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Pressure solution inhibition in a limestone–chert composite multilayer: Implications for the seismic cycle and fluid flow

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ABSTRACT

Pressure solution seams (PSSs) are frequent features in carbonate rocks undergoing tectonic shortening. In particular, pervasive, anticline-axis-parallel, bed-normal PSSs are known to develop during layer-parallel-shortening of (marly) carbonate rocks in fold-thrust belts. These pressure solution features can impact subsequent fracture development, fluid circulation, and strain localization including the seismic cycle. It is here demonstrated that the occurrence of frequent and continuous chert layers may strengthen a limestone sequence and inhibit pressure solution under layer-parallel-shortening. Field observations and laboratory determinations are reported from marly limestone with continuous chert layers of the Scaglia Fm. (Cingoli anticline, northern Apennines, Italy) exhumed from a depth of c. 1 km. In these outcrops, bed-normal solution seams do not occur or they occur only where infrequent chert layers have been shortened by small thrusts. In analogy with laminae-reinforced composite materials, a model is developed explaining the field observations with the strengthening effect of chert in the chert–limestone composite multilayer. During layer-parallel-shortening, the composite multilayer deforms under equal strain boundary conditions. In this situation, the tectonic load is mostly supported by the stiff and frequent chert layers and the strain of the whole chert–limestone composite remains in the elastic field, so that pressure solution seam development is prevented in the limestone beds. Our model may be applied down to a depth of a few kilometers in the upper crust that is relevant for the seismic cycle and fluid flow.

1. Introduction

The Cretaceous–Eocene marly limestone of the Scaglia Fm. in the northern Apennines (Italy) has been the topic of a number of studies concerned with the understanding of pressure solution mechanisms operating during syn-orogenic contraction (Alvarez et al., 1976, 1978; Engelder and Marshak, 1985; Marshak et al., 1982; Meike and Wenk, 1988; Tavani et al., 2008). In several documented instances, the Neogene Apennine orogenesis caused the formation of pervasive pressure solution seams (PSSs) in carbonate rocks as for the case of anticline-axis-parallel, bed-normal seams developed during the initial layer-parallel-shortening. These early structures may have influenced the subsequent formation of syn-folding brittle deformation (Graham Wall et al., 2003; Storti and Salvini, 2001; Tavani et al., 2008, 2015), the subsurface flow of several geo-fluids (Heap et al., 2014), and ultimately the seismic cycle (Gratier and Gamond, 1990; Gratier et al., 1999, 2013b, 2014; Tesei et al., 2013) by controlling seismic or aseismic fault slip (Fagereng et al., 2010; Petracchini et al., 2012; Viti et al., 2014). Understanding the development of PSSs is therefore relevant for many theoretical and practical geological applications (e.g., Aharonov and Katsman, 2009; Billi, 2003; Billi and Salvini, 2000; Gratier et al., 2013a; Koehn et al., 2012; Viti et al., 2014; Yasuhara et al., 2005).

One particular exception to the documented rule of pervasive bed-normal PSSs formed within the Scaglia Fm. of northern Apennines (e.g., Alvarez et al., 1976, 1978) is represented by some exposures from the Miocene–Pliocene Cingoli anticline located in the frontal part of the fold-thrust belt (Mazzoli et al., 2002; Fig. 1). In this anticline, the Scaglia Fm. and the entire Meso-Cenozoic pelagic carbonate sequence are heavily affected by anticline-axis-parallel, bed-normal PSSs (Fig. 2; Petracchini et al., 2012) except where chert occurs as continuous and frequent layers interposed between the carbonate beds. This evidence has never been documented and explained in the Apennines or elsewhere, although instances of pressure solution inhibition are known, as an example, in sandstones (Sathar et al., 2012).

The main aim of this paper is to address the following key questions concerning pressure solution mechanisms: why are anticline-axis-parallel, bed-normal PSSs absent where continuous and frequent layers of chert alternate with carbonate beds? May this absence be the effect of

