PETROPHYSICAL CHARACTERISATION OF FAULT ZONES IN CARBONATE ROCKS: IMPLICATIONS FOR THE EVOLUTION OF STRUCTURAL AND PERMEABILITY PROPERTIES

C-05

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Abstract

The evolution of fault cores from damage zones has relevant implications for the 4-D evolution of permeability in fault-controlled oil fields. Analyses of regional- to outcrop-scale extensional and strike-slip fault zones in carbonate rocks were performed to study the nucleation and growth of fault cores within damage zones. Analysed fault zones have similar lithology and similar sedimentary fabric of the protolith, but different geometry, kinematics, size, tectonic environment and deformation history. Fractures and solution cleavages affect rocks in damage zones, whereas cataclastic rocks occur in fault cores, where pre-existing structures or deformations are fully obliterated. Pseudocubic rock prisms occur at the damage zone-fault core transitions, generated by the intersection of at least three sets of tectonic surfaces. The aspect ratio computed from the rock prism sections has a systematic value of 1.4. This value is critical for triggering the development of cataclasis within fractured rocks. Results from this study shed light on the sealing versus leaching properties of fault zones at the reservoir scale. According to the proposed model, radical changes on the permeability properties are expected during the evolution of fault cores. The found particle size and shape data can substantially improve numerical modelling of the major conduit and barrier regions in fault-controlled reservoirs.

Introduction

The structural components that commonly characterise both mature and young fault zones are (Fig. 1a): (1) a damage zone and (2) a fault core (e.g. Chester et al., 1993; Caine et al., 1996). Fault cores and damage zones show different permeability properties amenable to different deformational fabrics of the rock (e.g. Antonellini and Aydin, 1994, 1995; Knipe, 1997; Manzocchi et al., 1999; Yielding et al., 1999). As a general rule (Main et al., 2000), fault cores consist of low permeability cataclastic rocks where pre-existing, sedimentary and tectonic fabrics are fully obliterated by granular flow, whereas damage zones consist of high permeability rock volumes affected by fault-related fracturing. In fault-controlled reservoirs, faults may represent hydraulic barriers or preferential fluid conduits (e.g. Coward et al., 1998). Within the same reservoir, faults with different orientations may show different permeability properties and also the permeability properties may be strongly variable along the same fault. This matter, although broadly studied, is still far to be fully understood. This, in particular, applies to carbonate rocks, for which a general dearth of data exists in the literature (Olsson, 1974; Vittori et al., 1991; Salvini et al., 1999; Billi and Salvini, 2001; Storti et al., 2001). Understanding the parameters that govern the structural architecture of fault zones in carbonate rocks and relating fault cores to damage zones in an evolutionary mechanism, has a crucial importance for accurate reservoir characterisation and 4-D permeability and transmissibility modelling.
In this paper we describe, in quantitative terms, structural fabrics developed in fault zones from shallow-water carbonate rocks in the Southern Apennines, Italy. In particular, we focus on the structural fabric developed at damage zone-fault core transitions in order to define the critical structural texture of rocks controlling the fault core nucleation. Similar results obtained from different fault zones allow us to propose a genetic model for fault core nucleation and development in carbonate rocks. Implications for the spatial and temporal evolution of permeability in fault-controlled carbonate reservoirs are discussed.

Fault zone structure and fabric

We analysed rock fabrics from ten fault zones exposed in shallow-water carbonate rocks from the Southern Apennines with the aid of DAISY (Salvini, 2002a) and FRAP (Salvini, 2002b) software. The

