Analogue modeling of lithospheric orocline bending. Implications on the development of the Ibero-Armorican Arc.

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Introduction

Oroclines were firstly described by Carey (1955) as "an orogenic system that has been flexed in plan to a horse-shoe or elbow shape." that implies an originally linear belt that is bent in a subsequent deformation event. Although the existence of oroclines is well-known, there are not many ways to understand their kinematic evolution and how they develop. There is even discussion on whether they develop as thin skinned structures or they have a lithospheric scale.

The Western European Variscan Belt resulted from the collision between Gondwana, Laurussia, and several microplates during Devonian-Carboniferous times (e.g., Martínez-Catalán et al., 2009). This belt is characterized by a highly arcuate geometry known as Ibero-Armorican Arc. The evolution of the arc has been constrained paleomagnetically as an orocline that was generated from an almost initially linear belt in its core, the Cantabrian Zone, northern Iberia (Weil et al., 2002, 2010). Oroclinal bending took place in the uppermost Carboniferous, between ca. 310 and 300 Ma (Weil et al., 2010; Pastor-Galán et al. in prep), and, among other interpretations, it is considered to have been ultimately caused by the self-subduction of the Pangean global plate (Gutiérrez-Alonso et al., 2008). Given the large scale of this plate-scale structure, it is bound to have had a profound effect on the whole lithosphere and consequently the effects of the involvement of the lithosphere should be recognized in structures and geological features of different nature and at different scales developed coevally with the orocline. Among the effects of the orocline development, continental-scale strike slip shear zones have been interpreted to accommodate the rotation in the outer parts of the Ibero-Armorican Arc. In addition to the shearing, coeval or subsequent voluminous magmatism, even present in the foreland fold-and-thrust belt, has also been interpreted as being related to the mass transfer processes taking place during the oroclinal bending of the mantle lithosphere which likely caused a lithospheric delamination process.

Because there is a good control on the crustal processes that accommodated the lithospheric buckling, and there are also intrusive rocks that were originated due to the involvement of the lithospheric mantle, we can try to model the response of the whole lithosphere that results from the buckling of the Variscan orogen. Nowadays, analogue modeling is the only reliable way to understand the lithospheric behaviour in 3D due to the computer calculating limitations for mathematical accurate 3D modeling.

Methods

In order to perform the modeling of the buckling process and it is subsequent lithospheric delamination we have performed a two stage experiment in which, using the same materials and thermal boundary contions, we have first simulated the buckling process in a thermo-mechanical apparatus (press). In this experiment we have obtained the resulting geometry after buckling an initially linear lithospheric segment. The second simulation was performed adding gravity to the previously obtained geometry, by means of a thermo-centrifuge machine, to test the possibility of lithospheric delamination where the mantle lithosphere had been previously thickened.

The initial experiment is based on shortening of a 30 cm long elongated model composed of four layers: (i) the sub-lithospheric mantle, made with *Beck's orange plasticine*, (ii) the listospheric mantle, consisting of *Weible red plasticine*, (iii) the lower crust made of *Becks's orange plasticine*, and the upper crust consisting of sand. The physical properties of these materials are described in Zulauf and Zulauf (2004) and Tkalcec (2010). The layer parallel shortening in a thermo-mechanical apparatus (Chowdhury et al. 2009) led to a buckle fold with a vertical axis. This experiment has been performed several times, at varying strain rates, using models with different thickness of the mantle lithosphere. All the experiments were performed at a constant temperature profile to hold the viscosity contrast between lithospheric and sublithospheric mantle. The deformed model of the first experiment was imaged using computer tomography (CT).

Once obtained the results of this former experiment we extended the experimentation with a second step, consisting in centrifuge experiments to study the effect of gravity on oroclinal bending. Because of the physical limitations of the experiment, we have carried this second step reproducing the obtained geometry in the original models with the same materials but re-scaled to the proportions of the centrifuge (8 cm long and 10 cm wide). The applied centrifuge is a Rotosilenta 630 RS. Models were preheated between 50º to 60°C and centrifuged at 300 G from 1 to 30 minutes.

