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Time dependent structural architecture of subsidiary fracturing and stress pattern in the tip region of an extensional growth fault system, Tarquinia basin, Italy

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ABSTRACT

Fault tip regions, relay ramps and accommodation zones in between major segments of extensional fault systems provide zones of additional structural and stratigraphic complexities and also significantly affect their hydraulic behaviour. The great interest for both academic and industrial purposes encouraged specific studies of fault tip regions that, in some cases, produced controversial results. We approached the study of fault tip regions by integrating structural, AMS and stratigraphic analyses of the tip of an extensional growth fault system in the Tarquinia basin, on the Tyrrhenian side of the Northern Apennines. Detailed structural mapping indicates the occurrence of systematic relationships between the orientation of the main subsidiary fault zones, the orientation and position of the two main joint sets developed in the fault damage zones, and the overprinting relationships between the two main joint sets themselves. Microstructural analysis of fault core rocks indicates a progression of deformation from soft-sediment to brittle conditions. The AMS study supports the evolution of deformation under a constantly oriented stress field. By combining this multidisciplinary information we propose an evolutionary model for the tip of the extensional growth fault system that accounts for the progressively changing sediment rheological properties, and for the time dependent subsidiary deformation pattern by invoking the interplay between the regional stress field and the local, kinematically-derived one by fault activity. We also speculate on the overall implications for fluid flow of the proposed evolutionary model.

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1. Introduction

Fault tip regions and relay ramps are common features of extensional fault systems at different scales and are typical sites of preferential deformation and structural complexities (e.g. Cowie and Scholz, 1992; McGrath and Davison, 1995; Cartwright et al., 1995; Martel, 1997; Cartwright and Mansfield, 1998; Ferrill and Morris, 2001; Davatzes and Aydin, 2003; Kim et al.; 2004; Davatzes et al., 2005; Johansen et al., 2005). These deformation structures mainly include joints and small-scale faults in low-porosity rocks, and deformation bands (namely cataclastic bands, dilation bands, compaction bands, disaggregation structures, etc.) and deformation band zones in high-porosity sandstones and loose sediments (e.g. Aydin, 1978; Antonellini et al., 1994; Mollema and Antonellini, 1996; Hesthammer and Fossen, 2001; Du Bernard et al., 2002; Rawling and Goodwin, 2003; Johansen et al., 2005; Fossen et al., 2007). In extensional tectonics, these subsidiary structures typically form parallel to the strike of master fault segments (e.g. Storti and Salvini, 2001; Shipton and Cowie, 2001), i.e. perpendicular to the minimum principal stress axis (Anderson, 1951). However, subsidiary deformation structures striking oblique or at high-angle to the master faults have also been described, particularly near fault terminations (i.e. tip regions and relay ramps) in both low- and high-porosity rocks (Mandl, 1988; Trudgill and Cartwright, 1994; McGrath and Davison, 1995; Destro, 1995; Cartwright et al., 1996; Kattenhorn et al., 2000; Stewart, 2001; Destro et al., 2003; Rotevatn et al., 2007). Their development generally implies local stress field perturbations (e.g. Pollard and Segall, 1987; Barton and Zoback, 1994; Kattenhorn et al., 2000) and the occurrence of a fault-parallel extensional component (e.g. Wu and Bruhn, 1994; Roberts, 1996; Medwedeff and Krantz, 2002).

The type, occurrence and spatial distribution of subsidiary deformation structures in fault tip regions deeply impact the pathways of groundwater flow and hydrocarbon migration in fault zones (e.g. Ferrill and Morris, 2001; Rotevatn et al., 2007). Despite the large amount of work performed on this subject, field evidence from fault tip regions and interpretations of their origin are, in some cases, still controversial. Uncertainties include the role of pristine rock initial porosity and grain size, of pore fluid pressure progression, of cementation, and of the peculiar stress distributions that characterise fault tip regions (e.g. Davatzes et al., 2005; Johansen et al., 2005). To obtain further constrains on these parameters, we carried out a multidisciplinary study of the three-dimensional deformation pattern and

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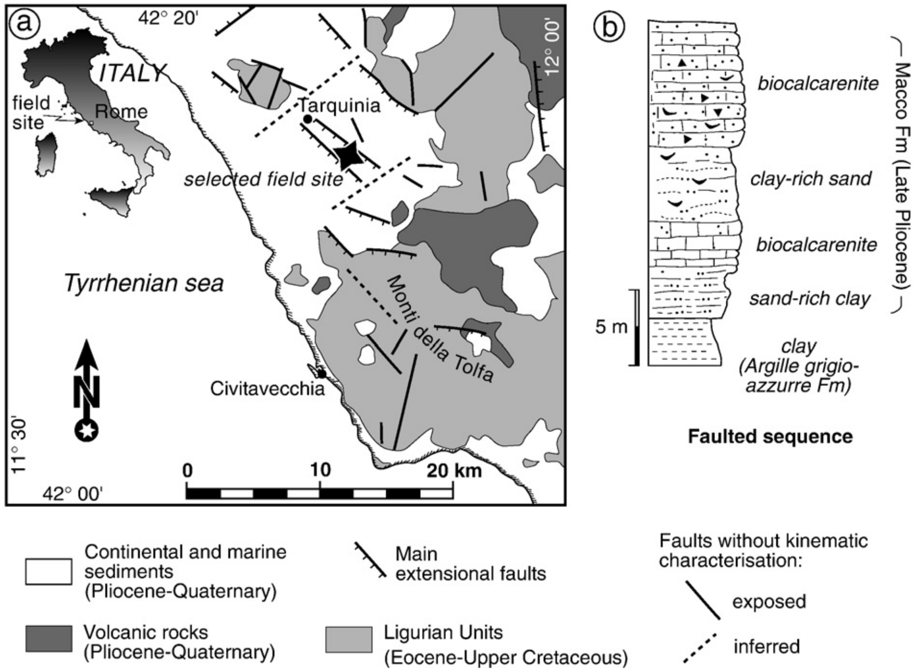

