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Hydraulic connection and fluid overpressure in upper crustal rocks: Evidence from the geometry and spatial distribution of veins at Botrona quarry, southern Tuscany, Italy

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Abstract

Veins are the geologic record of fluids that filled fractures at depth in the crust. In southern Tuscany (Italy), well-exposed Oligocene−Early Miocene sandstones hosting vein systems provide insight into the role of pore fluid and the stress state at the time of vein formation. The stress ratio ($\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$) and driving stress ratio ($R' = (P_f - \sigma_3)/(\sigma_1 - \sigma_3)$) were determined by analysing the distribution, length and aperture of fractures and veins and the magnitude of fluid overpressure. The derived fluid overpressure for the whole vein system ranges from 30 MPa to 64 MPa, with an average of 43 MPa; these values indicate that veins formed under supra-hydrostatic pressure conditions. Despite their spatial contiguity, two different vein arrays show very different stress and driving pressure ratios. One vein system is characterised by $\Phi = 0.62$ and $R' = 0.60$, the other by $\Phi = 0.54$ and $R' = 0.78$. The described vein systems are an example of a close spatial association of two non-hydraulically connected vein systems representing fluids focused through the upper crust.

Keywords: Fracture systems; Vein systems; Fluid overpressure; Sandstones; Tuscany

1. Introduction

Pore fluid pressure influences rock failure and the crack opening mode at depth in the crust, controlling the effective stress acting on a rock volume (Sibson, 2000 and references therein) and possibly triggering seismicity (Beeler et al., 2000; Miller et al., 2004). Fluids can saturate a rock volume or focus through fractures. Focused fluids in the crust are involved in metamorphic, magmatic and hydrothermal processes; they exploit the existing fracture network or generate new fractures. The connectivity and aperture of fractures provide a key for understanding the overall flow and transport properties of fracture networks (e.g. Darcel et al., 2003). Connectivity is important since not all the fractures in a rock volume can transport fluid, and connected fractures can create different hydraulic paths. Veins are defined as fractures that are mineralised at some depth in the crust, and can be used to study the geometric and hydraulic features of fracture networks in the crust (e.g. Vermilye and Scholz, 1995; Johnston and McCaffrey, 1996; Roberts et al., 1999). Veins are a record of fluid transport in fractures; when the fluid pressure builds up and then drops, minerals precipitate (Foxford et al., 2000; Bons, 2001; Cox et al., 2001). The geometric features and the spatial distribution of fractures and veins may thus be used to define parameters relating to fluid pressure, stress state and hydraulic connectivity between vein systems.

We report on the structural analysis of fracture networks and vein systems exposed in an abandoned sandstone quarry. The sandstones are well exposed in the quarry floors, allowing detailed mapping of fractures and veins at different depths (with a maximum step of about 10 m between floors). The calcite veins in the hosting sandstones formed in pre-existing fractures opened in pure extension and extensional shear

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modes. Results are used to constrain the local fluid pressure, stress state and fracture connectivity in a fracture network that developed at very shallow crustal levels. We demonstrate that different non-hydraulically connected paths were in close spatial association at the time of vein formation.

2. Rationale

The type of failure affecting an intact rock mass greatly depends on the fluid pressure (P_f), since the effective principal stresses (Sibson, 2000 and references therein) are defined as:

$$\sigma'_1 = (\sigma_1 - P_f) > \sigma'_2 = (\sigma_2 - P_f) > \sigma'_3 = (\sigma_3 - P_f) \tag{1}$$

where σ_i ($i = 1,2,3$) are the principal stresses.

The ratio of pore fluid pressure to lithostatic pressure (σ_v) is defined as:

$$\lambda = P_f/\sigma_v = P_f/\rho g z \tag{2}$$

where ρ is the rock density and g is the gravitational acceleration.

Hydrostatic fluid pressure is attained when pores and fractures are interconnected up to the water table, which is assumed to reach the ground surface ($\lambda \sim 0.4$). Supra-hydrostatic fluid pressure conditions are defined by $0.4 < \lambda < 1.0$, while supra-lithostatic ones are defined by $\lambda > 1.0$ (Sibson, 2000).

Rock failure depends on the friction coefficient and on the equilibrium between differential stress ($\sigma_1 - \sigma_3$) and rock tensile strength T (Secor, 1965; Brace, 1978; Byerlee, 1978).

