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Transfer of deformation in back-arc basins with a laterally variable rheology: Constraints from analogue modelling of the Balkanides–Western Black Sea inversion

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A B S T R A C T

The balance between extension and contraction in back-arc basins is very sensitive to a number of parameters related to on-going subduction and collision processes. This leads to complex back-arc geometries, where a lateral transition between crustal blocks with contrasting rheologies is often recorded. One good example is the back-arc region of the Balkanides–Pontides orogens, where lateral variations in rheologies are observed between the Balkanides–Moesian block and the Pontides–Western Black Sea Basin. The latter opened during Cretaceous–Eocene, and has been inverted together with the former starting during late Middle Eocene. The inversion generated contrasting geometries along the orogenic strike, with a narrow zone of high deformation in the Balkanides–Moesia region, wide areas of thrusting with low offsets in the Pontides–Western Black Sea Basin and a transitional zone characterized by highly curved geometries. This overall type of inversion is investigated here by the means of analogue modelling testing the role of inherited crustal geometries during inversion. Our modelling suggests that the contrasting architecture of inverted structures observed in the Balkanides–Pontides domain are the result of pre-existing crustal stretching geometries of various blocks inherited from the Cretaceous–Eocene extension. The stretched and weak back-arc basins can transfer contraction deformation at large distances, explaining structures derived by observational studies. The collisional deformation recorded in the Pontides was transmitted at large distances that are in the range of the contraction structures observed in the centre and northern part of the Western Black Sea. In the light of analogue modelling results we argue that the Western Black Sea was a rheologically weaker domain when compared with the adjacent western onshore at the beginning of the inversion, in contrast with previous results derived from numerical modelling studies that argued for a strong West Black Sea domain at the beginning of inversion.

1. Introduction

Transmission of contractional deformation at far distances from plate boundaries into orogenic forelands and hinterlands has been the object of a number of studies based on geophysical and geological observations (e.g. Roure, 2008; Ziegler et al., 1998, 2002) as well as analogue modelling (e.g. Del Ventisette et al., 2006; Dombrádi et al., 2010; Luth et al., 2010; Smit et al., 2003; Willingshofer and Sokoutis, 2009). These studies have demonstrated the effectiveness of strain transfer at large distances from the active deformation area, as a function of the (inherited) crustal or lithospheric rheology. Analogue and numerical modelling studies investigating the inversion of extensional basins, such as back-arc basins (e.g. Bonini et al., 2012; Brun and Nalpas, 1996; Buiter et al., 2009; Dubois et al., 2002; Nalpas et al., 1995; Panien et al., 2005) have tested the influence of graben geometries, the obliquity of inversion when compared to the strike of normal faults, the brittle–ductile coupling and also the balance between the amounts of deformation during inversion following extension of the crust and lithosphere. These studies have demonstrated the significance of inherited normal fault geometries and stretching parameters in controlling the amplitude and localisation of deformation in close proximity or at far distances from the moving indenter. The balance between extension and contraction in back arc-basins is very sensitive to a large number of parameters related to the on-going subduction and collision processes (Dewey, 1981; Doglioni et al., 2007; Uyeda and Kanamori, 1979 and references therein). This leads to complex back-arc geometries, where a lateral transition between crustal blocks with contrasting

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rheologies is often recorded (Dvorkin et al., 1993; Huismans et al., 2001). Inverting such mechanically different blocks can lead to significant variations in thrust geometries along the strike of an orogen. The inherited weakness of extensional back-arc basins at short times after extension may focus deformation at the transition between mechanically strong and weaker crust or lithosphere (e.g. Jarosinski et al., 2011) that is often in close proximity to the indenter. Hence, thermal anomalies associated with extension weaken the lower crust and form layers that, potentially, would transmit deformation at large distances by reducing the brittle/ductile coupling (Smit et al., 2003).

An area that shows crustal domains with distinct lateral strength variations is the Pontides–Western Black Sea Basin and the westerly adjacent Balkanides–Moesian onshore, situated in the back-arc of the northward subduction of the Neotethys beneath the Rhodope–Pontides volcanic arc (e.g. Letouzey et al., 1977; Okay et al., 1994; Zonenshain and Le Pichon, 1986). The Cretaceous–Eocene basin opening and enlargement of the Western Black Sea (Dinu et al., 2005; Görür, 1988) was subsequently followed by a compressional episode starting during the late Middle Eocene, which inverted large areas of Pontides and Western Black Sea Basin. On its western onshore margin, the inversion has created the Balkanides nappe stack by duplicating large areas of the Rhodope–Moesian hinterland (Finetti et al., 1988; Georgiev et al., 2001; Ivanov, 1988; Stuart et al., 2011; Yilmaz et al., 1997). Recent correlations of these inversional structures infer a constant amount of shortening along the strike of the Pontides–Rhodope back-arc system, accommodated by a concentration of deformation in the Balkanides sector that is replaced laterally in the Pontides–Black Sea by a wide zone of deformation recognized as far north as the Odessa Shelf (Munteanu et al., 2011). In between the two areas, a transitional zone concentrates deformation along a swing in the thrust system that connects the Balkanides with the Pontides (Fig. 1, Bergerat et al., 2010; Doglioni et al., 1996; Stuart et al., 2011). The mechanism controlling the transmission of deformation into the two rheologically and kinematically different areas and the role of inherited crustal structures over the localisation of strain is not well constrained.

The mechanics of back-arc basin inversion over a laterally variable crustal rheology is investigated in this study by means of analogue modelling with the main variables being the role of the inherited geometries during the subsequent inversion.

