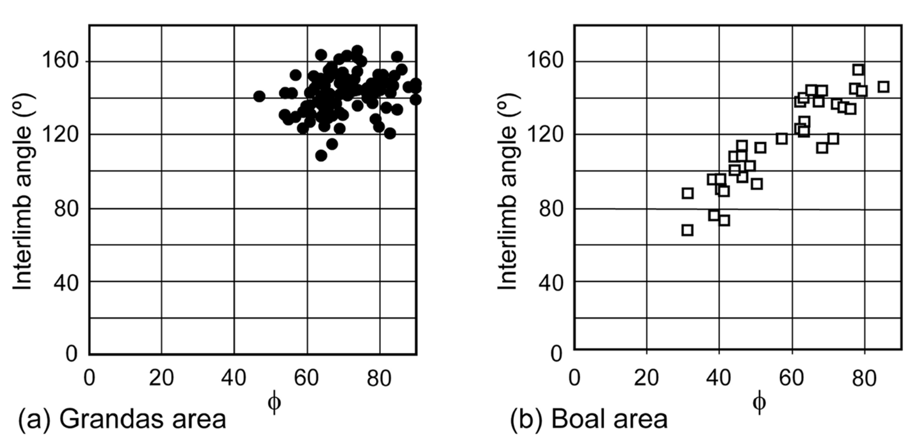

Fig. 6. Interlimb angle ($\phi + \phi_K$) against ϕ for the Grandas area (a) and the Boal area (b).

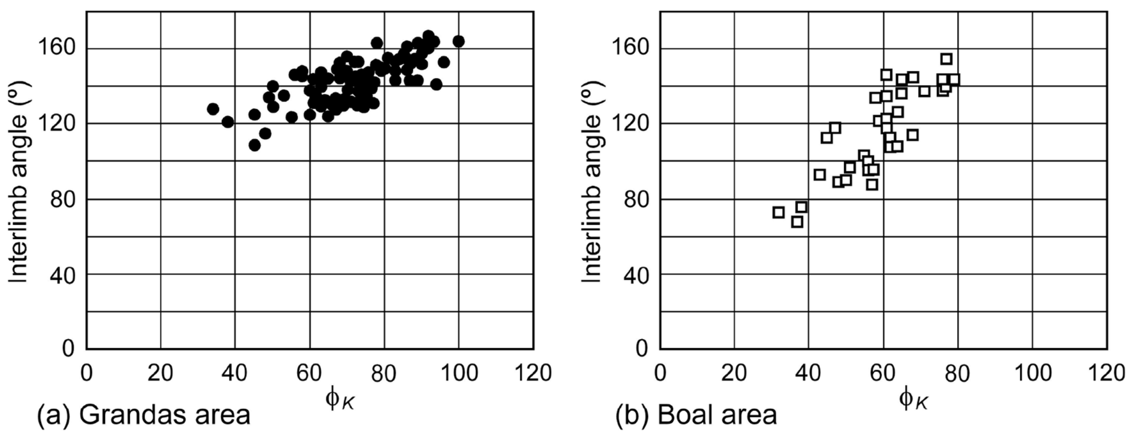

Fig. 7. Interlimb angle ($\phi + \phi_K$) against ϕ_K for the Grandas area (a) and the Boal area (b).

Fig. 8. Small chevron folds formed by juxtaposition of kink bands (Boal area).

the reason for only a single set of kink bands appearing, conjugate kink bands being very rare.

The understanding of how the progressive deformation operated during the development of kink bands is required in order decipher the mechanisms involved in their formation. This is possible in some experimentally generated kink bands, but it is a difficult task in natural kink bands. In fact, sinusoidal waves corresponding to the early stages of folding, as predicted by some theoretical studies (Cobbold *et al.*, 1971; Honea and Johnson, 1976; Price and Cosgrove, 1990), or small cores of kink bands, as observed in some experiments (Paterson and Weiss, 1966; Weiss, 1969), have not been found in the studied areas. However, there are some indications that can help explain the kinematic development of these structures.

