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Slip-rates of blind thrusts in slow deforming areas: Examples from the Po Plain (Italy)

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ABSTRACT

We calculate Plio-Pleistocene slip rates on the blind thrusts of the outer Northern Apennines fronts, that are the potential sources of highly damaging earthquakes, as shown by the M_W 6.1–6.0, 2012 Emilia–Romagna seismic sequence. Slip rates are a key parameter for understanding the seismogenic potential of active fault systems and assessing the seismic hazard they pose, however, they are difficult to calculate in slow deforming areas like the Po Plain where faulting and folding is mostly blind. To overcome this, we developed a workflow which included the preparation of a homogeneous regional dataset of geological and geophysical subsurface information, rich in Plio-Pleistocene data. We then constructed 3D geological models around selected individual structures to decompact the clastic units and restore the slip on the fault planes. The back-stripping of the differential compaction eliminates unwanted overestimation of the slip rates due to compaction-induced differential subsidence. Finally, to restore the displacement we used different methods according to the deformation style, i.e. fault parallel flow for faulted horizons, trishear and elastic dislocation modeling for fault-propagation folds. The result of our study is the compilation of a slip rate database integrating former published values with 28 new values covering a time interval from the Pliocene to the present. It contains data on 14 individual blind thrusts including the Mirandola thrust, seismogenic source of the 29 May 2012, M_W 6.0 earthquake. Our study highlights that the investigated thrusts were active with rates ranging between 0.1 and 1.0 mm/yr during the last 1.81 Myr. The Mirandola thrust slipped at 0.86 ± 0.38 mm/yr during the last 0.4 Myr. These rates calculated with a homogeneous methodology through the entire Po Plain can be charged entirely to the thrust activity and not to secondary effects like the differential compaction of sediments across the structures.

1. Introduction

The Po Plain stretches for over 400 km in a roughly east–west direction from the Western Alps to the Adriatic Sea, extending for over 15% of the national territory and comprising the largest alluvial plain of Italy. Geologically the Po Plain comprises the foreland area of the two active, oppositely-verging fold-and-thrust belts: the Northern Apennines (hereinafter also NA), to the south, and the Southern Alps (hereinafter also SA), to the north and to the west. Their uplifted, tightly folded and intensely eroded accretionary wedges encircle the Po Plain in all directions but to the east, marking its morphological boundaries. The outer deformation fronts of the two belts are currently buried below the thick Pliocene–Quaternary, marine to continental succession that fills-in the Po Plain; for this reason the surface evidence of the ongoing activity of the thrusts of the two belts is restricted to their exposed margins and to a few isolated spots in the plain proper. GPS data document active shortening across the NA and SA fronts with velocities up to 2.5 mm/yr (e.g. Devoti et al., 2011; Michetti et al., 2012). A fraction of this strain is released by moderate yet damaging earthquakes such as the recent 20 and 29 May 2012, M_W 6.1–6.0, Emilia events, generated by blind thrusts of the outermost front of the Northern Apennines (Anzidei et al., 2012; Govoni et al., 2014).

Earthquake activity in flat alluvial plains poses an especially insidious threat as most of the population and the largest industrial facilities normally take advantage of these gentle landscapes. The Po Plain does not escape this general rule as it hosts nearly a third of Italy's population along with important historical centers, many industrial facilities and lots of critical infrastructures. Even though on average the seismic hazard of the Po Plain is comparatively low (MPS Working Group, 2004), the 2012 earthquakes demonstrated that locally it may be rather high and comparable to the most earthquake-prone areas of Italy. In combination with the high exposure and vulnerability to earthquakes of most of the Po Plain, also its seismic risk may be locally very high. Once again this circumstance was tragically revealed by the 2012 earthquakes, that shattered a crucial industrial district causing a loss of about 2% in Italy's GNP despite their limited size.

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The 2012 earthquakes definitely raised awareness of the risk posed by the numerous blind thrusts buried beneath the Po Plain; but while assessing the region's exposure and vulnerability is relatively straightforward, little is known to date about how tectonic strain is partitioned across the different faults, that is to say, about their slip rates. This information is crucial for ranking the different active portions of the Po Plain and describing the spatial variability of seismic hazard, and hence of seismic risk.

Dealing with blind thrusts is neither easy nor straightforward, however, which partially explains why the seismogenic potential of Po Plain faults has gone unappreciated for so long. When blind faulting occurs in flat terrains like the Po Plain the associated hazard is generally not perceived by the population and by the decision makers — and sometimes even by scientists — due to the lack of associated morphologies. In fact, in most earthquake-prone areas worldwide the hazard posed by hidden and blind faults has been clearly recognized only after the publication of the seminal paper of Stein and Yeats (1989) based on their pioneering work in California. But compared to California strain rates, the low rates that are typical of the Po Plain result in long earthquake return times, further stressing the perception of a low local hazard. For the same reasons and for the inherent difficulty in identifying the hidden or blind seismogenic sources and characterize their seismic behavior, the hazard they pose is also difficult to assess using traditional geologic tools. Recent worldwide examples of earthquakes that were caused by blind, hard-to-identify or previously unmapped faults show that this issue is critical even in countries where active faulting studies are especially advanced, though mostly focused on surface cutting structures. The 25 March 2007, M_w 6.9, Noto-Hanto, Japan (Toda and Awata, 2008), the 4 September 2010, M_w 7.1, Canterbury, New Zealand (Quigley et al., 2010), and the 23 October 2011, M_w 7.1, Van, eastern Turkey earthquakes are examples of events that occurred on unidentified seismogenic sources and were hence largely unexpected.