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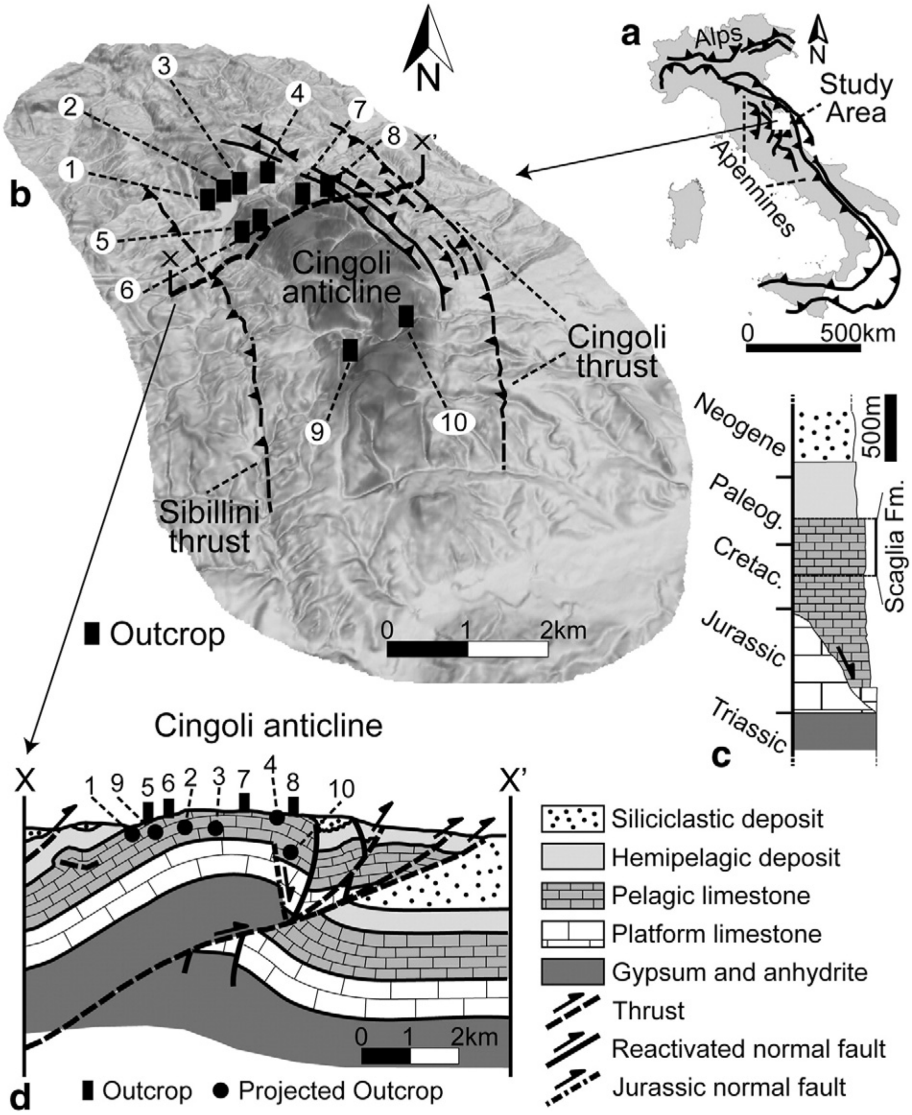

Fig. 1. (a) Location of the study area (Cingoli anticline) in the northern Apennines, Italy. (b) 3D rendering of the Cingoli anticline digital elevation model (vertical exaggeration = 2.5; resolution = 10 m). The anticline axis has a NW–SE trend curving to N–S in the southern part. The western sector of the anticline is limited by the Sibillini thrust, whereas the eastern sector by the Cingoli main thrust and associated hanging wall splays. The location of the studied outcrops in different structural domains across the anticline is also reported with numbers corresponding to records of Table 1. (c) Simplified stratigraphic column of the study area. The marly limestone with chert studied in this work is part of the Cretaceous–Eocene Scaglia Fm. (d) Geological cross-section through the Cingoli anticline (modified from Mazzoli et al., 2002). See the X–X′ track in Fig. 1(b). The study outcrops are plotted along the cross-sections with black rectangles and dots (along track and projected outcrops, respectively), and numbers corresponding to records of Table 1.

the carbonate sequence being strengthened under layer-parallel-compression by the chert layers?

We use field observations from the Cingoli anticline, laboratory analyses, and mechanical modeling to answer these questions. We then briefly and qualitatively discuss the related relevance for the process of fracturing, fluid flow, and earthquake nucleation across sedimentary carbonate strata.

2. Field observations

We analyzed the deformation of the Scaglia Fm. on a set of outcrops distributed in different structural domains of the Cingoli anticline (Fig. 1 and Table 1). This anticline is part of the external (eastern) front of the northern Apennines fold-thrust belt, which developed an eastward piggy-back thrusting sequence during Miocene–Pliocene time (Bally et al., 1986; Calamita and Deiana, 1986; Mazzoli et al., 2002). The first phase of growth of the Cingoli anticline occurred during late Messinian time and was followed by a later thrusting phase during early Pliocene time. The anticline shows gently dipping limbs and a NW–SE-trending flat hinge region curving to N–S toward the south (Fig. 1).

The studied outcrops are usually characterized by multiple sets of structures including PSSs and faults, which are variably oriented. In a previous work on the Scaglia Fm. from the Cingoli anticline, seven main sets of PSSs partly evolving into later small-displacement faults were observed (Petracchini et al., 2012). These PSSs nucleated in part during the layer-parallel-shortening phase and in part during the later folding phases, which also led to fault development. This deformation progression is schematically shown in Fig. 2 together with an example of Scaglia Fm. outcrop affected by multiple sets of PSSs and late faults. All these syn-tectonic sets of PSSs and faults were anticipated by the widespread formation of bed-parallel compaction stylolitic seams developed during syn-sedimentary burial of the Scaglia Fm.