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Numerical modelling of the role of salt in continental collision: An application to the southeast Zagros fold-and-thrust belt

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A B S T R A C T

The Zagros fold-and-thrust belt formed in the collision of Arabia with Central Iran. Its sedimentary sequence is characterised by the presence of several weak layers that may control the style of folding and thrusting. We use 2-D thermo-mechanical models to investigate the role of salt in the southeast Zagros fold-and-thrust belt. We constrain the crustal and lithospheric thickness, sedimentary stratification, convergence velocity, and thermal structure of the models from available geological and geophysical data. We find that the thick basal layer of Hormuz salt in models on the scale of the upper-mantle decouples the overlying sediments from the basement and localises deformation in the sediments by trench-verging shear bands. In the collision stage of the models, basement dips with $+1°$ towards the trench. Including the basal Hormuz salt improves the fit of predicted topography to observed topography. We use the kinematic results and thermal structure of this large-scale model as the initial conditions of a series of upper-crustal-scale models. These models aim to investigate the effects of basal and intervening weak layers, salt strength, basal dip, and lateral salt distribution on deformation style of the simply folded Zagros. Our results show that in addition to the Hormuz salt at the base of the sedimentary cover, at least one intervening weak layer is required to initiate fold-dominated deformation in the southeast Zagros. We find that an upper-crustal-scale model, with a basal and three internal weak layers with viscosities between 5×10^{18} and 10^{19} Pa s, and a basement that dips $+1°$ towards the trench, best reproduces present-day topography and the regular folding of the sedimentary layers of the simply folded Zagros.

1. Introduction

1.1. Salt in the Zagros fold-and-thrust belt

The low mechanical strength of salt layers can play a fundamental role in controlling the deformation style of fold-and-thrust belts (FTBs). Where salt forms a weak base to a FTB, its low strength reduces surface slope, promotes deformation far into the foreland, and leads to a more symmetric style of thrusting characterised by forward and backward thrusts (Bahroudi and Koyi, 2003; Buiter, 2012; Costa and Vendeville, 2002; Cotten and Koyi, 2000; Dahlen, 1990; Davies and Engelder, 1985; McQuarrie, 2004). Internal salt layers may control the style of folding and faulting, depending on the thickness and strength of the salt layers (Bahroudi and Koyi, 2003; Frehner et al., 2012; Mouthereau et al., 2012; Yamato et al., 2011). Salt layers occur in several fold-and-thrust belts around the world, such as Zagros, Jura, the southern Pyrenees, and the Salt Range and Potwar Plateau (Alavi, 1994, 2004; Cotten and Koyi, 2000; Davies and Engelder, 1985). Since the Zagros is one of the largest salt diapir provinces in the world, we here use this fold-and-thrust belt as an inspiration to investigate the role of salt in continental collision.

The Zagros FTB (Fig. 1a) extends over a vast area, with a width of 200–300 km (NE–SW) and a length of ca. 1800 km (NW–SE). This orogenic system formed when Arabia separated from Africa in the late Cretaceous and converged towards Eurasia, resulting in closure of the Neo-Tethys Ocean. The Neo-Tethys Ocean opened in the late Permian (Muttoni et al., 2009; Sengör et al., 1988; Stampfli, 2000) and at the time of collision the oceanic crust was therefore old. The Main Zagros Thrust Fault (MZTF) (Figs. 1b and 2b) is assumed to represent the suture of the collision of Arabia with Central Iran. Collision-associated deformation initiated at the MZTF and propagated southwestward through time (Hatzfeld et al., 2010). The timing of continental collision in the Zagros is still debated (Agard et al., 2005; Alavi, 2004; Dercourt et al., 1986; Dewey et al., 1973; Falcon, 1974; McQuarrie et al., 2003; Scott, 1981). Agard et al. (2005) infer that collision started at about 25–23 Ma from dating Blueschist facies rocks found in the Sanandaj–Sirjan Zone (Fig. 1b), which separates the Zagros FTB from Central Iran. In contrast, arc-related magmatism in Central Iran would support initiation of collision at 34 Ma (Ballato et al., 2011; Mouthereau et al., 2012). Since the onset of collision, ca. 500–800 km of convergence has occurred and GPS measurements show that convergence is still ongoing today (Vernant et al.,