In this work we focused on the compressional structures of the outer Northern Apennines thrust fronts and calculated slip rates for several blind thrusts of this buried mountain belt. To this end we used a compilation of geophysical and stratigraphic subsurface data from various sources, merged into a homogenized regional 3D dataset and analyzed with standardized procedures. We followed the approach discussed by Maesano et al. (2013) to quantify the active deformation of the Emilia and Ferrara–Romagna arcs of the Northern Apennines outer buried thrust fronts using a regional dataset of homogenized geological cross-sections and a few selected Pliocene–Quaternary chronostratigraphic horizons covering the southern part of the Po Plain (i.e. to the south of the Po River). From this dataset we constructed a regional 3D geological model from which we extracted four regional geological sections and seven shallow sections of local extent, all of which were used in subsequent calculations. The procedure we used to calculate the slip rates of the buried thrust faults included i) the definition of the sedimentary and structural architecture, ii) the decompaction of clastic units, where needed, and iii) the restoration of slip on the fault planes.

The calculation of the slip rate of individual faults may be based on different methodological approaches at different space and time scales: geomorphic and geologic marker analysis (e.g. Ponza et al., 2010), restoration of seismic exploration data (e.g. Maesano et al., 2013), geodetic leveling and GPS observations (e.g. D'Anastasio et al., 2006), and numerical modeling (Barba et al., 2013; Kastelic and Carafa, 2012). We will discuss case by case what strategy or combination of strategies was adopted, depending on the availability of data and on the characteristics of each specific fault.

The main result of our study is the compilation of a database which integrates previously published values with 28 new estimates of slip rate. Our dataset spans the time interval from Pliocene to the Present, constraining the recent activity of the outer Northern Apennines thrust fronts in an unprecedented detail; it contains data concerning 14 individual blind thrusts, including the seismogenic source of the 29 May 2012, M_W 6.0 earthquake. This database can be integrated into seismogenic source models like the DISS seismogenic source database (Basili et al., 2008; ISIDe Working Group, 2010), thus contributing to future more accurate seismic hazard estimates.

2. Regional geological and tectonic setting

The Northern Apennines are a folded mountain chain that exhibits north–northeastward vergence and convexity (Fig. 1), generated starting in the Eocene by westward subduction of the Adriatic lithosphere in the framework of the Africa–Europe plate convergence (for a review see Carminati and Doglioni, 2012, and references therein). The NA are composed of i) a buried depositional wedge covered by the Plio-Quaternary sediments of the Po basin, which started to deform by thrust propagation during the late Messinian–Early Pliocene (Ghielmi et al., 2010, 2013), and ii) an exposed erosional wedge cropping out in the Apennines region proper. Activity of the NA fronts currently concentrates either along blind thrusts buried beneath the Po Plain, or along the partially exposed structures forming the mountain front that bounds the plain to the southwest.

In the absence of direct surface evidence, the buried compressional structures of the Po basin have been extensively investigated for hydrocarbon exploration by means of industrial seismic lines and deep well logs (e.g. Fantoni and Franciosi, 2010; Ghielmi et al., 2010, and references therein). These data revealed a system of N to NE-verging blind thrusts organized in three main folded arcs, which from west to east are as follows: (i) the Monferrato arc, that underwent the smallest amount of shortening and was not considered in this study; (ii) the Emilia arc, that started deforming in the Tortonian and experienced its maximum activity in Piacenzian–Gelasian times; and (iii) the Ferrara–Romagna arc, active since the Messinian (Ghielmi et al., 2013). The structural evolution of the outer NA arcs was not simultaneous across the whole Po Plain: while the Emilia arc reached its present-day configuration in the Zanclean, to the east the outward propagation of the thrust fronts continued until the Zanclean–Piacenzian and the Gelasian, respectively for the inner and for the outer Ferrara arcs (Ghielmi et al., 2010).

At the back of the Emilia and Ferrara–Romagna arcs the subemergent Pedeapenninic thrust front (PTF, Boccaletti et al., 1985; Bigi et al., 1990) forms the NA mountain front. Its continuing Quaternary activity, although associated with an elusive topographic expression, is recorded by deformation and tilting of river terraces and of exposed syntectonic sediments (Boccaletti et al., 1985; Boccaletti et al., 2011; Picotti and Pazzaglia, 2008; Wegmann and Pazzaglia, 2009; Ponza et al., 2010). Conversely, out in the plain there are only few exceptions to the general blind geometry of the buried outer fronts of both the SA and NA chains (Fig. 1).

The stratigraphic succession of the Po basin is characterized (from base to top) by a late Paleozoic–Mesozoic evaporitic–silicoclastic and carbonatic sequence deposited on the Adriatic paleomargin and covering the Variscan basement, by Cenozoic deposits of the SA and NA foredeeps, and by Quaternary shallow marine and continental sediments deposited in a generally regressive sequence (Fig. 2) (Argnani and Ricci Lucchi, 2001; Bertotti et al., 1993; Dondi and D'Andrea, 1986; Fantoni and Franciosi, 2010; Ghielmi et al., 2010). The structural style of the NA fold-and-thrust belt was governed by the presence of two major detachment levels in the stratigraphic sequence (Fig. 2): a deeper one located at the base of the Mesozoic carbonate units within the Triassic evaporites, and a shallower one that can be identified in deposits of upper Oligocene to lower–middle Miocene age, being younger in the eastern part of the Po Plain (e.g. Massoli et al., 2006). The shallow and deep detachments produce structures having shorter and longer wavelength, respectively.

During the Cenozoic compressional cycles the southern part of the Po Plain hosted the foredeep of the NA chain. The associated deposits exhibit a thickness in excess of 8000 m and are generally subdivided