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Fluid seepage variability across the external Northern Apennines (Italy): Structural controls with seismotectonic and geodynamic implications

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ABSTRACT

The relations between fluid seeps and tectonic structures have been targeted in some key areas of the axial sector, and partly at the edge of the exposed Northern Apennines (Pede-Apennine margin). In the axial zone, fluid seepage is dominated by methane venting, which may occur in the form of dry seeps or associated with mineral springs. Surface venting is linked to the presence of foreland-dipping normal faults, or related to reservoirs localised at inactive anticlines. The Pede-Apennine margin is instead dominated by thrusting and mud volcanism. The two different categories of fluid seepage appear strongly coupled to the dissimilar stress fields (compressional or extensional) operating in these sectors. Pressure data inferred from deep wells delineate an overall fluid pressure increase from the axial zone toward the Pede-Apennine margin, possibly as a result of the growth of tectonic compaction in this direction. The increase of fluid pressure at the Pede-Apennine margin is thus interpreted as the primary control on the transition from dry vents to mud volcanism. The intimate association between seepage modes and distinct tectonic structures involves relevant consequences on fluid–fault interactions and seismotectonics, and also shows connections with processes dictating the internal deformation of evolving fold-and-thrust belts.

1. Introduction and aims of the work

It is well established that tectonic processes may exert a strong control on the characteristics and type of fluid venting. Examples of structural controls can be identified at various scales of observation and in various structural contexts. For instance, mud volcanoes are often coincident with the crests of anticlines (Jakubov et al., 1971), and giant serpentinite mud volcanoes form on the Marianas forearc as a consequence of the processes related to the recycling of oceanic lithosphere at subduction zones (e.g., Fryer et al., 2000). In these settings, structural controls on fluid seepage can be also identified at smaller scales, such as the fractures associated with anticline folds (e.g., Roberts et al., 2011), or the large normal faults feeding the submarine mud volcanoes of Marianas (e.g., Fryer et al., 2000). Mud volcanism and gas escape have also been documented along structures of strike–slip fault systems, such as the San Andreas Fault (e.g., Lynch and Hudnut, 2008; Rudolph and Manga, 2010).

The nearly invariable coincidence of seepage with tectonic discontinuities may also suggest an intimate connection with active movements. Overpressured fluids have in fact been shown to strongly affect the fluid–rock interaction at seismogenetic depths in terms of fault weakening and cementation during fault failure cycles (Sibson, 1992). Therefore, these fluid–fault relations may establish a positive feedback loop that is likely to be important for the transfer of deep fluids to the surface (see also Rojstaczer et al., 2008). Aim of this paper is to analyse the relations between the modality of fluid release (i.e., mud volcanoes, dry gas vents, seeps expelling hydrous fluids, etc.) and the different structural settings that may characterise across-strike sectors of active fold-and-thrust belts.

This work has considered the external Northern Apennines, from its axial zone to the Pede-Apennine margin in the foreland, which is characterised by active compression and the presence of mud volcanoes. A number of papers have addressed the interactions between mud volcanism and tectonic structures along the Pede-Apennine margin (Bonini, 2007; Capozzi and Picotti, 2002; Capozzi et al., 1994), while these relationships remain less investigated in the axial sector of the Northern Apennines. Therefore, we first focus on the axial zone of the belt, which is characterised by diffuse methane venting, seismicity, and ongoing uplift. The availability of records of past gas seep location (Camerana, 1926; Camerana and Galdi, 1911), and the accessibility of historical earthquake catalogues (e.g., Rovida et al., 2011), seismic surveys carried out after local earthquakes (Amato et al, 2008; Ripepe et al., 2008), and extensive thermochronological dating (Thomson et al., 2010), make this an ideal sector where looking at the relationships

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between fluid venting and the structural setting of the axial part of an evolving fold-and-thrust belt.

2. Methane venting in the Northern Apennines

2.1. Geologic setting and structural framework of the Northern Apennines

The Northern Apennines thrust wedge resulted mainly from the Oligocene-Miocene continental collision between the western margin of the Adria microplate and the Corsica–Sardinia block, in a geodynamic context that is normally related to the eastward rollback-retreat of the W-dipping continental Adriatic slab (e.g., Doglioni, 1991; Doglioni et al., 1999; Faccenna et al., 2001, 2003; Malinverno and Ryan, 1986). The main structure of Northern Apennines consists of stacked NE-verging tectonic units, the oldest and uppermost of which are the Ligurian Units. The latter are composed of ophiolites, and highly deformed pelagic and terrigenous sedimentary rocks accreted during the Late Cretaceous to Eocene subduction of the Ligurian–Piedmont oceanic crust (Principi and Treves, 1984).

Foredeep basins formed in front of the fold-and-thrust belt migrating toward the Adriatic foreland (i.e., eastward) as a consequence of the ensuing continental collision (Ricci Lucchi, 1986). Thick Tertiary siliciclastic turbidite deposits filled the foredeep basins, and the related foredeep sequences are currently referred to as (from west to east) (1) Macigno and Modino, (2) Cervarola–Falterona, and (3) Marnoso Arenacea. These synorogenic deposits rest over a substratum made of (from bottom to top) Paleozoic–Early Triassic crystalline basement, Late Triassic evaporites and Mesozoic–Cenozoic carbonate rocks. During orogenesis, these tectonostratigraphic turbidite units were progressively involved in the mainly in-sequence thrusting and accreted, together with their substratum, into the orogenic wedge as a series of NE-verging thrust sheets (e.g., Ricci Lucchi, 1986).

