

Analogue modelling of non-cylindric fold-and-thrust belt around diapirs: preliminary results

Modelos analógicos de un cinturón no cilíndrico de pliegues y cabalgamientos alrededor de diapiros: resultados preliminares

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RESUMEN

Los modelos analógicos representan una herramienta muy útil para investigar el desarrollo progresivo de cinturones de pliegues y cabalgamientos. En este artículo, se presentan resultados preliminares de una serie de modelos realizados para estudiar el patrón estructural, alrededor de diapiros, de estructuras compresivas desarrolladas sobre un sustrato dúctil. Sobre los diapiros, simulados por cilindros de silicona, se generan pliegues y cabalgamientos. Esta debilidad mecánica produce también falta de cilindrismo.

Palabras claves: Modelos analógicos, diapiros, sustrato viscoso, cinturón de pliegues y cabalgamientos, patrón estructural

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Introduction

Analogue modelling provides a powerful tool to investigate the progressive development of fold-and-thrust belts, although the geometry and rheology of analogue models necessarily simplify the complexities of the natural cases under investigation. The non-cylindricity in fold-and-thrust belts developed over viscous materials has been investigated successfully through this methodology, in particular in the case of heterogeneities in the substrate (e.g. Bahroudi and Koyi 2003), or in the case of salients and recesses of the backstop (e.g. Likhonin *et al.* 2002, Crespo-Blanc, 2008, respectively). Salt diapirs can also be heterogeneities which may enhance the lack of cylindricity of compressive structures situated in their vicinity (Molinari *et al.*, 2004). As a matter of fact, in the Subbetic units of the central Betics (derived from sediments deposited on the South Iberian paleomargin and floored by Triassic evaporites), their presence have been evoked to explain strong variations of the structural trend of the Subbetic fold-and-thrust belt (Sanz de Galdeano, 1973). Nevertheless, very scarce literature can be found about analogue models describing diapirs affected by shortening (Roca *et al.*, 2006;

Rowan and Vendeville, 2006). Moreover in the cited models, the shortening imposed to the sandpack floored by silicone was very low.

In order to test the role of diapirs as heterogeneities which can produce variations of the structural trend of compressive structures that developed around them, a series of analogue experiments have been realized in the Analogue modelling Laboratory of the Geodynamic Department of the University of Granada. Diapirs have been simulated by cylinders of silicone surrounded by layers of sand, in turn situated over a viscous substrate. Then, the whole has been shortened. In this paper, we will present the progressive deformation of two models in which the

size of the cylinder varied. In both models, the structures nucleate on the silicone diapirs, which are weaker than the surrounding brittle material. Moreover, they are responsible for the lack of cylindricity of the folds and thrusts that developed around them. This lack of cylindricity is more pronounced when the diapirs are larger.

Model set up and experimental conditions

In the experiments, sand and silicone were used as analogue materials in a natural gravity field to simulate the brittle behaviour of upper crustal sedimentary rocks (e.g. Davy and Cobbold, 1991) and the ductile flow of evaporitic rocks (e.g.

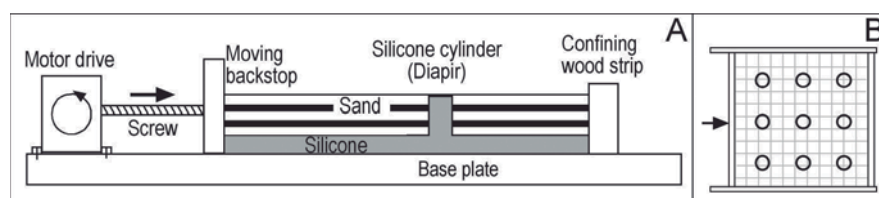


Fig. 1.- A. Simplified sketch of the experimental apparatus and model setting in cross section. B. Initial top surface of the model, with the position of the silicone cylinders (black circles).

Fig. 1.- A. Corte esquemático del aparato experimental y de los materiales que conforman el modelo inicial. B. Superficie superior del modelo, con la posición de los cilindros de silicona (círculos negros).