Although it is generally accepted that the mechanism of hinge migration implies that $\phi_K = \phi$, and that the foliation rotation stops when this equality is met (Anderson, 1969), a large dispersion of values of these angles occurs in the kink bands analyzed, with $\phi_K < \phi$ being very common (Fig. 4a). Comparable angular relations have been obtained by Anderson (1969) and Fyson (1969) in natural kink bands of Nova Scotia and Northern Ireland respectively, and by Donath (1969) in experimental kink bands. The inequality between ϕ and ϕ_K provides a first argument in favor of rotation and slip along the foliation in the development of the kink bands. The thermobarometric data from quartz veins suggest that the kink bands formed under conditions of low confining pressure. The experimental tests carried out in rocks by Anderson (1974) show that under these conditions (confining pressure < 250 MPa) the development of shear fractures predominates. However, these experiments were carried out at room temperature, while in the kink bands under study the temperature was probably > 100 °C, which increased the ductility of the rock, facilitating the coexistence of kink bands and fractures. This interpretation agrees with the common occurrence of fractures along the kink planes, even in gentle kink bands; this fact does not preclude a thickening of the band to the present fractured state, but does preclude any subsequent evolution by hinge migration. In addition, the mechanism of hinge migration involves an increase of the deformed area but not an increase in the intensity of the deformation inside the band, which hinders the development of fractures. In contrast, the mechanism of rotation of the folia implies an increase of the deformation inside the band, which may lead to the development of fractures. This interpretation is in agreement with the Anderson's (1974) conclusion that states that the experimental kink bands in slates form by slip and rotation of the folia under low pressure conditions.

The graphs that relate S_1 dip, ϕ, ϕ_K and the interlimb angle ($\phi + \phi_K$) in the areas of Grandas and Boal provide insights into kinematics. The general decrease of the angle ϕ when S_1 dip decreases (Fig. 4b) can be interpreted in two ways:

- it may be due to a variation of the obliquity angle between the foliation and the direction of maximum compression. According to the theoretical results obtained by Cobbold *et al.* (1971) and Price and Cosgrove (1990), an increase of the obliquity between the anisotropy and the direction of the maximum compression causes an increase of the angle ϕ, so that when the obliquity angle is 45°, the angle ϕ reaches 90° and the kink band is placed at the boundary between the compressional and extensional types;
- it may be due to a rotation of the foliation outside the kink bands in order to decrease ϕ. This rotation would have been greater in the Boal area than in the Grandas area.

Figure 6 shows that in the Grandas area it is difficult to discriminate between the two previous options (Fig. 6a). However, in the Boal area (Fig. 6b) the second option seems the most appropriate, since the decrease in ϕ is associated with a decrease in the interlimb angle, that is, a tightening of the fold and consequently a rotation of the limb. In any case, the occurrence of obliquity between the anisotropy and the direction of the maximum compression could explain the development of high ϕ angles in some kink bands of the studied areas.

The observation of Figures 6 and 7 allows interpreting that, in the Grandas area, the tightening of the kink bands is related to the decrease of the angle ϕ_K more than to the decrease of ϕ, while in the Boal area, this tightening is associated with the decrease of both angles (ϕ and ϕ_K). The resulting lower interlimb angles in the Boal area than in the Grandas area (Fig. 5) relate with the greater bulk shortening associated with the kink bands in Boal. Therefore, in this case, both limbs undergo appreciable rotation and deformation.

Small chevron folds in the Boal area, and to a lesser extent in the Grandas area, occur in outcrops with more intense bulk shortening, which has led to the occurrence of very numerous close kink bands. This closeness leads to a loss of asymmetry of the kink bands that become chevron folds. This indicates that these chevrons are not generated by intersection of conjugated kink bands, which do not exist in this area. The development of chevron folds involves the formation of numerous parallel kink bands very close to each other and the rotation of both limbs, with the consequent decrease in the angle between them. Thus, the chevron geometry of these folds is characterized by a lower interlimb angle and a lower asymmetry than in the case of kink bands, with a complete transition existing between these two types of folds. Therefore, the development of chevron folds is associated with an increase in the amount of shortening, and not with a change in lithology.