The Ligurian Units represent an accretionary prism that progressively overthrust the Tertiary foredeep systems. Such a transfer interrupted the syn-tectonic deposition, and led the Ligurian Units to achieve their current position tectonically overlying the foredeep deposits (Principi and Treves, 1984). The emplacement of the Ligurian prism onto the Adriatic foredeep system occurred along an extensive basal deformation zone marked by the 'Sestola–Vidiciatico' tectonic unit; the 'Sub-Ligurian' units form the basal part of the Ligurian nappe and occur to the northwest of the Sestola–Vidiciatico unit, in the same structural position (Remitti et al., 2011). Satellite marine basins developed above the migrating Ligurian thrust nappes and hosted deposition of the Eocene-Pliocene 'Epi-Ligurian Sequence' (Ricci Lucchi, 1986). For simplicity, the Ligurian, Sub-Ligurian and Sestola–Vidiciatico units, and the Epi-Ligurian Sequence are collectively referred to hereinafter as Ligurian Units *s.l.* (LIG).

The Northern Apennines can be subdivided into a north-western Emilia sector characterised by the widespread outcropping of the LIG, and a south-eastern Romagna sector where these units have been mostly eroded and turbidite sediments (essentially Marnoso Arenacea) dominate. The axial topographic culmination (and primary watershed), and the Pede-Apennine margin represent the main physiographic elements of the Emilia-Romagna Apennines. The Pede-Apennine margin separates the exposed Apennine foothills from the Po Plain, and corresponds to a SW-dipping active thrust system that is responsible for the rapid uplift of the Apennine belt (Doglioni et al., 1999). Thick successions of Messinian to Early Pleistocene marine sediments filled piggyback basins that formed ahead of Pede-Apennine margin and are now hidden beneath the Middle Pleistocene to Holocene continental deposits of the Po Plain (Pieri and Groppi, 1981; Rossi et al., 2002; Fig. 1b).

2.2. The axial zone of the Northern Apennines

Recent thermochronological data have revealed age patterns and age-elevation relationships showing a continuous post-late Miocene (ca. 8 Ma) vertical material motion, with maximum exhumation rates localised around the main axial zone, and mostly coincident with the highest topographic ridge (Thomson et al., 2010). This suggests an obvious structural connection with the tectonic setting of the axial zone, which consists of a continuous linear ridge exposing the Tertiary siliciclastic turbidites in both the Emilia and Romagna sectors. The axial zone experienced a complex tectonic evolution recorded by the superposition of successive deformation events, which explicated in dominant NE-verging thrusting. In particular, thrust reactivation and out-of-sequence thrusts are common features that have been related to the emplacement of thrusts in the basement (Boccaletti and Sani, 1998; Finetti et al., 2001). This thrust kinematics often led to the inversion of the original stacking order with the superposition of foredeep deposits over the LIG (e.g., Anelli et al., 1994; Plesi et al., 2000).

The age of these thrust phases postdates the overthrusting of the LIG over the Cervarola–Falterona foredeep that closed deposition around the Burdigalian–Langhian boundary (ca. 16 Ma). However, the accurate dating of these events is poorly constrained hitherto. The marked increase in exhumation rates from ~0.4 mm yr^{-1} (post-8 Ma) to ~1 mm yr^{-1} determined at ca. 3–4 Ma in the axial zone (Mt. Cimone transect; Thomson et al., 2010) could mark one of these phases. Later on, the axial zone has experienced Quaternary normal faulting on both the northeastern and southwestern sides. In particular, normal faults are the latest deformation event recorded by the intermountain continental basins that bound the axial zone to the southwest (Mugello and Upper Tiber basins; Sani et al., 2009). Similarly, active high-angle normal faults cutting through the Apennines relief are inferred to dissect the nappe pile in the Emilia sector northeast of the main divide, and to control some of the spontaneous seeps (Capozzi and Picotti, 2010). This scenario accords with the focal mechanism solutions of earthquakes showing in the axial zone low-to-moderate magnitude shallow (<15–20 km) seismic events consistent with dominant ~NE–SW-oriented T axes (Chiarabba et al., 2005; Pondrelli et al., 2006; Sani et al., 2009).

2.3. Historical overview of methane venting

Surface escape of methane and oil was a phenomenon widespread throughout the Emilia-Romagna Apennines. Ignition of this gas produced typical everlasting fires (in the past referred to as *fuochi*, *terreni ardenti*, or *fontane ardenti* = blazing fountains; Bianconi, 1840) several centimetres up to few metres high, which impressed the local peoples and travellers. A variety of legends arose about these fires, which showed peculiar characters unexplainable to the people, such as the fact that the flames – visible during the day but particularly bright at night – were not associated with smoke, the soil around the fires was inexplicably cold, and the flames could not be extinguished by rain, snow or wind (unless extremely tempestuous), but rather they seemed larger during damp weather (e.g., Spallanzani, 1795; Volta, 1784a,b, and references therein). Last but not least, another mysterious aspect simply regarded the perpetual character of the flames, which were lasting for centuries. For instance, Lazzaro Spallanzani (1795) could infer that the Barigazzo fires (mentioned later by Govi, 1906) had lasted for at least 200 years, and Bianconi (1840) supposed that the Roman writer Plinius referred to those fires in his *Historia Mundi Naturalis*.

For centuries these places were believed to manifest hidden (or the remnant of) volcanoes, and regarded as gates to hell, and for this frequently termed *inferno* or *vulcano*. Sometimes these features, or the area where they occurred, were referred to as *dragone* (= dragon) (i.e., the Dragone valley, the Dragone di Sassuno mud volcano) because the popular belief imaged the flares and hisses to be produced by fabulous dragons hidden underneath the Earth's surface. The famous physicist Alessandro Volta visited the popular Pietramala fires in September 1780 (see Section 3.2.3), and provided the scientific explanation that such fires were produced nothing more than by the self-combustion of methane ('air of the swamps') leaking out