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

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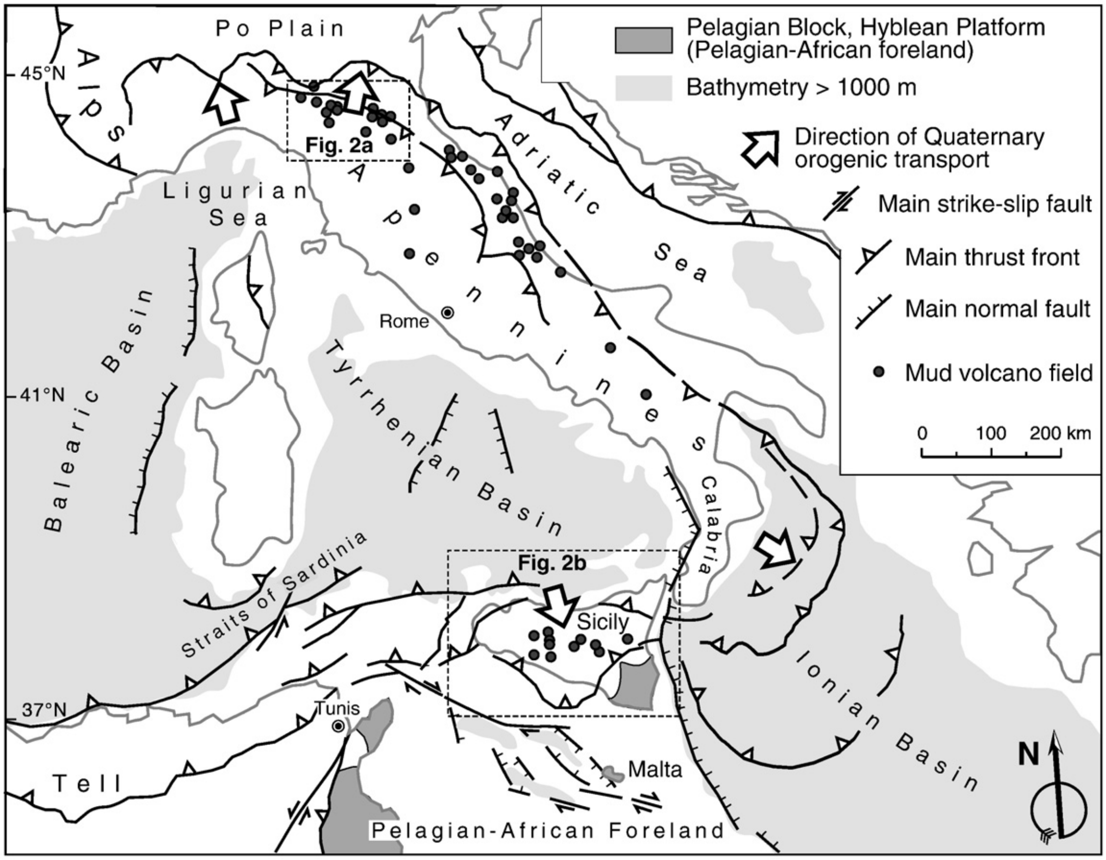

Fig. 1. Structural framework of the Apennines, Italy, and location of the study areas of mud volcanism. The main mud volcano fields are from Martinelli and Judd (2004).

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 (≤ 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