From the above it is clear that, with the exception of the first stages of development of the kink bands, for which there is no evidence of the operating mechanisms, the dominant mechanism for development of kink bands was slip between the folia and their rotation. This is particularly clear in the Boal area, where both limbs most frequently rotated to eventually result in small chevron folds. This mechanism also agrees with the common occurrence of different values of ϕ_K in kink bands of the same outcrop, in which the values of ϕ are almost constant, and also with the fact that ϕ and ϕ_K are generally different.

The conclusion that the mechanism involved in the formation of the kink bands in the studied areas is the rotation and slip of the foliation contrasts with the results obtained in some experiments, which suggest a hinge migration mechanism (Paterson and Weiss, 1966; Weiss, 1969; Stewart and Alvarez, 1991). This discrepancy is due to the limitations of the experiments in simulating natural kink bands, because they are carried out under different conditions than those occurring in the natural ones. The experiments using rocks are carried out in triaxial presses in which the samples are surrounded by a metal or rubber jacket, while the experiments with cards are carried out employing presses with two pistons exerting compressive stresses in perpendicular directions, with the plane that contains these two directions unconfined (Weiss, 1969). In addition to the difference in size of the samples in the two types of experiments (greater in the case of cards), and in the way of applying the compressive stresses, the progressive development of the kink bands can be observed in the card experiments, whereas only the final stage can be observed in the rocks experiments. This may lead us to think that the experiments with cards are more advantageous; however, the rheological behavior of the cards is very different from that of the rocks. The cards do not break during the experiments, whereas the rocks can break; in fact, in the natural example studied, kink planes are very often fractures. Another important drawback of all of the experiments is that the effects of temperature, pore-fluid pressure, and strain rate were not considered. The absence of fractures and the difficulty of undergoing volume changes in card experiments facilitates hinge migration in the kink bands formed in these materials, which seems more difficult in natural kink bands.

The incipient oblique crenulation cleavage that appears in alternating limbs involves pressure solution. It is probably a late structure in the evolution of the kink bands that developed in the limbs with more favorable orientation in relation to the compressive stress. This cleavage mainly appears when the shortening is important and very close kink bands develop.

According to the rotation model, the inequality $\phi_K < \phi$ implies a decrease in area in the kink band, which in many cases exceeds 20%. The decrease in area would have been lower if the foliation, in addition to undergoing rotation, had suffered longitudinal stretching within the band when $\phi_K < \phi$. Thus, in the limit case in which the deformation happened to be by simple shear, there would be no change in area. Unfortunately, no structural evidence of this stretching has been found.

The dominant mechanism in the development of the studied kink bands, slip between folia and their rotation, can be described by the type of deformation called "rotation shear" (Bastida *et al.*, 2018; Bobillo-Ares *et al.*, 2018). We can assume that these structures are generated in a rock band whose boundaries have an invariant direction defined by vector $\hat{\mathbf{h}}$ (Fig. 9); segments with this direction do not undergo any change in length. Inside the band, the folia rotate through an angle ψ without undergoing any change in length. Then, in the vector basis ($\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$), the corresponding matrix of the deformation gradient is (Bobillo-Ares *et al.*, 2018):