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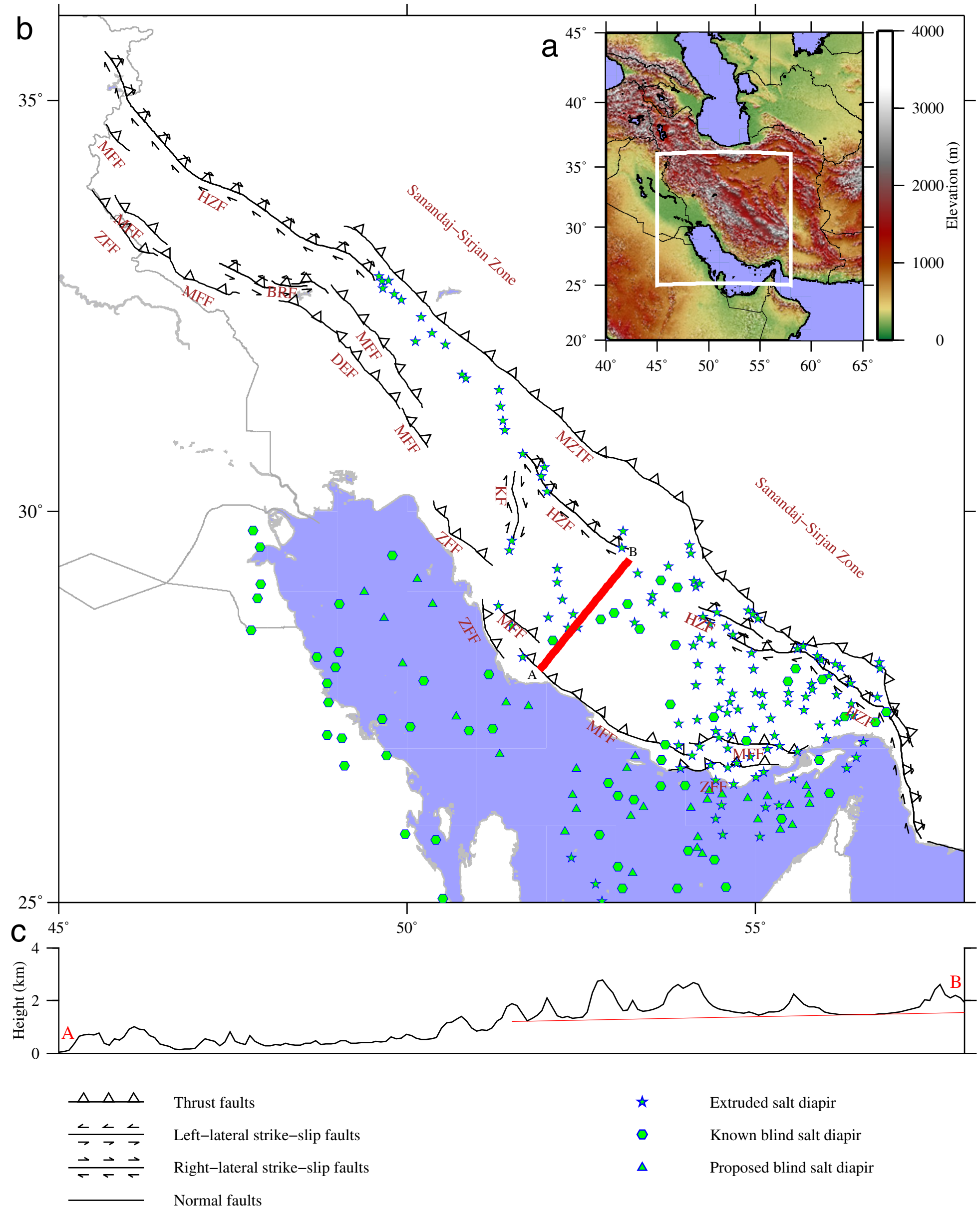

Fig. 1. a) Surface topography of the Zagros fold-and-thrust belt. Surface shaded from resampled SRTM data to 250 m resolution (Jarvis et al., 2008). b) Main structural elements of the region inside the white rectangle in a). MZTF = Main Zagros Thrust Fault, HZF = High Zagros Fault, MFF = Mountain Frontal Fault, KF = Kazerun Fault, DEF = Dezful Embayment Fault, BRF = Balarud Fault, and ZFF = Zagros Foredeep Fault. Blue circles show salt diapirs from Bahroudi and Koyi (2003). Our models can be seen as a simplified representation of a cross-section along the red line (AB). c) Present-day topography along the red line (AB) in the SE Zagros from resampled SRTM data to 250 m resolution (Jarvis et al., 2008).

2004; Hessami et al., 2006; Hatzfeld and Molnar, 2010; Hatzfeld et al., 2010).

Tomography data suggest steepening or break-off of the subducted slab in the NW Zagros, which is likely concurrent with slab break-off in Anatolia at about 12 Ma (Agard et al., 2011; Authemayou et al., 2006; Faccenna et al., 2006; Hafkenscheid et al., 2006; Regard et al., 2005; Vergés et al., 2011). However, more recent tomographic inversions imply a continuous underthrusting of the Arabian plate with a low dip angle beneath the Central Iranian block in the SE Zagros (Chang et al., 2010; Simmons et al., 2011).

Using 3D numerical models, van Hunen and Allen (2011) show that in a subduction–collision system slab break-off could start ca. 16 Myr after the onset of collision near the edge of a continental block and propagate along-strike. Their results can explain slab break-off under the NW Zagros and continuous slab underthrusting under the SE Zagros.

The NW Zagros and SE Zagros are separated by the north–south trending Kazerun fault (Hatzfeld et al., 2010). Across this fault the surface expression of salt-related deformation changes. Several salt layers were deposited on a highly metamorphosed Proterozoic basement in the SE Zagros (Alavi, 2004; Hatzfeld et al., 2010). The presence of these weak layers between other (mechanically stronger) sedimentary layers has been shown to have a significant impact on the style of deformation in the SE Zagros by introducing detachment layers and complex salt diapir structures (Alavi, 2004; Bahroudi and Koyi, 2003; Colman-Sadd, 1978; Davies and Engelder, 1985; Talbot and Alavi, 1996; Yamato et al., 2011). In the NW Zagros such salt diapirs are absent. The Neoproterozoic–Cambrian Hormuz salt with a thickness of 1–2 km is the oldest and most important weak layer in the Zagros FTB. It rests directly on the crystalline basement (Alavi, 2004; Talbot and Alavi, 1996). Previous studies pointed out that this layer behaves as a viscous