Tectonophysics 687 (2016) 232–244

Contents lists available at ScienceDirect

Tectonophysics

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

Slip rate depth distribution for active faults in Central Italy using numerical models

Debora Finocchio [1], Salvatore Barba, Roberto Basili *

Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

ARTICLE INFO

Article history:
Received 2 April 2016
Received in revised form 23 July 2016
Accepted 28 July 2016
Available online 30 July 2016

Keywords:
Slip rate
Numerical model
Fault
Rheology
Central Italy

ABSTRACT

Slip rate is a critical parameter for describing geologic and earthquake rates of known active faults. Although faults are inherently three-dimensional surfaces, the paucity of data allows for estimating only the slip rate at the ground surface and often only few values for an entire fault. These values are frequently assumed as proxies or as some average of slip rate at depth. Evidence of geological offset and single earthquake displacement, as well as mechanical requirements, show that fault slip varies significantly with depth. Slip rate should thus vary in a presumably similar way, yet these variations are rarely considered.

In this work, we tackle the determination of slip rate depth distributions by applying the finite element method on a 2D vertical section, with stratification and faults, across the central Apennines, Italy. In a first step, we perform a plane-stress analysis assuming visco-elasto-plastic rheology and then search throughout a large range of values to minimize the RMS deviation between the model and the interseismic GPS velocities. Using a parametric analysis, we assess the accuracy of the best model and the sensitivity of its parameters. In a second step, we unlock the faults and let the model simulate 10 kyr of deformation to estimate the fault long-term slip rates.

The overall average slip rate at depth is approximately 1.1 mm/yr for normal faults and 0.2 mm/yr for thrust faults. A maximum value of about 2 mm/yr characterizes the Avezzano fault that caused the 1915, Mw 7.0 earthquake. The slip rate depth distribution varies significantly from fault to fault and even between neighbouring faults, with maxima and minima located at different depths. We found uniform distributions only occasionally. We suggest that these findings can strongly influence the forecasting of cumulative earthquake depth distributions based on long-term fault slip rates.

1. Introduction

Fault slip rate is a fundamental quantity in studies on rock mechanics, tectonics and geodynamics, and seismic hazards. In the latter, slip rate is used to predict earthquake rates of the major active faults. However, geologically-derived slip rate is often an elusive quantity because its estimation requires that both the amount and age of the offset features be known. In most field studies, one or a few data points are commonly accepted as representing some presumed average displacement along the fault strike, and the time component is often associated with significant uncertainties and may span considerably different time frames (i.e., from a few tens to hundreds of years in the historical record, to tens of thousands of years in paleoseismology, to millions of years in some geologic studies). Numerical models provide more comprehensive estimates of fault slip rates when an independent method that includes the overall deformation, both on- and off-fault strain, is necessary. Geological restoration algorithms (as the trishear, Hardy and Ford, 1997; Allmendinger, 1998) work well when the fault geometry and the embedding chronostratigraphic units are adequately known (e.g., Gold et al., 2006; Maesano et al., 2015). Conversely, finite-element modelling is especially advantageous when the rock mechanical and rheological properties are well known. Finite-element models may incorporate various degrees of complexity of the structure under study. For example, Bird (1989, 1999) developed the program SHELLS for modelling a two-layer crust and lithospheric mantle, incorporating faults, lithospheric and rheological characteristics, laterally varying thermal structure, and geodynamic boundary conditions. This approach has been already applied in various cases and tectonic settings (e.g., Geist and Andrews, 2000, for California strike-slip faults; Bird, 2009, for active faults in the western US; Kastelic and Carafa, 2012, for thrusts and strike-slip faults in the Dinarides). Finite element models with mechanical layering and variable rheology have also been used to reproduce the long-term regional state of stress and strain or the forces that act on faults (e.g., Vergne et al., 2001; Hsu et al., 2003; Chamlagain and Hayashi, 2005; Carafa and Barba, 2011; Trubienko et al., 2013; Carafa et al., 2015). In more general terms, two main strategies can be followed to determine fault slip rates through numerical models:

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* Corresponding author at: Via Vigna Murata, 605, 00143, Roma, Italy.
E-mail addresses: debora.finocchio@ingv.it (D. Finocchio), salvatore.barba@ingv.it (S. Barba), roberto.basili@ingv.it (R. Basili).