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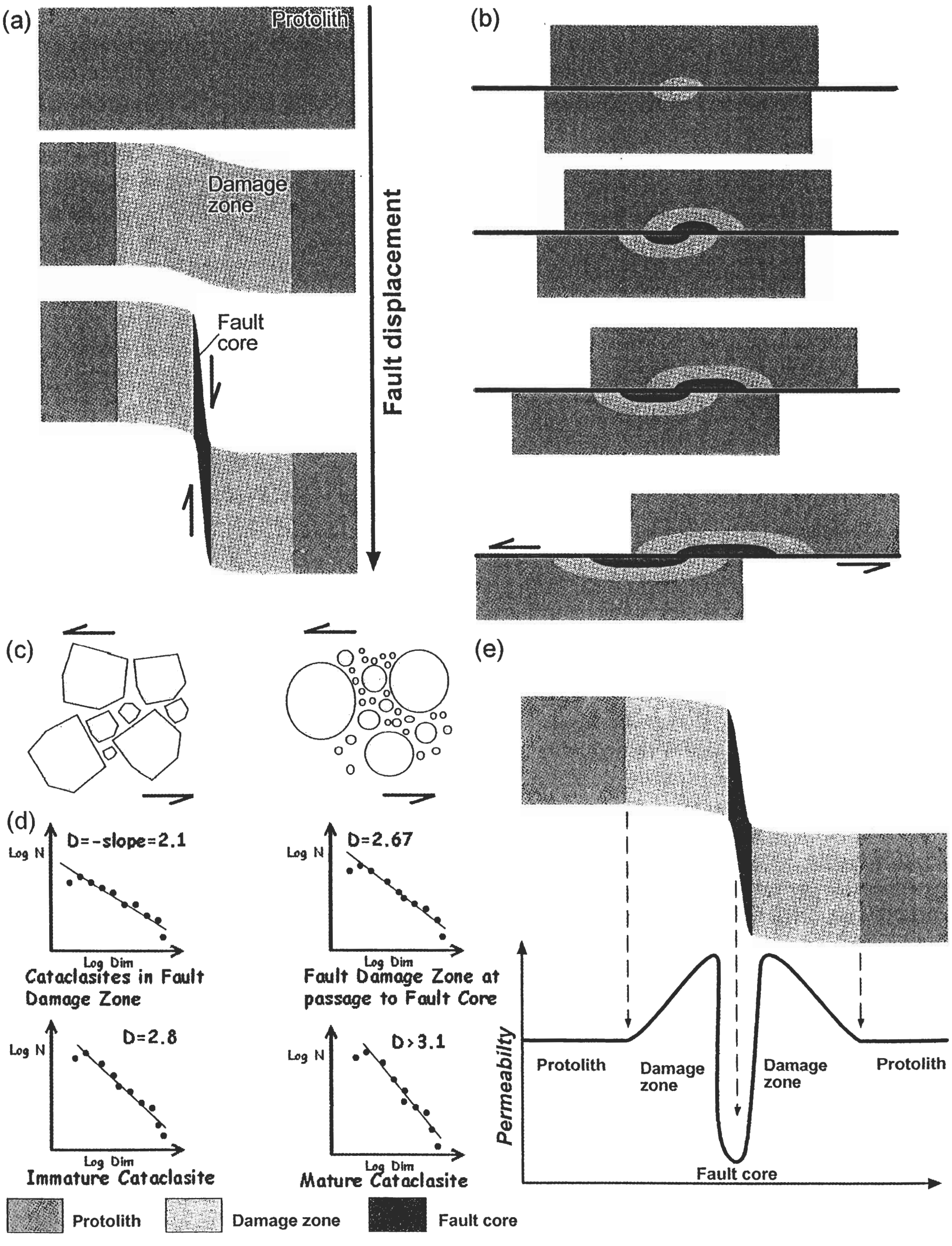

Fig. 1 - (a) Conceptual model for development of a fault zone with progressing the fault displacement. The damage zone forms from a protolith, wheras the fault core forms from a pre-existing damage zone. (b) As fault displacement increases, fault core migrates along the fault. (c) As displacement progresses, particle grinding occurs and (d) fractal number, D, of the particle size distribution increases. (e) The permeability in the protolith depends upon the rock deformation history. In the damage zone, the permeability is increased up to a maximum in the transitional region near the fault core. In the fault core, permeability is significantly reduced.

studied fault zones have similar lithology and sedimentary fabric of the host rock, but different geometry, kinematics, size, tectonic environment and deformational history. In the field, we recognised three structural components that are common to all the studied fault zones: (1) the damage zone, (2) the fault core, (3) the master fault surface and (4) the damage zone-to-fault core transition zone.

(1) Damage zones contain layered carbonate rocks with primary, subparallel fractures and/or solution cleavages. This set of tectonic surfaces is often subvertical and defines elongated orthorhombic rock lithons a few millimetres to centimetres in thickness. These lithons are commonly dissected by perpendicular fractures that abut against the primary fracture/cleavage surfaces.