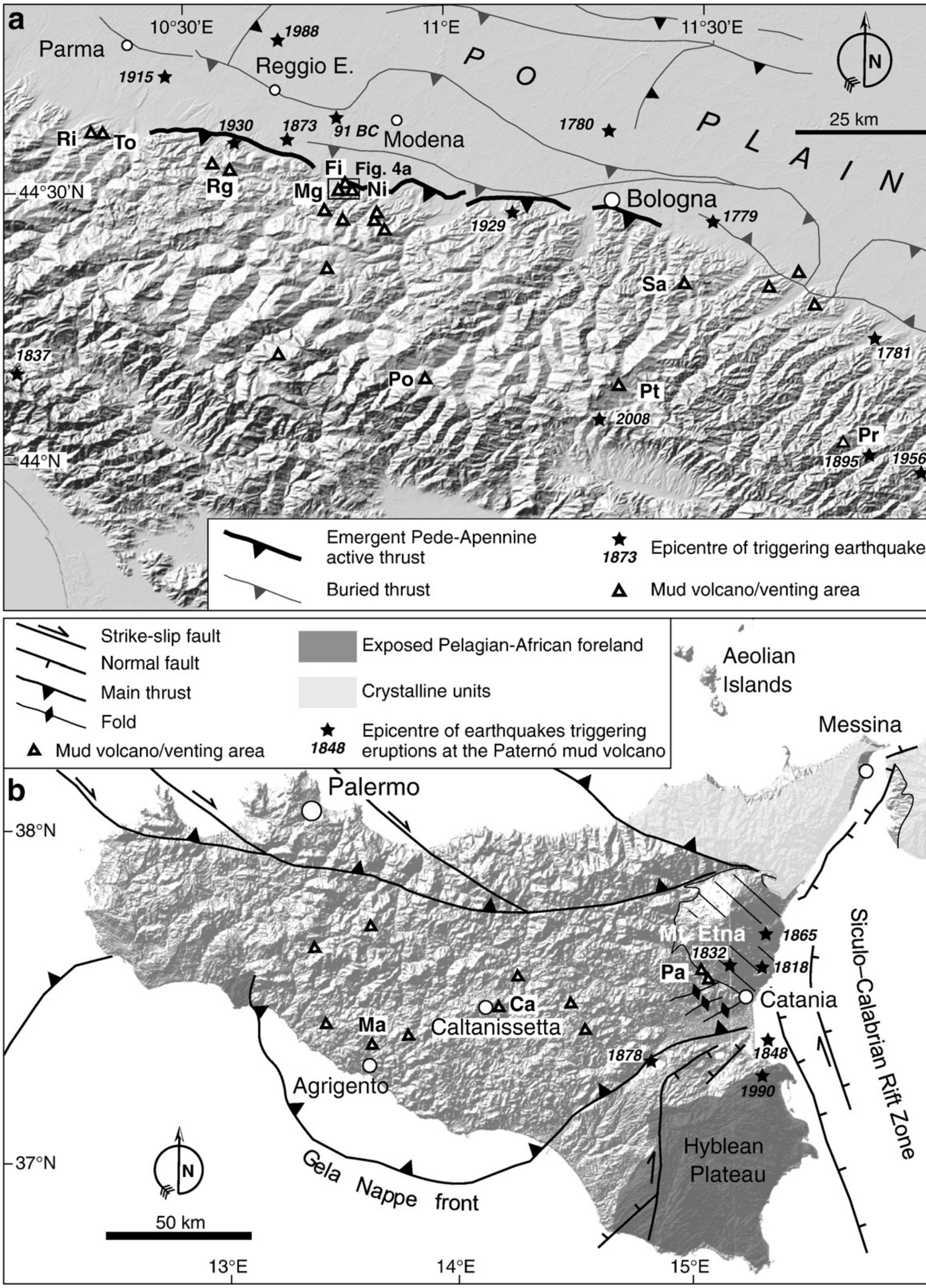

Fig. 2. (a) Tectonic sketch map of the eastern Northern Apennines, including the main mud volcanoes and venting areas cited in the text (Fi, Fiorano; Mg, Montegibbio; Ni, Nirano; Po, Porretta; Pr, Portico di Romagna; Pt, Pietramala; Ri, Rivalta; Rg, Regnano; Sa, Sassuno;To, Torre). (b) Tectonic sketch map of Sicily (modified after Catalano et al., 2008), including the main mud volcanoes cited in the text (Ca, Caltanisetta; Ma, Macalube di Aragona; Pa, Paternó). The main mud volcanoes and the structural elements are plotted onto a digital shaded-relief elevation model (USGS, Shuttle Radar Topography Mission, available from: http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm). Location is indicated in Fig. 1. The triggering earthquakes refer to Table 1.

data set of earthquake-induced mud volcano responses is a difficult task. From one side, a number of historical archives may have been overlooked; from the other side, parossistic activity may have not been reported in the historical chronicles, a possibility that obviously increases going back in time. In other words, the absence of reports does not necessarily mean that a specific mud volcano has not responded to specific historical earthquakes.

Eruptions of mud volcanoes can be explosive or effusive, and may show a variable degree of activity, but the determination of these characteristics (nature and size) may be difficult for historical eruptions.

Table 1
Correlation between earthquakes and mud volcano paroxysmal/anomalous activity.

