Tectonophysics 656 (2015) 202–214

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Graviquakes in Italy

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ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form 15 June 2015
Accepted 1 July 2015
Available online 9 July 2015

Keywords:
Normal fault earthquakes
Graviquakes
Italian seismicity
Seismic volume

ABSTRACT

We discuss the mechanics of crustal normal fault-related earthquakes, and show that they represent dissipation of gravitational potential energy (graviquakes) and their magnitude increases with the involved volume (delimited by the seismogenic fault and an antithetic dilated wedge in its hangingwall), and the fault dip. The magnitude increases with the deepening of the brittle–ductile transition (BDT), which in turn enlarges the involved volume. The fault dip seems rather controlled by the static friction of the involved crustal layers. We apply the model to the extensional area of the Italian peninsula, whose geodynamics is controlled by the Alpine and Apennines subduction zones. The latter has a well-developed backarc basin and a large part of the accretionary prism is affected by on-going extensional tectonics, which is responsible for most of peninsular Italy seismicity. Analyzing the seismic record of the Apennines, the length of seismogenic normal faults tends to be at most about 3 times the hypocenter depth. We compile a map of the brittle–ductile transition depth and, assuming a fixed 45° or 60° fault dip and a dilated wedge developed during the interseismic period almost perpendicular to the fault plane, we compute the maximum volume of the hangingwall collapsing at the coseismic stage, and estimate the maximum expected magnitude. Lower magnitude values are obtained in areas with thinner brittle layer and higher heat flow. Moreover, lower magnitude relative to those theoretically expected may occur in areas of higher strain rate where faults may creep faster due to lower frictional values.

1. Introduction

Earthquakes nucleate where pressure gradients are sufficiently large to overcome rock strength, such as at the boundary between crustal layers having contrasting rheology or at the brittle–ductile transition (BDT). Normal fault-related crustal earthquakes, like all seismic events, are controlled by friction (Marone, 1998; Niemeijer et al., 2010; Ruina, 1983; Schleicher et al., 2010), fluid pressure, strain rate, brittle–ductile transition (BDT) depth, etc. However, unlike earthquakes generated by thrusts (e.g., Cooke and Murphy, 2004) and strike–slip faults, which are fed by elastic energy, normal faults release mostly gravitational potential energy (Dahlen, 1977; Dempsey et al., 2012; Doglioni et al., 2011, 2014; Savage and Walsh, 1978) and for this reason they can be classified as graviquakes (Doglioni et al., 2015b). Since they work in favor of gravity, they show a different mechanical evolution with respect to other seismogenic faults that instead dissipate elastic energy accumulated during the interseismic period to move crustal volumes against (thrust) or at neutral (strike–slip) gravity. The magnitude of graviquakes is mostly controlled by the mass involved in the collapse at the coseismic stage (Fig. 1). The graviquake model proposed here predicts the generation of a dilated wedge, almost perpendicular to the fault plane in the upper brittle crust during the interseismic period, caused by strain partitioning between the steady-shearing mylonitic portion of the shear zone in the lower crust (e.g., Rutter, 1986) and the locked overlying portion of the fault in the upper brittle layer (Fig. 1). When the dilated wedge and the locked brittle portion of the fault cannot sustain anymore the overlying volume, the fall of it will produce the earthquake. The earthquake magnitude increases proportionally to the logarithm of the involved volume and the vertical component of slip along the fault (Fig. 1). Therefore, the bigger the falling mass and the steeper the fault, the larger will result the magnitude. Peninsular Italy, characterized by extensional tectonics and consequent normal faulting-related moderate seismicity, is used as a natural laboratory to test the validity of the graviquake model. In the past, Bath and Duda (1964) have already evidenced an empirical linear correlation between the earthquake magnitudes and the logarithm of the involved volumes.

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http://dx.doi.org/10.1016/j.tecto.2015.07.001
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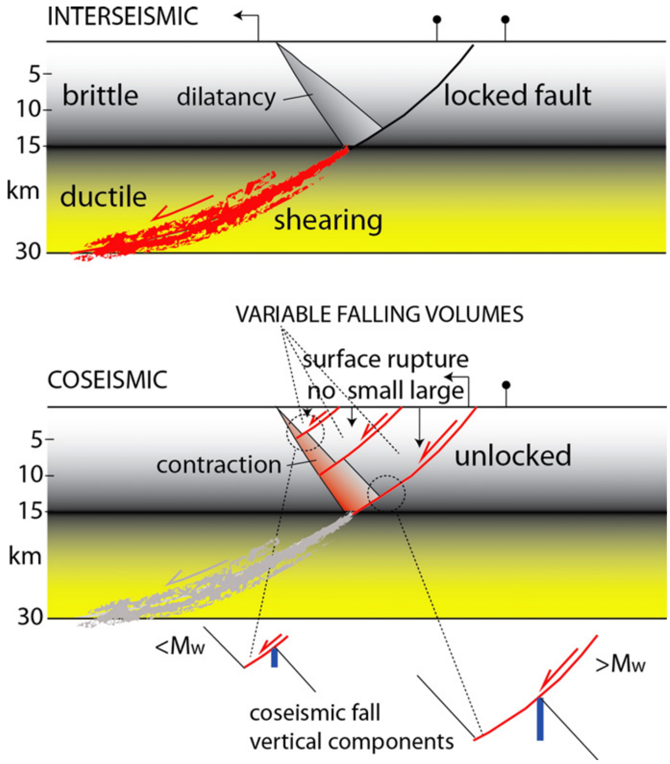

Fig. 1. Geological model of the seismic cycle associated with a normal fault. During the interseismic period, while the lower crust is shearing in a steady state, the brittle upper crust is locked and a dilating wedge is inferred. The coseismic collapse of the hangingwall will recover part of the total extension and it will be a function of the depth of the tip line of the activated normal fault. The deeper the fault, the bigger the falling volume and the larger is the fault displacement. Therefore the deeper the fault, the larger is also the vertical component of the displacement, and the larger will be the magnitude of the earthquake. Since the motion of the hangingwall mostly dissipates gravitational potential energy, we adopt the term graviquakes (Doglioni et al., 2015b).

