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Formation of chocolate-tablet boudins: Results from scaled analogue models

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ABSTRACT

We used power-law viscous plasticine as a rock analogue to simulate chocolate tablet boudinage of rocks undergoing dislocation creep. A competent plasticine layer, oriented perpendicular to the main shortening direction, *Z*, underwent two phases of plane strain in a weaker plasticine matrix, with the principal stretching axis, *X*, and the axis of no-change, *Y*, replacing each other from the first to the second phase. In each phase of plane strain, boudinage was controlled by an initial phase of viscous necking followed by extension fracture along the neck domain. Increase in the magnitude of finite strain (e) and decrease in layer thickness (H_i) result in a decrease in the boudin width (W_a) and an increase in the number of boudins (N). Given the viscosity ratio between layer and matrix (m) is higher than ca. 5, the number of boudins decreases and the boudin width increases with increasing values of m. An unexpected result of the present study is that in each experiment, the number of boudins was significantly higher during the second phase of plane strain. This difference should be related to additional drag of the matrix plasticine on the stiff layer in the neck domains formed during the first phase of boudinage. The aspect ratio of the second generation of boudins ($W_d = W_a/H_i$) is compatible with aspect ratios of natural boudins and with aspect ratios calculated using analytical solutions.

1. Introduction

Boudinage is a deformation process where a competent layer embedded in an incompetent material is segmented as a result of stretching parallel to the layer. The geometry of boudins is one of a complete spectrum of geometries from isolated rectangular blocks (*torn boudins* of Goscombe et al., 2003) to a regular thickening and thinning of the competent layer known as pinch-and-swell structure (*drawn boudins* of Goscombe et al., 2003). This spectrum results from a range of rheological behavior of the competent layer from brittle, when tensile fracture occurs, to ductile, when 'failure' occurs by localized necking (Abe and Urai, 2012). Most studies of boudins are restricted to in-plane stretching of the competent layer under bulk plane strain. Boudinage, however, is also possible in three-dimensional strain fields like bulk constriction or bulk flattening (Ghosh, 1988; Zulauf et al., 2003; 2011a,b; 2012).

Wegmann (1932) found non-cylindrical boudinage where two perpendicular sets of boudin necks occur. He termed such boudins with rectangular plan-view *chocolate tablet structure*. Similar structures are described from natural rocks deformed in various conditions for different tectonic settings on Earth (Ramberg, 1955; Coe, 1959; Fyson, 1962; Ramsay, 1967; Schwerdtner and Clark, 1967; Crespo-Blanc, 1995; Casey et al., 1983; Tricart et al., 2004; Reber et al., 2010; Zulauf et al., 2011c; Marques et al., 2012) and from the Meshkenet Tessera on Venus (Raitala, 1996). Chocolate-tablet boudins are frequently well developed in competent pyrite-rich layers of diagenetic origin contained in incompetent sediments (Casey et al., 1983; Ramsay and Huber, 1983: Figs. 13.29 and 13.30).

In former times, chocolate-tablet boudinage was generally assumed to be characteristic for oblate deformations where the principal shortening axis, *Z*, is perpendicular to the boudinaged layer (e.g. Weijermars, 1997, p. 250; Zulauf et al., 2003). However, if the boudins arise *during a single oblate deformation*, their necks should be generally rather irregular, or mostly radial as has been confirmed experimentally using rock analogues (Ghosh, 1988; Zulauf, 2004; Zulauf et al., 2011b) and rock-salt/anhydrite samples (Zulauf et al., 2011a). These experiments have shown that boudinage for a flattening bulk strain with equal layer-parallel extension in all directions leads to the development of roundish or polygonal boudins in plan-view, referred to as *tablet boudins*.

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Table 1
Geometrical and rheological parameters related to the experiments of the present study. Variable parameters shown in yellow.

