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

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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.

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 (Pamploña 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 1018-1019 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 $10^2$-$10^{10}$ Pa.s (range of viscosities for rhyolitic/dacitic magmas; Mc Birney, 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 asymmetrical 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 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 latter 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., Druget 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-

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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).

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References


