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Finite element modelling of stress field perturbations and interseismic crustal deformation in the Val d'Agri region, southern Apennines, Italy

Stefania Candela [a], Stefano Mazzoli [b], Antonella Megna [c], Stefano Santini [a,*]

[a] Dipartimento di Scienze di Base e Fondamenti (DiSBeF), Università di Urbino, Via Santa Chiara 27, 61029 Urbino, Italy
[b] Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), Università di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Sezione di Sismologia e Tettonofisica, via di Vigna Murata 605, 00143 Roma, Italy

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ABSTRACT

The Val d'Agri area provides the opportunity to analyse active structures in a seismic region for which a large amount of subsurface data is available. This area, which was struck in 1857 by one of the most destructive earthquakes in Italy (MW = 7.03), represents a unique natural laboratory to gain new insights into geometry, modes and rates of faulting controlling crustal deformation in an actively extending orogen. In this study, a crustal geological section through the southern Apennines is discretized into a finite element model (FEM). We present a 2D elastoplastic FEM that reproduces stress perturbations and strain field around the Val d'Agri active fault system. The influence of fault strand activity on interseismic crustal deformation is tested by a series of computer models, whose predictions are compared with the horizontal velocity components of continuous GPS sites in the region and with stress directions and geological data. The best fit with available geological and geophysical constraints is obtained with a 300 km long, 29 km deep model formed by a multilayer including three components having different rheological characteristics and including several shallow, locked fault segments, which branch into a freely slipping major basement fault at depth. Finite element modelling provides new insights into the controversial and widely debated active tectonic setting of the study area, pointing out the fundamental role played by a structural reactivation process involving inherited, long-lived, mature fault systems at depth. Our FEM, reconciling apparently contrasting geological and geophysical constraints from the study area, points to maximum stress build up and strain accumulation at a depth of 15 ± 5 km. Such a depth range is suggested as the most likely one for the nucleation of large events such as the 1857 Val d'Agri earthquake.

1. Introduction

Interseismic deformation characterising (e.g.) subduction zones and areas of large strike-slip faulting is commonly analysed by the theory of elastic dislocations (Okada, 1992) as the result of the elastic deformation of a brittle layer resting above a ductile half-space (Savage, 1983). In this framework, the brittle layer is the model thickness for which faults have a stick-slip behaviour, whereas faults in the underlying half-space are characterised by aseismic creep. A similarly layered crust, involving the presence of elastic and viscous layers, has been assumed in the analysis of a series of geological problems, such as the development of low-angle normal faults (e.g. Melosh, 1990; Westaway, 1999; Yin, 1989). In order to study subtle variations in the velocity gradients, several authors have considered a more complex vertical layering of the viscoelastic lower layer (e.g. Johnson et al., 2007; Pollitz and Nyst, 2005). Further authors have modelled interseismic deformation by finite element methods, which are able to introduce also complex lateral rheological heterogeneities (Liu et al., 2015; Vigny et al., 2009; Zun and Zhang, 2013).

In this work, a crustal geological section through the southern Apennines is discretized into a 2D elastoplastic finite element model, in order to gain new insights into the modes of active faulting and stress accumulation in a seismic area characterized by large (Mw ≈ 7) historical earthquakes. The southern Apennine mountain chain consists of a Neogene to Early Pleistocene fold and thrust belt dissected by active normal faults. These have been variably mapped as an assemblage of segments of different length and continuity (e.g. DISS Working Group, 2010; Pantosti and Valensise, 1988). The degree of linkage, both along strike and at depth, is widely debated for active normal faults in southern Italy (e.g. Amicucci et al., 2008; Ascione et al., 2013; Faure Walker et al., 2012). In the area of the present study, in particular, the subsurface kinematic and/or mechanical interaction between two outcropping fault systems has been suggested as being responsible for the nucleation of large (Mw = 7.0–7.5) earthquakes characterized by composite ruptures (Cello et al., 2003). Taking into account that fault aspect ratios (length/height) around 2 characterize vertically unrestricted faults (e.g. Soliva and Benedicto, 2005; Soliva et al., 2005), long (>30 km),

