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Active tectonics of the outer northern Apennines: Adriatic vs. Po Plain seismicity and stress fields

Stefano Mazzoli[a,*], Stefano Santini[b], Chiara Macchiavelli[c], Alessandra Ascione[a]

[a] Dipartimento Scienze della Terra, Università di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy
[b] Dipartimento di Scienze di Base e Fondamenti, Sezione di Fisica, Università di Urbino "Carlo Bo", Via Santa Chiara 27, 61029 Urbino, Italy
[c] Scuola di Scienze e Tecnologie, Università di Camerino, Via Gentile III da Varano, 62032 Camerino (MC), Italy

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ABSTRACT

The recent earthquake sequences of 2012 (northern Italy) and 2013 (Marche offshore) provided new, fundamental constraints to the active tectonic setting of the outer northern Apennines. In contrast to the Po Plain area, where the 2012 northern Italy earthquakes confirmed active frontal thrusting, the new focal mechanisms obtained in this study for the 2013 Marche offshore earthquakes indicate that only minor thrust fault reactivation occurs in the Adriatic domain, even for a theoretically favourably oriented maximum horizontal compression. Recent seismicity in this domain appears to be mainly controlled by transcurrent crustal faults dissecting the Apennine thrust belt. The along-strike stress field variation from the Po Plain to the Adriatic area has been quantitatively investigated by applying the multiple inverse method (MIM) to the analysis of the entire seismicity recorded from January 1976 to August 2014, from the top 12 km of the crust (fault plane solutions from 127 earthquakes with $M_W \geq 4$), allowing us to obtain a comprehensive picture of the state of stress over the outer zone of the fold and thrust belt. The present-day stress field has been defined for 39 cells of $1.5^\circ \times 1.5^\circ$ surface area and 12 km depth. The obtained stress field maps point out that, although the entire outer northern Apennines belt is characterized by a sub-horizontal maximum compressive axis (σ_1), the minimum compression (σ_3) is sub-vertical only in the Po Plain area, becoming sub-horizontal in the Adriatic sector, thus confirming that the latter region is dominated by an active tectonic regime of strike-slip type.

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1. Introduction

The Apennine mountain belt in the central Mediterranean region (Fig. 1a) is generally considered as a World-class example – or even the paradigm – of 'paired' tectonic belt, characterized by hinterland extension balancing shortening in the frontal part of the orogen (Butler et al., 2004, and references therein). The most widely accepted explanation for this behaviour lies in the process of rollback of the foreland (Adria) lithosphere as a result of slab pull (Faccenna et al., 2001) and/or eastward mantle flow (Doglioni et al., 2007). However, the rollback process has progressively interacted with – and has been substantially affected by – slab breakoff (Spakman and Wortel, 2004). Although various modes and timing of slab detachment beneath the Apennines have been proposed (van der Meulen et al., 1998, 1999, 2000; Rosenbaum et al., 2008), the integration of seismic tomography evidence with robust geological data indicate that this process has become increasingly more important during the Pleistocene (Ascione et al., 2012). Slab breakoff and associated rebound of the foreland lithosphere resulted in extension affecting the axial zone of the Apennine chain, where the main active structures consist of dominantly NW-SE striking normal faults bounding Quaternary continental basins (e.g. Galadini et al., 2000; Caiazzo et al., 2006; Ascione et al., 2007, 2013; Spina et al., 2008; Faure Walker et al., 2012, and references therein). For the southern Apennines, apart from a few exceptions (e.g. Catalano et al., 2004; Ferranti et al., 2009), it is widely accepted that extension became dominant since ca. 0.7 Ma and is still acting over the whole chain including the outer zones, as shown by breakout data and seismicity (Montone et al., 2004, 2012; Frepoli et al., 2011; Pierdominici and Heidbach, 2012), as well as by geological and tectonic geomorphology analyses (e.g. Cello et al., 1982; Cinque et al., 1993; Hippolyte et al., 1994; D'Agostino et al., 2001; Villani and Pierdominici, 2010). The active tectonics and seismotectonic behaviour of the outer zones of the northern Apennines is much more controversial. On one hand, the 2012 northern Italy earthquakes testified active thrusting in the Po Plain area (Fig. 1b). On

* Corresponding author. Tel.: +39 0812538121; fax: +39 0812538121.
E-mail address: stefano.mazzoli@unina.it (S. Mazzoli).

