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Brittle and ductile deformation around partially melted stepped dykes: insights from analogue modelling

Deformación frágil y dúctil alrededor de diques escalonados parcialmente fundidos: apreciación mediante modelización analógica

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ABSTRACT

We present the analysis of two analog modelling experiments that studied the processes related to deformation in syntectonic "en echelon" dykes. The analogue materials used are white plasticine for the brittle-ductile host rock, and partially molten chocolate couverture for the melted dykes. The results show the highly heterogeneous distribution of strain around the deforming dykes due to the strong competence contrast between the materials. Dykes stretch and rotate at a higher rate than the host material. The higher strain is concentrated at the tips and the outer margins of the dyke, where shear zones localize. New fractures grow and propagate across dyke overlapping zones. The differences in the initiation and evolution of ductile and brittle structures between the two experiments are related to the initial arrangement of the dyke system (within the shortening or the extensional strain field). This work gives insight into the relations between structures found in syntectonic dykes and the process and conditions responsible for it developing in nature.

Key-words: *Analog modeling, deformation, dykes, rheology.*

RESUMEN

Presentamos el análisis de dos experimentos realizados mediante modelización analógica para el estudio de procesos de deformación en diques sintectónicos dispuestos "en echelon". Los materiales analógicos utilizados son plastilina blanca para el encajante frágil-dúctil, y cobertura de chocolate parcialmente fundida para los diques. Los resultados muestran una distribución de la deformación altamente heterogénea alrededor de los diques debido al gran contraste de competencias entre los materiales. Los diques se elongan y rotan a una tasa mayor que el encajante. La mayor deformación se concentra en las puntas y en los márgenes exteriores de los diques, donde se localizan cizallas. Crecen nuevas fracturas y se propagan a través de las zonas de solapamiento entre los diques. La diferente evolución de las estructuras en ambos experimentos se debe a la orientación inicial del sistema escalonado de diques (dentro del campo de esfuerzos de acortamiento o extensional). Este trabajo muestra las relaciones entre las estructuras asociadas a diques sintectónicos y el proceso y condiciones necesarios para su desarrollo en la naturaleza.

Palabras clave: *Modelo analógico, deformación, diques, reología.*

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Introduction

Syntectonic magmatic dykes are important geological structures because they carry information on many aspects of magmatic and tectonic processes. They are present at all crustal levels and scales and under different tectonic regimes, and are useful to recognize the interaction between deformation processes and emplacement of magmas (Petford *et al*., 2000).

At mid- to lower crustal domains where ductile conditions prevail, hydrofracturing produces an episodic embrittlement of the wall rocks, and dykes intrude at dilation sites (Davidson *et al.,* 1994; Brown and Solar, 1998). Until full crystallization, brittle and ductile processes can operate simultaneously in the dyke-wall rock system. After dyke emplacement, the system recovers the original overall ductile behavior, and veins or dykes and their host rocks deform depending on their relative competences. It is interesting to note that at these latest stages of solid-state ductile behavior, mafic dykes may keep an incompetent behavior compared to the host rocks, developing a characteristic internal foliation (Gayer *et al*., 1978; Talbot and Sokoutis, 1995). To date, little attention has been paid to these complex magmatic-tectonic interactions in terms of modelling (e.g., Grujic and Mancktelow, 1998; Galland *et al*., 2003; Druguet and Carreras, 2006), compared to the more abundant literature on fracture and dyke propagation along elastic media (e.g., Spence *et al.,* 1987; Lister and Kerr, 1991; Maccaferri *et al.,* 2010).

Here we present some preliminary results of analogue modelling experiments on the deformation of syntectonic "en echelon" or stepped dykes, which represent a particular but very common geometry in nature (e.g., Ehlers and Ehlers, 1977; Nicholson and Pollard, 1985; Martínez-Poza *et al*., 2014; Fig. 1). We analyze the deformation processes occurred during the variable time period when dykes are not fully crystallized

Fig. 1. – Examples of "en echelon" mafic dykes. A) Independence Dyke Swarm (California, USA). Notice the effects of superimposed ductile strain (foliations and shearing). B) Aiguablava dyke swarm (Costa Brava, Girona). C) SE Sardinia dyke swarm (Italy).

Fig. 1.- Ejemplos de diques máficos "en echelon". A) Enjambre de diques Independence (California, EEUU). Nótese los efectos de la deformación dúctil sobreimpuesta (foliación y cizallas). B) Enjambre de diques de Aiguablava (Costa Brava, Girona). C) Enjambre de diques al SE de Cerdeña (Italia).

and thus are less competent than the ductile host rock.

Experimental setting

Two experiments were performed using the deformation apparatus BCN-stage (Univ. Autònoma de Barcelona). Several previous works have experimentally studied the deformation around molten bodies in the same deformation Stage (Druguet and Carreras, 2006; Bons *et al*., 2008; Druguet and Castaño, 2010).

