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Geometry of torn boudin–An indicator of relative viscosity

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ABSTRACT

The present study determines the role of viscosity on the development of rectangular torn boudin and its various types, defined by the curvature of their exterior and face margins. Numerical modeling was performed with the help of Finite Element Method considering Maxwell visco-elastic materials in commercial code ANSYS. Seven different viscosities were used and interchanged among the boudin, inter-boudin and matrix materials to understand the effect of viscosity ratios, specifically of relative viscosity of inter-boudin material. Results show that the viscosity of inter-boudin material has significant control on the shape of torn boudins apart from the viscosity ratio of boudin to matrix material. Bone-shaped boudin develops only when the inter-boudin is more competent than boudin and it becomes more prominent when matrix is also competent than boudin, but incompetent than inter-boudin. When boudins are stiffer than inter-boudin, barrel-shaped and fish-head boudins with concave faces develop. Exterior or face margins remain almost straight when boudin is relatively rigid compared to its surrounding matrix materials, or when there is no or very little viscosity contrast between boudin and inter-boudin material even in case of large boudin-matrix viscosity contrast. Therefore, the relative viscosity among the boudin, inter-boudin and matrix materials can be estimated qualitatively by studying the shape of boudin in the field.

1. Introduction

Boudinage structures are common features in deformed layered rocks, especially with contrasting rheologies, forming under layer parallel extension. These structures are often used to estimate finite strain in deformed rocks. The shape of an individual boudin object, defined by the geometry of outer margins in profile section, is also very useful for determining the modes of fracture and the rheological contrast of the boudinaged layers with respect to the embedding medium (Treagus et al., 1996; Marques et al., 2012; Abe and Urai, 2012). In nature, varieties of boudin geometries are observed which are controlled by the competence contrast between layer and the embedding host materials, the type of deformation, pre-to post-boudinage plastic deformation (Ramberg, 1955; Wilson, 1961; Ramsay, 1967; Strömgård, 1973; Ghosh and Ramberg, 1976; Lloyd and Ferguson, 1981; Treagus et al., 1996; Ghosh and Sengupta, 1999; Treagus and Lan, 2000, 2004; Passchier et al., 2005; Maeder et al., 2009; Fossen, 2010; Samanta and Deb, 2014) and also by the angular relationships between the layer and the deformation (kinematic) axes (Goldstein, 1988; Passchier and Druguet, 2002).

In nature, after fragmentation of stiffer layer, the inter-boudin zones are commonly filled either by host material or by siliceous or calcareous material which behave softer than boudin or/and matrix in geological condition. During subsequent deformation in presence of inter-boudin material, the rectangular boudin may gradually change resulting in boudins with concave faces, and bi-convex exteriors, forming ‘barrel-shaped’ boudins (Lloyd and Ferguson, 1981), ‘extreme barrel-shaped’ boudins (Lloyd et al., 1982), ‘fish-mouth’ or ‘false-isocline’ boudins (DePaor et al., 1991; Swanson, 1992), ‘fish-head’ boudins (Wegmann, 1932; Ghosh and Sengupta, 1999). In such situation, the compositions of boudin, inter-boudin and matrix may also change due to metamorphism, migmatization or fluid-rock chemical reactions (Ray et al., 2011), which lead to a change in their relative viscosities. As a result of that boudin may even behave incompetently with respect to both matrix and inter-boudin materials resulting in ‘bone-shaped’ boudin with concave exterior margins and straight or little convex face margins (Malavielle and Lacassin, 1988; Swanson, 1992). The effects of such rheological changes on the development of sequential boudins are reported from nature (Ghosh and Sengupta, 1999; Ray et al., 2011) and are also simulated in analogue and numerical modeling (Druguet and Carreras, 2006; Samanta and Deb, 2014). However, similar kinds of structures may also form in nature during subsequent layer-parallel shortening or extension of single layer that is segmented by layer perpendicular veins (whether formed by the process of boudinage or by the process of hydraulic fracturing) stiffer than host rock. They are described as shortened torn boudins (‘double-sided mullions’ or ‘extreme

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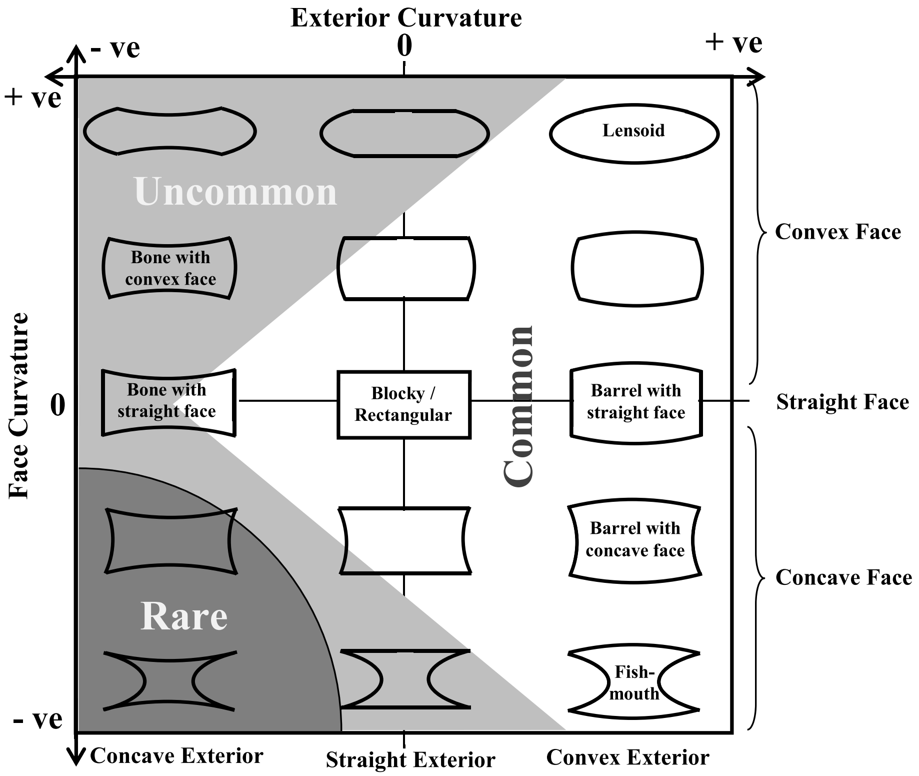

