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Seismic sources and stress transfer interaction among axial normal faults and external thrust fronts in the Northern Apennines (Italy): A working hypothesis based on the 1916–1920 time–space cluster of earthquakes

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ABSTRACT

In this study we analyse the main potential seismic sources in some axial and frontal sectors of the Northern Apennines, in Italy. This region was hit by a peculiar series of earthquakes that started in 1916 on the external thrust fronts near Rimini. Later, in 1917–1921, seismicity (up to Mw ≈ 6.5) shifted into the axial zone and clearly migrated north-westward, along the belt of active normal faults. The collection of fault-slip data focused on the active normal faults potentially involved in this earthquake series. The acquired data allowed us to better characterize the geometry and kinematics of the faults. In a few instances, the installation of local seismic networks during recent seismic sequences allowed the identification of the causative faults that are hinted to be also responsible for past earthquakes, particularly in the Romagna region and north-eastern Mugello. The Coulomb stress changes produced by the historical earthquakes generally brought closer to failure all the faults that supposedly caused the main seismic events of 1916–1921. However, the stress change magnitude is generally small and thus the static stress interaction among the main seismic sources is not supported by a significant seismic correlation. Significant stress change loading may be instead inferred for the triggering of a number of seismic events on neighbouring normal faults by the Garfagnana 1920 earthquake. In addition, the computation of the seismic stress changes suggests that seismic events with magnitude ≥ 6 may transmit stresses from the axial normal faults to specific external thrusts and vice versa. It is possible that a correlation may be made between loading applied by the major 1917–1920 extensional ruptures and the increased seismicity on the distal external thrusts.

1. Introduction

Long-term seismic activity is clearly governed by geodynamic processes resulting from interactions along plate boundaries. On the other hand, different seismic sources may interact with each other in the short-to-middle term by transferring static and dynamic stresses produced during earthquakes. Mutual interaction and stress transfer between seismogenic structures with different kinematics and also between faults and volcanoes have long been identified (e.g., King et al., 1994; Nostro et al., 1998; Lin and Stein, 2004; Lin et al., 2011). Here, we focus on the Northern Apennines fold-and-thrust belt, where the seismicity is essentially caused by active thrusting along the external Adriatic fronts and by normal faulting along the axial zone of the belt, which is about 40–60 km far from the former sector (Fig. 1a; e.g., Basili et al., 2008; DISS Working Group, 2015). The axial sector is characterized by a belt of Quaternary intramontane basins that bound the main watershed to the southwest. This area represents the major seismic zone of the Northern Apennines, where a few historical earthquakes have reached a macroseismically-derived magnitude of Mw ≈ 6.5 (Rovida et al., 2011). The highest macroseismic magnitude estimated along the external thrust fronts is of Mw ≈ 6.1 instead.

A sequence of moderate-to-strong seismic events hit the Northern Apennines and clustered in the period between 1916 and 1920 (Fig. 1b). This earthquake cluster started with an intense series of earthquakes along the external compressive fronts, which culminated in two main seismic events of Mw ≈ 6–6.1 (May and August 1916). The location of the main shocks then shifted into the axial sector: here the main seismic events showed a clear time–space migration from southeast to northwest, as indicated by the macroseismically-derived earthquake

