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Hot fluid pumping along shallow-level collisional thrusts: The Monte Rentella Shear Zone, Umbria Apennine, Italy

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ABSTRACT

The characteristics of a shallow-level shear zone that is representative of the deformation in the external sectors of the Northern Apennine fold-and-thrust belt are described. The characterization involved an integrated approach using microstructural analysis of deformation fabrics, vitrinite reflectance measurements, XRD analysis on clay minerals and carbon and oxygen stable isotopes analyses. This data set provides the evidence that the thrust was active at very shallow depths (ca. less than 3 km), with maximum paleotemperatures ranging from 60° to 100–110 °C. The regime during fault activity evolved through cycles of compaction and dilation linked to transient build up of fluid overpressure and injection. The alternating cycles of fluids supply generated a fault-fracture mesh with a complex network of blocky and striped veins that formed at temperatures ranging from 150° to 200 °C, not compatible with the conditions in the host rocks. This evidence implies that the shear zone was flooded by hot fluids coming upward from diagenetic and low-grade metamorphic dehydration of clay minerals active at deeper structural levels. The fluids were thus highly channelled and focused where deformation also focused, producing a local pronounced isotopic difference between fluids and host rock.

1. Introduction

The hydrogeologic characteristics of fault zones are matter of deep structural and economic geologic interest, particularly during the last half of the century, because of their crucial role in influencing heat and mass transport, healing processes, overall fault strength, fault mechanical evolution and economic importance. After all, hydrothermal mineral deposits, as well as the production of hydrocarbons and gas, rely on the availability of large volumes of fluids that in many cases flowed along faults (e.g. Newhouse, 1942; Hubbert and Rubey, 1959; Fyfe et al., 1978; Hunt, 1990; Cox et al., 1991, 2001; Fournier, 1991; Sibson, 1990, 1994; 1996, 2001; Law et al., 1998; Hillis, 2001; Leader et al., 2010 and references therein). In particular, starting from the work by Hubbert and Rubey (1959), the feedbacks between cycling of stress and fluid pressure have interested many scientists, and the fluid migrations with pressures well in excess of hydrostatic, are considered to play a fundamental role in weakening low and high displacement fault zones, because of the efficiency of high pressure fluids for reducing the effective normal stress prior to slip. The effects of fluid-rock interaction along faults are also crucial at the tectonic scale, as first suggested by Davis et al. (1983), in the context of the dynamics of accretionary prisms (e.g. Saffer and Bekins, 2002 and references therein).

Since Hubbert and Rubey's contribution, many field, laboratory, and geophysical studies have worked to unravel the mechanical involvement of fluids in the faulting process. Evidence of fluid circulation along fault-related fracture systems have come from *in situ* measurements in active tectonic regions (thermal, chemical and porosity anomalies, negative seismic reflectors: Shipley et al., 1995; Bangs et al., 1999, 2004; Brown et al., 2001), and from the occurrence of mineral-infused vein systems in the faults of ancient orogenic belts (e.g. Labaume et al., 1991; Fisher and Brantley, 1992; Moore and Vrolijk, 1992; Chester et al., 1993; Fisher, 1996; Lewis et al., 2000; Collettini at al., 2006; Meneghini et al., 2007). Special attention has been devoted to the relationships between fluids flow and pore fluid pressure with the seismic cycle (e.g. Hill, 1977; Ramsay, 1980; Sibson, 1987, 1996, 1990; Cox et al., 1991; Chester

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et al., 1993; Evans and Chester, 1995; Hickman et al., 1995; Faulkner and Rutter, 2001; Meneghini and Moore, 2007; Rowe et al., 2009).

The coupling of structural and geophysical analyses of fluid-infused faults with other laboratory-based techniques such as fluid inclusion studies, isotopic and geochemical characterization of veins infillings, cathodoluminescence analyses, have confirmed that fluids can circulate via intergranular flow or be highly channelled; they can either have a local origin, or they can move over distances of hundreds of kilometres along faults of regional extent (e.g. fluids released at depth by low-grade metamorphic reactions in sedimentary rocks, see Moore and Saffer, 2001); and they can interact differently with the surrounding rocks depending on the water/rock volume ratio (Fyfe and Kerrich, 1985; Moore et al., 1990; Kastner et al., 1991; Kirschner et al., 1995; Conti et al., 2001; Brown et al., 2001; Goldstein et al., 2005; Hilgers et al., 2006; Vannucchi et al., 2010 and references therein). In line with these contributions, we have conducted a multidisciplinary study on a well-exposed shallow shear zone that is responsible for thrust sheet development during the building of the Apennine collisional prism, and host to a complex system of calcite veins. To reconstruct the structural and temperature fluid rock-interaction during shear zone development, we performed a detailed field and microstructural analysis of the Monte Rentella shear zone structure and deformation fabrics, including vitrinite reflectance measurements, XRD analysis on clay minerals (composition of mixed-layer illite-smectite) and carbon and oxygen stable isotopes analyses. The combined use of vitrinite reflectance and mixed-layer illite-smectite, which is one of the best approaches for unravelling the maximum burial of sedimentary basins in fold-and-thrust belt (Corrado et al., 2005; Aldega et al., 2007, 2011), was applied to regionally contextualize this zone in the framework of the Apennine collisional belt, and to constrain the depth and temperature conditions during fault activity. Stable isotopes were used to identify fluid sources, estimate the temperatures of vein formation and unravel any fluid-rock interaction. The comparison of $\delta^{18}O$ and $\delta^{13}C$ between vein fillings and host rock, and its use with petrological, geological and structural analyses, allowed us to speculate on the origin of the fluids and their interaction with deformation.