In their case the volumes were seismologically defined as the portion of space filled by the aftershocks. We follow here a different approach, putting together different pieces of evidence with a multidisciplinary approach.

2. Seismotectonics of Italy

The Apennines formed in the hangingwall of a W-directed and easterly retreating slab (Barba et al., 2008; Carminati and Doglioni, 2012; Carminati et al., 2012). The easterly migration of the subduction system has generated a single verging accretionary prism located in the eastern flank of the Apennines, mostly buried beneath the Po Basin, the western Adriatic Sea and Ionian Sea. The accretionary prism is active as indicated by deformation of Quaternary sediments, seismicity (Fig. 2) and GPS data (Figs. 3 and 4). To the west of it, the Apennines are affected by extensional tectonics associated with backarc rifting, in which the inherited accretionary prism is crosscut by normal faults. Most of the more energetic extensional earthquakes are concentrated along the ridge of the Apennines (Fig. 2), possibly because it is characterized by the thickest and coldest crust, with maximum values of lithostatic load ($\sigma 1$) at the bottom of the brittle layer (Doglioni et al., 2015a).

2.1. Geodetic constraints

The increased number of GNSS (Global Navigation Satellite System) networks in the Italian area allows more detailed spatial and temporal resolutions of the on-going crustal deformation (Riguzzi et al., 2012, 2013), providing an unprecedent map of intra-plate kinematics of the region (Fig. 3). The current archiving and daily data processing concern 21 different Italian GNSS networks established with different aims and other 50 sites belonging to EUREF and/or IGS networks used for the ITRF2008 reference frame definition. The overall dataset comes from more than 900 GNSS sites, 1998 being the initial recording epoch.

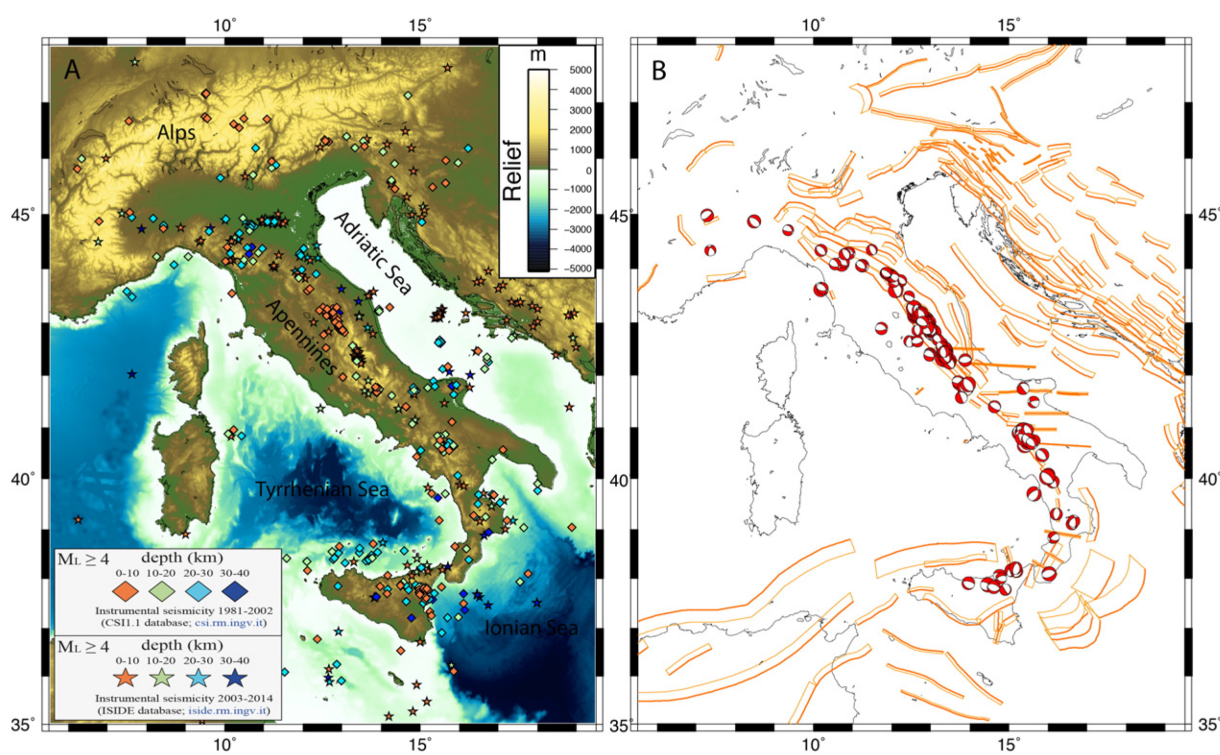

Fig. 2. A) Seismicity of the Italian area and surroundings with M > 4 (1981–2014, from CSI1.1 and ISIDE database). B) Normal fault-related earthquakes along the peninsula and Sicily, and seismogenic faults (M > 5.5) of the DISS and EDSF databases (Basili et al., 2008; Basili et al., 2013). Extensional tectonics can be inferred as related to the easterly retreating Apennines slab and associated backarc basin formation.