Mud volcano eruption/anomalous activity					Triggering earthquake						
No. Date		MV/Vent	Source	EP	Date	Lat.	Long.	*Mw*	*Ms*	Source	ED (km)
Northern Apennines											
1	27/02/2008	Pt	A. Granaiola, May 2008	F	01/03/2008	N44.086	E11.309	4.6		INGV (2008a)	9.0
2	15/03/1988	Rg	Martinelli et al. (1989)	E?	15/03/1988	N44.788	E10.684	4.73		CPTI (2008)	26.9
3	15/03/1988	Ni	Martinelli et al. (1989)	E?	15/03/1988	N44.788	E10.684	4.73		CPTI (2008)	32.4
4	26/05/1956**	Pr?	Guidoboni et al. (2007)	D	26/05/1956	N43.983	E11.920	5.10	4.68	CPTI (2008)	15.5
5	19/10/1930	Rg	Martinelli et al. (1989)	?	24/09/1930	N44.600	E10.600	4.83	4.30	CPTI (2004)	5.0
6	Post-seismic	Po	Guidoboni et al. (2007)	D	20/04/1929	N44.470	E11.130	5.55	5.36	CPTI (2004)	37.2
7	Post-seismic	Fi	Attestations, March 2009	C	20/04/1929	N44.470	E11.130	5.55	5.36	CPTI (2004)	26.5
8	11/10/1915	Rg	Martinelli et al. (1989)	?	10/10/1915	N44.732	E10.469	5.01	4.57	CPTI (2004)	21.0
9	04/09/1895	Pr	Trabucco (1895)	D	04/09/1895	N44.030	E11.820	5.03	4.60	CPTI (2004)	4.1
10	05/1873	Ni	Coppi (1875)	E	16/05/1873	N44.612	E10.701	5.13	4.74	CPTI (2004)	14.6
11	05/1873	Mg	Mercalli (1883)	?	16/05/1873	N44.612	E10.701	5.13	4.74	CPTI (2004)	12.1
12	Post-seismic	To?	Strobel (1888)	?	16/05/1873	N44.612	E10.701	5.13	4.74	CPTI (2004)	28.8
13	Post-seismic	Ri?	Strobel (1888)	?	16/05/1873	N44.612	E10.701	5.13	4.74	CPTI (2004)	29.8
14	Post-seismic	Mg	Martinelli et al. (1989)	?	11/04/1837	N44.174	E10.181	5.65	5.51	CPTI (2004)	61
15	05/04/1781 (t. 12.00 a.m.)	Mg	Avv. Panini in Calegari and Canestrini (1867)	A	04/04/1781 (t. 10.00 a.m.)	N44.235	E11.797	5.84	5.80	CPTI (2004)	87.0
16a	07/1780	Sa	Calindri (1781–1783)	B	04/06/1779	N44.450	E11.520	4.97	4.51	CPTI (2004)	13.7
16b	07/1780	Sa	Calindri (1781–1783)	B	04/02/1780	N44.620	E11.320	4.85	4.32	CPTI (2004)	33.2
17	91 BC**	Mg?	Guidoboni (1989)	A	91 BC	N44.650	E10.780	5.66	5.53	CPTI (2004)	15.5
18	91 BC**	Ni?	Guidoboni (1989)	A	91 BC	N44.650	E10.780	5.66	5.53	CPTI (2004)	14.5
Sicily											
19	13/12/1990	Pa	D'Alessandro et al. (1996)	E	13/12/1990	N37.266	E15.121	5.68	5.26	CPTI (2004)	39
20	Post-seismic	Pa	Silvestri (1878, 1879)	B	04/10/1878	N37.300	E14.700	5.17	4.80	CPTI (2004)	34
20a	24/12/1878**	Pa	Silvestri (1879)	B	24/12/1878 (t. 9.20 p.m.)					Silvestri (1879)	
21	Post-seismic (01/1866)	Pa*	Silvestri (1866)	B	19/07/1865	N37.700	E15.150	5.03	4.59	CPTI (2004)	27
22	Post-seismic	Pa	Silvestri (1866)	C?	11/01/1848	N37.367	E15.154	5.48	5.26	CPTI (2004)	33
23	Post-seismic	Pa*	Silvestri (1866)	C?	24/11/1832	N37.602	E15.003	4.82	4.28	CPTI (2004)	10.6
24	05/03/1823**	Ca	La Via (1825, 1828)	C	05/03/1823 (t. 5.25 p.m.)	N38.000	E14.100	5.87	5.84	CPTI (2004)	56
25	Post-seismic	Ca	Li Volsi (1828)	C?	02/05/1819	N37.930	E14.050	5.40	5.14	CPTI (2004)	48
26	20/02/1818**	Pa	Guidoboni et al. (2007)	C	20/02/1818	N37.600	E15.130	6.00	6.00	CPTI (2004)	22
27	Post-seismic	Ca	Li Volsi (1828)	C?	05/02/1783	N38.300	E15.970	6.91	6.91	CPTI (2004)	188

Northern Apennines: Fi, Fiorano; Mg, Montegibbio; Ni, Nirano; Po, Porretta; Pr, Portico di Romagna; Pt, Pietramala; Ri, Rivalta; Rg, Regnano; Sa, Sassuno (Dragone di Sassuno); To, Torre. Sicily: Ca, Caltanisetta (Macalube di Terrapelata); Pa, Paternó.
*Eruption related to the activity of the Mount Etna volcano; **coseismic triggering (i.e., eruptions triggered immediately or within a few hours after the passage of the seismic waves); the term "post-seismic" is used when no precise indications of activity onset are available, but only generic indications that this started after a triggering earthquake. MV, mud volcano; ED, epicentral distance; t, local time as reported in the bibliographic source; EP, qualitative parameterisation of eruptions/anomalous activity: A: large explosive eruption with self-ignition of methane and sky-scraping fire/smoke-columns accompanied by strong ground shaking, bursts, extensive eruption of mud breccia and mud flows; B: extensive effusive eruption of mud breccia flows, associated with violent ejection of mud/gas from gryphon/cone craters, and possibly preceded by, or associated with, ground tremors, roars, and bursts; C (less intense than B): mud breccia flows, in case associated with ground tremors, violent mud/gas ejection from gryphon/cone craters and gryphon bursts; D: large increase in gas discharge with self-ignition of methane, bursts, ground shacking/tremors; E: post-seismic increase in fluid and gas discharge; F: geochemical variations in expelled fluids.

Apart from the 1835 Montegibbio eruption described by Dé Brignoli di Brunnhoff (1836), detailed descriptions are normally lacking. However, given the relevance of this aspect, a rough qualitative parameterisation of eruptions and anomalous activity characteristics has been attempted in Table 1.

3.1. Pede–Apennine margin

The oldest and perhaps most famous chronicle reporting an apparent link between a mud volcano eruption and an earthquake is likely that provided by the Roman writer Plinius, who reported evidence in his *Historia Mundi Naturalis* for a large eruption contemporaneous with the destructive earthquake of 91 BC that struck important towns (Reggio Emilia and Modena) nearby the Pede–Apennine margin (Guidoboni, 1989; Fig. 2a). This writer described the 91 BC eruption as sky-scraping flames and two steam columns seen from ca. 10-km distance to occur in the Apennines foothills, which are still the locus of current mud volcano activity. The locality of this relevant historical eruption has been traditionally placed at the Montegibbio salsa (e.g., Bianconi, 1840), but to date its exact position is still not clearly defined (see also Casoli, 2001). Given its importance, this topic is further discussed in the following Section 4.1.3.

In any case, more recent earthquake-related paroxysmal activity is described for the Montegibbio mud volcano, which violently erupted on 05 April 1781 one day after a strong regional earthquake (Avv. Panini in Calegari and Canestrini, 1867; Table 1). A far-field response to distant earthquakes can be inferred also for the Nirano mud volcano field, which recorded relevant postseismic increase in fluid emission following the seismic event of 15 May 1873 that struck the Reggio Emilia Pede–Apennine margin (Coppi, 1875; Fig. 2a and Table 1). At the present time, monitoring of Radon emissions from the mud volcanoes of the Emilia–Romagna region has allowed to attribute the peaks in the emission of

Table 2
Mud volcanoes/vents that have recorded the paroxysmal/anomalous activity mentioned in the text.

