SGE Sociedad Geológica de España

GEOGACETA, 55, 2014

Folding as a precursor of asymmetric boudinage in shear zones affecting migmatitic terranes

El plegamiento como precursor del "boudinage" asimétrico en zonas de cizalla de terrenos migmatíticos

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ABSTRACT

The process responsible for the genesis and the initial morphological evolution of shearband boudins is controlled by the buckling laws. In this model, the generation of boudins begins with folding of tabular competent veins of different thickness immersed in a less competent matrix. Veins thicker than a given critical value form initial asymmetric open folds that evolve by asymmetric antithetical rotation and later by an internal mass redistribution with translation along the interface vein-matrix. On the other side, the veins thinner than the critical value follow the folding process until it culminates with the coalescence and stacking of the folds. By this mechanism the critical thickness is reached and these bodies are prone to suffer a new phase of boudinage similar to that followed by the originally thicker veins. Therefore, all deformed tabular veins, embedded in a ductile matrix, converge to classical shearband boudin morphology, independently from their original thickness.

Key-words: *Folding, asymmetrical boudinage, fold-boudin, synthetic shear planes.*

RESUMEN

La génesis y evolución morfológica inicial de los "boudins" de tipo "shearband" están controlados por mecanismos de plegamiento. En este modelo, el "boudinage" comienza con el plegamiento de cuerpos tabulares (venas) de diferentes espesores, inmersos en una matriz menos competente. Las venas más gruesas exceden un espesor crítico que determina la formación inicial de un pliegue abierto. Posteriormente evoluciona por rotación antitética en relación con la cinemática de la zona de cizalla y por traslación de masa a lo largo de la interfase vena-matriz, conduciendo a la morfología clásica de un "shearband boudin". Por su parte, los cuerpos comparativamente más delgados continúan plegándose hasta que se produce la unión y apilamiento de los flancos de los pliegues ("stacked-folds"). Mediante este proceso se alcanza el espesor crítico necesario para que se desarrolle una nueva fase de "boudinage" similar a la seguida por las venas gruesas.

Palabras clave: *Plegamiento, "boudinage" asimétrico, pliegue-"boudin", planos de cizalla sintéticos.*

Geogaceta, 55 (2014), 15-18.
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 1 de julio de 2013
Fecha de revisión: 22 de octubre de 2013
Fecha de aceptación: 29 de noviembre de 2013

Introduction

A recent boudin definition considers it as a structure resulting from a process of disintegration of layers, bodies or foliation planes within the rock mass as a response to extension throughout the surrounding area (Goscombe *et al*., 2004).

The contribution of the present work is to propose a conceptual model to explain the initial evolution stages of generation of shearband boudins in high-temperature (HT) shear zones affecting migmatitic terranes (the present work is focused on HT shear zones, but similar examples could be found in, e.g. greenschist facies shear zones). The shearband boudin evolution is here conceived as the consequence of an initial folding mechanism, which is supported with real examples from the Malpica-Lamego Ductile Shear Zone (MLDSZ, N of Portugal). MLDSZ extends ca. 275 kilometres with a NW-SE orientation parallel to the trend of the Variscan belt of NW Portugal. In the studied sector is recorded as a high temperature (HT) heterogeneous and progressive, sub-vertical, simple shear zone, with bulk left-lateral kinematics (Pamplona and Rodrigues, 2011b). The point of this contribution is that folds and shearband boudins of the MLDSZ affect surfaces located in the same quadrant of the sectional deformation ellipse. Therefore, the association of shearband boudins and folds is not a consequence of extension in one direction and shortening in other direction (e.g. Xypolias, 2010), and a progressive (time strain partitioning) evolution is invoked instead in this work.

The structural evolution of tabular bodies (veins and dikes) embedded in a less competent matrix in HT, simple shear zones, follows two successive stages: firstly, tabular like bodies are generated or emplaced; secondly, they behave like competent bodies. In these zones, and in migmatitic conditions, three types of tabular bodies with relevance to the analysis of the boudinage process frequently occur: (i) those resulting from crystallization of quartz-feldspar fluids generated by migmatitic diffusion processes; (ii) peraluminous partial melts forming leucosome veins; (iii) granitic dikes. During the deformation process, the viscosity of the host rock of these veins or dikes, considered as a mid-crustal metapelitic rock, falls in the range 10^{18}-10^{19} Pa.s (partial melting of micaschists at 500ºC-700ºC, Davidson *et al*., 1994). The segregation of fluids or melt and emplacement of tabular bodies (migmatitic veins and dikes) represents the generation of a second rheological system initially equivalent to an aluminous-silicate liquid with a viscosity varying from 10^{-4} Pa.s (typical values for fluids in the middle or lower crust; Ague, 2003), to 10^{7}-10^{10} Pa.s (range of viscosities for rhyolitic/dacitic magmas; McBirney, 1984). Therefore, the tabular bodies are generated and emplaced like a mobile viscous liquid, while their host rock is a visco-plastic, comparatively rigid material. However, the viscosity of the veins or dikes increases with their crystallinity. This increase in the effective viscosity of the intrusive fluids and melts produces a reversal in the competence contrast relative to the enclosing host rock (Druguet and Carreras, 2006), achieving the mechanical condition for folding and boudinage of the veins or dikes.