The resulting models are compared with the Late Eocene–Pliocene inversion of the Western Black Sea, with special focus on the role of lateral variations in crustal strength in strain localisation. Hence, the interplay between the degree of vertical coupling and lateral differences in crustal strength is the primary focus of this study.

2. Constraints from the evolution of the Balkanides–Pontides–West Black Sea system

The Black Sea Basin is traditionally divided two sub-basins, i.e. western and eastern, which are floored by thinned transitional or oceanic crust. These basins are separated by the uplifted Andrusov Ridge or Mid Black Sea High continental block (Fig. 1, e.g. Edwards et al., 2009; Starostenko et al., 2004; Yegorova et al., 2010). The opening of these sub-basins took place in two main successive phases. A first Early Cretaceous (Barremian–Albian) extensional episode opened the Western Black Sea sub-basin (Görür, 1988; Nikishin et al., 2003; Robinson et al., 1995; Tambrea, 2007) in the back-arc region of the N-ward subduction of the Neotethys, behind the Serbomacedonian–Rhodope–Pontide arc (Letouzey et al., 1977; Okay et al., 1994; Robinson et al., 1996; Sengör and Yilmaz, 1981; Yilmaz et al., 1997). Reconstruction of extensional geometries indicates small offset normal faults organized in asymmetric half-grabens in the central and northern part of the Western Black Sea (Dinu et al., 2005; Khriachtchevskaia et al., 2010) and symmetric grabens in its southern part (Banks and Robinson, 1997; Georgiev et al., 2001; Yilmaz et al., 1997). The overall orientation of these grabens is E–W, changing locally to NW–SE, such as in offshore Romania (Nikishin et al., 2003; Tambrea et al., 2002).

Renewed extension took place during latest Cretaceous–Paleogene times, with the opening of the Eastern Black Sea Basin and the enlargement of the already opened Western Black Sea Basin (Fig. 1, Banks and Robinson, 1997; Spadini et al., 1996). In particular, the Late Cretaceous–Eocene extension is well observed near the southern margin of the system (i.e. Balkanides–Western Pontides). Here, large E–W oriented grabens were filled with more than 3 km syn-kinematic volcano-clastic sediments (Bergerat et al., 2010; Georgiev et al., 2001; Görür, 1997; Sunal and Tuysuz, 2002; Tüysüz, 1999). In the north, the Late Cretaceous–Paleogene stretching has reduced effects, the Early Cretaceous rift stage being followed by an overall passive margin evolution of the Western Black Sea area and by a tectonic quiescence along the neighbouring Moesian onshore margin (Dinu et al., 2002; Khriachtchevskaia et al., 2010; Tambrea et al., 2002). In the transitional area (i.e. offshore Romania and Bulgaria), the Eocene stretching created normal faults with offsets in order of tens to hundreds of metres (Dinu et al., 2005; Robinson et al., 1996; Tambrea, 2007; Tari et al., 2009; Tugolesov et al., 1985).

Basin inversion started shortly after extension during the late Middle Eocene and is generally interpreted as far-field transmission of compressional stresses during the final closure and collision of the Neotethys (Finetti et al., 1988; Munteanu et al., 2011; Stephenson et al., 2004; Yilmaz et al., 1997). The continental collision between the Sakaria and Istanbul blocks induced large scaled basin inversion, which was recorded in their entire hinterland (Okay et al., 1994), including the backward thrusting of Balkanides–Pontides orogens onto the former back-arc domain. The shortening gradually propagated northwards and affected the entire Western Black Sea domain during Oligocene–Miocene times (Dinu et al., 2005; Khriachtchevskaia et al., 2010; Moro anu, 2002; Munteanu et al., 2011; Tugolesov et al., 1985). The continuation of the inversion during the Pliocene has been recorded only on the northern Odessa Shelf (Khriachtchevskaia et al., 2009). Hence, the Late Eocene–Pliocene inversion structures form a coherent thick-skinned thrust system that can be connected across the entire Western Black Sea shelf (Fig. 2), associated with foreland- and thrust sheet top basins, like the Kamchya and Histria depressions, which have been filled with kilometres thick syn-tectonic Paleogene sediments (Fig. 2, Dachev et al., 1988; Doglioni et al., 1996; Harbury and Cohen, 1997; Munteanu et al., 2011; Stuart et al., 2011).

2.1. Along strike variations in the kinematics of inversion

The sequence of deformation observed along the Balkanides–Pontides–Western Black Sea system shows that the age of shortening is late Middle Eocene to Late Eocene in the southern Pontides–Balkanides transect, migrating gradually northwards along the Bulgarian and Romanian offshore to Late Miocene–Pliocene in the Odessa Shelf (Fig. 1, Munteanu et al., 2011). Interestingly, the amount of shortening varies along strike of the system.

Along a N–S transect in the western onshore area, the cumulated shortening of the Srednogorie, East Balkan and Central Balkan units is in the order of ~30 km, with additional 1–2 km cumulated shortening along minor offset structures observed as far north as the Peceneaga–Camena and Sfântul Gheorghe faults (Fig. 2a, Bergerat et al., 2010; Georgiev et al., 2001; Hippolyte, 2002; Stuart et al., 2011).

Along an N–S transect crossing the Pontides and the centre of the Western Black Sea Basin, the inversion cumulates the internal Pontides contraction and their thrusting over the Western Black Sea with the structures recorded in the central and northern part of the Western Black Sea basin. Although the vergence of the major structure accommodating the contraction observed between the Pontides and the Western Black Sea is not yet fully constrained as both N-