[1] Permanent address: Bury Street, M3 7DX Manchester, UK.

http://dx.doi.org/10.1016/j.tecto.2016.07.031
0040-1951/

1) the amount of slip is imposed on the fault plane (e.g., Ward and Valensise, 1996; Hardy and Ford, 1997; Wang et al., 2006), or 2) the fault under the drive of tectonic forces is left to slip freely (e.g., Cowie et al., 1993; Bird, 1999). In both cases, the correct amount of slip rate is found by fitting the model results to a given set of deformation data. Geologic field studies and numerical models often rely on deformation data collected from the ground surface or shallow geologic probing. Such slip rate determinations thus exploit the effect onto the free surface of the actual slip on the fault plane at depth. Therefore, those values are often assumed to be the same as, or the average of, the slip rate at depth. However, knowing the slip rate distribution at depth, rather than just its inferred average, can be useful for improving our understanding of Earth's crust behaviour and bettering our estimates of earthquake rates.

In this work, we use finite-element models to calculate the slip rate distribution at depth. To this end, we set up a 2D-cross-sectional multilayer finite-element model in the central Apennines, Italy. The Apennines is an example of a youthful extensional system that progressively overprints an older contractional belt. More specifically, the contractional fold-and-thrust system migrates toward the east and is replaced by extension to the west (Elter et al., 1975), and the contraction and extension systems coexist at short distances from one another (e.g., Negredo et al., 1999; Pondrelli and Morelli, 2008). Among the numerous active normal and thrust faults in the central Apennines, several are deemed to be seismogenic (Fig. 1), and a few of them have actually generated damaging earthquakes in the last century or so (e.g., Avezzano 1915, Mw 7.0; Colfiorito 1997, Mw 6; L'Aquila 2009, Mw 6.3 for normal faulting; Senigallia 1930, Mw 5.8; Porto San Giorgio 1987, Mw 5.1 for thrust faulting).

As regards normal faults, several attempts using geological field data provided vertical throw rates in the range of 0.1 to 1.0 mm/yr (e.g., Roberts et al., 2004; Papanikolaou et al., 2005) and slip rates in the range of 0.2 to 1.3 mm/yr (e.g., Benedetti et al., 2013) derived from exhumed bedrock fault scarps. Similar values were obtained from broader Quaternary geologic data on intermountain basins by Pizzi et al. (2002). A few higher slip rates were instead proposed from paleoseismic trenching, such as the 1.6 mm/yr for the Fucino fault (Michetti et al., 1996), and the 2.5 mm/yr for the Ovindoli-Pezza fault

