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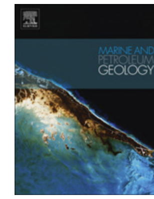

Deriving thrust fault slip rates from geological modeling: Examples from the Marche coastal and offshore contraction belt, Northern Apennines, Italy

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A B S T R A C T

We present a reconstruction of the central Marche thrust system in the central-northern Adriatic domain aimed at constraining the geometry of the active faults deemed to be potential sources of moderate to large earthquakes in this region and at evaluating their long-term slip rates. This system of contractional structures is associated with fault-propagation folds outcropping along the coast or buried in the offshore that have been active at least since about 3 Myr. The ongoing deformation of the coastal and offshore Marche thrust system is associated with moderate historical and instrumental seismicity and recorded in sedimentary and geomorphic features. In this study, we use subsurface data coming from both published and original sources. These comprise cross-sections, seismic lines, subsurface maps and borehole data to constrain geometrically coherent local 3D geological models, with particular focus on the Pliocene and Pleistocene units. Two sections crossing five main faults and correlative anticlines are extracted to calculate slip rates on the driving thrust faults. Our slip rate calculation procedure includes a) the assessment of the onset time which is based on the sedimentary and structural architecture, b) the decompaction of clastic units where necessary, and c) the restoration of the slip on the fault planes. The assessment of the differential compaction history of clastic rocks eliminates the effects of compaction-induced subsidence which determine unwanted overestimation of slip rates. To restore the displacement along the analyzed structures, we use two different methods on the basis of the deformation style: the fault parallel flow algorithm for faulted horizons and the trishear algorithm for fault-propagation folds. The time of fault onset ranges between 5.3 and 2.2 Myr; overall the average slip rates of the various thrusts are in the range of 0.26–1.35 mm/yr.

1. Introduction

The slip rate, together with other geometrical parameters of seismogenic sources, is one ingredient of the seismic hazard models, useful for determining the activity rates of the faults, i.e. how often they generate earthquakes, and for understanding the long-term fault behavior. Slip rate calculation can be performed using different methodological approaches at different space and time scales (paleoseismological trenches, restoration of seismic exploration data, numerical modeling, GPS velocities).

The measurement of slip rates along buried or offshore tectonic structures can be carried out through the use of seismic data and exploration wells. The large amount of data for oil exploration in the Adriatic Sea and the surrounding areas, made available in part from the ViDEPI database (http://unmig.sviluppoeconomico.gov.it/videpi/en/) and in part from scientific papers, allow reconstructing three-dimensional models relative to some key chronostratigraphic horizons. In this study we investigate the area around the Conero promontory (Marche Adriatic coast, Northern Apennines, Italy), where Plio-Pleistocene contractional tectonic structures are well known and have maximum principal stress axes oriented perpendicular to the mean structural trends (Boncio and Bracone, 2009; Heidbach et al., 2010). The ongoing activity of the more external Apennine thrust fronts is questioned on the basis of seismic line interpretations (Coward et al., 1999; Di Bucci and Mazzoli, 2002) and geomorphic analysis (Troiani and Della Seta, 2011), but is supported by historical and instrumental seismicity (Calderoni

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et al., 2009; Chiarabba et al., 2005) and geological–geomorphological studies (Carminati et al., 2003; Lavecchia et al., 2003, 2007; Negredo et al., 1999; Scrocca, 2006; Scrocca et al., 2007; Vannoli et al., 2004; Wegmann and Pazzaglia, 2009). Considering also the occurrence in the area of several historical and instrumental earthquakes (e.g. 1269, 1474, 1690, 1870, 1924, 1930) with M > 5 (see Rovida et al., 2011) and an important seismic sequence in 1972 (Console et al., 1973) many of the outer structures in the Umbria–Marche Apennines were included in the Italian database of seismogenic sources (Basili et al., 2008; DISS Working Group, 2010; see also Kastelic et al., 2013). The capability of these thrust faults to also generate tsunamis and their potential threat level on the Adriatic coast has been evaluated by Tiberti et al. (2008).

In this study we develop a workflow for the calculation of slip rates using 3D modeling of subsurface data for the restoration of some structures that runs from the Marche coastal anticlines to the more external Apennines thrust front in the Adriatic offshore. The surrounding areas were investigated in works dealing with the identification of potential seismogenic sources (Basili and Barba, 2007; Vannoli et al., 2004) and the evolution of the external Apennines thrust fronts (Cuffaro et al., 2010; Scrocca et al., 2007). Our study focuses on the evaluation of the onset age of activity, displacement, and shortening of the thrusts. The aim of this paper is to give a quantitative estimate of slip rates for the considered time interval on thrust faults in this sector of the Umbria–Marche Apennines, some of which are deemed to be seismogenic structures, contributing to earthquake recurrence time studies and seismic and tsunami hazard modeling.