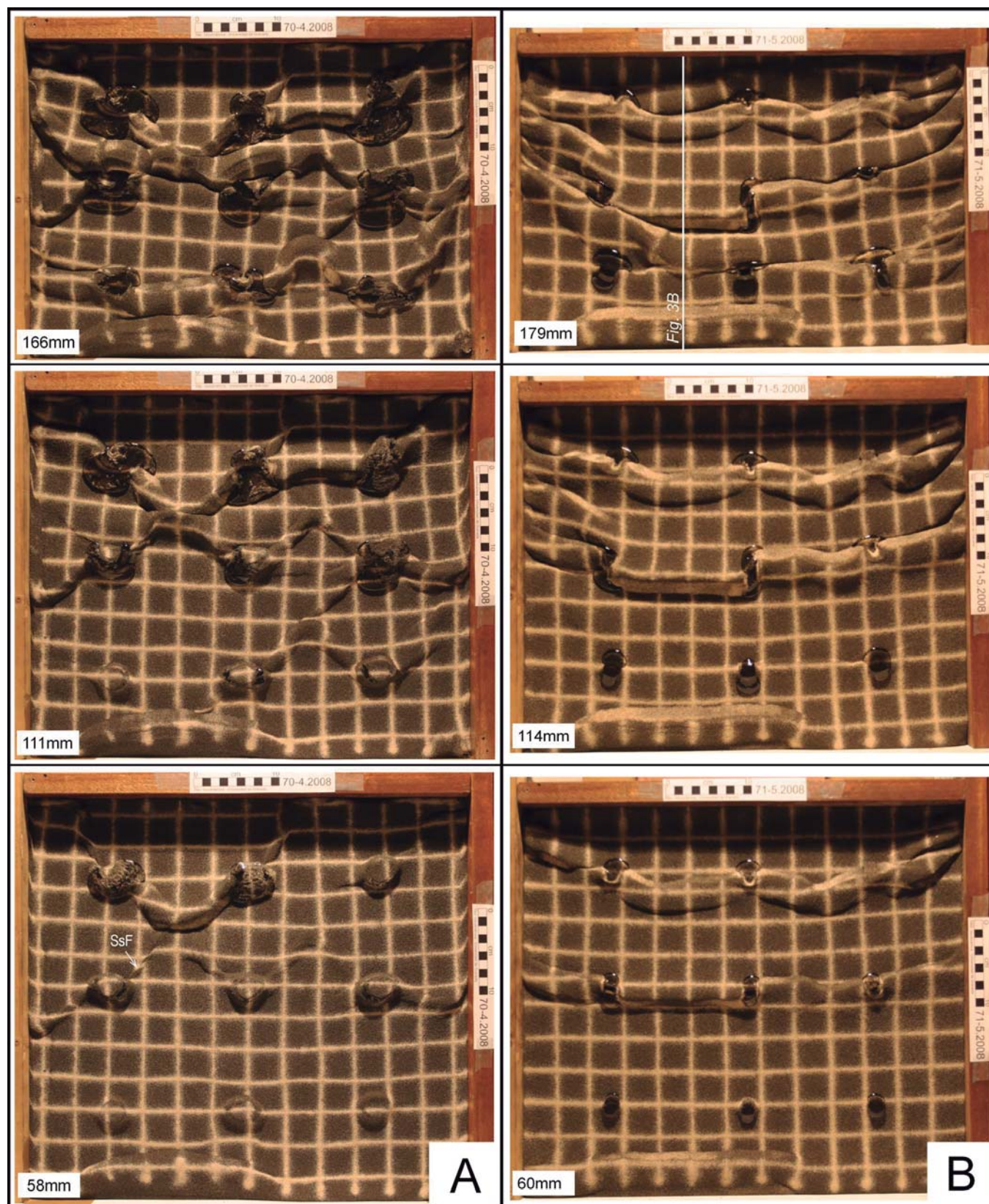


Fig. 2.- Photographs of map view of Models 70 (A) and 71 (B) for various amounts of shortening indicated as total movement of the backstop in millimetres. SsF: Strike-slip fault.

Fig. 2.- Fotografía de las plantas de los modelos 70 (A) y 71 (B) para varias cantidades de acortamiento, expresadas como movimiento total del backstop, en milímetros. SsF: Falla de salto en dirección.

Weijermars *et al.*, 1993; Cotton and Koyi, 2000), respectively. Dry quartz sand was used, with a grain size varying between 0.2 and 0.3 mm, a coefficient of internal friction $\phi = 37^\circ$, and density $\rho_{\text{BM}} = 1.77 \text{ g/cm}^3$. Coloured sand provided horizontal passive markers within the undeformed experimental multilayer. The silicone putty used in our experiments (transparent Rhodosil Gum FB of Rhone-Poulenc) is a Newtonian material, with a density $\rho_{\text{dM}} = 0.98 \text{ gr cm}^{-3}$ and a viscosity $\eta_{\text{M}} = 0.5 \times 10^5 \text{ Pa s}$ at room temperature.

