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# Fault architecture and deformation mechanisms in exhumed analogues of seismogenic carbonate-bearing thrusts

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A B S T R A C T

Faults in carbonates are well known sources of upper crustal seismicity throughout the world. In the outer sector of the Northern Apennines, ancient carbonate-bearing thrusts are exposed at the surface and represent analogues of structures generating seismicity at depth. We describe the geometry, internal structure and deformation mechanisms of three large-displacement thrusts from the km scale to the microscale. Fault architecture and deformation mechanisms are all influenced by the lithology of faulted rocks. Where thrusts cut across bedded or marly limestones, fault zones are thick (tens of metres) and display foliated rocks (S-CC′ tectonites and/or YPR cataclasites) characterized by intense pressure-solution deformation. In massive limestones, faulting occurs in localized, narrow zones that exhibit abundant brittle deformation. A general model for a heterogeneous, carbonate-bearing thrust is proposed and discussed. Fault structure, affected by stratigraphic heterogeneity and inherited structures, influences the location of geometrical asperities and fault strain rates. The presence of clay minerals and the strain rate experienced by fault rocks modulate the shifting from cataclasis-dominated towards pressure-solution-dominated deformation. Resulting structural heterogeneity of these faults may mirror their mechanical and seismic behaviour: we suggest that seismic asperities are located at the boundaries of massive limestones in narrow zones of localized slip whereas weak shear zones constitute slowly slipping portions of the fault, reflecting other types of "aseismic" behaviour.



## 1. Introduction

Faults hosted in carbonatic sedimentary sequences are frequent structures in a variety of geodynamic settings, including accretionary prisms of some subduction zones, fold-thrust belts and passive margins (e.g. Bally et al., 1966; Marshak and Engelder, 1985; Alvarez, 1990; Holl and Anastasio, 1995; Willemse et al., 1997; Stern, 2002). Carbonate-bearing faults are important targets for scientific investigation because these lithologies frequently host ore mineralization (e.g. Guilbert and Park, 1986; Anderson and Macqueen, 1982; Gökce and Bozkaya, 2007) and important hydrocarbon reserves (e.g. Archie, 1952; Borkhataria et al., 2005; Ehrenberg and Nadeau, 2005). Also, in Italy and other parts of the world, shallow earthquakes nucleate within or propagate through thick carbonatic sequences in all tectonic regimes (e.g. Chiaraluce et al., 2003; Miller et al., 2004; Di Bucci and Mazzoli, 2003; Bernard et al., 2006; Burchfiel et al., 2008; Mirabella et al., 2008; Ventura and Di Giovambattista, 2013).

Past studies have focused on the deformation of carbonates (e.g. Rutter, 1983; Hadizadeh, 1994; Kennedy and Logan, 1998; Billi, 2010; Smith et al., 2011) and depicted models of carbonate-bearing mature faults in which cataclasis is the main deformation mechanism and strain increases towards fault cores composed of localized slip surfaces and pulverized rock (e.g. Hadizadeh, 1994; Agosta and Aydin, 2006; Billi and Di Toro, 2008). However, in fault-related carbonate rocks significant influence in deformation is exerted by other mechanisms, such as pressure-solution (e.g. Alvarez et al., 1978; Rutter, 1983; Gratier and Gamond, 1990; Collettini et al., 2009). Some fault zone structures are not consistent with a localized fault core, but display thick bodies of variously foliated rocks (e.g. Koopman, 1983; Lavecchia, 1985; Ghisetti, 1987; Marshak and Engelder, 1985; Bussolotto et al., 2007; Calamita et al., 2012).

The aim of this paper is to understand and unravel different faulting styles and deformation mechanisms of mature, thrust

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faults cutting through carbonatic multilayers with strong rheological contrasts. In particular, we focus on three faults that represent exhumed analogues of active thrusts of the Apennines now buried below the Po Plain foredeep deposits in Northern Italy ($M_{max} = 6.0$, e.g. Selvaggi et al., 2001; Lavecchia et al., 2003; Ventura and Di Giovambattista, 2013).

### 1.1. Adopted terminology

In the present study, we adopt a mechanics based terminology that can be tied to simple geometrical observations in the outcrop and in microstructures. This terminology allows making inferences on failure modes and mechanisms of observed geological bodies.

From a macroscopic point of view (i.e. outcrop-to-hand sample scale), the terms *brittle failure* and *ductile flow* reflect a difference in the failure mode of the material. Brittle vs. ductile behaviour fundamentally depends on the space- and time-scale of observation (e.g. Rutter, 1986) but in general, *brittle failure* is associated with localization of deformation in a small portion of the considered physical system. In experiments, brittle failure usually involves an appreciable stress drop. On the other hand, *ductile flow* is associated with distributed deformation within a shear zone and occurs without a significant stress drop (e.g. Paterson, 1958; Rutter, 1986; Sibson, 1986; Scholz, 2002; Paterson and Wong, 2005 and others). Within this framework, we refer to the brittle–ductile transition as the shift from a localized to de-localized deformation in the architecture of fault zones.

