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Fluid flow compartmentalization in the Sicilian fold and thrust belt: Implications for the regional aqueous fluid flow and oil migration history

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ABSTRACT

The fluid flow history in the frontal part of the Sicilian fold and thrust belt (FTB) has been reconstructed using an integrated structural, petrographic, geochemical and microthermometric approach. The study focused on comparing fluid flow during progressive deformation along major thrust horizons and in pelagic sediments occurring in the associated thrust sheets (foot- and hanging wall). A fluid flow model is constructed for the frontal part of the Sicilian FTB.

Syn-deformational quartz and calcite have been precipitated along décollement horizons in the Iudica–Scalpello study area. The microthermometric analysis of fluid inclusions in the quartz and calcite indicated migration of low saline high temperature aqueous fluids ($-1.5<Tm<-0.2$ °C and $80<T_h<200$ °C) and hydrocarbons along the main thrusts. Geochemical and petrographic analysis showed the presence of high manganese (2500–25,000 ppm) and iron (300–7000 ppm) contents in certain calcite phases, suggesting that the migrating fluids originate from clay dewatering and clay–water interactions.

The fluid flow history in the thrust sheets can be subdivided into two stages. Calcite of types 1 and 2 has identical light orange cathodoluminescence as the surrounding mudstone. Furthermore, its isotope signature ($2<\delta^{13}C<3$‰ and $-6<\delta^{18}O<-2$‰) and minor element content are also in line with closed, host rock buffered fluid flow during the initial stages of the fluid flow history. Type 3 calcite is volumetrically by far the most important calcite phase. It occurs in (hydro-)fractures that are limited to the hanging wall of major thrusts and within major strike-slip faults that are interpreted as transfer faults as a result of thrust development. The presence of associated fluorite suggests more open fluid flow conditions during the final stages of the fluid flow history. Fluorite is characterized by low salinity fluid inclusions ($-2.6<T_m<-1.6$ °C) with T_h between 80 and 140 °C. Type 3 calcite has less depleted $\delta^{18}O$ values compared to calcite of types 1 and 2 and the $\delta^{18}O$ from calcite in faults is even positive. During the final stages of fluid flow with precipitation of calcite type 3, the fluid flow model invokes infiltration of overpressured fluids that migrated along the décollement zone. These fluids only infiltrate the thrust sheet in the hanging wall of the thrust, leading to a compartmentalized fluid flow pattern.

An identical fluid flow pattern with migration of low and hot saline fluids, associated with hydrocarbons, was observed in other parts of the Sicilian fold and thrust belt. With identical structural deformation and fluid flow patterns, the study confirms the suitability of the frontal part of the Sicilian fold and thrust belt as an outcrop analog for deeply submerged accretionary prisms. The study thus offers unique insights in expected fluid flow patterns in thrust sheets of deeply submerged accretionary complexes.

1. Introduction

Fluid flow in accretionary wedge sediments has been the focus of numerous studies of which the main outcome is that advective fluid flow along décollement horizons plays a major role in accretionary prisms (e.g. Byrne and Fisher, 1990; Ge and Screaton, 2005; Kastner and Le Pichon, 1992; Lallemant et al., 1990; Moore, 1989; Moore and Vrolijk, 1992; Vrolijk, 1987; Vrolijk et al., 1988). Fluid flow in décollement zones from accretionary wedges is thus fairly well understood. However, fluid flow in the fractured and deformed thrust sheets in accretionary complexes is not well studied. This bias is caused by the submerged nature of currently active accretionary wedges in subduction zones. Fluid sampling in boreholes focuses on sites with abundant advective fluid flow, mainly major structural surfaces. Study of fluid flow in ancient and emerged subduction zones is very difficult because the accretionary complex has often been strongly metamorphosed during continent–continent collision.

The frontal part of the Sicilian fold and thrust belt (FTB) offers a unique opportunity to study deformation and fluid flow in an outcrop analog for currently active and deeply submerged accretionary complexes

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(Roure et al., 1990). Although the area is not an oceanic subduction complex sensu stricto (Keary, 1996), the style of deformation, the seismic and structural architecture of the area and certain features such as the presence of tectonic mélanges and clay diapirs are all comparable to what is frequently encountered in accretionary complexes (Larroque, 1993). The study area exhibits some world class exposures of tectonic mélange thrust horizons and Mesozoic limestones in associated thrust sheets that are well-exposed in different quarries in the northern and southern flank of the Iudica–Turcisi ridge. All rocks show ample evidence for intense periods of fluid flow with veins and/or hydrofractures.

The principal aim of the study in Iudica–Scalpello is to establish the chronology of the different fluid flow events and compare fluid flow in the thrust zone (tectonic mélange) with fluid flow in the associated thrust sheets (fractured Mesozoic cherty limestones). Fluid migration in the upper and lower tectonic mélange in the Sicilian FTB has been studied in the past by Larroque (1993),Guilhaumou et al. (1994) and Larroque et al. (1996). Their conclusions were solely based on structural and petrographic observations, X-ray studies of the clay matrix and microthermometric data from syn-tectonic quartz and calcite veins in the tectonic mélange. This dataset was integrated with new field, petrographic and geochemical data from the thrust zone carried out in the frame of the present study. No data or studies exist on fluid flow in the thrust sheets. For this reason and to make the text more comprehensible with abundant data being presented and discussed from two different structural environments, data presentation, interpretation and discussion for fluid flow in the thrust zone and the associated thrust sheets have been entirely separated. Afterwards, fluid flow in both environments is compared and a regional fluid flow model is worked out and discussed in the larger context of fluid flow reconstruction in Sicily.