2. Geologic setting

The eastern side of the Northern Apennines, corresponding to the Umbria-Marche areas (Fig. 1), is characterized by a fold-and-thrust belt built since Oligocene time, after the closure of the oceanic basin and the collision between the continental margins of the Adria and Europe plates (Marroni et al., 2010 and references therein). The fold-and-thrust belt originated during the progressive migration of the deformation front towards the eastern domains of the Adria plate (e.g., Costa et al., 1998; Barchi et al., 2001). This evolution was associated with the development of foredeep and piggy-back basins of different ages that were progressively incorporated into the belt. As a result, a pile of Adria-derived tectonic units was detached at different structural levels and subsequently deformed by E- to NE-verging thrusts and associated folds (e.g., Barchi et al., 1998). Contractional tectonics was followed by an extension, that caused the development of marine to continental basins bordered by high angle normal faults, segmenting the pre-existing structural stack of tectonic units (e.g. Lavecchia et al., 1987 and Pauselli et al., 2006).

The Lago Trasimeno area (Umbria, Central Italy) is a good study site for structures formed prior to the extensional phase (Fig. 2). Here, the Tuscan Nappe thrusts onto the Umbria-Romagna Unit, which are both derived from different sectors of the Adria plate (Fig. 3). Whereas the Tuscan Nappe originated from the westernmost area of the Adria continental margin, the Umbria-Romagna Unit is interpreted as paleogeographically derived from the innermost zones. Recent field mapping and data collection in the Lago Trasimeno area by Barsella et al. (2009) revealed the occurrence of additional thrust sheets (Sansepolcro-Monte Filoncio and Rentella Unis) between the Tuscan Nappe and Umbria-Romagna Unit (Figs. 2 and 3). Among them, the Rentella Unit is derived from an area originally interposed between the Tuscan and Umbria-Marche units (Barsella et al., 2009). Accordingly, the data collected in the Lago Trasimeno area by Barsella et al. (2009) indicate that the deformation of the Tuscan, Tuscan-Umbria and Umbria-Marche sectors occurred during Aquitanian, Burdigalian and Langhian times, respectively. In addition, scattered "klippen" of the Ligurian units, i.e. the remnants of the oceanic and transitional units belonging to the Late Cretaceous-Middle Eocene accretionary wedge, are identified at the top of the Tuscan Nappe.

The succession of the Rentella Unit includes Rupelian-Aquitanian varicoloured pelagic and hemipelagic marls (Monte Rentella Formation) conformably topped by Aquitanian-Burdigalian siliciclastic turbidites (Montagnaccia Formation), representing the foredeep deposits. This succession is arranged in a stack of imbricate slices bounded by N-S striking thrusts that show ramp-and-flat geometry (Fig. 2). Both boundaries and internal thrusts in the imbricate system are marked by cataclastic shear zones that are metres thick. The studied Monte Rentella Shear Zone (hereafter reported as MRSZ) occurs at the edge of one of the slices. Thrusts can include meso- to mega-scale fault-propagation folds, with sub-horizontal axis striking NW-SE to N-S. These folds, showing concentric geometry, are frequently asymmetric with a well-developed SW-dipping back-limb, whereas the forelimb dips vertically or is overturned. Their axial-plane foliation can be described as a disjunctive cleavage in the pelitic and marly fine-grained lithotypes that is variably spaced in the coarse-grained lithotypes, such as the sandstones.

3. The Monte Rentella collisional thrust in the regional context

Vitrinite reflectance and XRD clay minerals analyses were performed across the studied thrust as part of a regional-scale sampling process, to estimate maximum paleotemperatures and the sedimentary/tectonic burials experienced by the rocks, and to reconstruct the geometry and structure of the units composing the eastern side of the Lago Trasimento area before the extensional development of the Trasimeno basin (Fig. 2). A brief description of these data and related interpretation is helpful to better place the Rentella Unit and the MRSZ in this sector of the Apenninic collisional prism.

For vitrinite reflectance analysis, whole-rock samples and picked coaly particles were collected from sandstone and siltstone lithologies across the section AB of Fig. 2, and in the Montagnaccia Formation of the Rentella Unit. For each sample, we selected only slightly fractured and/or altered vitrinite fragments with grain-size of at least 5 μm, on which at least 20 measurements were performed (Borrego et al., 2006). Mean reflectance (R_o%) and standard deviation values were calculated from measurements. For XRD analysis of pelitic fraction of sediments, randomly-oriented whole-rock powders and oriented <2 μm grain-size fractions were run by a Scintag X1 XRD system (CuKα radiation) at 40 kV and 45 mA. Expandability measurements for both illite-smectite (I-S) and chlorite-smectite (C-S) mixed layer minerals were determined according to Moore and Reynolds (1997), using the delta two-theta method after decomposing the composite peaks between 9 and $10°2\theta$ and $16–17°2\theta$ for I-S and between 10 and $12.3°2\theta$ and $25–26°2\theta$ for C-S using Pearson VII functions.