Results and Discussion

The first type of experiments show that during orocline buckling, regardless of the thickness of the different layers used or the strain rate, the mantle lithosphere is thickened in the core of the orocline and is thinned in the outer arc (Fig 1). Differences in the way the mantle lithosphere thickens are observed in relation with the initial lithospheric thickness considered. While the thickest mantle lithosphere thickens by generating a cone shaped mullion or a very tight conical fold, the thin matnle lithosphere thickens by conical and recumbent folding or is duplicated by thrusting in a similar way to subduction zones. On the other hand, the thinning in the outer arc is always obtained by radial tension fractures. Moreover, in some experiments strain was accommodated by dextral shear zones.

Lithospheric thickening has been studied as causing lithospheric delamination in different scenarios (eg. Nelson, 1992; Schott, B., and Schmeling, 1998; Pysklywec et al., 2010). The centrifuge experiments reveal that delamination of the lithospheric thickening (root) with the analogue materials selected is possible and easy to get when the model is heated over 55ºC. This is the temperature at which the viscosity contrast between *Beck's orange* and *Weible red plasticine* is greater (around three orders of magnitude) which is consistent with the viscosity contrast of the mantle lithosphere and the astenosphere. Nevertheless, at T < 55º there is no evidence for delamination even if centrifuging lasted more than 20 minutes at 300 G.

The new experimental results are in agreement with the models proposed by Gutiérrez-Alonso et al. (2004) about the expected lithospheric thickening under orocline bending conditions and provide new possible geometries for this thickened lithosphere that back up the digital models proposed by Pysklywec et al (2010). Furthermore, the delamination of the selected materials to model the lithosphere behavior is possible under analogue conditions and can explain the abundance of post-orogenic magmatic rocks in the core of the Ibero-Armorican Arc.

FIGURE CAPTIONS

Figure 1: A) CT image of an originally 2cm thick mantle lithosphere analogue after orocline buckling. The image depicts that the lithosphere has thickened as a conical tightened fold in the core of the orocline. B) CT image of an originally 1cm thick mantle lithosphere analogue after the buckling. This model has thickened duplicating the mantle lithosphere as a conical recumbent folding in in the outer part and in a thrust way y the inner root.

Figure 2: CT image of a centrifuge model take in the moment the lithospheric root is delaminating viewed from the top side (A) and from the bottom (B).

References

Carey, S.W. (1955) The orocline concept in geotectonics. *Royal Society of Tasmania Proceedings*, 89, 255–288.

Chowdhury, B., Dietl, C., Zulauf, G., Peinl, M., Zanella, F. (2009) – A new thermomechanical deformation apparatus for 3D coaxial deformation and its application to rheologically stratified models. Geotectonic Research, 96, 03–19.

Gutiérrez-Alonso, G., J. Fernandez-Suarez, and A.B. Weil, (2004) – Orocline triggered lithospheric delamination: *Geological Society of America Special Paper*, 383, 121-131.

Gutiérrez-Alonso, G., Fernandez-Suarez, J., Weil, A.B., Murphy, J.B., Nance, R.D., Corfu, F., and Johnston, S.T., (2008) – Self-subduction of the Pangaean global plate. *Nature Geoscience*, 1, 549-553.

Martínez Catalán, J. R., et al. (2009), A rootless suture and the loss of the roots of a mountain chain: The Variscan Belt of NW Iberia, *Comptes Rendus Geoscience*.

Nelson, K.D. (1992) – Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithospheric delamination?. *Geology*, 20, 488–502.

Pastor-Galán, D., Gutiérrez-Alonso, G. (2010) – Orocline timing through joint analysis. Insights from Ibero Armorican arc (in prep)

Pysklywec, R.N., Gogus, O., Percival, J., Cruden, A.R., Beaumont, C. (2010) – Insights from geodynamical modeling on possible fates of continental mantle lithosphere: collision, removal and overturn. *Canadian Journal of earth Sciences*, 47, 541-563.