Fig. 1. Types of torn boudin and their positions with respect to their face and exterior curvature (redrawn from Goscombe et al., 2004). +ve and –ve indicate the convex and concave curvature respectively.

convex surface') and bone-shaped structures ('dog-bones' or 'trapezoidal boudins') (Kenis et al., 2002; Goscombe et al., 2004).

Torn boudin is described as symmetric boudin formed due to segmentation of layer by high angle, sharp, apparently 'brittle' planes of failure. Although, classical torn boudin is angular- and blocky-shaped with parallel edges, they often deform internally after fragmentation resulting in objects with curved exterior or face margins (Fig. 1). Goscombe et al. (2004) divided the torn boudins into straight-face and concave-face boudins as per the natural evidences from a wide variety of geological contexts worldwide. Straight-face boudins are sub-divided into blocky boudins (parallel margins), bone-type boudins (concave exterior margins) and straight-face with vein infill boudins. Blocky boudins are also described as rectangular or extension fracture or rectilinear boudins where the faces are aligned at a high angle and typically orthogonal to the boudinaged layer (Lloyd and Ferguson, 1981; Lloyd et al., 1982; DePaor et al., 1991; Mandal et al., 2000; Zulauf et al., 2009). Concave face boudins are sub-divided into bow-tie vein boudins and barrel boudins, where latter transforms to fish-mouth or fish-head or lensoid-shaped boudins with increasing finite strain. This classification is presented on the basis of the sense and amount of curvature of boudin's exterior and face margins, which may be straight, convex or concave in shape (Fig. 2). In this classification, shape of barrel and bow-tie boudin is same except the geometry of the inter-boudin, whereas geometries of blocky and straight-face with vein infill boudins are also identical except the absence and presence of inter-boudin respectively. Therefore, all symmetric boudins with combinations of straight, convex and concave margins are considered as torn boudins in the present study. Although all types of torn boudins are not very common, the concave-face boudins are observed frequently in nature. The torn boudin with convex face is rarely found in nature (less than 5% of investigated torn boudins of Goscombe et al., 2004). In such case, the amount of convexity is very less.

Shapes of boudinage structures and their progressive development have been subject of research over the last few decades. Stress and displacement analysis of boudinage and their influence on the shapes of boudins was first investigated by Selkman (1978). Lloyd and Ferguson (1981) performed series of numerical experiments considering elastic-plastic rheology to reveal the effects of material properties and amount of deformation on boudin shape. Treagus et al. (1996) and Treagus and Lan (2000) thoroughly investigated the effect of viscosity ratio of object to matrix considering both as Newtonian fluids. They showed that an isolated square object deforms to a 'barrel-shape' and 'bone-shape' if its viscosity is greater and lesser than the viscosity of the embedding medium respectively. The study was also extended to objects of power-law rheology with different values of power-law stress exponent (Treagus and Lan, 2004). However, their models do not exactly replicate natural situation where square or rectangular objects (boudins) are arranged in a row separated by inter-boudin areas of different material. Later, Kenis et al. (2006) simulated various bone- and barrel-shaped objects in Finite Element Method (FEM) analysis considering volume-constant steady-state power-law creep rheology by changing viscosity ratio between host and vein-infill material, initial aspect ratio of host-rock segments between two veins and the amount of finite deformation. In spite of quite a lot of studies on this subject, there is no such work considering the effect of relative viscosity of inter-boudin on the shape of torn boudin. The present work is intended to reveal the role of viscosity ratios among boudin, matrix and specially the inter-boudin materials on the post-fracture evolution of rectangular torn boudin, aiming to utilize their geometry for estimating the relative viscosities among boudin, inter-boudin and matrix. With the help of 2-D finite element modeling, we demonstrate that a boudin object, surrounded by a matrix and inter-boudin material of contrasting viscosity, is modified to objects of various shapes with curved margins under pure shear condition resulting from the mutual interaction of material flow within boudin, inter-boudin and matrix regions.

2. FEM modeling

2.1. Model considerations

Progressive development of torn boudin is a very complex process which is influenced by several independent parameters like aspect ratio