Site	Type	Lat.	Long.
Northern Apennines			
Rivalta	Mud volcano field	N44°37′50″	E10°19′34″
Torre	Mud volcano field	N44°37′16″	E10°20′15″
Regnano	Mud volcano field	N44°33′29″	E10°34′33″
Fiorano	Mud volcano field	N44°31′55.5″	E10°48′32″
Montegibbio (Salsa di Sassuolo)	Mud volcano field	N44°31′07″	E10°46′45″
Nirano (Bombi del Gazzòlo)	Mud volcano field	N44°30′49″	E10°49′25″
Sassuno (Dragone di Sassuno)	Mud volcano field	N44°20′09″	E11°27′16″
Pietramala (Fuoco del Legno)	Everlasting fires	N44°09′39″	E11°20′54″
Porretta (Sasso Cardo)	Everlasting fires	N44°09′16″	E10°58′09″
Portico di Romagna (Casa Forte)	Everlasting fires	N44°02′47″	E11°46′26″
Sicily			
Paternó (Salinelle)	Mud volcano field	N37°34′22″	E14°53′23″
Caltanisetta (Macalube di Terrapelata)	Mud volcano field	N37°29′48″	E14°05′26″
Maccalube di Aragona	Mud volcano field	N37°22′33″	E13°35′58″

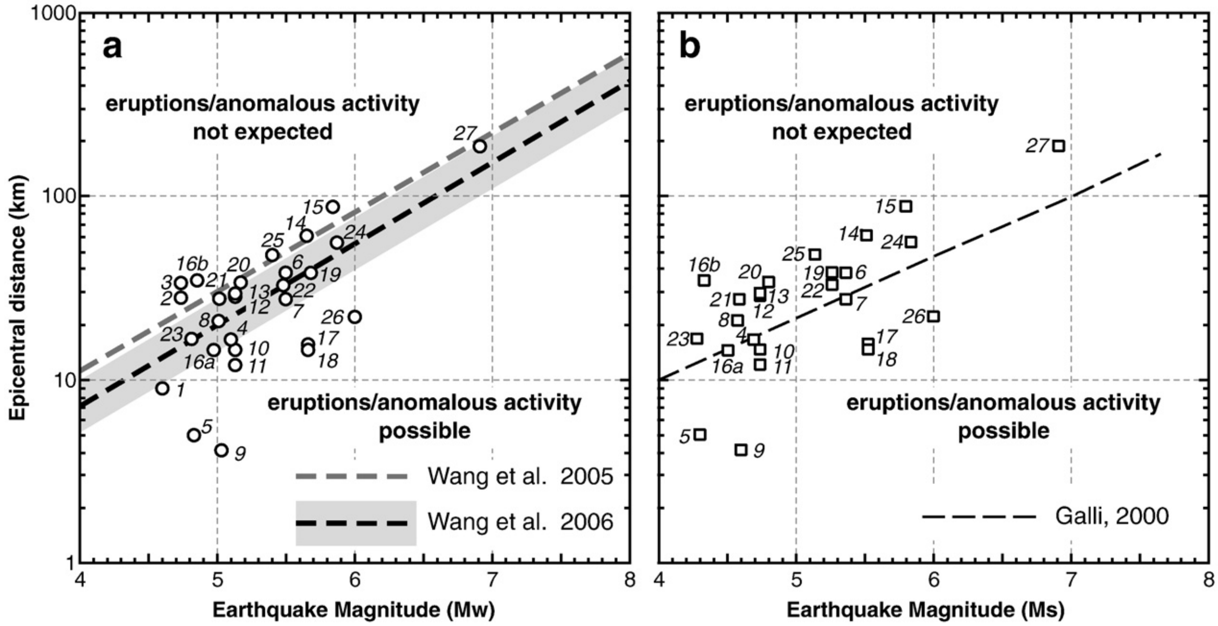

Fig. 3. Epicentral distance to mud volcano/vent response as a function of earthquake magnitude for the Northern Apennines and Sicily regions (data from Table 1). (a) Comparison of earthquake/eruption observations with the empirical upper bounds for liquefaction limit determined by Wang et al. (2005) (Eq. (1)) and Wang et al. (2006) (Eq. (2)). (b) Comparison of earthquake/eruption observations with the empirical upper bound for liquefaction (1117–1900 AD period) from Galli (2000, his Eq. 12): $Ms = 1.0 + 3.0 \log Re$, where Re is the epicentral distance. Numbers refer to those of Table 1.

^{222}Rn to sharp pressure variations at depth correlated with low magnitude ($M<4.5$) local earthquakes (Martinelli and Ferrari 1991; Martinelli et al., 1995).

The everlasting fires (in the past referred to as *fontane ardenti*, i.e., blazing fountains) associated with the escape of methane are mostly located over the axial zone of the Northern Apennines (Fig. 2a), and have shown clear relations with earthquakes as well. Relevant increase in CH_4 emission associated with spectacular self-ignition processes were reported near the epicentre of the 1895 Portico di Romagna earthquake (Trabucco, 1895; data point 4). This area (Portico) presumably also originated the flares seen during the 1956 Santa Sofia seismic event, and the flames of the Porretta everlasting fires (Sasso Cardo) rose up considerably during the seismic sequence of April–May 1929 (Guidoboni et al., 2007; data points 6 and 9). Importantly, a few witnesses still recall that after this latter earthquake sequence (even though one of them reminds the 1928 earthquake) the small salsa near Fiorano (Stöhr, 1867; Govi, 1908) increased relevantly its activity, and the mud expelled along the adjacent creek reached Fiorano, ca. 1 km away (data point 7, Figs. 2a, 3 and 4a and Table 1).