Description of the structures

Several field observations in the MLDSZ, like the presence of shearband boudins and folds affecting parallel surfaces, are difficult to interpret or even paradoxical. These observations constitute by themselves the key-points to the understanding of the boudinage genesis in this type of high-grade shear zones. Moreover, the field evidence obtained in the MLDSZ is the basis to develop a model of boudinage in high temperature shear zones.

The presence of structures indicative of folding and boudinage in adjacent, sub-parallel veins of the MLDSZ merits a detailed description (Fig. 1A). The analysis presented in this work considers the maximum vorticity surface (normal to the shear zone boundaries and parallel to the shear direction). Although it is here considered that this surface contains the basic kinematic information relevant to this simple study, future analysis will consider a more complete 3D evaluation of the shear zone characteristics. The structural information gathered in the MLDSZ shows that boudinaged leucocratic veins (stretched bodies) occur side-by-side with asymmetrically folded leucocratic veins (shortened bodies) in the same observation surface, affecting identical material (from both compositional and rheological points of view), and during the same deformation phase. This feature can be statistically illustrated by computing and representing the angles between the orientation of either the

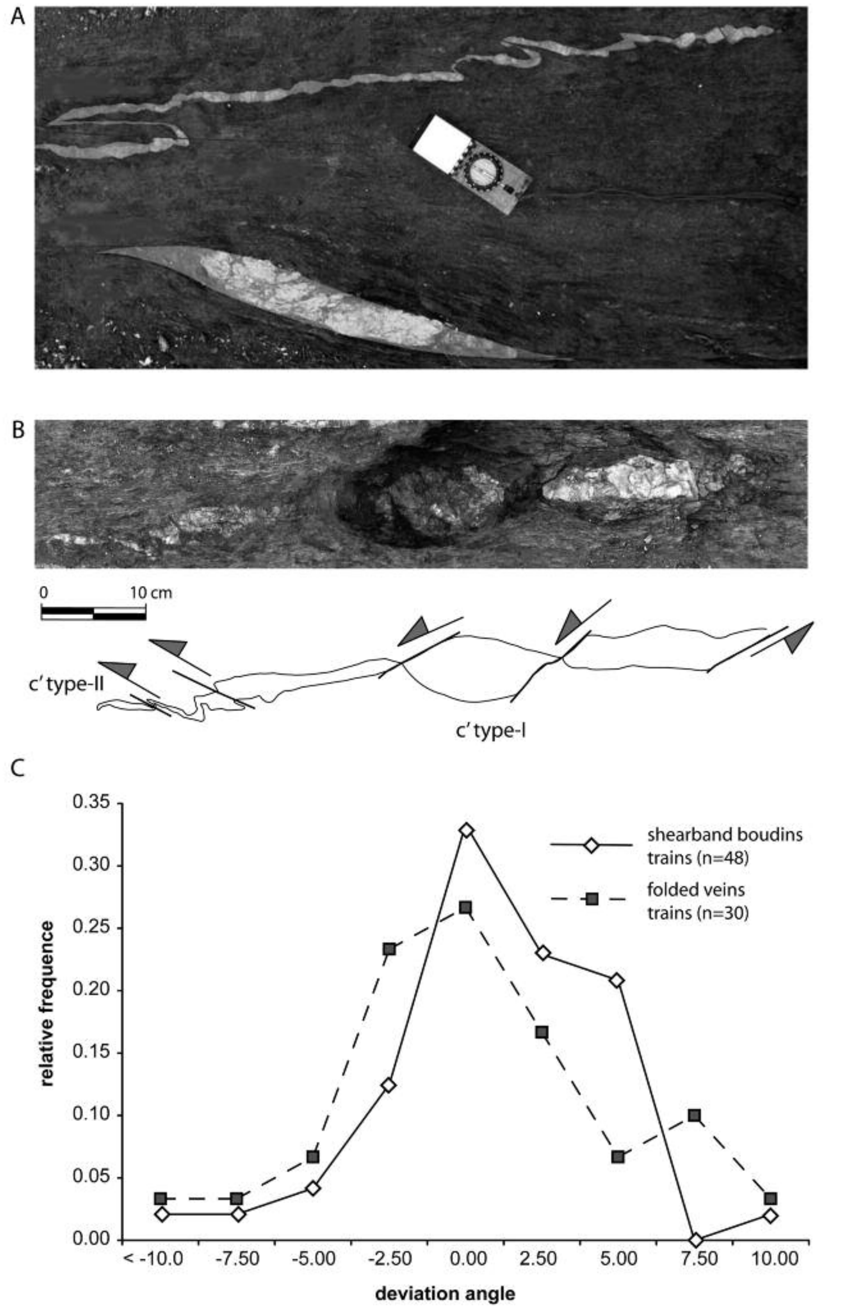

Fig. 1.- Folding and boudinage structures of the MLDSZ: A) In side-by-side bodies (top: folded vein; bottom: shearband boudin); B) In the same body (left: folded vein; right: boudins); C) Histogram with orientations of folded veins trains vs. orientation of shearband boudin trains. The deviation angle corresponds to the angle between the foliation trace and the enveloping surface to the vein or boudin train. Positive values are measured clockwise.

Fig. 1.- Pliegues y "boudins" en la zona de cizalla dúctil de Malpica-Lamego: A) Venas paralelas que muestran pliegues (arriba) y "shearband boudins" (abajo); B) Disposición lateral de pliegues (izquierda) y "boudins" (derecha) en la misma vena; C) Histogramas con las orientaciones de la envolvente de las venas plegadas y de los "shearband boudins". El parámetro "deviation angle" corresponde al ángulo entre la traza de la foliación y la envolvente de las venas deformadas. Se consideran positivos los ángulos medidos en sentido horario.