Series	Sample	Sample dimension [mm]	Stress exponent layer n_L	Stress exponent matrix n_M	Viscosity layer η_L [Pa s]	Viscosity matrix η_M [Pa s]	Viscosity contrast m	Strain $e_{X(A)}$ [%]	Strain $e_{X(B)}$ [%]	Initial layer thickness H_i [mm]	Final layer thickness $H_{f(A)}$ [mm]	2σ	Final layer thickness $H_{f(B)}$ [mm]	2σ	Number of boudins $N_{(A)}$	2σ	Number of boudins $N_{(B)}$	2σ	Boudin width $W_{a(A)}$ [mm]	2σ	Boudin width $W_{a(B)}$ [mm]	2σ	Aspect ratio $W_{d(A)}$	2σ	Aspect ratio $W_{d(B)}$	2σ	theoretical aspect ratio L_d
1	1/1	120x120x120	7	7	9.4×10^6	2.1×10^6	4.6	20		1.5	1.6	0.3			10	2			9.8	6.8			6.6	4.5			4.1
									20				1.7	0.2			14	2			6.8	3.2			4.5	2.1	4.1
	1/2	120x120x120						20		2.5	2.7	0.3			5	2			20.3	14.0			8.1	5.6			4.1
									20				2.8	0.2			9	2			9.3	4.0			3.7	1.6	4.1
	1/3	120x120x120						20		3.5	4.0	0.3			2	1			32.3	18.0			9.2	5.1			4.1
									20				4.1	0.3			5	1			17.2	8.0			4.9	2.3	4.1
	1/4	120x120x120						20		4.5	5.1	0.2			3	1			34.4	18.0			7.6	4.0			4.1
									20				5.0	0.4			4	1			21.4	9.6			4.8	2.1	4.1
2	2	120x120x120	7	7	9.4×10^6	2.1×10^6	4.6	5		1.5	1.9	0.2			3	1			12.0	2.0			8.0	1.3			4.1
								10		1.9	1.9	0.2			4	1			10.0	5.0			5.3	2.6			4.1
								15		1.9	2.0	0.1			7	1			9.0	5.0			4.7	2.6			4.1
								20		2.0	2.0	0.2			10	2			8.0	4.0			4.0	2.0			4.1
									5	2.0			2.0	0.3			9	1			9.0	4.0			4.5	2.0	4.1
									10	2.0			2.1	0.2			13	2			8.0	5.0			4.0	2.5	4.1
									15	2.1			2.0	0.2			18	2			5.0	3.0			2.4	1.5	4.1
									20	2.0			2.1	0.1			19	2			4.0	2.0			2.0	0.9	4.1
3	3/1	120x120x120	6	7	2.8×10^6	1.7×10^6	2.0	20		1.5	1.5	0.2	1.5	0.1	2	1			–				–				
									20								9	2			10.8	8.0			7.2	5.3	3.1
	3/2	150x150x150	7	7	9.4×10^6	2.1×10^6	4.6	20		1.6	2.1	0.1	2.3	0.2	8	1			14.5	8.0			9.3	5.2			4.1
									20								17	3			5.5	4.0			3.6	2.6	4.1
	3/3	100x100x100	6	9	2.2×10^7	2.3×10^6	9.7	20		1.8	2.4	0.2	2.3	0.2	4	1			15.0	7.0			8.3	3.9			5.8
									20								5	1			11.9	7.0			6.6	3.9	5.8
	3/4	120x120x120	6	7	2.2×10^7	1.7×10^6	13.0	20		1.5	1.9	0.2	1.9	0.3	3	1			–				–				6.1
									20								7	1			11.4	7.0			7.6	4.7	6.1

Chocolate-tablet boudins, on the other hand, should develop as a result of *polyphase deformation* or could be controlled by a *mechanical anisotropy in lineated rocks* (Ramsay and Huber, 1983, p. 65; Ghosh, 1988; Reber et al., 2010; Zulauf et al., 2011c; Marques et al., 2012). In the present study, we examine the formation of chocolate-tablet boudins using plasticine as rock analogue. It will be shown that chocolate tablet boudins develop during two-phase plane-strain deformation with the orientation of the principal shortening axis, Z, being constant in orientation (perpendicular to the layer), whereas the principal stretching axis, X, and the axis of no-change, Y, are parallel to the layer and replacing each other from increment to increment.

