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Investigating fault reactivation during multiple tectonic inversions through mechanical and numerical modeling: An application to the Central-Northern Apennines of Italy

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ABSTRACT

Within inversion tectonic contexts, the reactivation of pre-existing discontinuities depends upon many structural, stratigraphic and mechanical factors. Among these, a fundamental aspect is represented by the orientation and attitude of pre-existing discontinuities with respect to the new stress field. The aim of this work is to evaluate the stress regimes and the mechanical conditions that controlled the reactivation of segmented pre-thrusting normal faults in the Central-Northern Apennines of Italy. These faults were involved both in positive and negative inversion tectonic events during Tertiary-Quaternary times. Mechanical (slip tendency analysis) and numerical (using COULOMB 3.3 software) models allowed us to reconstruct a 3D stress field for both inversion events and to evaluate the effect of many parameters (orientation of faults, fault dip-angle and mechanical parameters) on fault reactivation. Our results highlighted that the orientation of pre-existing faults with respect to the stress axes represents the main factor controlling inversion tectonic phenomena, where other mechanical and geometric variables exert a subordinate role. The models well reproduce the Neogene-Quaternary deformation history reconstructed from detailed geological and structural analyses for the Central-Northern Apennines of Italy and could be applied to other regions that have experienced inversion tectonic processes.

1. Introduction

Inversion tectonics refers to regions that experienced a switch in the stress regime. Both positive and negative inversion tectonic processes exist. In the first case the stress field changes from tensional to compressional. In the second case the opposite process occurs. Within these contexts, pre-existing faults can or cannot be reactivated (e.g., Ziegler, 1987; Cooper and Williams, 1989; Coward, 1994).

When positive inversion involves paleodomains characterized by complex structural architectures, derived from differently oriented pre-existing discontinuities and high variability of lithofacies and layer thickness distribution, composite inversion features (e.g., shortcut faults or partially inverted normal faults) can develop (Gillcrist et al., 1987; Butler, 1989; Cooper and Williams, 1989; Scisciani et al., 2002; Scisciani, 2009). Abrupt lateral changes in the stratigraphic successions and the presence of ancient tectonic discontinuities can exert a strong control in the evolution of a fold-and-thrust belt and could influence the localization of thrust ramps (Calamita, 1990; Tavarnelli, 1996a,b; Tavarnelli et al., 2004; Butler et al., 2006; Carrera et al., 2006; Bonini et al., 2010). In such a scenario, positive inversion tectonics is expressed through simple fault reactivation (e.g., Williams et al., 1989) or through passive shortcut involvement of pre-existing fault planes by newly formed compressive structures (i.e., folds and thrusts) (e.g., Butler, 1989; McClay, 1989; Coward, 1994; Alberti et al., 1996; Tavarnelli, 1996a,b; Scisciani et al., 2000, 2002).

Fault reactivation implies that pre-existing discontinuities are mechanically weaker than the host rock (Rutter et al., 2001) and depends upon a wide number of factors such as: complexities in the pre-orogenic structural and stratigraphic setting (e.g., Tavarnelli, 1996a,b; Tavarnelli et al., 2001, 2004; Scisciani, 2009; Cunningham, 2013), orientation of the pre-existing discontinuities with respect to the new stress field (e.g., Coward, 1994; Carrera

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et al., 2006; Calamita et al., 2009, 2011; Di Domenica et al., 2012; Cunningham, 2013), mechanical properties of the fault zones (e.g., Sibson, 1985; Yin and Ranalli, 1992; Collettini and Sibson, 2001; Rutter et al., 2001) and fluid pressure (e.g., Sibson, 1995).

Several numerical (e.g., Vanbrabant et al., 2002; Buiter and Pfiffner, 2003; Jarosinski et al., 2011), analog (Bonini et al., 2012; Di Domenica et al., 2014 and references therein) and mechanical (Sibson, 1985, 1995; Yin and Ranalli, 1992; Collettini and Sibson, 2001) models have been developed to address the conditions under which pre-existing discontinuities can be reactivated. Strong importance is ascribed to the mechanical properties of fault zones. These studies show that the remobilization of high-angle discontinuities within a compressional stress field is possible only for high fluid pressure or for low friction along the faults (e.g., Sibson, 1985, 1995; Collettini and Sibson, 2001). On the other hand, initially high-angle faults may be reactivated with transpressional kinematics (e.g., Doubois et al., 2002; Del Ventisette et al., 2006) or may rotate towards low dip-angle when involved in a fold, being or not reactivated (e.g., McClay, 1989; Cunningham, 2013; Pace et al., 2014). An additional controlling factor can be represented by departures of the principal stress axes from horizontal and vertical orientations (Bonini et al., 2012 and references therein). Moreover, these mechanical assumptions and observations need to consider the spatial distribution of pre-existing faults in terms of trend variations with respect to the stress tensor orientation. Some analog models (e.g., Brun and Nalpas, 1996; Dubois et al., 2002; Del Ventisette et al., 2006; Di Domenica et al., 2014) investigated the impact of the obliquity between the shortening direction and the graben/fault trend. Often, in these analog models and in numerical simulations the occurrence of sinuous or variably oriented discontinuities is neglected (e.g., Vanbrabant et al., 2002; Buiter and Pfiffner, 2003; Jarosinski et al., 2011). As a matter of fact, structural, stratigraphic and seismic data collected within fold-and-thrust belts highlight the importance of the orientation of pre-existing discontinuities. Fault orientation influences the modes of interaction between thrusting and pre-existing normal faults and determines different geometries and degrees of inversion (Carrera et al., 2006; Calamita et al., 2009, 2011; Cunningham, 2013). Less investigated is negative inversion (e.g., Williams et al., 1989; Faccenna et al., 1995; Tavarnelli, 1999; Tavarnelli and Prosser, 2003). Analog models show how the normal reactivation of a pre-existing discontinuity basically depends upon the original dip-angle of the fault (Faccenna et al., 1995).