folded or boudinaged veins and a given datum line (e.g., the foliation trace), measured on planes normal to the shear zone boundary and parallel to the simple-shear direction, which show consistently similar patterns and average directions (Fig. 1C). Even more interesting is the observation that a single vein can show both types of structures without significant changes in strike (Fig. 1B). In all cases, the shear sense indicated by the asymmetrical folds and the shearband boudins are consistently sinistral (Fig. 1).

The most significant geometrical differences between folded veins and shearband boudin veins are, first, the vein thickness and, second, the orientation of shear planes (c´ type-II, Fig. 1B) and axial planes of folded veins relative to that of shear planes (c' type-I, Fig. 1B) of shearband boudins.

Discussion: proposal of a model

The coexistence of cogenetic folding and boudinage in the MLDSZ could be interpreted as the result of a non-coaxial deformation history on veins with distinct initial orientations. However, in the studied outcrops folded and boudinaged veins are sub-parallel, as explained above (Fig. 1A, C). This later feature cannot be interpreted as a result of polyphase deformation according to the regional understanding of this shear zone in the studied sector (Pamplona and Rodrigues, 2011b). The boudin definition by Goscombe *et al*. (2004) implicitly assume that all the processes generating boudins, under all flow types, can be assigned to stretching of the competent layer or vein. Under simple shear flow with the shear plane subparallel to the competent body, simple 2D models only work properly for extremely large values of shear strain (e.g., Llorens *et al*., 2013). On the other hand, super-simple shearing histories (Passchier, 1990) can potentially account for veins suffering first stretching and then shortening (a possible explanation for Fig. 1C), but again this kinematic evolution was not accomplished in the MLDSZ (Pamplona and Rodrigues, 2011b). Other authors (e.g., Druguet *et al*., 2009), have also reported elsewhere the presence in the same vein of folds and boudins. However, as explained above, a remarkable feature in all the observed field cases of the MLDSZ is that folds commonly affect thin veins or vein segments, while thicker veins or vein segments appear boudinaged.

