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Mud volcano eruptions and earthquakes in the Northern Apennines and Sicily, Italy

Marco Bonini

Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, Via G. La Pira 4, I-50121 Florence, Italy

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ABSTRACT

The relations between earthquakes and the eruption of mud volcanoes have been investigated at the Pede–Apennine margin of the Northern Apennines and in Sicily. Some of these volcanoes experienced eruptions or increased activity in connection with historical seismic events, showing a good correlation with established thresholds of hydrological response (liquefaction) to earthquakes. However, the majority of eruptions have been documented to be independent of seismic activity, being mud volcanoes often not activated even when the earthquakes were of suitable magnitude and the epicentre at the proper distance for the triggering. This behaviour suggests that paroxysmal activity of mud volcanoes depends upon the reaching of a specific critical state dictated by internal fluid pressure, and implies that the strain caused by the passage of seismic waves can activate only mud volcanoes in near-critical conditions (i.e., close to the eruption). Seismogenic faults, such as the Pede–Apennine thrust, often structurally control the fluid reservoirs of mud volcanoes, which are frequently located at the core of thrust-related folds. Such an intimate link enables mud volcanoes to represent features potentially suitable for recording perturbations associated with the past and ongoing tectonic activity of the controlling fault system.

1. Introduction and aims of the work

Mud volcanoes are usually cone-shaped edifices of variable dimensions constructed by the extrusion of mud, rock fragments and fluids, such as saline water and gases (e.g., Higgins and Saunders, 1974). These features can be found in different tectonic settings, but they typically predominate at converging plate boundaries and are disseminated all along the Alpine–Himalayan collision zone. Methane is the most frequent gas, and is normally linked to the formation and accumulation of hydrocarbons at greater depths. It is commonly accepted that overpressure generated by methane-rich fluids is one of the main driving mechanisms triggering mud volcanism (Brown, 1990). Though mud volcanoes exhibit smaller dimensions than the magmatic relatives, they can occasionally give rise to impressive explosive eruptions, with violent ejection of mud and rock blocks often accompanied by flames produced by self-ignition of the methane contained in the mud.

In magmatic volcano systems, triggering of eruptions by distant earthquakes has been identified (Linde and Sacks, 1998). In the same way, some mud volcano eruptions occurred some hours to a few days after large earthquakes (e.g., Mellors et al., 2007), but a correlation between these events is not always straightforward. In this regard, exemplificative is the interesting debate about the causative trigger (drilling vs. earthquake) invoked for the extraordinary eruption of the LUSI mud volcano (Indonesia), which has been erupting since May 2006 (see Mazzini et al., 2007; Davies et al., 2008).

The relationship between earthquake magnitude and distance over which various types of hydrological responses (streamflow changes, liquefaction) have been reported is effectively described by empirical scaling (Montgomery and Manga, 2003). Liquefaction typically occurs after earthquakes in shallow soils, and is often manifested by sand volcanoes (e.g. Galli, 2000). Liquefaction caused by shaking (dynamic strain) has been proposed to be a potential mechanism for triggering the eruption of mud volcanoes expelling mud from depths exceeding a few kilometres (Manga and Brodsky, 2006). Interestingly, the relationship between earthquake magnitude and the distance from the epicentre determined for hydrological responses in the shallow subsurface (upper tens of meters) resembles the threshold for seismic liquefaction, and thus it has been suggested to be potentially representative also for genuine mud volcanoes fed from greater depths (Manga and Brodsky, 2006; Manga, 2007; Davies et al., 2008).

This paper aims to contribute to the understanding of this topic by analysing the relations between parossistic mud volcano activity and earthquake magnitude in the Apennines, a region characterised by recurrent seismic and mud volcano activity that provide an unique length of the historical record. The availability of records of past mud volcanoes activity and the accessibility of detailed historical earthquakes catalogues (CPTI Working Group, 1999, 2004, 2008) help to constrain the relation of earthquake magnitude–hydrological response distance, and allows to speculate about eruptive and dormant stages characterising the evolution of the mud volcano systems.

2. Regional setting

Mud volcanoes of the Apennines essentially occur along the external active compressive thrust front, and are clustered in three main geographical groups (Martinelli and Judd, 2004): (1) Northern

E-mail address: mbonini@geo.unifi.it.