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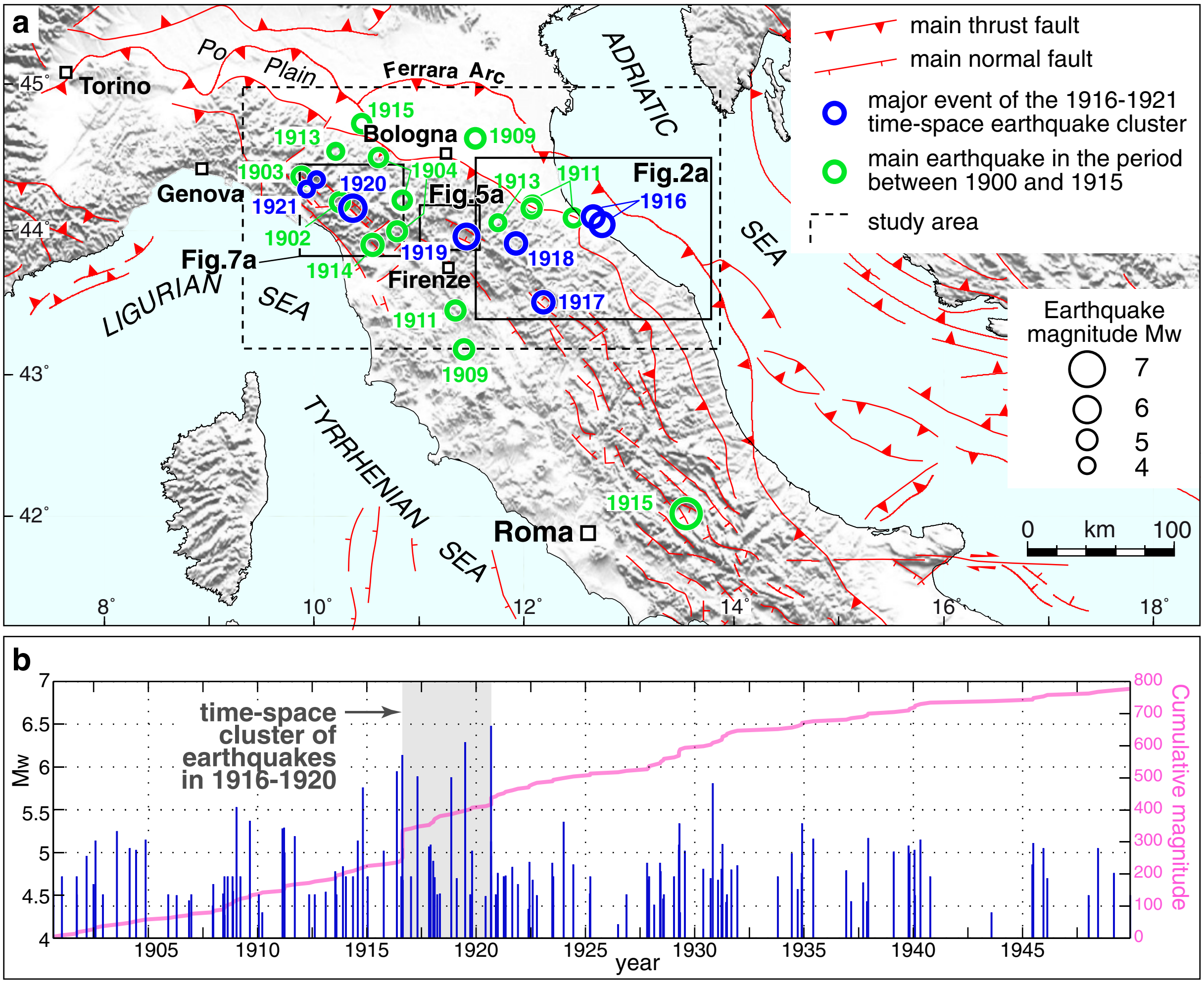

Fig. 1. Time–space cluster of earthquakes that hit the Northern Apennines (Italy) between 1916 and 1921. The open blue circles indicate the epicentres of the 1916–1921 main earthquakes. The open green circles indicate the main seismic events ($Mw \geq 5 \pm 0.25$) within the study area (dashed black box) in the period between 1900 and 1915 (thus before the main 1916–1921 earthquake cluster) (macroseismic data from Rovida et al., 2011). (b) Magnitude Mw of earthquakes in the period between 1900 and 1950 in the Northern Apennines, plotted against the cumulative magnitude (purple line). Note the marked step in the cumulative magnitude in 1916. The seismicity is calculated over the study area (dashed black box in panel a).

parameters (CPTI11; Rovida et al., 2011) by using the boxer code after Gasperini et al. (1999, 2010). These events are represented by the $Mw \approx 5.9$ Valtiberina earthquake of April 26, 1917, the $Mw \approx 5.9$ Romagna earthquake of November 10, 1918, the $Mw \approx 6.3$ Mugello earthquake of June 29, 1919, and the $Mw \approx 6.5$ Garfagnana earthquake of September 7, 1920 (Fig. 1a). Two earthquakes with $Mw \approx 4.7$ occurred in 1921 northwest of Garfagnana (Lunigiana). Although their magnitude is smaller than that of the 1917–1920 events, they denote a clear progression of the normal faulting toward the northwest (Fig. 1a). Therefore we consider such events as the continuation of the series of earthquakes along the axial zone.

The large release of seismic energy in such a relatively short time span may suggest an interaction among the various seismic sources, and also indicate that the main earthquakes of the cluster were triggered in some ways by previous events. In particular, published numerical models (Viti et al., 2012) of elastic-viscous post-seismic relaxation have taken into account the role of the $Mw \approx 7.0$ Avezzano earthquake that struck the Fucino basin (in the central Apennines) on January 13 1915. This seismic event occurred more than 200 km south of the fault that ruptured in 1917 (Fig. 1a), and the results of numerical modelling allowed the assumption that the Avezzano earthquake caused a significant increase of seismicity in the Northern Apennines (Viti et al., 2012), possibly in relation to a long-distance interaction between seismic sources (Mantovani et al., 2010). There is also a growing body of evidence suggesting that small permanent static stress changes in the crust due to an earthquake can accelerate the failure of neighbouring faults and trigger aftershocks and large earthquake sequences up to few fault lengths away from the epicentre area (e.g., King et al., 1994; Stein, 1999). In the present work, we explore the role that static stress changes may have played in the activation of the earthquake cluster in 1916–1921 and successive seismic events. Our aim is to use the knowledge gained from analysing the past events to develop improved future scenarios. This study may be relevant in helping understanding how earthquakes may influence the development of other earthquakes. More specifically, this study aims to explore the mutual relationships between the generation of normal earthquakes in the axial zone and the earthquakes on the external thrusts.

After reviewing the main seismic sources involved in the considered series of seismic events, we describe the method, and then we proceed in assessing the possible interactions between axial normal faults and external thrusts, and the relative roles of static stress changes.