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Towards subduction inception along the inverted North African margin of Algeria? Insights from thermo-mechanical models

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ABSTRACT

While ocean subduction at continental margins is a prominent process of plate tectonics, understanding how and where it begins is still being debated, especially because examples of emerging ocean–continent subduction in the world are rare. Northern Algeria is currently undergoing a slow compression deformation due to the ongoing African–Eurasian convergence. Active compressional seismic activity recorded both on land and at sea indicates that the margin might be transitioning from a passive stage to an active one.

In order to test this hypothesis, we perform thermo-mechanical models of margin inversion. Varying thermal and rheological parameters as well as the geometry of the margin boundary, we find that tectonic inversion of a young passive margin localizes at the margin toe only if the latter is strongly heated (i.e., with an abrupt thermal gradient between oceanic and continental lithospheres); otherwise, deformation propagates into the weak, hot oceanic lithosphere. The presence of a thinned continental crust at the ocean–continent transition favors either subduction of the oceanic lithosphere when the transition zone plunges towards the continent, or an indentation of the lower continental crust by the oceanic lithosphere when the transition zone is vertical. If the oceanic lithosphere is directly in contact with the continental margin, subduction-like deformation occurs during the early stages of the model but rapidly gives place to intra-oceanic buckling and faulting.

Comparing the results of the simulation to the active tectonic structures of the Algerian margin, we conclude that both processes (emerging subduction or indentation) are possible and that the presence of a thermal anomaly beneath the thinned continental margin is probable, in relation with slab rupture at depth or with other thermal weakening processes.

1. Introduction

North Algeria is currently undergoing a slow compressional deformation due to the convergence between Africa and Eurasia. Horizontal movements resulting from this convergence are today absorbed in large part by the deformation of the North Algerian margin (Frizon de Lamotte et al., 2011), as evidenced by the seismicity recorded both on land and at sea (Meghraoui et al., 2004). Part of this deformation (estimated at one third or half of the total deformation, i.e., 1 to 2 $\mathrm{mm\,yr^{-1}}$ according to Serpelloni et al., 2007) is located near the margin toe and results into the downward bending of the oceanic plate against the continental plate, with an isostatic signature similar to that of an active margin (Hamai et al., 2015). The North African margin in Algeria can therefore be considered as in a transitional stage between active and passive margin settings and is ideally suited to study the way subduction initiates at continental margins.

A large number of studies have focused on the parameters controlling subduction inception (e.g., Cloetingh et al., 1982; Goren et al., 2008; Hall et al., 2003; Leng and Gurnis, 2011; Marques et al., 2014; Niu et al., 2003; Stern, 2004; Stern and Gerya, 2017; Toth and Gurnis, 1998). For instance, Stern (2004) examined how subductions can theoretically initiate depending on the far-field kinematic conditions ("induced" subduction) or on local (body) forces ("spontaneous" subduction). A type of spontaneous subduction occurs when the lithosphere reaches negative buoyancy due

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to cooling and starts to subduct by itself. However, the progressive increase of the total strength of the oceanic lithosphere with time should limit its flexural deformation and therefore the triggering of subduction (Cloetingh et al., 1982; Gurnis et al., 2004; Leroy et al., 2008). Numerical models of intra-oceanic subduction use thermal or compositional buoyancy contrasts within the oceanic lithosphere to localize deformation (e.g., Leng and Gurnis, 2011; Niu et al., 2003). When subduction initiates at the ocean–continent transition (OCT), chemical and thermal buoyancy contrasts between the oceanic and continental lithosphere, as well as differential sediment loading or stress transfer from a nearby collision zone, are often invoked to play a key role (e.g., Cloetingh et al., 1982; Goren et al., 2008; Marques et al., 2014; Nikolaeva et al., 2010). Weakening processes (shear heating, increase of water content) in deforming zones then contribute to the development of a long-lived plate boundary (e.g., Regenauer-Lieb et al., 2001; Thielmann and Kaus, 2012). Most authors also point out the importance of well-oriented, pre-existing weak zones in the initiation of subduction. In intra-oceanic settings, these may be transform faults or fracture zones (Hall et al., 2003; Toth and Gurnis, 1998), while in the case of ocean–continent subduction, the OCT could bear suitable weak zones inherited from the former passive margin structure (e.g., Goren et al., 2008).

The inception of subduction along an OCT, i.e., the transition from a passive to an active margin (similar to North Algeria) therefore depends not only on the age of the oceanic plate or on the boundary conditions, but on a combination of various parameters, including the rheological properties of the lithosphere, thermal instabilities and/or potential areas of weakness inherited from the geodynamical history of the study area. In these conditions, the combination of numerical models with a well-constrained (structure geometry, thermal history) natural example of incipient subduction could help deciphering the conditions leading to the initiation of a subduction.

In this study, we use the thermo-mechanical code pTatin2D (May et al., 2014, 2015) to test the effect of thermal and rheological parameters on the tectonic inversion of a passive margin characterized by a young, hot oceanic domain adjacent to a cooler continental plate, following a setting similar to the North Algerian margin. We try to address the following questions: i) what rheological and thermal parameters control compressional strain localization at the foot of the former passive margin? ii) are those parameters suitable for a long-term evolution of the North Algerian margin towards a mature subduction zone?