However, many phases of parossistic activity recorded at the Pede–Apennine mud volcanoes are unrelated to seismic events (e.g., Biasutti, 1907). Exemplificative in this regard is the abovementioned impressive eruption of the Montegibbio mud volcano, which started independently of any regional seismic triggering and lasted for some days in June 1835 giving rise to a large mudflow (Dé Brignoli di Brunnhoff, 1836; Stöhr, 1867). Also the several violent eruptions documented for the sane locality (e.g., Dé Brignoli di Brunnhoff, 1836; Biasutti, 1907) occurred in the absence of seismicity (Table 3). Again, crosschecking with seismic catalogues has allowed to establish that none of the 15 phases of paroxysmal activity (some of these were very strong) recorded at the Regnano mud volcano between 1754 and 1907 (Govi, 1908) can be linked to seismic events (Fig. 2a; Table 3).

3.2. Sicily

Clear correlations with regional seismic events have been documented for some mud volcanoes of Sicily (Fig. 2b). In this regard, the Paternó mud volcano field ("Salinelle") presents a rather extensive number of observations. Specifically, the eruptions recorded in 1818, 1832, 1848, 1866 and 1878 have been found to be coincident with seismic events (Silvestri, 1866, 1878, 1879). Whereas some of these are related to regional earthquakes (1818, 1848, and 1878 events), others (1832 and 1866 events) are linked to increased igneous activity and/or local earthquakes associated with the near Mount Etna volcano (Fig. 2b; Tables 1 and 3). Besides, increase in fluid discharge and compositional variations of the released gases (He and CH_4) at this mud volcano field were related to the seismic shock that struck the eastern Sicily in 1990 (D'Alessandro et al., 1996; Table 1). On the other hand, the paroxysmal episode in 1953 documented at the same mud volcano was not correlated to any earthquake (Cumin, 1954; Table 3).

In the same way, the paroxysmal activity of the "Maccalube di Aragona" mud volcano (1936 and 1940 events; Abbruzzese, 1954) was not apparently related to regional seismicity (Etiope et al., 2002; Fig. 2b). Another recent mud volcano eruption unrelated to earthquakes occurred on the 11 August 2008 at the "Macalube di Terrapelata"mud volcano, near Caltanissetta (see http://www.pa.ingv.it/caltanissetta/index.html; Fig. 2b). However, most of the impressive eruptions reported by historical chronicles for this site (La Via, 1825, 1828; Li Volsi, 1828) are related to seismic shocks of tectonic origin (Tables 1 and 3). Notable was the eruption of 5 March 1823 that coincided with the same-day regional earthquake (La Via, 1825, 1828), and the 1783 paroxysmal event (Li Volsi, 1828) correlatable to the destructive seismic swarm that struck Calabria with a number of shocks close to magnitude 7 (Table 1).

4. Discussion

4.1. Relations between earthquake magnitude and epicentral distance of mud volcano/vent response

4.1.1. Comparison of Italian mud volcanism with triggering thresholds

The good correlation between past seismic events and the activity of mud volcanoes reported in Table 1 provides an explicit link between these phenomena for the Northern Italy and Sicily regions. There is in fact a significant number of same-day earthquake/eruption pairs. On the other hand, such a direct earthquake-eruption connection has been determined only for a limited number of cases, as the great majority of mud volcano