The experiments were performed in a 52cmx52cm sandbox schematically illustrated in Figure 1. Wood strips were used to confine the whole model, and a drafting film sheet floored the sandbox. The sheet was pulled at a constant rate of $2.25 \times 10^{-6} \text{ m s}^{-1}$ (0.81 cm h^{-1}) by an electric motor, causing the collision of the undeformed multilayer against the rigid, vertical backstop (Fig. 1). The rheological stratification of the undeformed model consisted of: i) a lower ductile layer of silicone putty (0.5cm thick), over which nine cylinders of silicone simulated diapirs (1cm thick, from the top of the silicone basal layer to the top of the cylinder), and (ii) an upper brittle layer (1cm thick) composed of alternating layers of coloured and uncoloured dry sand. The nine diapirs are situated initially along a square which sides are perpendicular to and parallel with the backstop. They are separated 15cm from each other (Fig. 1). The diameter of the diapirs varies: 3.8cm in Model 70, and 2.1cm in Model 71. The total shortening is similar for both experiments: 16.6cm and 17.9cm, respectively. A 4cm-side grid was sieved on top of the multilayer, including the diapirs. After completion, each model underwent serial sectioning parallel to the shortening direction.

Effects of diapirs on structural trend of the fold-and-thrust belt

The progressive deformation of the models with diapirs of two different sizes is illustrated by photographs of the top surface for various amounts of shortening (Fig. 2A and 2B). A general progression of the deformation from the frontal to the rear part of the model can be observed. In both models, shortening is associated mainly with box folds, accompanied by their corresponding forward and rearward vergent thrusts, which developed almost simultaneously. The photograph of Figure 3A shows a representative cross-section that illustrates the finite 2D

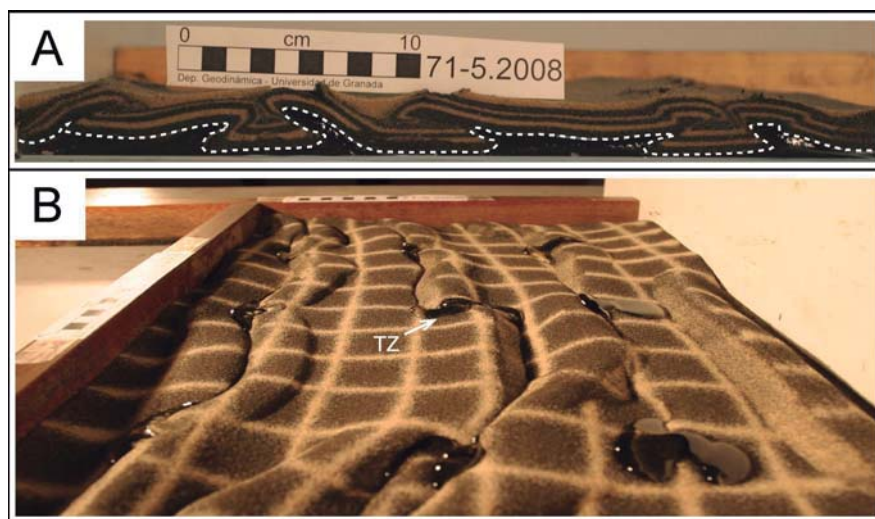


Fig. 3.- A. Cross-section representative of the structural style of the experimental wedges. (localized in the final stage of Model 71, Fig. 2B). Dashed white line: boundary between sand and silicone. B. Oblique view of the final stage of Model 71. TZ: Transfer Zone.

Fig. 3.- A. Corte representativo del estilo estructural de una cuña experimental (localizado en el estadio final del Modelo 71, Fig. 2B). Línea punteada: límite entre arena y silicona. B. Vista oblicua del estadio final del Modelo 71. TZ: Zona de Transferencia.

geometry. A very low surface wedge taper enhanced by the lack of dominant vergence, is also clearly illustrated with the oblique photographs of the final stage of Model 71 (Fig. 3B). In Figures 2 and 3B, silicone that reached the surface of the sandpack can be observed. Indeed, when shortening proceed, buoyancy-driven processes were enhanced, the silicone were squeezed and the diapirs grew until the silicone reached the top of the model.

The box-folds and thrust nucleated on the diapirs, linking the closest ones. Accordingly, as the diapirs are initially regularly distributed (Fig. 1), two possibilities exist concerning the orientation of the folds and thrusts: either subparallel to the backstop in the case of the smallest diapirs (Model 71), or at 45° of the backstop when the diapirs are broader (Model 70).

In the case of the smallest diapirs, the first compressive structures developed in the most external part of the model, linking the diapirs parallel to the backstop. They show a feston-like structural trend, convex towards the backstop (Fig. 2B). The angle between the laterals of the feston-like structures is around 130° . When shortening proceed, a transfer zone developed on the central diapir of the model, linking two thrusts with opposite vergence. Its progression is shown in the central part of Figure 2B. Its final geometry is also illustrated on the oblique photograph of Fig. 3B (TZ). In the final stage of Model 71, the box folds are roughly cylindrical and subparallel to the

backstop, with exception of the structures dragged by the wood strips which confine laterally the silicone and sandpack.