(2) In fault cores, we recognised a gouge zone lying along the fault plane, and an adjacent cataclastic breccia zone. Particle size distributions of rock samples from fault cores are well fitted by fractal functions of the type,

$$\log(y) = -D^{*}\log(x) + A \qquad (1)$$

where D is the fractal dimension (Turcotte, 1986). Ds from the analysed samples vary in the 1.9 to 3.1 range depending upon the structural location of the sample within the fault core. As a general rule, we observed that D increases with approaching the master fault surface (e.g. Storti et al., 2001).

(3) The master fault surface commonly constitutes the abrupt boundary between the damage zone and the fault core on at least one side of the fault core. The 3-D architecture of damage zones, fault cores and master fault surfaces depends also upon the fault displacement (Fig. 1b).

(4) On the other side, the fault core fades into the damage zone in a few centimetres to meters. In this transition zone, the pristine orthorhombic lithons that occur in the damage zone are intensely fractured such that their shape tends to an isometric symmetry. Rock lithons in this transitional region have a typical two-dimensional aspect ratio of 1.4.

Conclusions

The petrophysical characterisation of fault zones in shallow water carbonate rocks from Southern Apennines allows the following conclusions.

(1) Despite different size, kinematics, and inherited structural fabrics of the protolith, rocks in damage zones adjacent to fault cores show very similar structural fabrics, which consist of tightly juxtaposed and interlocked, nearly isometric lithons a few centimetres in size, having a cross-sectional aspect ratio of about 1.4. We interpret this value as the shape upper limit for the systematic initiation of particle rotation and grinding, which enhance the formation of fault core rocks by cataclastic flow (Fig. 1c).

(2) Structural observations at the damage zone-fault core transition and the particle size distribution of bulk fault core rocks (e.g. in Fig. 1d) in the studied fault zones support a two-stage evolutionary model. The first stage is dominated by fracturing during the evolution of the damage zone, which provides a high permeability conduit for fluid flow. The second stage includes the development of the fault core, which occurs in the most fractured region of the damage zone by rotation and comminution of rock particles once they reach a nearly isometric shape.

(3) Such evolutionary pathway, when applied to the four-dimensional evolution of fault zones, gives complex permeability patterns that have important implications for hydrocarbon migration and accumulation in fault-controlled reservoirs (Fig. 1e).

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AVERAGE STRAIN RATE IN THE ITALIAN CRUST INFERRED FROM A PERMANENT GPS NETWORK — C-06

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Abstract

We have computed time series of the horizontal coordinates of 30 permanent GPS stations in the Alpine Mediterranean area with the intent of estimating velocities and their uncertainties, on account of the detailed structure of their noise. The power spectral densities demonstrate that colored noise, mostly flicker phase and -more occasionally- random phase walk noise, can be present at low frequencies, typically below five cycles per year. At higher frequencies the spectrum tends to a regime of white noise. We use this statistical information to estimate the uncertainty of the velocities, in analogy with time series of frequency standards (two-samples Allan variance), as the 1σ probability of a change in the slope of two consecutive, equal length batches of a time series, as a function of the length of the batch. Taking into account the correct time correlation among the samples, the slope of each series is estimated by least squares. Stations with only one year tracking history and a standard least squares ('pure white noise') formal velocity error of ~0.1 mm yr^{-1} have a velocity uncertainty, in the sense of Allan variance, of 2 - 3 mm yr^{-1}, which drops to 0.6 - 0.7 mm yr^{-1} with a five years tracking history. We use these velocity estimates to analyze the large scale intraplate kinematics of the area. This is characterized by a wide range of tectonic phenomena and is accompanied by a relatively intense volcanism and seismicity, which justify the expectation of small but theoretically measurable horizontal and vertical displacements. We show that the estimated strain rate is everywhere smaller than 50 10^{-9} yr^{-1} with a mean uncertainty between 13 and 20 10^{-9} yr^{-1} (1σ). The areas with largest strain rate are the Central Apennines and Eastern Alps, while in the Western Alps the estimated strain rate is smaller than 15 -20 10^{-9} yr^{-1}, hence comparable with its uncertainty. The geodetic strain rate is compared with the co-seismic strain rate estimated from shallow earthquakes of M>5 occurred in the past 400 years, using the Kostrov formula and the summation of the seismic moments over an area. We focus on the Eastern Alps, outer side of the northern Apennines, both under compression, and inner side of the North Central Apennines, under extension. We show that if the two strain rates are to coincide, then the seismogenetic area has an extension very nearly comparable with that containing the epicenters of the contributing earthquakes.