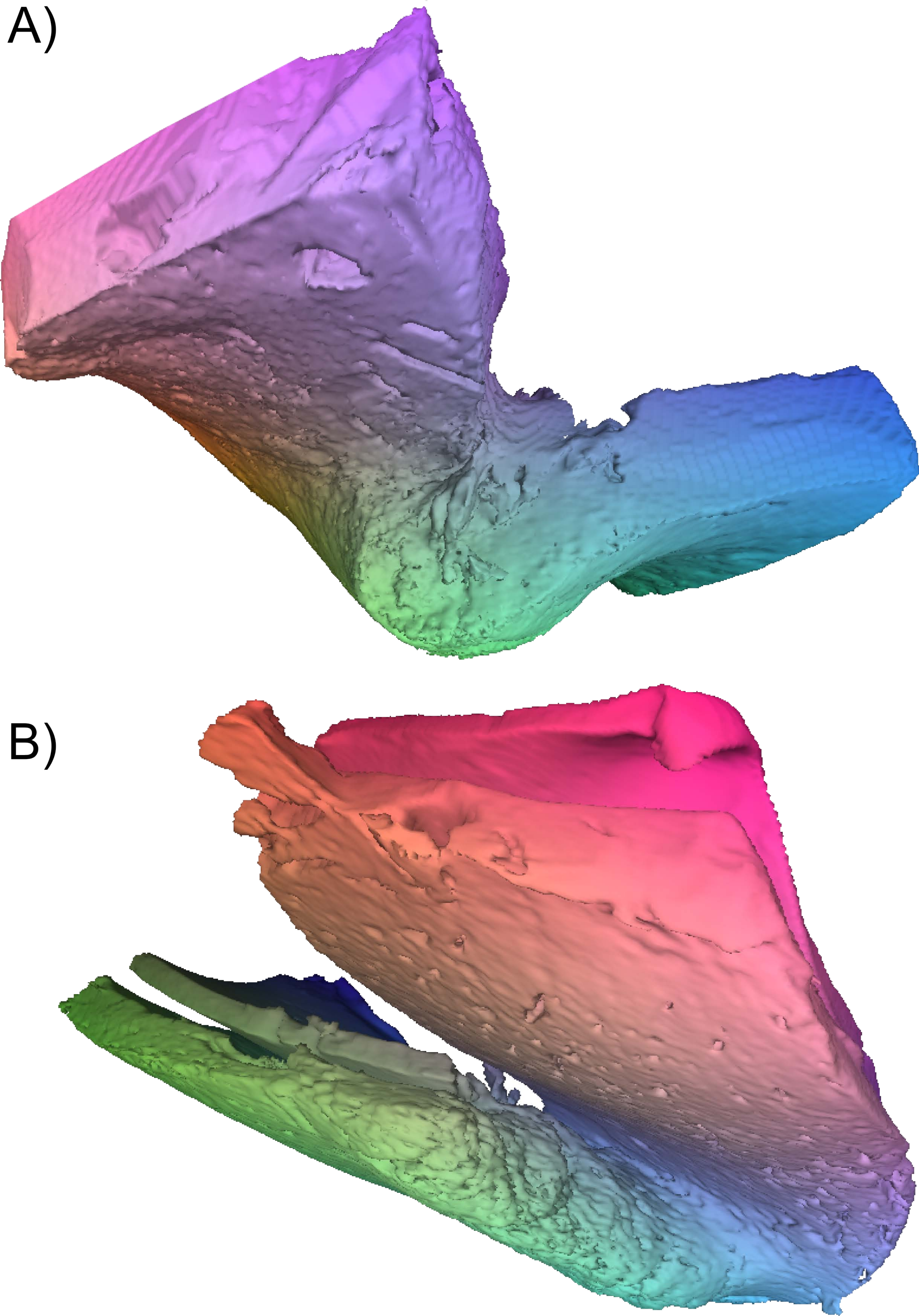
Schott, B., and Schmeling, H. (1998) – Delamination and detachment of a lithospheric root: *Tectonophysics*, 296, 225–247

Tkalcec, B. (2010): Variscan Orogenic Collapse in the Bohemian Massif: Results from Analogue Modelling. MsC Thesis, Frankfurt am Main. Unpublished.

Weil, A.B., van der Voo, R., and van der Pluijm, B.A., (2001) – Oroclinal bending and evidence against the Pangea megashear: The Cantabria-Asturias arc (northern Spain). *Geology*, 29, 991-994.

Weil, A.B., Gutiérrez-Alonso, G., and Conan, J., (2010) – New time constraints on lithospheric-scale oroclinal bending of the Ibero-Armorican Arc: a paleomagnetic study of earliest Permian rocks from Iberia. *Journal of the Geological Society*, London, 167, 127-143.

