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Fault geometry and mechanics of marly carbonate multilayers: An integrated field and laboratory study from the Northern Apennines, Italy

C. Giorgetti [a,*], C. Collettini [a,b], M.M. Scuderi [a], M.R. Barchi [c], T. Tesei [b]

[a] Dipartimento di Scienze della Terra, Università degli Studi La Sapienza, Piazzale Aldo Moro 5, 00185 Rome, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy
[c] Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Via Alessandro Pascoli, 06123 Perugia, Italy

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ABSTRACT

Sealing layers are often represented by sedimentary sequences characterized by alternating strong and weak lithologies. When involved in faulting processes, these mechanically heterogeneous multilayers develop complex fault geometries. Here we investigate fault initiation and evolution within a mechanical multilayer by integrating field observations and rock deformation experiments. Faults initiate with a staircase trajectory that partially reflects the mechanical properties of the involved lithologies, as suggested by our deformation experiments. However, some faults initiating at low angles in calcite-rich layers ($\theta_i = 5°–20°$) and at high angles in clay-rich layers ($\theta_i = 45°–86°$) indicate the important role of structural inheritance at the onset of faulting. With increasing displacement, faults develop well-organized fault cores characterized by a marly, foliated matrix embedding fragments of limestone. The angles of fault reactivation, which concentrate between 30° and 60°, are consistent with the low friction coefficient measured during our experiments on marls ($\mu_s = 0.39$), indicating that clay minerals exert a main control on fault mechanics. Moreover, our integrated analysis suggests that fracturing and faulting are the main mechanisms allowing fluid circulation within the low-permeability multilayer, and that its sealing integrity can be compromised only by the activity of larger faults cutting across its entire thickness.

1. Introduction

The presence of directional heterogeneity (anisotropy) (e.g., Peacock and Sanderson, 1992) in sealing layers strongly affects their mechanical and hydrological properties. Low-permeability layers, acting as efficient seals, are often represented by sedimentary sequences characterized by the alternation of weak, clay-rich lithologies, e.g., marl and shale, and strong lithologies, e.g., sandstone and limestone. Directional heterogeneity is possibly associated with mechanical stratigraphy, defined as the presence in a given formation of stratigraphic layers with different mechanical properties (e.g., Corbett et al., 1987; Wilkins and Gross, 2002). Within multilayers, these competence contrasts have a key role in fault initiation and growth (e.g., Peacock and Sanderson, 1992; Schöpfer et al., 2006, 2007; Ferrill and Morris, 2008; Childs et al., 2009; Roche et al., 2012). In the incipient phase, faults hosted in multilayers develop a staircase trajectory with plane refraction at competence contrasts. This staircase trajectory results in a variable fault orientation that can be described by the angle of fault initiation. The angle of fault initiation θ_i is defined as the angle between the maximum principal stress and the fault plane and it depends on the failure strength of the faulted rocks (Anderson, 1951). In a mechanical multilayer, the strength heterogeneity results in different θ_i values within each different stratigraphic layer. The overall strength of a layer can also be influenced by the presence of pre-existing cohesionless surfaces, such as joints, that can further deflect the trajectory of the fault and thus change the θ_i value (e.g., Peacock and Sanderson, 1992; Crider and Peacock, 2004; Roche et al., 2012). Furthermore, an additional directional heterogeneity is related to the intrinsic anisotropy of weak layers, i.e., the planes of weakness resulting from rock foliation (e.g., Shea and

* Corresponding author.
E-mail addresses: carolina.giorgetti@uniroma1.it (C. Giorgetti), cristiano.collettini@uniroma1.it (C. Collettini), marco.scuderi@uniroma1.it (M.M. Scuderi), massimiliano.barchi@unipg.it (M.R. Barchi), telemaco.tesei@ingv.it (T. Tesei).

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Kronenberg, 1993; Massironi et al., 2011; Bistacchi et al., 2012; Misra et al., 2015). Deformation experiments on intact rocks show that the orientation of foliation with respect to the maximum principal stress strongly influences the strength of the rocks (e.g., Jaeger, 1960; Donath, 1961; Jackson and Dunn, 1974; McCabe and Koerner, 1975; Bolognesi and Bistacchi, 2016). Shear fractures in foliated rocks, developed during triaxial experiments, may reactivate the planes of weakness, even when the maximum principal stress is inclined at high angles, such as 45°–60°, to the pre-existing surface (Donath, 1961).

In the first stages of growth, slip along staircase faults causes the development of dilational jogs within competent layers (e.g., Sibson, 1996). The presence of dilational jogs has strong implications on fluid circulation in low-permeability multilayers, often promoting fluid flow in the direction parallel to the intersection of the fault plane and the bedding (e.g., Sibson, 1996; Ferrill and Morris, 2003). Structural studies on the distribution of displacement in mechanical multilayers are essential in order to better understand fluid flow properties within fault zones (e.g., Manzocchi et al., 2008, 2010; Childs et al., 2009). However, most of the previous field-based studies have only given a detailed geometrical description of complex faults within mechanical multilayers (e.g., Peacock and Sanderson, 1992; Nicol et al., 1996; Gross et al., 1997; Wilkins and Gross, 2002; Soliva and Benedicto, 2005; Schöpfer et al., 2006; Antonellini et al., 2008; Ferrill and Morris, 2008; Childs et al., 2009; Ferrill et al., 2011; Roche et al., 2012; Kristensen et al., 2013), while a complementary mechanical characterization is still lacking. In this paper we integrate field observations with rock deformation experiments to investigate fault evolution within a mechanical multilayer consisting of alternating limestones and clay-rich marls. We aim to better characterize the role of mechanical properties on the overall deformation style and fluid circulation.