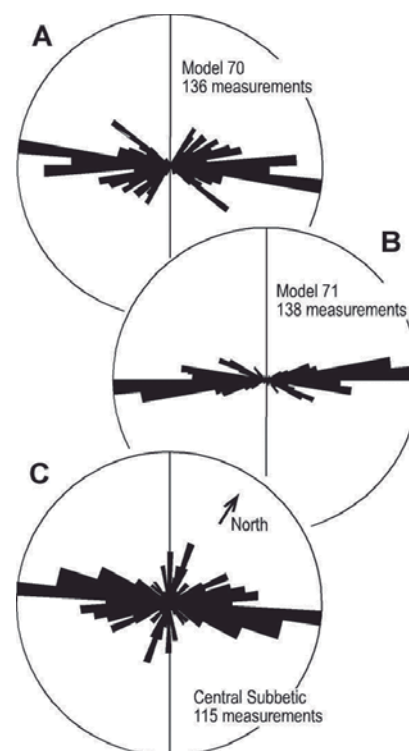


Fig. 4.- Rose diagrams illustrating the structural trend of the models (A, B) and of the central Subbetic (C, Crespo-Blanc, 2008).

Fig. 4.- Diagrama de rosas ilustrando el patrón estructural de los modelos (A, B) y del Subbético central (C, Crespo-Blanc, 2008).

When the diapirs are broader, the final result is much less cylindrical (Model 70, Fig 2A). In the first stage of the experiment, it can be seen how the box-folds and thrust generated on the diapirs, as in the previous model. Nevertheless, in this case, they link the diapirs along diagonals of the square defined by adjacent diapirs. Accordingly, they are oriented at an angle of 45° with respect to the backstop. As the structures developed simultaneously along both diagonals, they join in the square center, drawing a knee-like structural trend, in which both part of the knee are at an angle of 90°. Moreover, in this model, a discrete strike slip fault (SsF of Fig.2A) evolving later to an oblique thrust is observed. When shortening proceed, the box-folds and thrust generated in the first stage of the experiments are slightly rotated and reached a position more parallel to the backstop.

Discussion and concluding remarks

The experiments presented in this paper show that in a sand pack situated over a silicone layer, silicone cylinders represent a mechanical weakness which is high enough to enhance the nucleation of compressive structures when shortening take place. These structures are box folds accompanied by their corresponding forward and rearward vergent thrusts, characteristic of the deformation of a sandpack above a ductile substrate (e.g. Cotton and Koyi, 2000; Bahroudi and Koyi, 2003; Luján *et al.*, 2003).

The generated structures link adjacent cylinders, whose diameter is an important factor which controlled the structural trend and the degree of cylindricity of the fold-and-thrust belt. The spatial distribution of the structures and their grade of obliquity can be quantified through rose diagrams (Fig. 4). On the photographs of the final stage, the structure lines were divided into segments of 2cm length and their mean orientation measured. The north of the rose diagrams corresponds to the

backstop movement and each petal represents a variation of 5° of strike orientation. The folds and thrusts situated at less than 4cm from the lateral wood strips that confined the models were not considered, as they were twisted by the friction of the strips. In our experiments, smaller diapirs are less efficient for producing lack of cylindricity. Indeed, the rose diagram of Model 71 shows a smaller orientation variation of the structures than that of Model 70, where the silicone cylinders are broader (Fig. 4A and B).

It must be stressed that both models presented in this paper belong to a series of experiments raised to address the origin of strong variations of the structural trend of the Subbetic fold-and-thrust belt observed in the central Betics (Crespo-Blanc, 2007). Rose diagram C represents the variations of structural trend for that area (Fig. 4). It was constructed in order to respect the scaling factor, that is, the quotient between the physical parameters such as length, density or viscosity of the materials in both the model and the natural case. As this scale factor is 2×10^5 , the structural lines of the Subbetic fold-and-thrust belt of the central Betics were divided into segments of 4 km length, and their mean orientation was measured. The north of the stereoplot corresponds to the supposed compression direction (see more explanations in Crespo-Blanc, 2008). By comparing diagrams A and B (models) with diagram C (natural case), it can be observed that the structural trend of the central Subbetic shows a much higher variation than the models presented in this paper. Accordingly, the presence of diapirs previous to the Subbetic fold-and-thrust belt formation is not sufficient to induce such trend variation, at least with the initial geometric distribution of Models 70 and 71. More analogue modelling with different geometries of the silicone cylinder (size, position with respect to the backstop, height, ...) should be realized in order to test if the presence of diapirs

before the main compressional event is responsible for the structural variation in the Subbetic units of the central Betics.

Acknowledgments

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