* Corresponding author at: Dipartimento di Scienze di Base e Fondamenti (DiSBeF), Sezione di Fisica, Università di Urbino, Via Santa Chiara 27, 61029 Urbino, Italy.
E-mail addresses: stefania.candela@uniurb.it (S. Candela), stefano.mazzoli@unina.it (S. Mazzoli), antonella.megna@ingv.it (A. Megna), santini@fis.uniurb.it (S. Santini).

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continuous – or discontinuous at surface but interacting in the subsurface, as in the model proposed by Cello et al. (2003) – fault zones should affect the whole depth of the seismogenic layer of the southern Apennines (as defined by Bernard and Zollo, 1989). However, substantially larger aspect ratios – up to a critical maximum value around 10 – characterize vertically confined faults observed from outcrop up to the crustal scale (e.g. Soliva et al., 2005, and references therein). Therefore, in extensional fault systems affecting preexisting fold and thrust belts such as the Apennines, which are commonly characterized by multiple décollement levels and strong rheological contrasts, even tens of kilometres long, continuous faults could actually have a limited depth extent and be restricted to a shallow structural unit (e.g. thrust sheet or stack of thrust sheets). On the other hand, short (<10 km long), discontinuous fault segments observed in map view may either be isolated (i.e. not connected in three dimensions) and confined within shallow structural levels, or they may branch into a single, continuous fault at depth (e.g. Willemse, 1997). Assuming a shallow confinement of non-linked fault segments observed in map view may be too simplistic, as the overstepping, closely spaced segments forming a normal fault array could merge vertically and be directly linked to a deeper, seismogenic basement fault.

Unravelling the geometry, degree of linkage, modes and rates of deformation of both shallow and deep portions of active faults is fundamental for different fields of geosciences, including seismic hazard studies and hydrocarbon/water/CO_2 reservoir management. The vertical continuity or confinement of faults in the subsurface strongly affects their potential as compartmentalizing structures and control their aspect ratios, which in turn substantially influence fault displacement profiles and maximum displacement-length relationships. Furthermore, rheological layering may limit displacement accumulation along normal fault segments and inhibit their growth in the vertical direction, thus exerting a major control on the propagation of normal fault earthquake ruptures (Soliva et al., 2005). The area of the upper course of the Agri River valley (Alta Val d'Agri; Basilicata, southern Italy; Fig. 1) is particularly suitable for analyzing these issues, as it hosts an active fault system and an earthquake with Imax = XI in MCS scale and estimated magnitude Mw = 7.03 struck the region in 1857 (Rovida et al., 2011 — CPTI11). There, seismological information can be effectively integrated with subsurface data – particularly seismic reflection profiles and well logs – acquired by the oil industry, thus providing a detailed, reliable description of seismogenic fault zones in the upper crust. Besides the large amount of published subsurface data (e.g. Butler et al., 2004; Carbone et al., 1991; Casero et al., 1991; Mazzoli et al., 2000, 2001; Menardi Noguera and Rea, 2000; Morandi and Ceragioli, 2002; Mostardini and Merlini, 1986; Roure et al., 1991; Shiner et al., 2004), fundamental subsurface constraints for geological modelling can now be obtained by the data included in the ViDEPI (Visibility of Petroleum Exploration Data in Italy) project (ViDEPI, 2010). This project is a collection of all