2. Tectonic setting of the Algerian margin and SW Mediterranean

The Algerian margin, which bounds the Algero-Provencal basin, formed in Miocene times in a back-arc setting in response to the southward retreat of the Tethyan slab (Jolivet and Faccenna, 2000; Rosenbaum et al., 2002). Slab roll-back ended with the collision between European-derived continental blocks (AlKaPeCa) and the North African continent (Frizon de Lamotte et al., 2000; Lonergan and White, 1997; Mauffret et al., 2004). A first stage of opening of the Algerian basin is assumed to occur from 35 Ma to 16 Ma in a north–south direction and was followed by an east–west opening from 16 to 8 Ma, i.e. parallel to the margin strike (Mauffret et al., 2004; van Hinsbergen et al., 2014). During that second stage, the North Algerian continental margin has probably been heated up by the adjacent hot oceanic lithosphere (Chazot et al., 2017). Since the upper Tortonian, the still ongoing convergence between Africa and Europe results into a tectonic inversion of this margin, as evidenced by numerous strike-slip and compressional focal mechanisms and by the deformation of late Miocene to Pliocene sediments on the continental margin, both on-shore and off-shore (Meghraoui et al., 2004; Déverchère et al., 2005; Mauffret, 2007; Strzerzynski et al., 2010; Arab et al., 2016) (Fig. 1). Recently, an analysis of the flexural state of the lithosphere along 4 margin-perpendicular wide-angle seismic profiles evidenced an isostatic anomaly close to that of typical active margins on at least two of those profiles (Jijel and Greater Kabylia, Fig. 1 and Hamai et al., 2015). This study shows that the continental and oceanic parts behave as two different plates with opposite senses of flexure, on both sides of a weak zone located at the margin toe, which may be inherited from the structuration of the former passive margin, or from a posterior thermal event due to slab break-off. Moreover, deep seismic sections processed and interpreted off Algeria (Déverchère et al., 2005; Aidi et al., 2018; Leprêtre et al., 2013; Mihoubi et al., 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Arab et al., 2016) provide straightforward evidences that the central and eastern Algerian margin and the adjoining OCT (and sometimes also the deep oceanic basement of the basin) are actively deforming and faulted by a set of south-dipping active thrusts rooted in the mid- to lower continental crust. The onland margin also evidences recent uplift of ∼400–1000 m (Strzerzynski et al., 2010; Authemayou et al., 2017).

In North Algeria, a new set of offshore geophysical data gathered since 15 years testify that a compressional strain reactivates large-scale structures inherited from the passive margin stage (Medaouri et al., 2014; Bouyahiaoui et al., 2015), among which the OCT. In the literature, the OCT in non-volcanic margins is often defined as the area where sub-continental mantle is exhumed and serpentinized (e.g., Brun and Beslier, 1996). However, wide-angle seismic velocity models of the North Algerian margin show that, in contrast to such "classic" passive margins of the so-called hyper-thinned Atlantic type (e.g., Sutra and Manatschal, 2012; Peron-Pindivic et al., 2013), the OCT is very narrow (<20 km) and depicts intermediate velocities between oceanic and continental crusts (Aidi et al., 2018; Badji et al., 2015; Bouyahiaoui et al., 2015; Leprêtre et al., 2013; Mihoubi et al., 2014). These intermediate velocities could be merely due to the low lateral resolution of the velocity models, suggesting the that the OCT (in its classical definition of exhumed sub-continental mantle) is either absent or very narrow, due to the transform character of the North Algerian passive margin formation, at least in its western part. Therefore, it is unlikely that a large body of exhumed and serpentinized mantle at the ocean–continent transition could play the role of an inherited weak zone during the recent inversion of the North Algerian margin.

Besides this weak zone, the presence of a thermal anomaly at the Algerian margin could also have helped localizing compressional deformation. Indeed, several studies point that a thermal perturbation of the mantle along the margin could have been caused by (1) the detachment of the Tethian slab responsible for important coastal magmatism in early Miocene times (Carminati et al., 1998; Faccenna et al., 2004; Spakman and Wortel, 2004; Chazot et al., 2017), and (2) the westward propagation of a lateral slab tear at depth, forming a STEP (Subduction Transform Edge Propagator) fault along the Western Algerian margin (Badji et al., 2015; Govers and Wortel, 2005; Leprêtre et al., 2013; Medaouri et al., 2014). Van Hinsbergen et al. (2014) propose that another STEP fault propagated eastward between the East Algerian margin and the Calabrian arc (Fig. 1). Tomographic models by Spakman and Wortel (2004) and Fichtner and Villaseñor (2015) evidence negative velocity anomalies at sublithospheric depths, suggesting the presence of a hot mantle beneath the North Algerian margin and the Algerian basin. Koulakov et al. (2009) show that this thermal anomaly is relatively important both in height (>200 km in vertical) and in width (∼100 km). Fichtner and Villaseñor (2015) image in detail the shape of this thermal anomaly, which seems much larger westwards, close to the Alboran block, than in the center of the margin. The onset of calco-alkaline and