2. Geologic and tectonic framework

The investigated area is located in the central Marche (central Italy) coastal and offshore zones (Fig. 1) and covers part of the external domain of the Umbria–Marche fold and thrust belt (Umbria–Marche Apennines). The Umbria–Marche Apennines is part of the larger Outer Northern Apennines, an arc-shaped northeast-verging thrust belt that originated in the Middle Miocene by the complex tectonic interaction between the African and European plates; this tectonic process is still active and determines active thrusting along the Adriatic coast (e.g. Barchi et al., 1998; Barchi et al., 2001; Pialli et al., 1998; Vai and Martini, 2001). The inner contractional tectonic structures have been deactivated and dissected by extensional structures which started to affect the Umbria–Marche Apennines in the Gelasian. The compression–extension pair progressively migrated in time and space from West to East generating an overprint of contractional and extensional features in adjacent regions (e.g. Barchi, 2010; Elter et al., 1975; Frepoli and Amato, 1997).

The deep and shallow geometry of the Umbria–Marche fold and thrust belt was provided by Barchi et al. (1998) and Pialli et al. (1998) using the regional seismic line CROP03 as well as by Bally et al. (1986), Coward et al. (1999) and Scarselli et al. (2007) using shorter profiles, giving different structural interpretations. Concerning the deformation style of the region, different models have been proposed: a thin-skinned model in which the contractional structures are all detached on an undeformed basement deepening from about 5 km in the Adriatic Sea to about 8 km below the Adriatic coastline and to 13–14 km below the Umbria–Marche Apennines (Bally et al., 1986); a combined thin/thick-skinned model in which the basement is partially involved in the contractional deformation and multiple detachment levels at different depths control the development of different wavelength structures (Barchi et al., 1998) and leads to shortening rates in the order of 1.5–3.0 mm/yr (Basili and Barba, 2007); a thick-skinned model characterized by the involvement of the basement in the major thrusts which would have reactivated pre-existing Triassic faults within the basement (Coward et al., 1999; Lavecchia et al., 2003).

Reconciling these different interpretations is beyond the scopes of this work and we thus adopt the thin/thick-skinned model for which we have the largest amount of coherent data. Our study area is characterized by at least two main detachment levels that control the geometry of the contractional structures: a deep detachment located at the base of the Mesozoic–Paleogene sedimentary cover (within the Anidriti di Burano fm., Triassic evaporites) and a shallower detachment level located at the base of the Schlier fm. (Early Miocene) in the Neogene foredeep clastic successions (Barchi et al., 1998). The deep detachment controls the development of northeast-verging anticlines bounded by major thrust ramps and backthrusts, separated by wide synclines (Umbria–Marche folds). The anticlines have a wavelength of 5–10 km, and detach at a depth of 6–10 km. The shallow detachment controls the formation of short-wavelength folds (of the order of tens to hundreds of meters) detached at 2 km of depth, and involving the terrigenous foredeep and/or wedge-top successions (Barchi et al., 2001; Massoli et al., 2006). The shallow detachment level produces folds with less developed lateral continuity (non-cylindrical), a characteristic that strongly affects the thickness distribution of the Pliocene sediments deposited in the sub-basins developed in the foredeep (Argnani and Gamberi, 1995; Coward et al., 1999). Below the Umbria–Marche folds, the interpretation of the deep CROP03 seismic profile revealed that the upper part of the basement is also partly involved in the contractional structures with a wavelength of 25–35 km (Barchi et al., 1998). In the inner part of the Apennines, the Umbria–Marche folds layer comprises seven long-wavelength folds; our study area (Fig. 1) includes the more external ones, i.e. the Coastal Anticline and the Offshore Anticline. The onset age of these two structures was constrained by the analysis of the syntectonic deposits, and is of Piacenzian (3.1 ± 0.5 Ma) and of Gelasian (2.2 ± 0.4 Ma), respectively (see Basili and Barba, 2007 for a summary).

The main terrigenous units in our study area are characterized by Neogene–Quaternary clastic wedges representing the foredeep turbidites of the Umbria–Marche Apennines. The foredeep deposits overlay a Jurassic–Paleogene multilayer known as Umbria–Marche stratigraphic succession (Cresta et al., 1989) which crops out in correspondence of the main north-east and east-verging anticlines and synclines of the Umbria–Marche Apennines to the west (Fig. 1). The lower part of the Umbria–Marche stratigraphic succession is characterized by evaporitic upper Triassic rocks, Anidriti di Burano fm. (Martinis and Pieri, 1964), overlying the basement, formed by Paleozoic and Triassic clastic rocks (continental and shallow marine environment) and metasedimentary rocks (Mirabella et al., 2008). Both the basement and evaporites do not have surface exposure in the study area and were identified in boreholes only (Anelli et al., 1994; Bally et al., 1986; Barchi et al., 1998).

The late Messinian–Quaternary sedimentary record is exposed along the Adriatic coastal belt where it is largely incomplete because of uplift and erosion. It is instead preserved in the subsurface of the Adriatic Sea and the Po Plain (Bigi et al., 1999; Calamita et al., 1999). The main events recorded by the sedimentary successions are: a sahelian cycle in the early Messinian (Ricci Lucchi, 1986a,b); a middle Messinian increment of anoxic episodes due to a crisis of salinity in the Mediterranean region with consequent evaporitic (Gessoso Solfifera fm.) sedimentation (Gelati et al., 1987); a post-evaporitic sandstones and mudstones formation up to 900 m thick (Barchi et al., 2001; Bassetti et al., 1994).

Both the Gessoso Solfifera fm. and the Messinian sediments are marked by strong angular unconformities due to sub-aerial erosion.