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Effects of lateral variations of crustal rheology on the occurrence of post-orogenic normal faults: The Alto Tiberina Fault (Northern Apennines, Central Italy)

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ABSTRACT

The Northern Apennines (NA) are characterized by formerly compressive structures partly overprinted by subsequent extensional structures. The area of extensional tectonics migrated eastward since the Miocene. The youngest and easternmost major expression of extension is the Alto Tiberina Fault (ATF). We estimate 2D rheological profiles across the NA, and conclude that lateral rheological crustal variations have played an important role in the formation of the ATF and similar previously active faults to the west. Lithospheric delamination and mantle degassing resulted in an easterly-migrating extension-compression boundary, coinciding at present with the ATF, where (i) the thickness of the upper crust brittle layer reaches a maximum; (ii) the critical stress difference required to initiate faulting at the base of the brittle layer is at a minimum; and (iii) the total strengths of both the brittle layer and the whole lithosphere are at a minimum.

Although the location of the fault is correlated with lithospheric rheological properties, the rheology by itself does not account for the low dip (~20°) of the ATF. Two hypotheses are considered: (a) the low dip of the ATF is related to a rotation of the stress tensor at the time of initiation of the fault, caused by a basal shear stress (~100 MPa) possibly related to corner flow associated with delamination; or (b) the low dip is associated to low values of the friction coefficient (≤ 0.5) coupled with high pore pressures related to mantle degassing.

Our results establishing the correlation between crustal rheology and the location of the ATF are relatively robust, as we have examined various possible compositions and rheological parameters. They also provide possible general indications on the mechanisms of localized extension in post-orogenic extensional setting. The hypotheses to account for the low dip of the ATF, on the other hand, are intended simply to suggest possible solutions worthy of further study.

1. Introduction

The Alto Tiberina Fault (ATF, Northern Apennines, Central Italy; see Fig. 1) was originally imaged by the CROP03 deep seismic reflection profile (Pialli et al., 1998). It has been widely studied over the last few years in order to understand its role in the present-day deformation and seismicity of the Northern Apennines (cf. e.g. Barchi et al., 1999; Boncio et al., 2000; Collettini and Barchi, 2002; Piccinini et al., 2003; Chiaraluce et al., 2007; Mirabella et al., 2011).

The ATF is the westernmost E to NE-dipping low-angle normal fault along the Northern Apennines and represents the response to regional extension that has been a continuous process since middle Miocene, following convergence beginning in Late Oligocene – Early Miocene, with the compression-extension front migrating progressively from west to east (Fig. 1). The ATF is thought to be the main structure accommodating extension in the region at the present time, even if few large earthquakes have been documented on or near the fault for > 2 ka (Hreinsdóttir and Bennett, 2009), with most seismicity concentrated on antithetic normal faults. The geometry of the ATF is clearly defined by geological, seismic, and borehole data (e.g. Boncio et al., 1998, 2000; Barchi et al., 1998; Collettini, 2002; Collettini and Barchi, 2002; Chiarabba et al., 2005; Moretti et al., 2009; Chiaraluce et al., 2014, 2017). It has an average dip of 20°, normal displacement, and cuts the entire upper crust, lowering the base of the sedimentary cover from 5 to 6 km to the west down to about 10 km to the east (Barchi et al., 1998).

Receiver function analysis (Piana Agostinetti and Amato, 2009; Bianchi et al., 2010), seismic refraction (Ponziani et al., 1985) and geological studies (Barchi et al., 2006 and references therein) show that

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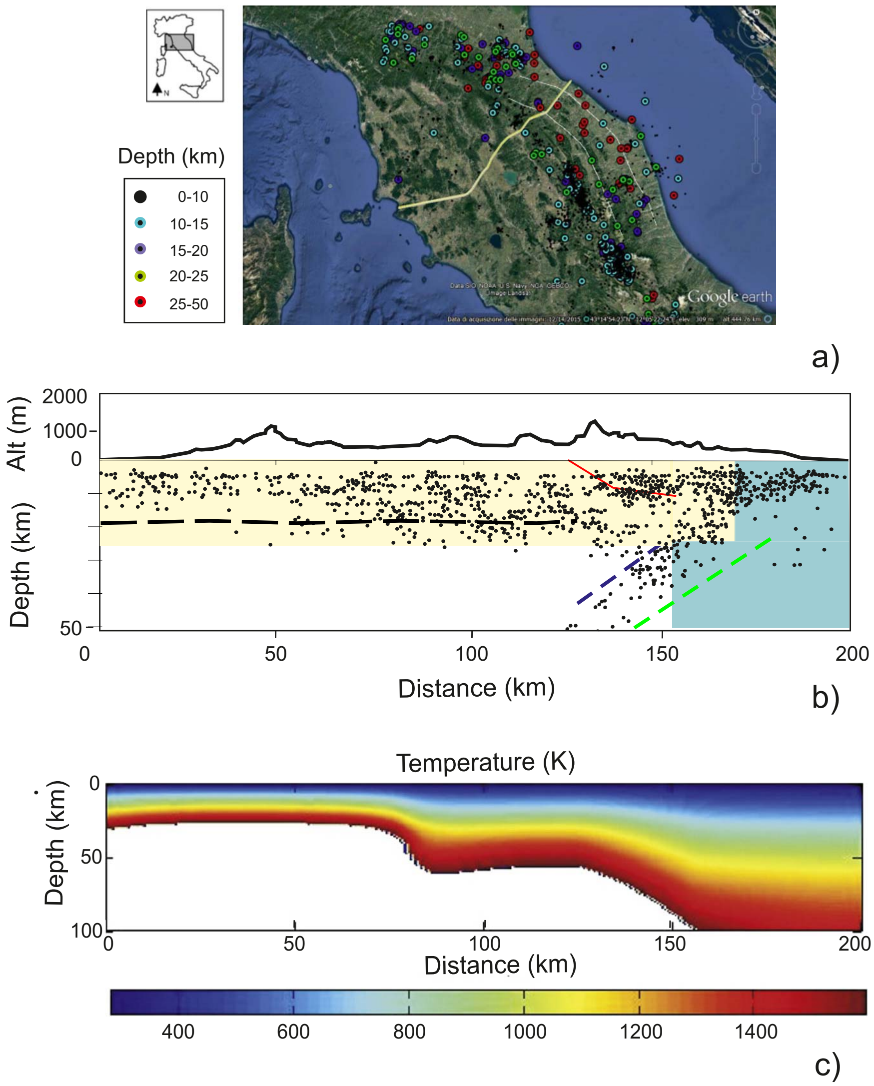