2. Experimental procedure and analytical techniques

a) Material and models

The rock analogues used for the experiments consist of plasticine, which behaves as a strain-rate softening material, meaning that the effective viscsosity decreases with increasing strain rate. The rheological parameters of the different kinds of plasticine used in the experiments are based on uniaxial compression tests of previous investigations (for details concerning composition, rheological properties and supplier, see Zulauf and Zulauf, 2004, and below). The initial samples of the rock analogues were in most cases cubes with maximum model dimensions of 15 × 15 × 15 cm (Table 1). Three sets of experiments have been carried out at a temperature, T, of 25 °C and a constant strain rate, $\dot{e}$, of around $5 * 10^{-4}\ s^{-1}$. To make the deformation procedure clear to the reader, we introduced sample co-ordinates, with A- and B-axes oriented parallel to the competent layer, and the C-axis oriented perpendicular to the layer (Fig. 1). The principal directions of finite strain are labelled as $X > Y > Z$. The experiments were carried out under plane strain, meaning that the length of the Y-axis did not change ($e_Y = 0$). In each experiment, the C-axis was parallel to the principal shortening axis, Z, whereas the orientation of the A- and B- axis was changed with respect to the Y- and X-axis. A-type boudins developed if $A//X$, whereas B-type boudins developed if $B//X$ (Fig. 1).

In a *first series of experiments* we investigated the influence of the layer thickness, H_i, on the deformation geometry. H_i was set at 1.5 mm, 2.5 mm, 3.5 mm and 4.5 mm. The uncertainty of the layer thickness is ±0.1 mm. To produce a chocolate tablet structure, each sample underwent a two-phase plane-strain deformation. During the first increment (D_A), the A- and B-axis of the sample were oriented parallel to the X- and Y-axis, respectively. During the second increment (D_B), the A- and B-axis were exchanged and oriented parallel to Y- and X-axis, respectively. In both deformation increments the amount of stretching along the A-axis, $e_{X(A)}$ and along the B-axis, $e_{X(B)}$, was 20%. After having imposed the respective incremental strain, the sample was removed from the deformation apparatus and analyzed using computer tomography (CT), as described below.

The experiments were carried out using Beck's orange plasticine, mixed with 100 ml oil/kg, for the matrix, and Kolb brown plasticine, mixed with 50 ml oil/kg, for the stiff layer. Adding oil to these plasticine resulted in a reduction of the viscosity and in a change of the stress exponent. In the present case, the viscosity (η) and the stress exponent (n) for layer and matrix had been determined at $9.4 * 10^6$ Pa s and 7, respectively, and 2.1×10^6 Pa s and 7, respectively (Zulauf and Zulauf, 2004), resulting in a viscosity ratio (m) of 4.6 (Table 1).

A *second series of experiments* was carried out to investigate the impact of incremental plane strain on the deformation geometry of the stiff layer, using an initial thickness of the competent layer of 1.5 ± 0.1 mm. The deformation ceased after strain increments of $e_{X(A)}$ and $e_{X(B)} = 5\%$ until a final strain of 20% was obtained in each direction (Table 1). After having imposed the respective incremental strain, the sample was removed from the deformation apparatus and analyzed using computer tomography (CT), as described below. The material used for the incremental experiment was the same as described above from the first series.

A *third series of experiments* was focusing on the influence of the viscosity contrast, m, on the geometry of the deformed layer. The m-values used are 2.0, 4.6, 9.7, and 13.0 (Table 1). The different viscosity contrasts were obtained by adding different amounts of medical white oil to the Beck's orange plasticine. Moreover, pure Kolb brown plasticine, without added oil, was used as stiff layer. To obtain a very low viscosity ratio of only 2, the matrix consisted of Beck's orange +125 ml oil/kg ($\eta = 1.7 \times 10^6$ Pa s). A viscosity ratio of 4.6 was given using the plasticine types described above in