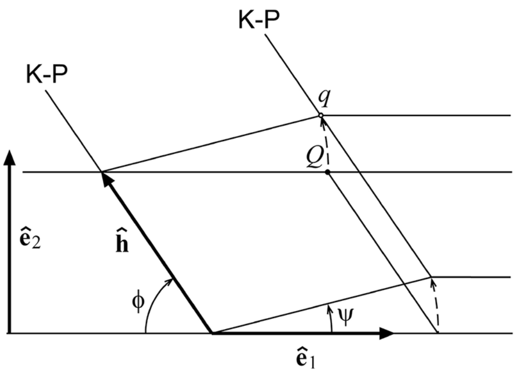

Fig. 9. Scheme showing the geometry of rotation shear in the development of a kink band. The direction defined by **h** (or ϕ) is invariant and of no longitudinal strain. Segments in the $\hat{e}_1$-direction undergo a rotation ψ inside the kink band but do not undergo changes in length. Lines marked K-P are the kink planes (or boundaries of the kink band). Point *Q* of the undeformed configuration is transformed into point *q* of the deformed configuration.

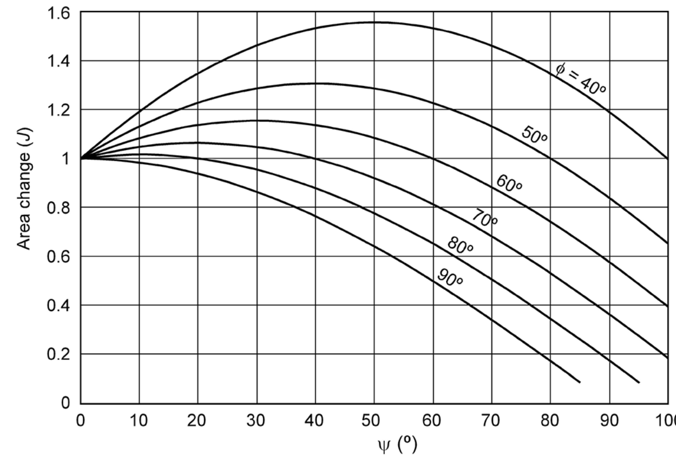

Fig. 10. Area change as a function of the angle ψ for several values of angle ϕ in a kink band formed by rotation shear (Clifford, 1969).