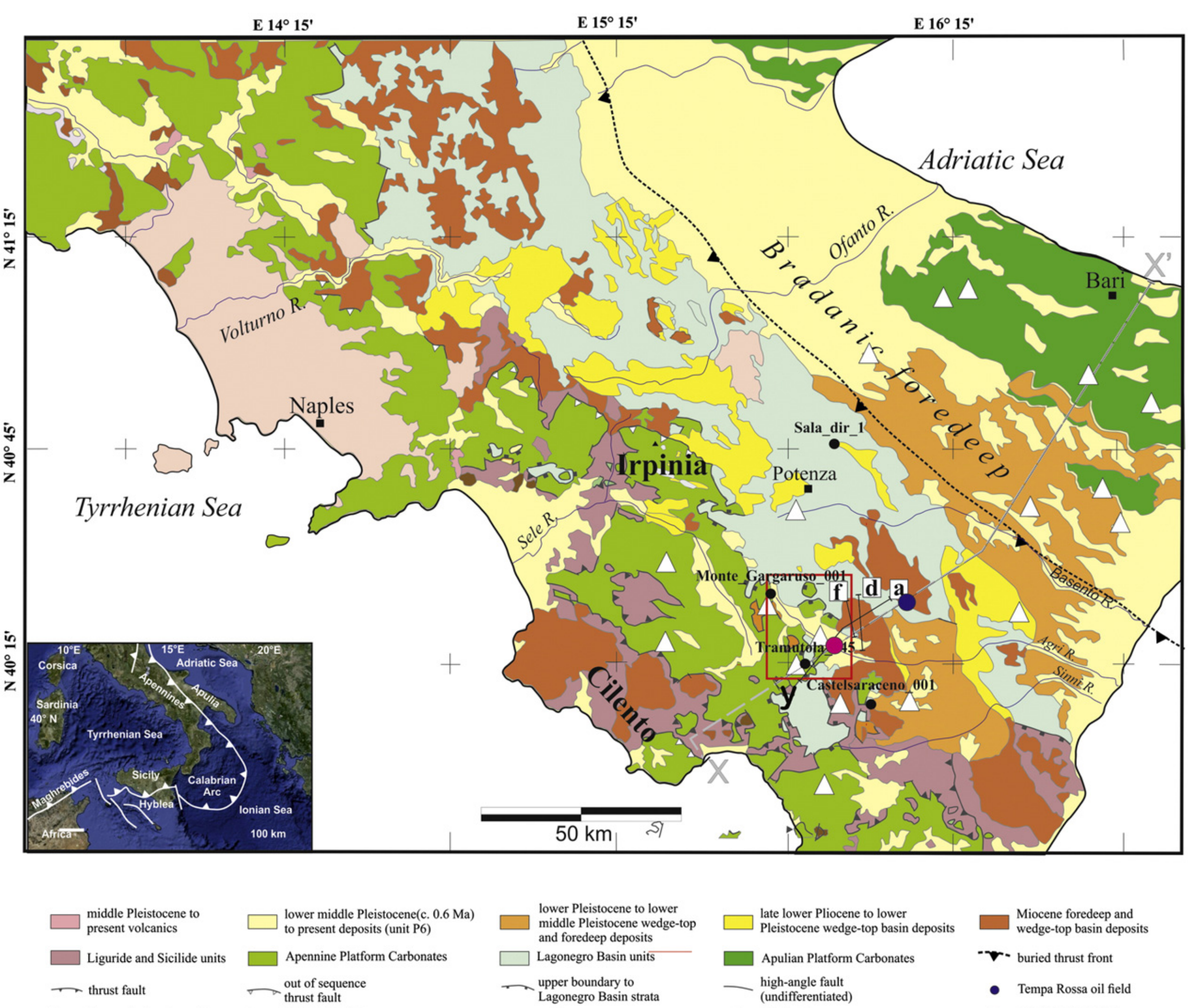

Fig. 1. Geological sketch map of the southern Apennines (after Ascione et al., 2012, modified), showing location of the map in Fig. 2 (box), trace of cross-section of Fig. 3, seismic lines of Fig. 4, sites of geotherm calculation and deep wells used for comparison with subsurface temperatures.