Zulauf J., Zulauf G. (2004) – Rheology of plasticine used as rock analogue: the impact of temperature, composition and strain. *Journal of Structural Geology*. 26(4), 725-737.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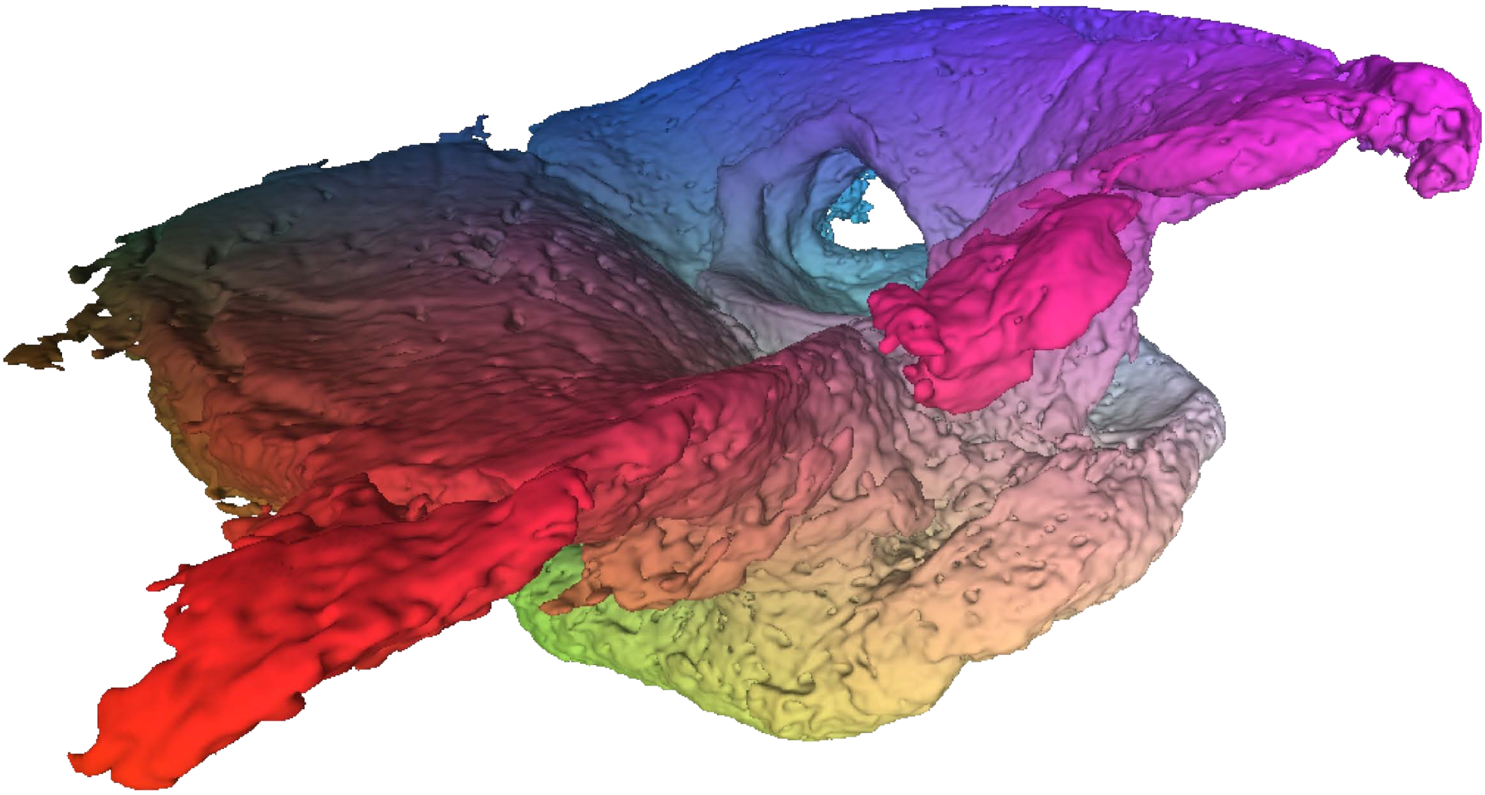

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