In this case, the first steps of the boudinage evolution can be associated with shor-

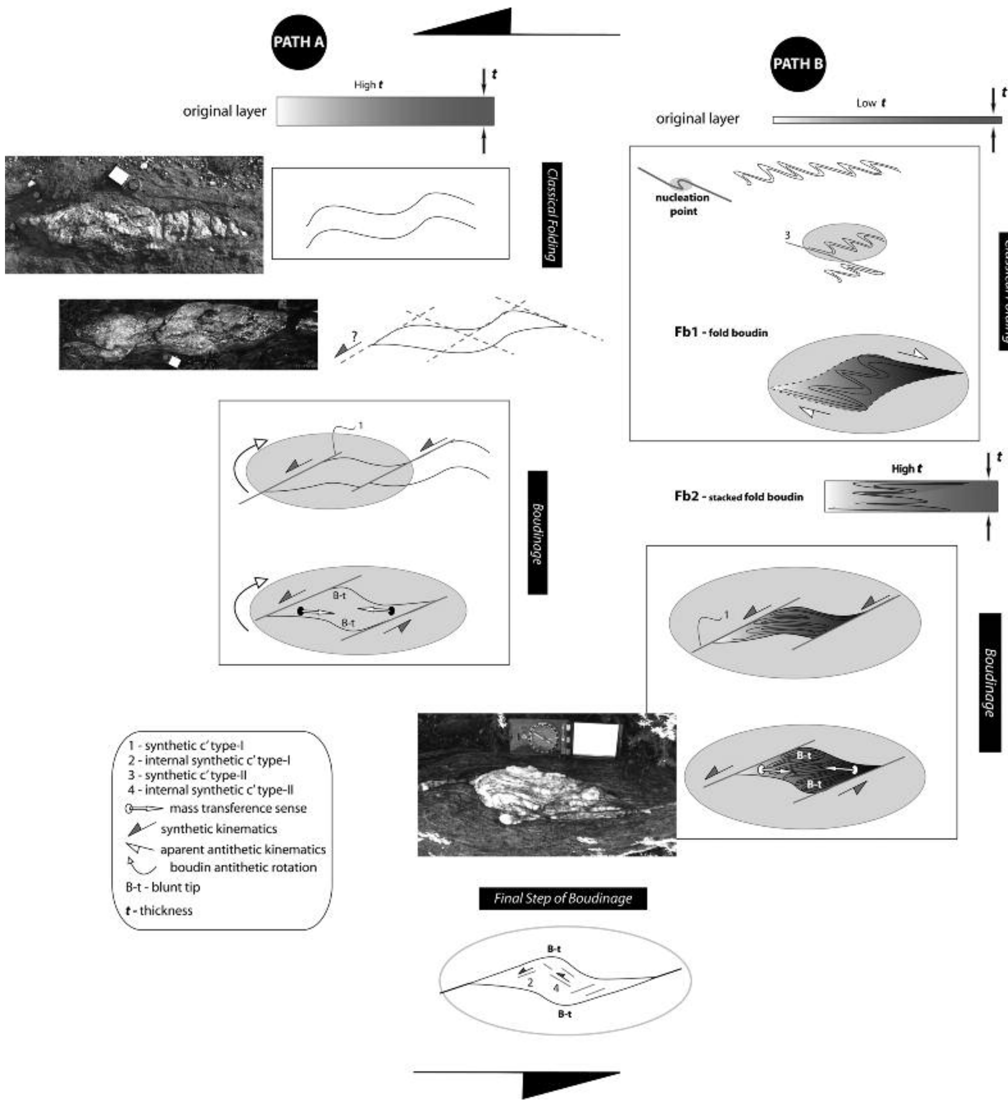

Fig. 2.- Model of shearband boudin evolution on high-temperature simple shear zones: Evolutionary path A (fold – shearband boudin); Evolutionary path B (fold – fold boudin – shearband boudin) – Adapted from Pamplona and Rodrigues (2011a). Structures in both paths evolve from the top to the bottom or their respective columns (path A, left column; path B, right column). The final step is common for both paths. The bulk shear sense is sinistral in both cases, although an apparent dextral shear sense could erroneously be inferred from stage Fb1 of path B.

Fig. 2.- Modelo de evolución de "shearband boudins" en zonas de cizalla simple de alta temperatura: Tipo evolutivo A (pliegue – "shearband boudin"); Tipo evolutivo B (pliegue – pliegue-"boudin" –" shearband boudin") – Modificado de Pamplona y Rodrigues (2011a). Las estructuras en ambos tipos evolucionan desde la parte alta hacia la baja de cada columna (tipo A, columna izquierda; tipo B, columna derecha). La estructura final es común para ambos tipos. El sentido de la cizalla es izquierdo en ambos casos, aunque un movimiento derecho podría ser deducido erróneamente a partir de la geometría resultante del estadio Fb1 del tipo evolutivo B.