Fig. 1. (a) Geological sketch map of the southern part of Tarquinia basin and location of the field site (black star). Modified from Structural Model of Italy and Gravity Map (CNR, 1991). (b) Stratigraphy of the faulted clastic sequence exposed in the study area (after Fazzini et al., 1972).

sedimentary architecture at the tip of an extensional growth fault system in Central Italy. In particular we used: (1) the type, orientation and location of outcrop-scale deformation structures, and the analysis of the anisotropy of magnetic susceptibility (AMS) to constrain the stress field pattern; (2) the fault core microstructural fabric to constrain the evolution of the environmental conditions of deformations through time; (3) the three-dimensional stratigraphic architecture of growth strata to constrain fault propagation history; (4) the three-dimensional deformation pattern in the growth strata to constrain the progressive evolution of damage during faulting, in concomitance with the increasing stiffness of granular material. The use of AMS was dictated by the evidence that development of a magnetic lineation in poorly deformed to apparently undeformed sediments is commonly related to the very early stages of extensional deformation (e.g. Sagnotti et al., 1994; Mattei et al., 2002; Borradaile and Hamilton, 2004; Cifelli et al., 2004). In particular, the magnetic lineation in extensional environments is expected to be oriented parallel to the tectonic transport direction (e.g. Mattei et al., 1997). The integration of this multidisciplinary information allowed us to propose a 4-D evolutionary model of the studied extensional fault tip region and to infer insights on its hydraulic architecture through time.

2. Geological outline

The study area is an abandoned quarry in the central part of the Tarquinia basin on the Tyrrhenian side of the central Apennines (Fig. 1a). The area is located in between two intra-basinal NW–SE striking extensional fault systems mapped at the regional scale. The exposed faulted sedimentary sequence is 50–60 m thick and mainly consists of marine Pliocene clastic rocks. In particular, a basal layer of grey clay (Argille grigio-azzurre Formation) is overlain by poorly lithified biodetrital calcarenites with intercalated beach silty and sandy levels (Macco Formation) often with lateral heteropic transitions (Fazzini et al., 1972; De Rita et al., 1997) (Fig. 1b). The evolution of the studied fault system tip region progressed in shallow marine conditions and produced small-scale fault-related depocentres, as indicated by the attitude of syn-tectonic strata and their lateral pinch-out migration.

3. Structural architecture

The structural and syn-depositional stratigraphic architectures of the extensional fault tip region were mapped at the 1:200 scale (Fig. 2). Deformation structures typically include dilation bands, joints and subsidiary faults. The NW–SE striking end segment of the master extensional growth fault segment (named fault A) is exposed at the northern end of the mapped quarry. The actual fault termination is not visible but the evidence that displacement at the exposed SE end of the fault segment is very low, and that the latter does not occur in an adjacent excavation front to the SE, support the proposed location of the fault tip region.

Subsidiary faults occur at different scales to the south of the fault tip and, based on their displacement, they were mapped as 2nd order fault segments (displacement$>$1 m) and 3rd order fault segments (displacement$<$1 m). According to this classification, five major 2nd order growth fault segments were identified in the exposed hangingwall tip region of fault A, which strike NW–SE in the northern sector (faults B, C and D) to roughly WNW–ESE (fault E) and E–W (fault F) in the southern sector (Fig. 2). Their structural architecture includes the fault core, in which most of total displacement was accommodated, encompassed by zones of fault-related deformation referred to as damage zones (e.g. Chester and Logan, 1986). The fault throw accumulated on each of the 2nd order fault segments was lower than about 20 m because the Macco formation is exposed in most of the faulted area regardless of the structural position. A small outcrop of the Argille grigio-azzurre Formation occurs in the footwall of fault F, while Macco sands occur in the hangingwall.

The mapped 2nd order fault segments have different separations and overlapping geometry (Fig. 2). Fault B occurs as isolated segment, while faults C and D, and E and F are partially overlapped and connected. Faults C and D are closely spaced (~10 m) and linked by a breached relay ramp (Peacock and Sanderson, 1991), while overlapping fault segments E and F are linked by a simple relay ramp where bedding is reoriented in the overstep (Larsen, 1988; Peacock and Sanderson, 1991). Much larger separations (~50 m) occur between faults A and B, fault B and the fault segment pair C–D, and between C–

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