According to Sibson (2000), in the case of extension (i.e. $\sigma_1 = \sigma_v$) the pure extensional failure mode occurs when:

$$(\sigma_1 - \sigma_3) < 4T \tag{3a}$$

$$P_f - \sigma_3 = T \tag{4a}$$

and the extensional-shear failure mode occurs when:

$$4T < (\sigma_1 - \sigma_3) < 5.66T \tag{3b}$$

$$P_f - \sigma_3 = \left[8T(\sigma_1 - \sigma_3) - (\sigma_1 - \sigma_3)^2\right]/3 \quad \text{for } \mu_i = 0.75 \tag{4b}$$

where μ_i is the internal friction of the material.

Several parameters related to both the effective stress field and fluid pressure can be derived through the analysis of vein geometry, including vein attitude and aspect ratio (e.g., Baer et al., 1994; Jolly and Sanderson, 1997; Gudmundsson, 1999; André et al., 2001).

The stress ratio (Φ) and the driving stress ratio (R') are defined in terms of the principal stresses (σ_1, σ_2, σ_3) and fluid pressure (P_f) (Baer et al., 1994; Jolly and Sanderson, 1997):

$$\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) \tag{5}$$

and

$$R' = (P_f - \sigma_3)/(\sigma_1 - \sigma_3) \tag{6}$$

The stress ratio Φ ranges from 0 to 1 and describes the Mohr circle configuration (Angelier, 1984; Baer et al., 1994; Orife and Lisle, 2003). The driving stress ratio R' (Baer et al., 1994) varies from -1 (no opening of fractures) to 1 (re-opening of pre-existing fractures), and describes the equilibrium between P_f and the minimum (σ_3) and maximum (σ_1) stresses.

The vein aspect ratio (W/L) is defined as the ratio between maximum vein aperture (W) and vein length (L). It can be used to derive static fluid overpressure (driving pressure) during vein formation, as it is assumed to be linearly related to fluid overpressure ($\Delta s_i = P_f - \sigma_3$) and the elastic properties of rocks (Gudmundsson, 1999 and references therein):

$$W/L = \Delta s_i 2(1 - \nu^2)/E \tag{7}$$

where ν and E are the Poisson ratio and Young's modulus, respectively.

Hydraulic and geometric features of veins and fractures such as length and aperture are characterised by scale invariance (e.g. Gillespie et al., 1999; Roberts et al., 1999; Bonnet et al., 2001; Bour et al., 2002; Darcel et al., 2003) and are analysed in terms of their cumulative frequency distribution and self-similar clustering.

The cumulative frequency distribution of the geometric features of fractures and veins (length, aperture) can be defined as:

$$N(>L) = \alpha L^a \tag{8}$$

where α is a normalisation constant, L is the fracture/vein length and a is the power law (fractal) exponent.

The spatial distribution (clustering) of fractures and veins is estimated through the computation of the respective correlation exponent D (e.g. Bonnet et al., 2001), which is a measure of how fractures (or veins) fill a space. In other words, two fracture networks with different correlation exponents exhibit different spatial distributions of fractures. The lower the D exponent, the higher the clustering of fractures. High D values indicate a homogeneous distribution of fractures. A homogenous distribution of fractures in trace maps yields $D = 2$. The two-point correlation method was used to measure the fractal dimension of the fracture/vein population. For a population of N points (fracture/vein barycentre) the correlation integral $C(l)$ is defined as the correlation sum that accounts for all the points at a distance of less than a given length l (Bonnet et al., 2001; Bour et al., 2002). In this approach, the term $C(l)$ is calculated as:

$$C(l) = 2N(l)/N(N-1) \tag{9}$$

where $N(l)$ is the number of pairs of points whose distance is less than l. If scaling holds, eq. (9) is valid, and the slope of the curve in a $\log(C(l))$ vs. $\log(l)$ diagram yields the D value.

Following eq. (9), the calculated D value is valid for a defined range of lengths (l). The distance interval over which eq. (9) is valid is defined by the size range. For each analysis, the size range of samples is in turn defined by a plateau in the local slope vs. $\log(l)$ diagram: the wider the range the better the calculation of the power law distribution (Walsh