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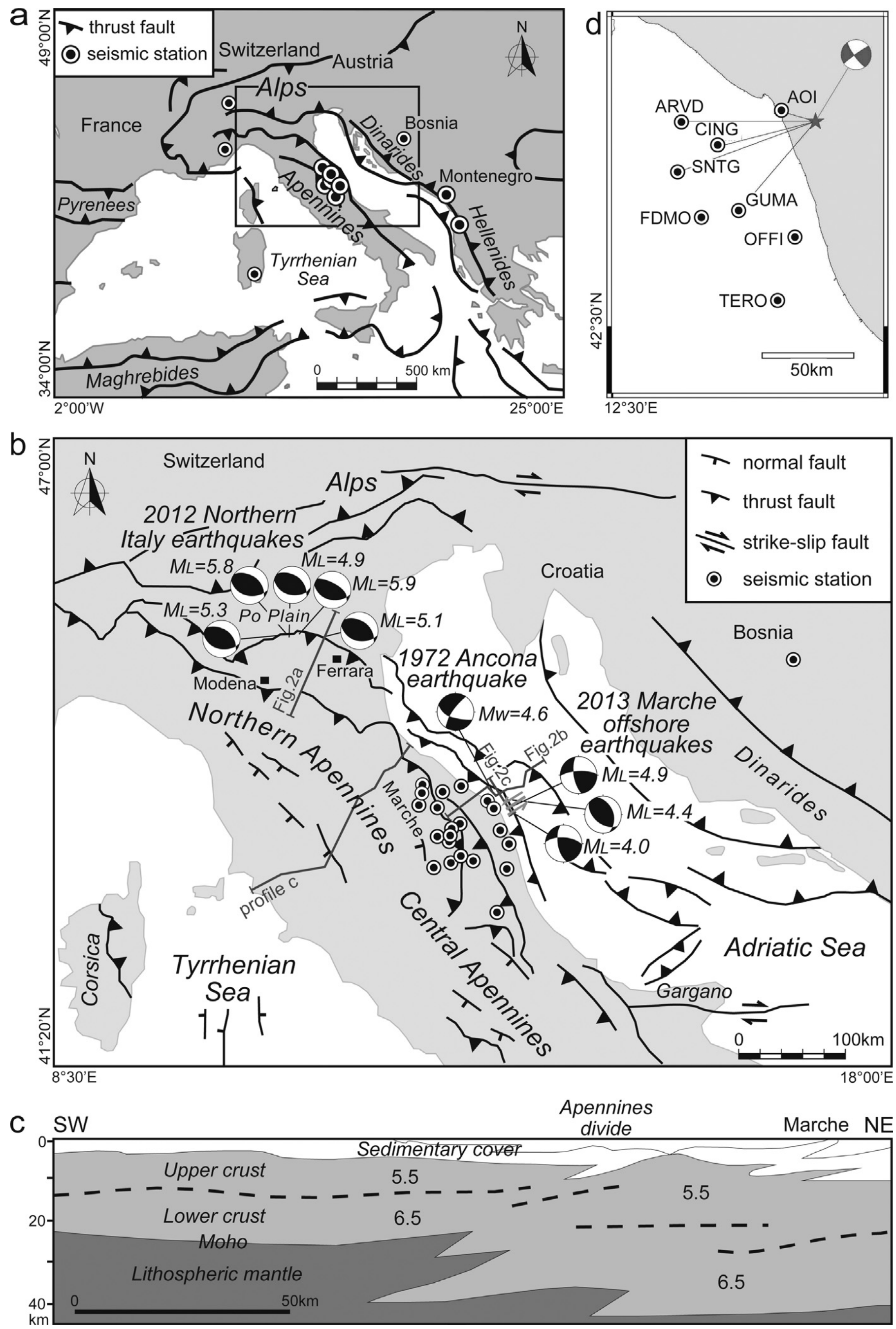

Fig. 1. (a) Tectonic sketch map of the central Mediterranean region, showing main Alpine features (after Piccardi et al., 2011) and location of the seismic stations used for the seismological analysis of the 2013 Marche offshore earthquakes. (b) Tectonic sketch map (after Mazzoli et al., 2014) showing focal mechanisms for the five largest events of the 2012 northern Italy earthquakes (INGV data, available at http://www.globalcmt.org/CMTsearch.html) and for the three largest events of the 2013 Marche offshore earthquakes (calculated and relocated in this study). Grey left-lateral strike-slip fault is the seismogenic structure (*Conero offshore wrench fault*) interpreted by Mazzoli et al. (2014) to have generated the 2013 seismic sequence. Focal mechanism for the M_W = 4.6 main shock of the 1972 Ancona earthquake (Gasparini et al., 1985; Rovida et al., 2011) is also shown, together with location of seismic stations. (c) Seismic-velocity model of the CROP 3 deep seismic reflection profile through the northern Apennines (modified after Morgante et al., 1998). V_P values are km/s. Dashed line represents the base of the upper crust, which is at a depth of ca. 20 km along the Adriatic coast. (d) Focal mechanism computed by INGV (http://cnt.rm.ingv.it/data_id//4004047121/map_dmt_review.pdf) for the M_W = 3.4, August 9, 2014 event. Seismic stations (triangles) are listed in Table 1.

the other hand, the 2013 Marche offshore earthquakes (Mazzoli et al., 2014) confirmed a more complex tectonic behaviour of the Adriatic sector of the outer northern Apennines already suggested by Macchiavelli et al. (2012) and Pierdominici and Heidbach (2012). There, focal mechanisms for events preceding the 2013 earthquakes were characterized by a wide range of orientation of P and T axes, and included thrust, strike-slip and extensional fault plane solutions (e.g. Gasparini et al., 1985; Zollo et al., 1995; Frepoli and Amato, 1997, 2000; Mariucci et al., 1999; Selvaggi et al., 2001; Di Bucci et al., 2003; Santini et al., 2011; Macchiavelli et al., 2012). Furthermore, thrusts buried beneath the Adriatic Sea appear to be sealed by undeformed Middle-Upper Pleistocene deposits (e.g. Bally et al., 1986; Coward et al., 1999; Di Bucci and Mazzoli, 2002; Di Bucci et al., 2003; Tozer et al., 2006; Bigi et al., 2013).

The aim of this paper is that of providing a comprehensive analysis of the present-day stress field affecting the various

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