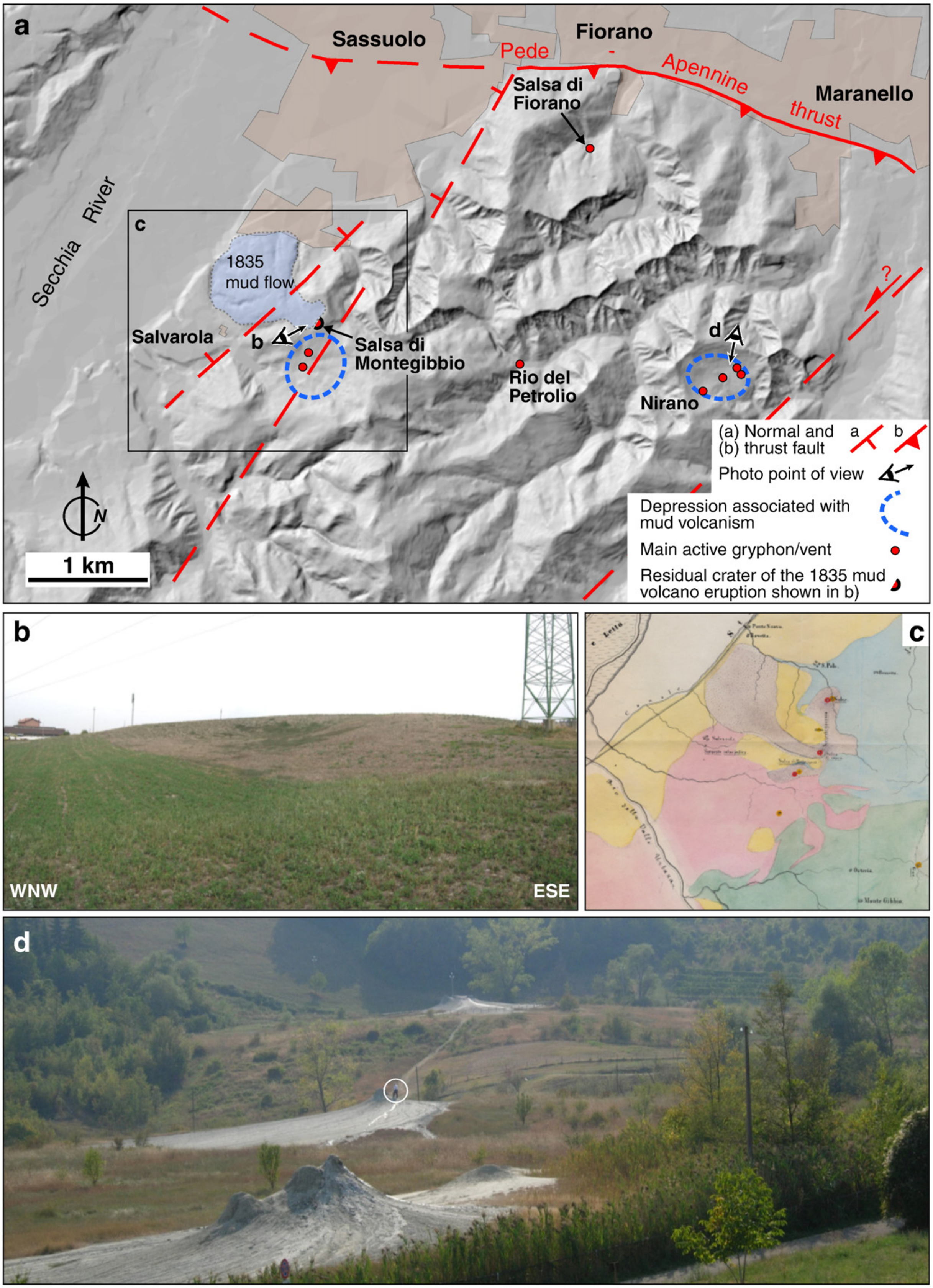

Fig. 4. (a) 5 m-resolution digital terrain model (DTM courtesy of Regione Emilia–Romagna) of the Pede–Apennine foothills between Montegibbio and Nirano mud volcano fields. Location is given in Fig. 2a. The red arrow indicates the expected sense of strike–slip fault component. (b) Relic cone (Salsa di Montegibbio, or Salsa di Sassuolo) from which the large 1835 Montegibbio eruption originated (October 2007); the cone is approximately 10 m tall. (c) Part of Stöhr's (1867) geological map showing the 1835 mudflow in grey. (d) View of the active gryphons inside the Nirano mud volcano depression (September 2006).

Table 3
Eruptions/paroxysmal activity of main mud volcano systems.

Northern Apennines
Montegibbio (Salsa di Sassuolo)
Triggered: 91 BC; 05/04/1781; 1837; 05/1873.
Not-triggered: 1592; 21/06/1594; 1599; 1601; 1603; 1628; 18/05/1684; 1689; 1711; 1772; 1784; 1786; 1787; 19/01/1789; 13/06/1790; 04/06/1835; 06/08/1855.
Nirano
Triggered: 91 BC; 05/1873; 15/03/1988.
Not-triggered: 03/1907; 16/06/1932; 10/08/1936; 30/05/1986; 04/1987.
Regnano
Triggered: 11/10/1915; 19/10/1930; 15/03/1988.
Not-triggered: 14/05/1754; 05/1772; 1792; 22/04/1796; 08/04/1815; 29/09/1833; 22/11/1833; 21/07/1848; 07/1851; 1872; 24/06–24/07/1881; 1884; 10/10/1889; 1895; 1907; 1932; 06/1957; 04/1987; 30/03/1999.
Sicily
Caltanisetta (Macalube di Terrapelata)
Triggered: 1783; 1819; 05/03/1823.
Not-triggered: 1817; 02/2002; 11/08/2008.
Paternó (Salinelle)
Triggered: 1818; 1832*; 1848; 15/01/1866*; 10–11/1878; 24/12/1878; 13/12/1990.
Not-triggered: 15/12/1953; 1989; 02/2002; 12/2003; 06/12/2005.

*Related to earthquakes associated with the Mount Etna volcano activity.
Montegibbio: Spallanzani, 1795; Dé Brignoli di Brunnhoff, 1836; Calegari and Canestrini, 1867; Govi, 1906; Martinelli et al., 1989. Nirano: Coppi, 1875; Biasutti, 1907; Martinelli et al., 1989. Regnano: Spallanzani, 1795; Biasutti, 1907; Govi, 1908; Milani, 1971; Martinelli et al., 1989; Capozzi and Picotti, 2002. Caltanisetta: La Via, 1828; Li Volsi, 1828; INGV, 2008b. Paternó: Silvestri, 1866, 1878, 1879; Cumin, 1954; D'Alessandro et al., 1996; La Manna and Carnazzo, 2000; Giammanco and Neri, 2005.

eruptions was not driven by regional seismicity. This observation thus raises the question: was coincidence between earthquake and eruption accidental, or did the earthquake really trigger the eruption?