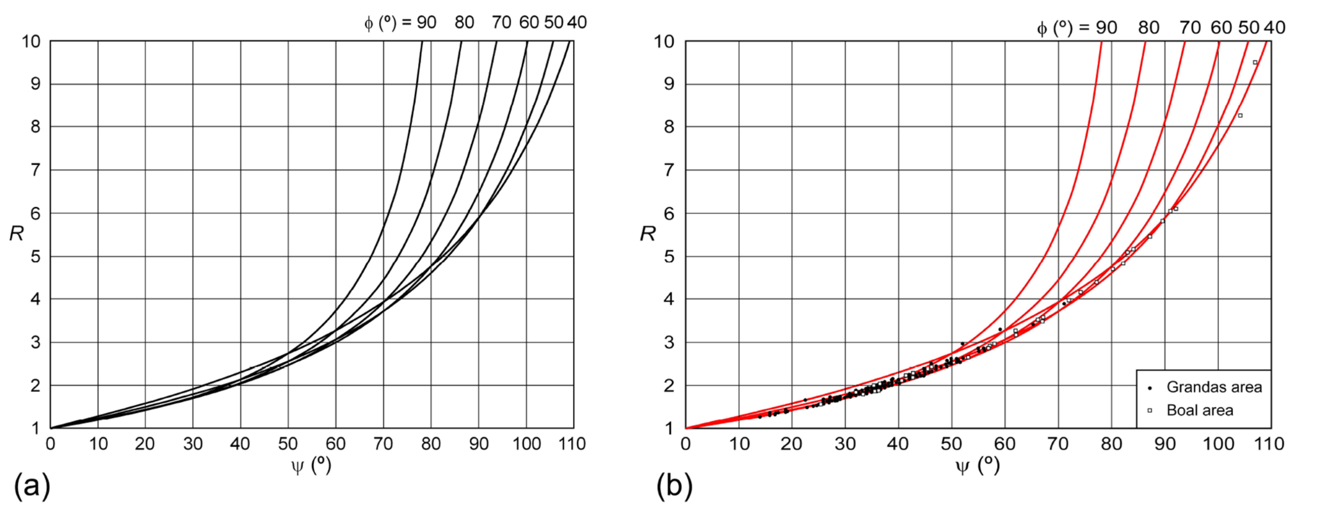

Fig. 11. (a) Ratio *R* between the strain ellipse axes as a function of the ψ angle for several values of angle ϕ in a kink band formed by rotation shear; (b) values of *R* obtained from measurements of ϕ and ψ made in kink bands of the Grandas and Boal areas.

$$F = \begin{pmatrix} \cos\psi & -\cot\phi(1-\cos\psi) \\ \sin\psi & 1+\cot\phi\sin\psi \end{pmatrix}. \quad (1)$$

The change in area is given by the determinant of the previous matrix:

$$J = |F| = \cos\psi + \cot\phi\sin\psi. \quad (2)$$

This function is equivalent to equation (7-53) by Ramsay (1967) and is graphically represented in Figure 10 for several ϕ values. Since changes in length do not occur at the boundary of a kink band, the curves in Figure 10 also show the change in thickness of the kink band during its development. With an exception when ϕ = 90°, we can observe that the initial area and thickness increase, followed by a decrease; the point at which $J = 1$ that separates the two parts of each curve corresponds to the stage with $\phi = \phi_K$.

The principal values of the strain are:

$$\sqrt{\lambda_1} = \frac{\sin[(\phi+\psi)/2]}{\sin(\phi/2)}, \quad \sqrt{\lambda_2} = \frac{\cos[(\phi+\psi)/2]}{\cos(\phi/2)}, \quad (3)$$

and the direction of the major axis of the strain ellipse is that of the bisector of angle ϕ_K. The corresponding ratio between the lengths of the axes of the strain ellipse is:

$$R = \sqrt{\lambda_1/\lambda_2} = \cot(\phi/2)\tan[(\phi+\psi)/2]. \quad (4)$$

This function is shown graphically in Figure 11a for several ϕ values. We can observe that for ψ values lower than 50°, the value of ϕ barely influences the value of *R*. Assuming a mechanism of slip between folia and their rotation, the results of the determination of *R* in kink bands of the Grandas and Boal areas are shown in Figure 11b. Values of ψ > 60° and

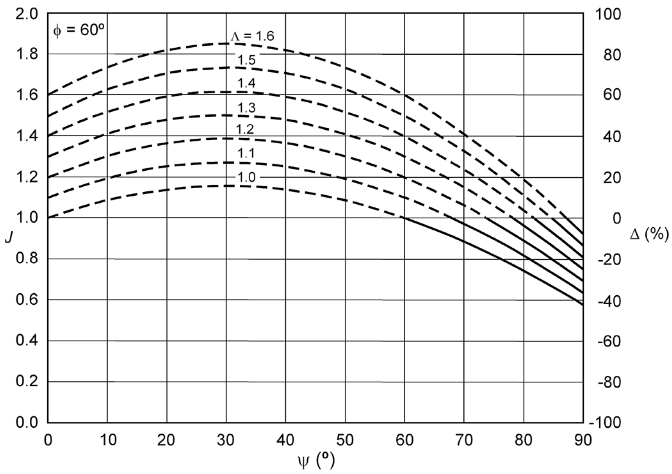

Fig. 12. Area change (J and Δ) in kink bands, with $\phi = 60°$, generated by foliation rotation (angle ψ) plus foliation stretching (numbers on the curves). Dashed lines indicate area increase and continuous lines indicate area decrease.

$R > 3$ are very rare in the Grandas area but common in the Boal area. We can confirm that these high values of ψ and R occur in localities of the Boal area where the kink bands are very close together and form chevron folds, indicating that the foliation has rotated in the two limbs of the structure. Because the model involves no rotation outside the kink band, it is not possible to establish from this figure, a discrimination of the cases with rotation of foliation outside the band from those that have not undergone rotation.