2. Geological framework

We studied outcrops of faulted multilayers located in the northeastern limb of the Monte Montiego Anticline (Fig. 1) in the Umbria-Marche Apennines that represent the outer part of the Northern Apennines (e.g., Bally et al., 1986; Barchi et al., 2012). The Northern Apennines are a complex, arc-shaped fold-and-thrust belt having an overall northeastward convexity and vergence (e.g., Carmignani et al., 2001; Barchi et al., 2001), developed in the framework of the Europe-Africa convergence (e.g., Reutter et al., 1980; Alvarez, 1991; Doglioni et al., 1998; Carminati and Doglioni, 2012). The Umbria-Marche Apennines are characterized by large asymmetric anticlines overturned eastward on tight synclines with fold axes trending NW-SE (e.g., Abbate et al., 1970; Lavecchia et al., 1988). Locally, the Monte Montiego Anticline has a fold axis trending WNW-ESE (Engelder, 1984).

The Mesozoic carbonates are folded coherently with the compressional regime and they are also affected by small-scale faulting. Specifically, we studied mesoscale faults showing subvertical dips with displacements ranging from less than 1 cm up to ~20 m. Kinematic indicators, i.e., bedding offsets, drag folds, and subhorizontal slickenfibers, indicate a strike-slip movement. The relationship of fault-bedding intersections and the sense of displacement are consistent with fold-axis-parallel extension (e.g., Marshak et al., 1982). Strike-slip faults are commonly found in fold-and-thrust belts (e.g., Sylvester, 1988; Hindle and Burkhard, 1999), including the anticlines of the Umbria-Marche Apennines (e.g., Marshak et al., 1982; Barchi et al., 1993). Moreover, a previous study (Marshak et al., 1982) in the same area of the Apennines proposed that the activity of strike-slip faults is, at least in part, contemporaneous with the formation of the anticline.

The studied faults developed within the Lower Cretaceous Marne a Fucoidi Formation. The lithology of the Marne a Fucoidi Formation is highly variable in terms of composition, with $CaCO_3$ content ranging from 4% to 75% (Giorgioni et al., 2016; Li et al., 2016). The remaining percentage is made of a homogeneous clay mineral assemblage consisting of ~50% smectite, ~30% illite and ~20% mixed layer illite-smectite (Coccioni et al., 1989). The Marne a Fucoidi Formation is also highly variable in terms of thickness and spacing of competent limestone layers (e.g., Tornaghi et al., 1989; Coccioni et al., 1989). The high lithological variability of this formation results in high variability of mechanical properties, thus defining mechanical multilayers, prone to develop complex fault geometries. Despite this high variability, the alternation of layers with higher and lower $CaCO_3$ content is always evident. In the present work, we define competent layers as those characterized by relatively high $CaCO_3$ content and incompetent layers as those characterized by low $CaCO_3$ content and the presence of sedimentary foliation.

3. Investigation methods

3.1. Theoretical framework for field observations

We studied the along-strike geometry of outcropping faults with increasing displacement from less than 1 cm to a few meters in order to reconstruct the initiation and early stages of faulting. Additionally, we studied a single fault with an apparent displacement (separation) of about 20 m to evaluate a more mature fault stage.

The mechanical characterization of the mapped faults is based on geometrical relationships between the slipping surfaces and the local stress field orientation. Fault initiation can be evaluated by using the Coulomb failure criterion (Coulomb, 1776):

$$\tau = c + \mu_i \left(\sigma_n - P_f \right) \tag{1}$$

where τ is the shear stress, σ_n is the normal stress on the failure plane, P_f is the fluid pressure, c is the cohesive strength and μ_i is the internal friction of the intact rock. The angle θ_i between the fault and the maximum principal stress σ_1 is defined as (e.g., Anderson, 1951; Mandl, 1988)

$$\theta_i = 45 - \frac{\varphi_i}{2} \tag{2}$$

where φ_i is the angle of internal friction, related to μ_i through the relation $\mu_i = \tan \varphi_i$. Amontons' law defines the shear stress necessary to reactivate a pre-existing, cohesionless fault (e.g., Jaeger and Cook, 1979) as follows:

$$\tau = \mu_s \left(\sigma_n - P_f \right) \tag{3}$$

where μ_s is the coefficient of sliding friction of the surface. The angle between the fault and the maximum principal stress σ_1 is defined as the angle of fault reactivation, θ_r.

We used both the geometry and the kinematics of the mapped faults to reconstruct the orientation of the stress field. The kinematic analysis was conducted through the linked Bingham distribution method (Marrett and Allmendinger, 1990), using all the calcite slickenfibers and striae with a strike-slip component (rakes <45°). Assuming a pure shear deformation, the resulting strain axes can be considered parallel to the stress axes. The pure shear assumption is reasonable for the studied outcrops since the fault system is characterized by small conjugate strike-slip faults occurring in a tectonic regime of shortening (e.g., Sylvester, 1988).