Fault rocks such as gouge, breccias and cataclasites–ultracataclasites (e.g. Sibson, 1977) with random-fabric and well-localized deformation along Principal Slip Zones (PSZ) represent *brittle* failure modes whereas foliated rocks with distributed deformation represent *ductile* failure modes. The foliated rocks are distinguished in two broad groups depending on the dominant deformation process (e.g. McClay, 1977):

(1) YPR (or foliated) cataclasites (after Logan et al., 1979) characterized by Y and Riedel shear surfaces mainly deformed by cataclasis and hydrofracturing;
(2) S-C or S-CC′ tectonites (e.g. Ramsay and Graham, 1970; Berthé et al., 1979; Bos and Spiers, 2001), form as consequence of pressure-solution and frictional sliding.

Although shifts in deformation mechanisms are not abrupt in nature, but rather transitional, the main process is recognizable among the competing mechanisms.

In both cases, YPR and S-CC′ surfaces define rock sigmoids affected by minor internal deformation. These surfaces have similar kinematic significance: P and S surfaces are perpendicular to the maximum flattening of the strain ellipsoid, Y and C are shear parallel surfaces, and $R_1$ and C′ are late, synthetic shear surfaces oblique with respect to the macroscopic shear sense (Platt, 1984; Scholz, 2002).

## 2. Geological framework

The Northern Apennines are an arcuate fold and thrust belt originated by collision of a formerly European continental block (Corsica-Sardinia) and the Adria microplate with African affinity (e.g. Reutter et al., 1980). Apennines development is embedded within the Europe–Africa convergence that initiated in the Cretaceous (Dewey et al., 1989). The belt has an E-NE vergence and its development generated a series of foredeep and piggy-back basins rejuvenating from W to E. The age of these synorogenic deposits constrains the timing of deformation from more internal Oligocene-Miocene domains (Tuscan domain) to the Pliocene-present day Adriatic foredeep (Merla, 1951; Boccaletti et al., 1990; Barchi et al., 2012). Present-day compression is active in the Adriatic foredeep that extends from the Po-Plain and continues along the Eastern Italian Coast and into the Adriatic Offshore (e.g. Pieri and Groppi, 1981; Doglioni, 1993; Chiarabba et al., 2005). Since the Miocene, extension roughly coaxial with compression has been active in dissecting previous compressional features (Elter et al., 1975).

The study area is part of the external relief of the Northern Apennines known as the Umbria-Marche Apennines; it is located between the Tuscan Domain to the W and the Adriatic Foothills to the E (Fig. 1a). The Umbria-Marche Apennines consist of a thick pile of Meso-Cenozoic passive margin-related carbonates that lie over Triassic rift-related deposits and Hercynian crystalline basement and below the foredeep turbidite cover.

The carbonatic multilayer constitutes the bulk of the outcropping orogen (e.g. Lavecchia et al., 1988) and presents strong rheological contrasts because of the alternation of limestone and marly

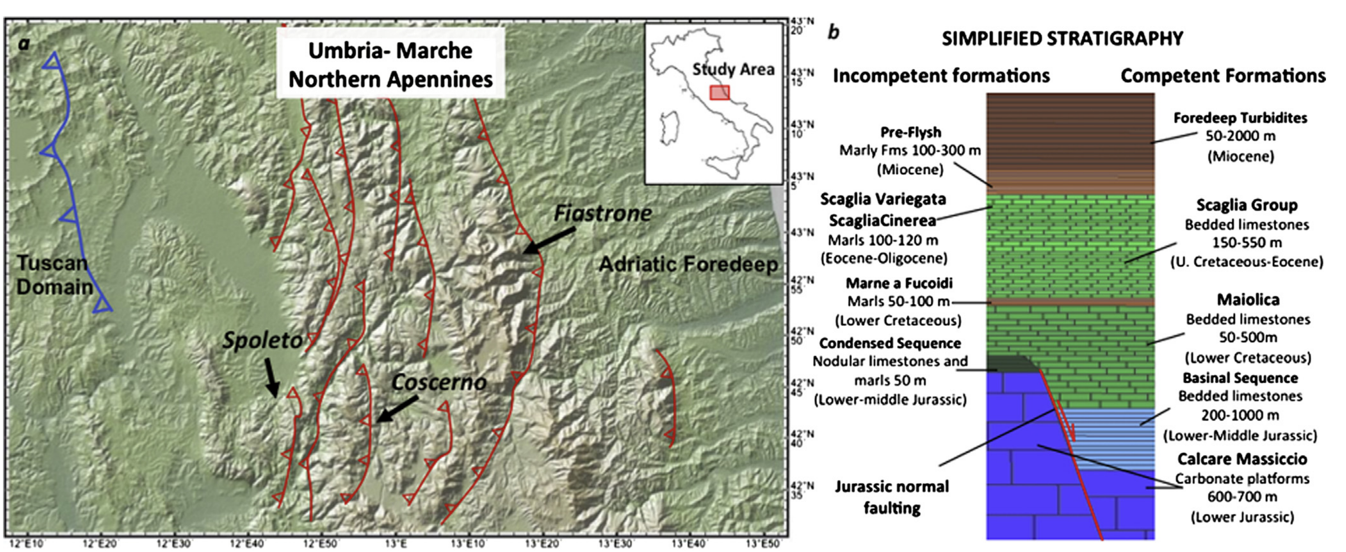


**Fig. 1.** (a) Digital elevation model of Umbria-Marche Apennines prepared with GeoMapApp (http://www.geomapapp.org) displaying traces of main thrusts and the location of studied faults. (b) Schematic stratigraphic column of the sedimentary sequence cropping out in the study area. A distinction between competent and incompetent formations has been highlighted.