One possible answer to this question may be explored in the framework of a triggering threshold, which depends upon the earthquake magnitude and the distance of the mud volcano response from the earthquake epicentre. The processes yielding liquefaction and fluidisation of sediments are considered to be essentially similar to those governing the eruption of mud volcanoes, in which subsurface sediments are mobilised from depth and transported to the surface. Liquefaction of sediments arises when effective stresses become zero, and sediments become fluidised when grains become buoyant, normally following the inflow of external fluids (Maltman and Bolton, 2003). Thus, the relations between epicentral earthquake magnitude and epicentral distance of observed liquefaction phenomena may be representative for mud volcanoes too (Manga and Brodsky, 2006). The relationship between earthquakes magnitude M and the maximum distance R_{max} at which liquefaction may occur has been determined by empirical approaches, which essentially result in linear relations between M and log R_{max} (Kuribayashi and Tatsuoka, 1975; Ambraseys, 1988; Papadopulos and Lefkopulos, 1993; Galli, 2000; Wang et al., 2005, 2006). These relations are consistent with the concept that ground motion attenuates away from the earthquake focus and ground shaking intensity increases with earthquake magnitude. In other terms, liquefaction of saturated soils and sediments documented during earthquakes is expected to be restricted within a specific distance from the epicentre as a function of the earthquake magnitude.

Testing of empirical scaling laws using recent mud volcano eruptions suggests that these liquefaction thresholds can be also applied to liquefaction at depth (Manga and Brodsky, 2006; Manga, 2007; Davies et al., 2008). Empirical relations for the liquefaction limit are reported in Wang et al. (2005):

$$M = -5.0 + 2.26 \log R_{\mathrm{max}}, \tag{1}$$

and Wang et al. (2006):

$$\log R_{\mathrm{max}} = 2.05(\pm 0.10) + 0.45M, \tag{2}$$

where R_{max} is expressed in meters, and in Eq. (2) the uncertainty of R_{max} is indicated as the standard error reported in the parentheses.

The earthquake-triggered mud volcanism reported in Table 1 shows a good agreement with the fields predicted by Eq. (1) (Fig. 3a). The triggered eruption data points essentially fall within the bound suggested by Eq. (1), and corroborate this relation over a range of earthquake magnitude varying between ca. 4 and 7 (Fig. 3a). Rather, the application of Eq. (2) to this data set bears the upper data points to fall above the predicted triggering threshold (Fig. 3a), while the majority of the data points fall in the field of not expected liquefaction determined for the Italian region (Galli, 2000) (Fig. 3b). This difference may be due to the fact that Galli (2000) considered only liquefaction data from Italy, while the bounds in Wang et al. (2005, 2006) were constructed by taking into account a wider and updated dataset.

Only very little earthquake-eruption data points fall slightly above the upper bound of Eq. (1), specifically, (1) the paroxysmal activity at the Sassuno mud volcano tentatively related to the 1780 (Mw < 5) seismic shock (data point 16b), (2) the 1781 Mw = 5.84 earthquake (data point 15), and (3) the two eruptions related to the 1988 Mw = 4.73 shock (data points 2 and 3; Fig. 3a). In case of historical earthquakes, this apparent discrepancy might result from the difficult determination of the precise magnitude and position of the event. For instance, in another catalogue the 1781 event is distinguished by magnitude Me = 6.2 (Guidoboni, 2007), and the related data point would fall in the field of expected liquefaction. Moreover, the correlation of earthquake-eruption for the 1780 event is only supposed, as there are not precise indications of the onset of the paroxysmal activity described by Calindri (1781–1783) on July 1780 — i.e., some months after a number of seismic shocks (see Table 1). The reason of the two exceptions related to the same-day 1988 earthquake-eruption pair is less clear, but a possibility may suppose that a strong directivity of macroseismic effects might have enhanced the local response above the expected threshold.

From the above observations it follows that the triggered mud volcanism considered for the Italian region is best described by the upper bound defined by Eq. (1). It is however worth mentioning that classical liquefaction phenomena, leading to the development of extrusive features similar to mud volcanoes (i.e., sand volcanoes), are generally fed form shallow depth (few to tens of meters), and, most important, normally they do not show the recurrent fluid emission that is typical of genuine mud volcanoes. Mud volcanoes are seemingly associated with more complicated plumbing systems (Mazzini et al., in press), and are connected at depth to confined reservoirs that may record volumetric strain fluctuations induced by the seismogenic processes (Albarello, 2005). However, liquefaction is suggested to occur also at greater depths as a result of permeability changes and/or breached hydraulic barriers that redistribute pore pressure, and thus liquefaction may be still considered a reasonable approximation for the triggering mechanisms of mud volcano eruptions (Wang and Chia, 2008; Manga et al., in press).

4.1.2. Earthquakes and gaseous emissions at mud volcanoes/vents

Geochemical anomalies associated with Radon have been monitored at the mud volcanoes of the Pede–Apennine margin. Peaks in ^{222}Rn contained in the expelled fluids have been found to correlate with low magnitude earthquakes (M < 4.5), and to provide sensitive precursors of forthcoming local seismic events (Gorgoni et al., 1988; Martinelli et al., 1989; Martinelli and Ferrari, 1991; Martinelli et al., 1995). The epicentral distance of earthquakes correlated to these variations in the emission rate of Radon (Gorgoni et al., 1988; Martinelli et al., 1995) often exceed the triggering thresholds shown in Fig. 3. Such variations in the flow rates of gaseous or liquid emissions may reflect pore pressure variations at depth connected to volumetric strain perturbations of confined reservoirs (Albarello, 2005), and could be more similar to other hydrological responses to earthquakes, including water well fluctuations and stream flow variations, which have been documented at distances above the thresholds of Fig. 3 (Montgomery and Manga, 2003). On the other hand, other studies on the Apennine mud volcanoes suggest that a relatively large number of unknown factors control the dynamics of Radon emissions, thus discouraging the use of bubbling gaseous emissions for the monitoring of geodynamic processes (Albarello et al., 2003).