In the Central-Northern Apennines, the crosscutting relationships between thrust and normal faults allowed the reconstruction of the relative chronology among the structures and the recognition of pre-thrusting discontinuities subsequently inverted during the Neogene growth of the chain (e.g., Alberti et al., 1996; Tavarnelli et al., 2001, 2004; Scisciani, 2009; Calamita et al., 2011). At the same time, some of the faults that show a pre-orogenic activity were also reactivated during the Quaternary extensional regime thus experiencing repeated inversion tectonic phases (both positive and negative) (Tavarnelli, 1999; Tavarnelli and Prosser, 2003; Di Domenica et al., 2012).

Many authors have investigated the influence of mechanical and geometric parameters in fault reactivation processes (e.g., Sibson, 1985; Bonini et al., 2012 and references therein). The aim of this work is to use a quantitative approach to analyze the tendency to reactivation of differently oriented faults, both in extensional and compressional tectonics, in the Central-Northern Apennines of Italy. However, our modeling techniques and inferences can be applied to other inverted tectonic settings worldwide. In the following, we first summarize geological field data that allow to constrain the degree of tectonic inheritance in the Apennine chain and to recognize contrasting styles of inversion tectonics deriving from the interaction between compressive structures and differently oriented normal faults (both pre- and post-thrusting). Successively, for the first time, mechanical (slip tendency analysis) (e.g., Morris et al., 1996) and numerical (using COULOMB 3.3 software) (Toda et al., 2011) models are implemented to evaluate the mechanical conditions that controlled the reactivation of segmented pre-thrusting normal faults during both the Neogene fold-an-thrust belt development and the active tectonics affecting the Apennines of Italy.

2. Geological setting

The Apennines are an Oligocene-Quaternary fold-and-thrust belt that developed during the convergence of the African and European continental margins (e.g., Boccaletti et al., 1990; Carmignani and Kligfield, 1990; Doglioni, 1991; Carminati et al., 2012). The orogenesis affected Triassic-to-Miocene sedimentary successions related to different basin and platform paleogeographic domains of the Adria Mesozoic paleomargin (e.g., Ciarapica and Passeri, 2002; Santantonio and Carminati, 2011). The overall structural architecture of the Central-Northern Apennines is composed by an imbricate fold-and-thrust system delimited by curve-shaped Neogene regional-scale thrust fronts: the Olevano-Antrodoco-Sibillini (OAS), the Gran Sasso (GS) and the Sangro-Volturno (SV) thrusts (Fig. 1). These cross-faults are oblique to the main trend of the NW-SE-trending Apennine folds, thrusts and normal faults and compartmentalize the Quaternary normal faulting that characterizes the axial zone of the chain (Tavarnelli et al., 2001, 2004; Pizzi and Galadini, 2009; Di Domenica et al., 2012).

The salient geometry of the OAS thrust is defined by NNW–SSE- and NNE–SSW-trending arms to the north and south of the Mt. Vettore, respectively. In the northern sector, this structure juxtaposes the Triassic-to-Miocene Umbro-Marchean-Sabina pelagic succession (hanging-wall unit) onto the Messinian siliciclastic deposits of the Laga Fm. (footwall unit). To the south, this feature separates the Umbro-Marchean-Sabina basin from the Latium-Abruzzi persistent platform domain and delimits the Northern Apennines from the Central Apennines. The wide Laga foredeep basin, resting on a basinal succession comparable to the Umbro-Marchean one, represents also the footwall of the E-W-trending arm of the GS curved thrust front which involves, in the hanging-wall, the Triassic-to-Miocene platform-to-slope succession of the Latium-Abruzzi paleodomain. A narrow corridor of Messinian foredeep deposits again crops out in the footwall block of the N–S limb of the GS thrust, juxtaposed onto Lower Pliocene siliciclastic sediments belonging to the outer tectono-stratigraphic units. Finally, the SV thrust delimits the Central Apennines from the Southern Apennines (Fig. 1).

These curved regional features behaved as oblique thrust ramps and show transpressional kinematics (e.g., Calamita et al., 1987; Calamita and Deiana, 1988; Tavarnelli et al., 2004; Turtù et al., 2013). Often they correspond with important lateral facies changes in the pre-orogenic stratigraphy (GS thrust and NNE-SSW-trending arm of the OAS thrust) indicating a degree of structural inheritance for the Apennine chain (e.g., Castellarin et al., 1982; Calamita and Deiana, 1988; Bigi et al., 1995; Tavarnelli et al., 2004; Satolli et al., 2005; Butler et al., 2006; Satolli and Calamita, 2012), also supported by the wide recognition of pre-orogenic (Meso-Cenozoic; e.g., Decandia, 1982; Winter and Tapponier, 1991; Calamita et al., 1998; Mazzoli et al., 2002; De Paola et al., 2007) and syn-orogenic (Neogene; e.g., Boccaletti et al., 1990; Alberti et al., 1996; Tavarnelli and Peacock, 1999; Scisciani et al., 2001a, 2001b; 2002; Carminati et al., 2014) normal faults.

The recent Quaternary extensional tectonic regime that affects the axial zone of the Apennine chain activated NW–SE normal faults. These are 15–35 km-long, segmented and seismogenic faults