The two models differ in the initial arrangement of the dyke system, within the shortening strain field in Exp. 16.03 (Figs. 2A, B and C) and extensional strain field in Exp. 16.04 (Figs. 2D, E and F). All the other geometric and deformation parameters remained constant in both models.

The analogue materials used for the experiments are white plasticine (from *Oclu-Plast S.A.*, with an effective viscosity ~10^7 Pa.s.), simulating the brittle-ductile host rock, and partially molten couverture chocolate (*Nestlé, S.A.*, with viscosity ranging from <100 Pa.s. and <10^7 Pa.s. at the experimental temperatures of 30-26 °C) as analogue for the melted dykes.

These are the same materials previously used in the experimental works by Druguet and Carreras (2006) and Druguet and Castaño (2010). Pairs of overlapping stepped elongated cavities displayed at 40° to the shortening Z axis of the BCN-Stage were filled with chocolate molten at 35-40 °C. As the dyke system arrangement vary from one to the other experiment, the resulting spacing between the chocolate filled dykes and the sides of the deformation cell are different in the two experiments (Figs. 2A and D).

Deformation conditions were those of pure shear at a fixed strain rate of 2.5 x 10^{-5}, with an initial room temperature of 25 °C. The duration of the experiments was around 7:00-7:30 hours, which represents almost a 50% bulk shortening along Z axis. During the experiments the temperature was eventually raised to maintain the viscosity of chocolate lower than that of the plasticine matrix.

Model analysis

Photographs of the upper surface of the models were taken with 10 min. interval, allowing us to record the deformation sequence of each model. Two main analyses of the different deformation steps were made after conducting the experiments.

The first approach was a contour analysis of strain intensity, by measuring the axial ratio R_{XZ} (X=long axis and Z=short axis of ellipses that resulted from deforming the circles drawn in the upper surface at the onset of the experiments, Fig. 2A and D). Although graphite pencil shavings had been disseminated on top of the chocolate dykes, these were not useful to analyze strain within dykes, since graphite markers tended to clump together. The strain contours were made for a ~25% bulk shortening stage (Figs. 2G and I) and for the final stage of ~50% bulk shortening (Fig. 2H and J).

A second analysis consisted of drawing continuous X axis traces by extrapolating the long axes of the elliptic markers in the plasticine. This was also performed for