Deformation Parameters	Rheological and Matrix Parameters	Strained Body Parameters		Shearband Boudin Characteristics and Field Occurrence
		Critical thickness (*t*) +/- vein thickness (+/- density contrast) (+/- material volume)	➔	Evolution following paths A or B
Bulk strain			➔	Maximum step achieved on the shearband boudin evolution
Variation on incremental strain	Viscosity contrast between boudin/matrix		➔	Statistical variation of occurrence of geometries corresponding to the distinct boudin steps
Finite shear strain or - strain rate ? - vorticity? Strain partitioning			➔	Geometrical parameters of each boudin (Bbs/c', Ψ, L/W, d'/W, etc.)* Symmetrical and asymmetrical boudins

Table I.- Phenomenological framework of shearband boudin genesis: relationship between geological parameters and shearband boudin characteristics. * Parameters of shearband boudins after Pamplona and Rodrigues (2011b).

Table I.- Marco fenomenológico para explicar la génesis de los "shearband boudins": relaciones entre parámetros geológicos y características de los "shearband boudins". * Parámetros de los "shearband boudins" según Pamplona y Rodrigues (2011b).

tening and folding, at least in the studied high-temperature MLDSZ, and shearband boudins should not be interpreted as merely extensional structures. To account for this particular type of unexplained structural features, a new conceptual model is proposed in this work, which is graphically presented at figure 2, with sketches illustrating different steps and ways of boudinage evolution in high-temperature simple shear zones. It is important to stress that this model does not exclude the generation of "classic" shearband boudins (Swanson, 1992) in veins subjected to stretching during the entire deformation history. Stretching of previously folded single layers or multilayers during progressive shear is indeed a possible explanation, although that mechanism gives place to asymmetric folds with a vergence that is opposite to that indicated by the shearband boudins, contrary to what is shown in figure 1.

According to the importance of the vein thickness, folding is conceived here as the bulk process responsible for the initiation of boudinage. In the considered cases, the vein is sub-parallel to the simple-shear plane boundary, although it is locally oriented to fall into the field of infinitesimal shortening. Two possible evolutionary paths (A and B) are proposed here (Fig. 2), which depend on a given critical value of initial thickness (*t*) of the competent layer that will be deformed. This critical thickness is a parameter of unknown mechanical significance, given the essentially phenomenological grounds of the model. For high *t* values (Fig. 2, path A), a segment of the vein suffers nucleation of folds with relatively large wavelength. For a sinistral shear zone, the clockwise-rotated limbs enter the field of infinitesimal stretching favoring migration of material towards the incipient hinges, while the counter-clockwise-rotated limbs are kinematically prone to nucleate synthetic c' type-I shear planes. The system quickly evolves towards typical shearband boudin geometries.

For low *t* values (Fig. 2, path B), the early folding develops a train of closed folds in the vein segment, with relatively small wavelength. Synthetic c' type II shear zones contribute to thicken the folded package. The result is a new tabular body, with a complex, internal structure, that exceeds the critical thickness. In some cases, this thickened body is able to follow a last evolutionary stage similar to that shown in figure 2. The presence in the MLDSZ of local shearband boudins with a folded internal structure supports this last interpretation.

The proposed model (Fig. 2) explains the evolution from tabular bodies up to classical shearband boudins, which includes all the boudin geometries identified at the MLDSZ. A set of parameters can be proposed to geometrically and mechanically characterize the field examples. The determination of these parameters is essential for assigning the analyzed shearband boudin to a given evolutionary path and step. Additionally, these parameters can be used as kinematic arguments of finite strain gauges. Four groups of parameters associated with the initial morphology of the veins, as well as the rheological and deformational behavior of the vein-matrix system (Table I), control the geometrical characteristics and evolutionary state of shearband boudins. Some of these relations are qualitatively shown in this work (i.e., evolution following paths A or B based on the initial or acquired thickness of the competent body), and others need still to be checked against natural examples (e.g., the validity of some geometrical parameters of the shearband boudins as deformation markers). In any case, the model proposed here requires further validation based on the analysis of new natural cases (particularly in low- to medium-grade metamorphic terranes), experimental work and numerical modelling. The significance and exact values of the critical thickness should also be clarified.

Acknowledgments

JP is supported by the national budget of the Portuguese Republic through FCT under the project PEst-OE/CTE/UI0697/2011. CF acknowledges support from the project CGL2010-22022-CO2-01 of the Spanish Ministry of Science and Innovation. Careful and constructive reviews by Jordi Carreras, Rui Dias and Andrés Gil-Imaz are gratefully acknowledged.

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