Fig. 1. (a) Location map with distribution of seismicity (from ISIDe, 2016; Chiarabba et al., 2015); yellow line is the trace of the CROP03 profile (Pialli et al., 1998). (b) Cross section along CROP03 (with origin on the Tyrrhenian coast). Dots represent earthquake foci (Chiarabba et al., 2015); dashed lines denote the schematic position of the Moho (modified from Piana Agostinetti et al., 2011): different colors indicate different sources: blue from Roselli et al., 2008; Piana Agostinetti et al., 2002 and Piana Agostinetti and Amato, 2009; green from Mele and Sandvol, 2003. The red thin line is the trace of the ATF from CROP03 interpretation (Pauselli et al., 2006). Areas of crustal extension: yellow; compression: blue (Lavecchia et al., 1994); (c) estimated distribution of temperature along the profile (Pauselli et al., 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the area in which the ATF is located is a transitional domain where a Moho doubling is present (Fig. 1). This area separates a western "Tyrrhenian domain" (TD), where extensional deformation has affected the pre-existing compressional belt, and an eastern "Adriatic domain" (AD), where the compressional structures are still preserved. The TD shows a strong reduction in lithospheric thickness (30–40 km; Calcagnile and Panza, 1981; Suhaldolc and Panza, 1989; Amato and Selvaggi, 1991; Selvaggi and Amato, 1992) reflected in the high surface heat flow (~150 mW m^{-2}) and positive Bouguer anomalies (Marson et al., 1998). The AD is characterized by a lithospheric thickness of about 70 to 90 km, with relatively low heat flow (between 40 and 70 mW m^{-2}), negative Bouguer anomalies, and shallow seismic events (< 10 km deep), with strike-slip and thrust solutions, indicating active compression in the more external areas of the domain. Different seismicity is present below the main ridge of the Apennines at different depths. Moderate earthquakes related to extensional faults are found at upper crustal levels (7–15 km deep). A light to moderate seismicity, probably compressive in character, is localized in deeper, subcrustal levels (30–90 km; Amato and Selvaggi, 1991).

In this paper, we explore the rheological conditions in the lithosphere correlated with the formation of new E-dipping low-angle normal faults in the Northern Apennines. After a brief review of the geodynamic framework, we focus on (i) the rheology of the crust and lithosphere across the extension-compression transition; and (ii) the role of the bulk rheology of the crust in the formation of the ATF. We also explore possible hypotheses which could account for the formation of low-angle normal faults.

Our approach uses standard rheological methodology, but goes further than previous analyses based solely on strength envelopes, by focusing on the correlation between three rheological factors (thickness of the topmost brittle layer, its total strength, and critical shear stress at its base) that play a part in the location of the ATF. The results may be of general applicability to other post-orogenic, delamination-related extensional faults.

2. Geodynamic framework

The occurrence of a Tyrrhenian extensional domain (TD) coupled with an Adriatic compressional domain (AD), the two being separated by an eastward-migrating delamination front (and consequent slab retreat) is well supported by geological and geophysical data. The early model by Channell and Mareschal (1989) has been supported by many recent models (Ueda et al., 2012; Duretz and Gerya, 2013). The Northern Apennines are an example of "decoupled collision zones" in the sense of Faccenda et al. (2009). The large-scale picture has been studied by seismic tomography (e.g., Di Stefano et al., 2009), which shows clearly that a significant part of the lower crust has been subducted, and that hot, upraised asthenosphere occupies the mantle wedge between TD and AD.

Although interpretations have been proposed (D'Agostino et al.,