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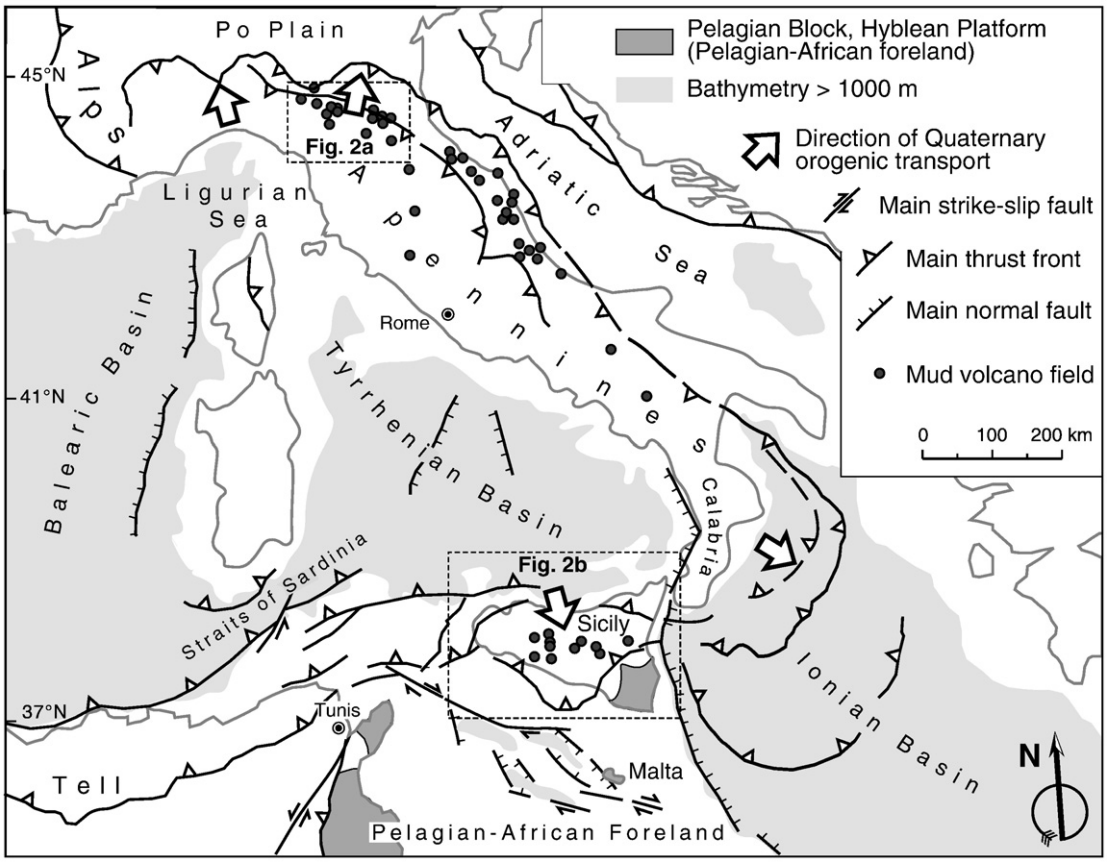

Fig. 1. Structural framework of the Apennines, Italy, and location of the study areas of mud volcanism. The main mud volcano fields are from Martinelli and Judd (2004).

Apennines (Pede–Apennine margin of Emilia–Romagna), (2) Central Apennines (eastern Marche–Abruzzo), and (3) Sicily (Fig. 1). The present work mainly focuses on the mud volcanoes of the Emilia Pede–Apennine margin, and Sicily.

Following the terminology in Planke et al. (2003) and Mazzini et al. (in press) the mud volcano features are referred to as (i) gryphons and (ii) mud cones for <3 m and <10 m high steep-sided cones, respectively, and (iii) salsas for water-dominated pools with gas seeps. The term mud volcano is used to indicate larger edifices or an area or field that contains a number of the above features.

Mud volcano features of relatively small size ($\leq$500 m in length) punctuate the Pede–Apennine front of the Northern Apennines and are associated with the expulsion of fluids generated in the underlying clastic foredeep deposits (Martinelli and Judd, 2004, and references therein; Fig. 1). Methane is the dominant gas, and the presence of ethane suggests a thermogenic component (Capozzi and Picotti, 2002; Martinelli and Judd, 2004). Seismicity is potentially associated with seismogenic frontal and lateral thrust ramps located both at the Pede–Apennine front and in the chain buried beneath the Po Plain deposits (Boccaletti et al., 1985, 2004; Selvaggi et al., 2001; Ciaccio and Chiarabba, 2002; Benedetti et al., 2003; Figs. 1 and 2a). The Pede–Apennine front of the Northern Apennines is marked by active thrust deformation mostly associated with the SSW-dipping Pede–Apennine thrust (Benedetti et al., 2003; Boccaletti et al., 2004). The mud volcanoes of the Pede–Apennine front are thus closely linked to the active tectonic compression.

Mud volcanoes of Sicily essentially occur over the accretionary wedge that developed in front of the Apennine–Maghrebian fold-and-trust belt, progressively migrating southward over the Pelagian–African foreland (e.g., Lentini et al., 1990). The mud volcanoes originate in the clastic sediments deposited in a system of amalgamated thrust-top basins (Caltanissetta Basin) that were progressively shortened and displaced during the late Miocene to Pleistocene (e.g., Monaco and Tortorici, 1996; Lickorish et al., 1999, and references therein). Both in western and eastern Sicily, seismological, structural and morphotectonic data indicate active thrust-related deformation near the frontal part of this belt, with the shortening generated by the NNW–SSE oriented Nubia–Eurasia convergence (Monaco et al., 1996; Catalano et al., 2007, 2008; Figs. 1 and 2b). The mud volcanoes of Sicily are normally driven by methane, with the exception of the Paternò mud volcano where carbon dioxide provided by the igneous activity of the near by Mount Etna volcano dominates (Etiope et al., 2002).

3. Earthquakes and mud volcano eruptions

Earthquakes have been considered to be a potentially important trigger for mud volcano eruptions (Mazzini et al., 2007), but several mud volcanoes have also erupted independently of seismic activity (e.g., Mellors et al., 2007). Essentially similar results have been obtained from the analysis of available sources reporting paroxysmal activity of mud volcanoes of Italy. A complete database of earthquake-related liquefaction events is available for the Italian region (Galli, 2000), but a catalogue of parossistic mud volcano eruptions does not exist so far. A correlation between earthquake and paroxysmal activity of Northern Apennine mud volcanoes was undertaken by Martinelli et al. (1989) before the publication of the most up-to-date earthquake catalogues (CPTI Working Group, 1999, 2004). The data reported in Martinelli et al. (1989) have been crosschecked by reference to such catalogues, and implemented by a number of events (see Table 1).

Table 1 is a compilation of the cases for which the relations between seismic events and mud volcano eruptions (or anomalous activity) are apparently unequivocal, but this dataset should be considered preliminary and far from being complete (location of mentioned mud volcanoes/vents is indicated in Table 2). The compilation of a complete