2. Geological setting

2.1. Sicily

Sicily is located in the Western Mediterranean and the island's landscape is dominated by the Sicilian thin-skinned FTB, which is part of the Maghrebides (Fig. 1). The Maghrebides, i.e. the western Alps and the Apennines in France and Italy, the Maghrebides in Sicily and Northern Africa and the Betic Cordillera in Spain encircle most of the western Mediterranean Sea (Rosenbaum and Lister, 2004a). They are the result of the convergence of the African and European plates and the northward subduction of the intermediate Ligurian Basin. By some authors, the latter basin is envisaged as a small oceanic domain (Elter et al., 2003; Rosenbaum and Lister, 2004b; Rosenbaum et al., 2002) while other authors propose that oceanic crust was never truly developed in the Ligurian Basin (e.g. Lentini et al., 2000).

Compressive deformation in Sicily started in the Late Oligocene but the most intense period of deformation is dated as middle Miocene (Bello et al., 2000; Catalano et al., 1996; Roure et al., 1990). Generally, it is believed that the deformation consisted of two phases with first a phase of shallow tectonic accretion mainly involving Neogene (foredeep) sediments followed by a second phase in which tectonically deeper levels were also taken up into the accretionary wedge (Bello et al., 2000; Catalano et al., 1996, 2000; Granath and Casero, 2004; Nigro and Renda, 2000).

Sicily is composed of a poorly deformed foreland in the south with a foredeep located just north of the foreland (Fig. 1B). The northern part of the island consists of an imbricate thrust stack in which three important tectonic units can be recognized (Catalano et al., 1996). From top to bottom in the structural edifice, these are: (1) the Peloritani units, (2) the Sicilide units and (3) the Internal units (Bello et al., 2000; Catalano et al., 1996, 2000; Elter et al., 2003) (Fig. 1B). (1) The Peloritani units consist of Mesozoic and Tertiary sediments underlain by a metamorphosed basement and European continental crust (Catalano et al., 1996). (2) The Sicilide units are made up by deformed Jurassic to Eocene clays and marls which formed the sediment cover of the Ligurian Basin. (3) The Internal units (Fig. 1B) consist of deformed Mesozoic and Tertiary sediments that are underlain by thinned African continental crust (Elter et al., 2003). The Internal sediments were deposited in different palaeogeographic domains (the Panormide, Saccense, Imerese, Sicani, Trapanese and Hyblean domains) (Catalano et al., 1996). The latter palaeogeographic domains were differentiated during Jurassic transtension and opening of the Tethys Ocean. At this time, tilted blocks created topographic highs (platforms) and lows (basins) on the African passive margin (Catalano et al., 1996; Stampfli and Borel, 2002). The Iudica–Scalpello study area is located in southeast Sicily, in the frontal part of the Sicilian FTB, just north of the Plio-Quaternary Gela foredeep system and the Hyblean foreland (Fig. 1B).

2.2. Iudica–Scalpello

2.2.1. Stratigraphy

Sediments exposed in the Iudica–Scalpello study area are generally interpreted as part of the Sicanian palaeogeographic domain (Carbone et al., 1990) although an Imerese origin cannot be entirely excluded. The stratigraphy consists of Triassic marls, Triassic–Jurassic cherty limestones, Jurassic chert and early Cretaceous marls and claystones (Fig. 2). This succession is unconformably covered by Eocene 'scaglia' marls. An important stratigraphic gap thus exists in the late Cretaceous which coincides with Cretaceous–Palaeogene inversion in the Mediterranean region. The Mesozoic and Eocene basinal succession is unconformably overlain by Oligocene and Miocene foredeep and Mio-Pleistocene syn- and post-tectonic sediments of

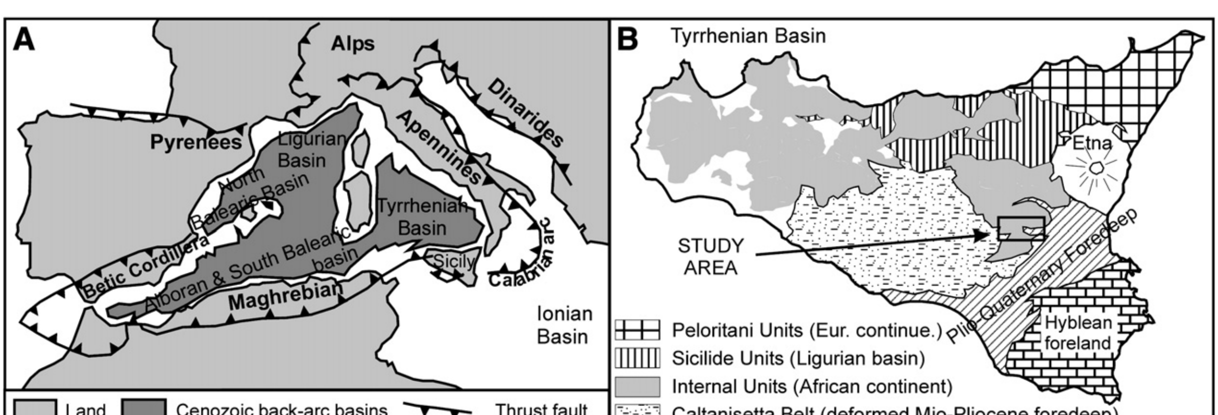

Fig. 1. (A) Geological setting of the study area in the Western Mediterranean where an arcuate-shaped mountain chain that encircles Cenozoic back-arc basins. (B) Simplified structural map of Sicily showing the main components of the Sicilian fold and thrust belt and the location of the study area.