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Far-field contractional polarity changes in models and nature

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ABSTRACT

A change in contractional polarity occurs when the direction of tectonic transport switches along strike. This switch is conditioned by lateral variations in rheology or inherited asymmetries, such as contrasts in structure or changes in the polarity of subduction zones. The parameters controlling contractional polarity changes are less understood in situations when the strain is transferred at large distances from indenters. Analysing this type of strain transfer is critical for understanding the mechanics of thrusting in fore- or back-arc settings of orogenic areas. Comparison of crustal-scale analogue modelling with the inversion of the Black Sea back-arc and the formation of the New Guinea–New Britain fore-arc suggest that far-field changes in contractional polarity are related to rheological contrasts across inherited normal faults. The initial extension creates rheological weak zones that localize the subsequent far-field contractional deformation along groups of thrusts with opposite vergence along the strike of the system. The largest amount of far-field contractional deformation is recorded in the transfer zone located between the two indenters moving in opposite directions and is particularly high when inverting oblique extensional systems.

1. Introduction

The inversion of extensional structures observed in rift-, fore-arc- or back-arc basins has been documented by numerous observational studies that have demonstrated the key role of inherited strength variations in crust and/or lithosphere during deformation (e.g., Roure, 2008; Ziegler et al., 1998). The kinematics and structural style of inversion is controlled by many parameters, such as the angle between the directions of extension and compression or the distance between the source of compression and the area of strain localization in weakness zones (Brun and Nalpas, 1996; Flottmann and James, 1997). In particular, lateral variations in rheologies commonly inherited from previous extensional times appear to play a critical role during the subsequent inversion (Aanyu and Koehn, 2011; Buiter et al., 2009; Ziegler and Cloetingh, 2004). These observations have been generally confirmed by other numerical modelling studies that have also underlined the critical role played by the increasing crustal strength during post-rift thermal relaxation (e.g., Beekman et al., 1996; Buiter et al., 2009; Cloetingh et al., 1995; Hansen and Nielsen, 2003; Mike, 1999). These results are in general agreement with analogue modelling studies (e.g., Aanyu and Koehn, 2011; Bonini et al., 2000; Dubois et al., 2002; Marques and Nogueira, 2008; Panien et al., 2006; Sokoutis and Willingshofer, 2011; Willingshofer and Sokoutis, 2009) that have suggested a number of additional parameters controlling the inversion of extensional structures, such as the presence of oblique to transversal basement ramps (e.g., Konstantinovskaya et al., 2007; Michon and Sokoutis, 2005; ter Borgh et al., 2011, and reference therein) or syn-kinematic sedimentation (Pinto et al., 2010; Smit et al., 2010). The along-strike variability of the mechanics of inversion may also be the result of the contraction transmitted by two different indenters moving in the same direction, but with different velocities, such as in the case of Pamir–Hindu Kush deformation (Burtman, 2000; Mohadjer et al., 2010; Reiter et al., 2011; Smit et al., 2013).

A change in contractional polarity occurs during inversion when the direction of tectonic transport switches along strike to an opposite one, the indenters (or backstops) deforming the former extensional basin from two sides. The most frequent type of contractional polarity change is observed in orogenic areas, when contraction during subduction and/or collision inverts the former passive continental margin and its buried continental rift. Such changes are observed in New Guinea–New Britain, Taiwan, New Zealand, Pyrenees, or the Alps–Dinarides system (Luth et al., 2010, 2013; Molli and Malavieille, 2011; Tregoning and Gorbatov, 2004; Reyners et al., 2002; Sibuet and Hsu, 2004; Sinclair et al., 2005;

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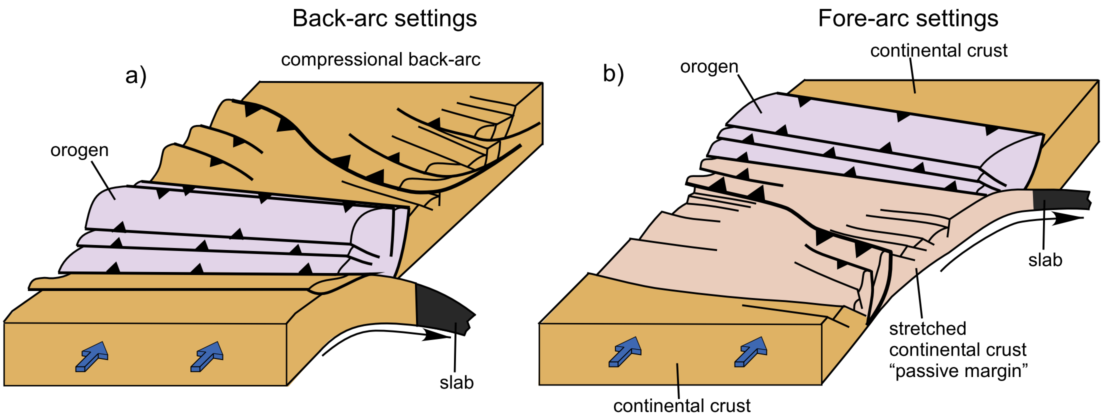

Fig. 1. Cartoon illustrating the concept of far-field contractional polarity change in orogenic areas: (a) inversion of, slab roll-back related, back-arc domain during continental collision; (b) incipient subduction of a passive continental margin and its buried continental rift.