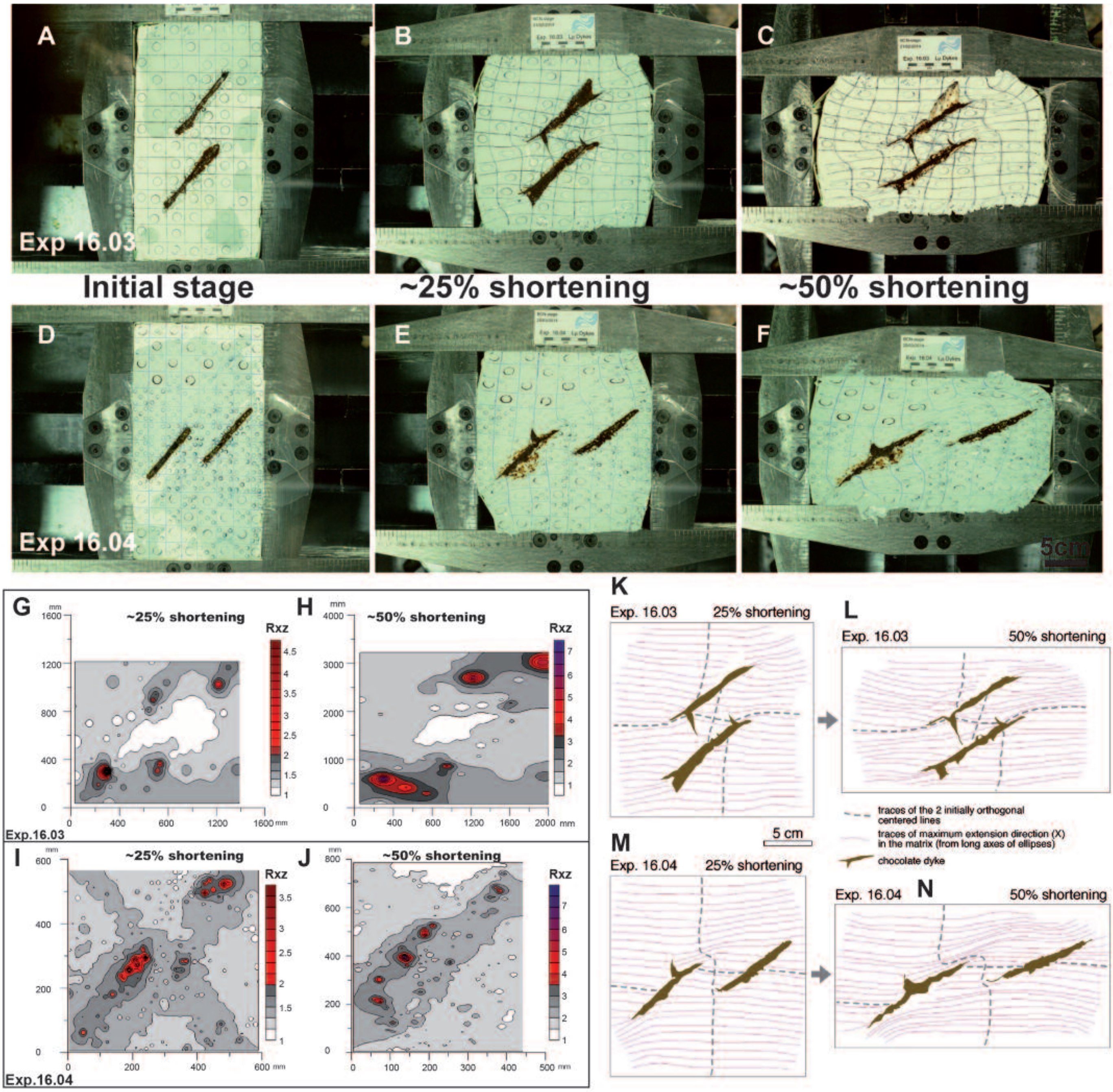

Fig. 2.- A), B) and C) experiment 16.03 setting. D), E) and F) experiment 16.04 setting. G), H), I) and J) contour analysis of R_{xz} for both experiments at ~25% and ~50% shortening. K), L), M) and N) X traces analysis for both experiments at ~25% and ~50% shortening.

Fig. 2.- A), B) y C) configuración del experimento 16.03. D), E) y F) configuración del experimento 16.04. G), H), I) y J) análisis de contornos de R_{xz} para ambos experimentos al ~25% y ~50% de acortamiento. K), L), M) y N) análisis de trazas de X para ambos experimentos al ~25% y ~50% de acortamiento.

the ~25% and ~50% bulk shortening stages (Fig. 2K, L, M and N), allowing us to achieve how deformation was accommodated in the matrix around the deforming dykes.

Finally, stretch and rotation of dykes and growth and development of new fractures in the plasticine were directly analyzed from the photographs of the upper surfaces.

Results

The performed analyses show the highly heterogeneous distribution of strain around the deforming dykes in both experiments 16.03 and 16.04 (Fig. 2). This occurs because of the strong competence contrast between the melted chocolate, which made little resistance to deformation, and the brittle-ductile plasticine matrix.

Dykes stretch and rotate at a higher rate than the matrix, leaving a strain shadow in the central part between the two dykes, which is almost free of strain in Exp. 16.03. On the contrary, strain is mostly concentrated at the tips of the dykes and, in the case of Exp. 16.04, also along the outer dyke margins, where the most prominent ductile shear zones develop. Values of $R_{XZ} > 7$ are recorded in these higher strain zones.

Thus, deformation is localized around dykes, whose longitudinal stretching and clockwise rotation is accommodated by the matrix in the form of ductile deflections and sinistral shear zones. This feature is very common in dykes-host rock systems deformed under ductile conditions in mid- to lower crustal domains (Fig. 1B). The strain shadow between the two dykes in Exp. 16.03 suffers rigid body rotation synthetic to rotation of the dykes (see the traces of the 2 initially orthogonal lines in Fig. 2K, L), whereas in Exp. 16.04, the central part is relatively more deformed, developing into a lozenge-shaped body surrounded by the shear zones. These significant differences in the structural evolution of the two models are due to the variation in the initial arrangement of the dyke system (within the shortening or the extensional strain field).

Moreover, initial arrangement of the dike system is also the main reason for differences in the evolution of the dyke-fractures themselves. The initial arrangement of dyke system in Exp. 16.03 (displaying a shortening strain field arrangement) leads to a drastic increase in dyke overlapping with progressive deformation, generating a local stress state favorable to the development of new fractures in the plasticine. These fractures are perpendicular to the dykes long axes and progressively propagate and become filled with the partially molten chocolate. One of these horn-like structures almost connects the two dykes with the other, forming a bridge in the central, overlapping area, a feature that resembles many natural structures in dykes (see e.g. Fig. 1).

On the contrary, in the Exp. 16.04(displaying an extensional strain field arrangement), dyke stretching led to a mutual separation between the dykes, and to the disappearance of the former dyke overlapping feature. The only new fracture opened in the model is in the outer part of the dyke, so no connection between the two dykes was possible.

Conclusions

This work allowed us to find the connection between a structure commonly found in syntectonic dykes and the process and variables responsible for its presence in the nature.

Despite some limitation of the experimental modelling, such as the boundary conditions effect and the absence of fluid/magma (chocolate in the experiments) pressure, information is gained on the main controls on the development of deformed stepped dykes. Deformation is localized at the dyke tips and margins, with development of deflections and zones of high strain (shear zones). This ductile behavior can be simultaneous to brittle deformation associated to the presence of a molten phase. The patterns of both ductile and brittle structures depend on the initial arrangement of the stepped dykes with regard to the imposed boundary conditions.

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