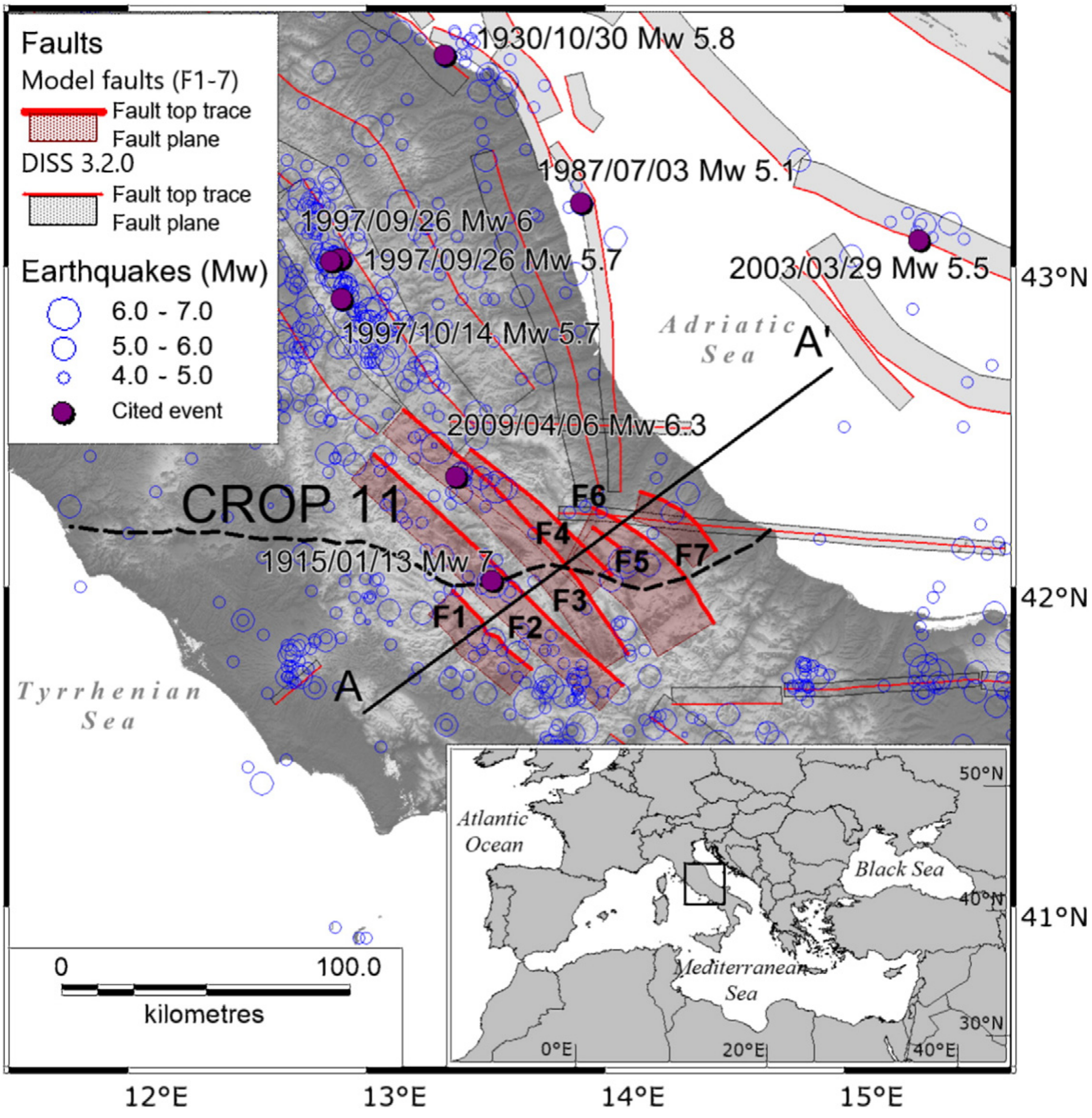

Fig. 1. Map of the study area. The modelled faults are labelled by F1–F7. Normal faults: F1, Val Roveto; F2, Avezzano; F3, L'Aquila-Borbona; F4, Sulmona; F5, Caramanico. Thrust faults: F6, Citeriore deep; F7, Citeriore shallow. All faults are from DISS 3.2.0 (DISS Working Group, 2015), except for the traces of F1 and F5, which are from Tozer et al. (2002) and Ghisetti and Vezzani (2002), respectively. A-A′ is the trace of the numerical model. The black dashed line represents the trace of the CROP11 seismic profile from Patacca et al. (2008). Historical earthquakes (years 1000–2006) are from CPTI11 (Rovida et al., 2011). The L'Aquila (2009-04-06) and Jabuka (200303-29) earthquakes are from Chiarabba et al. (2009) and Herak et al. (2005), respectively.