Vignaroli et al., 2008). One other common situation is when the sediment fill in the back-arc basins is inverted due to the change in tectonic regime from the extension due to the rapid roll-back of mature subducted slabs and the back-arc contraction that resulted from the subsequent continental collision, such as in the Pannonian Basin, Black Sea or Sunda Shelf–Bali Basin (e.g., Hall, 2002; Horvath et al., 2006; Letouzey et al., 1990; Royden and Burchfiel, 1989). Back-arc inversion is not directionally controlled by a major slab asymmetry, as in case of subduction systems. Instead, pre-existing strength variations at crustal or lithospheric scale along the strike of the system (e.g., Cloetingh et al., 2003; Sokoutis and Willingshofer, 2011) may control the location of backstops and, therefore, condition the direction of indentation.

A far-field transfer of deformation during contraction takes place when the strain is recorded at large distances from the place where the compressional stress is applied. This is generally influenced by the presence of inherited weak zones, or by the rheological strength contrast between areas separated by normal faults that formed during pre-dating extension, at crustal or lithospheric scale (e.g., Cerca et al., 2010; Willingshofer and Sokoutis, 2009). The presence of ductile decollements, such as salt layers, favour the concentration of thrusting near the margin of grabens and the far-field transmission of deformation during inversion (Brun and Fort, 2011; Smit et al., 2008). Furthermore, transfer zones situated obliquely to the shortening direction that recorded variable amounts of extension may play an important role in far-field strain transmission (Gartrell et al., 2005).

All the above wide variety of models and their application to natural scenarios share one common feature: the far-field contractional deformation is transmitted in one direction. However, the parameters controlling the combination between far-field transmission of deformation and contractional polarity changes are not yet fully understood. Such type of strain transfer is observed both in back-arc and fore-arc areas and is critical for understanding the mechanics of thrusting in orogenic zones, as conceptually illustrated in Fig. 1.

A far-field contractional polarity change requires three simultaneous conditions: a contractional polarity change along the strike of the orogen, contractional deformation is transmitted at large distanced from the opposite polarity indenters, and these indenters transmit deformation at the same time. A large variety of structural features observed in many natural scenarios could be the result of far-field contractional polarity changes. The Black Sea Basin is an example where the lateral change of thrusting direction was controlled by pre-existing extensional geometries (Finetti et al., 1988; Munteanu et al., 2011). Starting with the Early Cretaceous, the basin opened during the roll-back associated with the N-ward subduction of Neotethys under the Rhodope–Pontides Arc has (e.g., Görür, 1988; Okay et al., 1994) and was inverted starting with the late Middle Eocene times due to continental collision recorded in the Pontides (e.g., Yilmaz et al., 1997). The inversion resulted in a far-field contractional polarity change between the top-N thrusting recorded by the Western Black Sea (e.g., Munteanu et al., 2011) and top-S thrusting of Crimea and Caucasus (e.g., Nikishin et al., 2010), separated by a large transfer zone in the area of the Mid–Black Sea High (Finetti et al., 1988). Such types of back-arc far-field contractional polarity changes are widely observed also elsewhere, in particular frequent in the retro-arc foreland basin of the American Cordillera (e.g., Jordan et al., 1983; Cobbold et al., 1993; Roure, 2008). In the fore-arc domain, the Cainozoic oblique subduction and collision between the Pacific and Australia plates has resulted in a contractional polarity change demonstrated by the presence of two oppositely dipping slabs in the New Guinea–New Britain sector (e.g., Tregoning and Gorbatov, 2004). This change in subduction polarity could have been is accommodated by far-field strain transfer in the area of the Huon–Finisterre Arc, where an N-dipping collisional zone is accommodated by high angle faults that crosscut the Huon Peninsula (e.g., Pegler et al., 1995; Lee and Ruellan, 2006).

Below we quantify the geometries and mechanics of such strain partitioning and far-field transfer of deformation during inversion by means of crustal-scale analogue modelling, used here to evaluate the role of inherited extensional geometries and lateral variations in crustal strength on the changing polarities. In particular, the presence of single or multiple extensional grabens, which are either oblique or parallel to the direction of shortening, and the role of syn-extensional sediments in the subsequent inversion are investigated. The analogue modelling results are compared with natural scenarios focusing on the Black Sea back-arc basin and the New Britain–New Guinea fore-arc, shedding light on the mechanical evolution of these systems.

2. Analogue modelling design and strategy

Analogue models are particularly successful for the study of complex 3D geometries, which are partly the result of pre-existing structures. Examples are inverted extensional basins, where contractional strain is efficiently transferred to the basin interiors, particularly in cases of multiple indenters. Starting from simple setups (Fig. 2a) where rift structures are orthogonal (type 1 model, Fig. 2b) or oblique (type 2 model, Fig. 2b) with respect to the direction of shortening we subsequently investigated the influence of two indenters on basin inversion with variable initial basin geometry (symmetrical vs. asymmetric, types 3–6 models). The experiments at crustal scale provide valuable insights into these complex