Longitudinal stretching of the foliation may occur inside the band, which avoids the problem caused by an excessive decrease in area inside the kink band. In this case, the deformation gradient given by equation (1) changes to:

$$F = \begin{pmatrix} \Lambda\cos\psi & -\cot\phi(1 - \Lambda\cos\psi) \\ \Lambda\sin\psi & 1 + \Lambda\cot\phi\sin\psi \end{pmatrix}, \qquad (5)$$

where Λ is the stretch ($\Lambda = \sqrt{\lambda}$) in the foliation direction. The associated change in area is the determinant of this matrix:

$$J = |F| = \Lambda(\cos\psi + \cot\phi\sin\psi). \qquad (6)$$

This function has been represented in Figure 12 for $\phi = 60°$ and several values of the stretch Λ. Each curve contains a part that represents an area increase and that has been drawn with a dashed line. This increase involves an elongation in all directions that seems unlikely in kink bands. For values of ψ higher than a certain value, a decrease in area occurs, which is lower for higher stretch values. Thus, for example, a value of $\psi = 80°$, folia rotation ($\Lambda = 1$) would generate an area decrease of 26%, while a folia stretch of 1.2 would generate a decrease of 11%.

3 Conclusions

Late Variscan kink bands have been studied in three areas of the Westasturian-Leonese Zone (Grandas, Boal and Luarca areas). They developed in slates due to vertical compressive stresses of gravitational origin in areas where slaty cleavage was in a steep position. Kink bands formed with subhorizontal or gently dipping kink planes, and the obliquity between the direction of maximum compressive stress and cleavage planes prevented the development of conjugated link bands and favored the appearance of high ϕ angles.

In general, $\phi_K \neq \phi$ and the presence of fractures along the kink planes is very common. Then, excluding the first stages of the development of kink bands of the Grandas, Luarca and Boal areas, in which the formation mechanism could not be established, we suggest that slip between folia and their rotation is the dominant mechanism in the development of these folds. Discrepancies with some experimental results are due to differences in conditions of development of natural kink bands and those in experiments. For example, cards do not break during the experiments while rocks do.

In the Grandas area, the decrease of the interlimb angle associated with the evolution of the kink bands is mainly produced by rotation of the folia inside the band (decrease in ϕ_K), while in the Boal area, it occurs by rotation of the folia inside and outside the band (decrease of ϕ_K and ϕ). In highly shortened areas, many parallel kink bands develop next to each other, giving rise to chevron folds, which have interlimb angles lower than those of the isolated kink bands.

A geometrical analysis of kink bands developed by slip between folia and their rotation shows that the ratio between the lengths of the axes of the strain ellipse increases with increase in the deflection angle ψ of folded folia, and is almost independent of the orientation of the kink band boundaries (given by angle ϕ) when angle ψ is lower than 50°, a condition that is accomplished by most kink bands.

The development of the kink bands by rotation shear involves a change in area and thickness of the band. In general, these magnitudes increase up to a maximum and then decrease, and are capable of eventually reaching values lower than the initial ones. We propose that a low stretching of the foliation within the kink band could result in a decrease in area much lower than that caused by simple rotation of the foliation. This proposal remains as a hypothesis for further research.

Acknowledgements. The present paper has been supported by the CGL2015-66997-R project funded by the Ministerio de Economía y Competitividad of Spain. We are grateful to Josep Poblet and an anonymous reviewer for the many valuable suggestions that have notably improved the paper. We thank Luis Antonio Barrio Álvarez, John Hardwick and Robin Walker for their help with the language of the manuscript.

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Cite this article as: Aller J, Bastida F, Bobillo-Ares NC. 2020. On the development of kink-bands: A case study in the Westasturian-Leonese Zone (Variscan belt, NW Spain), *BSGF - Earth Sciences Bulletin* 191: 6.