Variations in fluid composition preceding a local earthquake have been recently recorded at Pietramala, which was an important methane-dominated venting field that attracted many scientists, like Alessandro Volta, for studying the everlasting fires (e.g., Vulcano di Peglio, Fuoco del Legno; Lotti, 1920; Fig. 2a). Currently, methane venting has almost ceased owing to hydrocarbon extraction. Monitoring of the pH of extracted hydrocarbons revealed a sudden increase from 4–5, stable on the period 2004–2008, to 7–8 two days before (i.e., on the 27 February 2008) the seismic swarm that started on the 01 March 2008 (Dr. Annalisa Granaiola, personal communication, May 2008). The phenomenon observed at Pietramala may reflect pre-seismic geochemical variations, but its identification as seismic precursor requires further confirmations and supporting material (see Roeloffs, 1988). Regardless, the epicentral distance was ca. 9 km, and thus the correspondent data point would fall in the triggering field (data point 1, Figs. 2a and 3a and Table 1).

4.1.3. Relevance for the positioning of the 91 BC eruption

The locus of the celebrated 91 BC eruption described by Plinius to be synchronous with a destructive seismic shock (Guidoboni, 1989) has been usually identified with the Montegibbio mud volcano (Fig. 4a, b). However, apart from the 1835 mudflow (Fig. 4a, c; Stöhr, 1867), no relevant features manifesting massive material expulsion–such as caldera-like depressions or large relic apparatuses–have been identified at Montegibbio so far, a fact that is surprising given this area was the locus of recurrent activity (Bianconi, 1840; see Table 3). Instead, the Nirano mud volcano field, which is located only a few kilometres (3.5 km) east-southeast of Montegibbio, displays several active gryphons/cones and occurs in a large elliptical depression that is inferred to have developed in response to a large evacuation of fluids (Fig. 4a, d; Bonini, 2008), suggesting that the Nirano field may represent another possible candidate for the 91 BC eruption (see also Coppi, 1875).

In contrast, the present surface manifestations at Montegibbio field consist of small pools with limited gas bubbling. The decreased activity could be partly explained by the exploitation of subsurface fluids for supplying the near Salvarola thermal plant (Fig. 4a). However, a careful examination of this field reveals the presence of a NNE-trending elongate depression, which is hosting the residual bubbling pools (Fig. 4a). Such a depression is currently eroded and filled with detritus and landslides, but it is suspected to have involved the same meaning as the Nirano caldera depression, specifically a potential manifestation of past massive evacuations of fluids. The long depression axis is approximately coincident with a NNE-striking fault (Fig. 4a). The extinct mud cone that gave rise to the 1835 mud eruption occurs over the northern edge of this depression (Fig. 4a–c).

Recent historical analyses and considerations still call upon Montegibbio as the most probable locus of the eruption (see Casoli, 2001), but this would raise the question to which event(s) refer the large expulsion of fluids that is necessary to explain the Nirano depression. The earthquake–distance relations could provide a possible solution. A moment magnitude $M\mathrm{w}=5.66$ has been estimated for the 91 BC earthquake, and its epicentre has been positioned in the Po Plain, at a distance of 14.5 km and 15.5 km form Montegibbio and Nirano, respectively (Figs. 2a and 4a; Table 1). However, both Nirano and Montegibbio data points fall well below the upper bound for hydrologic responses suggested by Fig. 3a (data points 17, 18). From this follows that both localities occur at a distance potentially very favorable for the seismic triggering in the far field of the 91 BC earthquake. The reference to the two steam columns reported in the Plinius' chronicle (*..in agro Mutinensi. Namque montes duo inter se concurrerunt, crepitu magno assultantes recedentesque, inter eos flamma fumoque in caelum exeunte interdiu,..*) may indeed suggest that both features were activated simultaneously by the same seismic event, but this is still a speculative possibility, and only the direct dating of the calderas (for instance, through coring and radiocarbon dating of the organic matter contained in the lowermost caldera fills, which may give an upper bound of ages) could solve this intriguing quandary.

4.2. Dynamics of mud volcano response to earthquakes

4.2.1. Why triggered and not triggered mud volcanism?

Even when the magnitude–distance parameters fall in the field in which eruption is expected, mud volcanoes do not always respond, if not rarely, to earthquakes. As noted above, the majority of eruption started, in fact, in the absence of seismic activity. This can be illustrated for the Montegibbio mud volcano, whose eruptive activity is rather well defined owing to its vicinity to the town of Sassuolo (Table 3). Here, many earthquakes did not trigger eruptions despite distances/intensities parameters enter the apparent triggering threshold, whereas triggered eruptions can be established for a few cases only (Fig. 5).

The insensitivity of mud volcanoes to earthquakes may indicate that the fluid pressure internal to the mud volcano plumbing system is under critical, and thus not adequate for priming the system to eruption. This implies that only near-critical mud volcanoes (i.e., sufficiently next to the eruption) can be triggered by an increase of reservoir pressure, which may be generated by transient dynamic stress changes caused by propagating seismic waves (Manga and Brodsky, 2006; Mellors et al., 2007; Manga et al., in press). As previously suggested, large eruptions could thus require a minimum healing and recharge period before the system can reaccumulate pressure and become critical and inclined to erupt again (Mellors et al., 2007; Davies et al., 2008). Manga et al.,

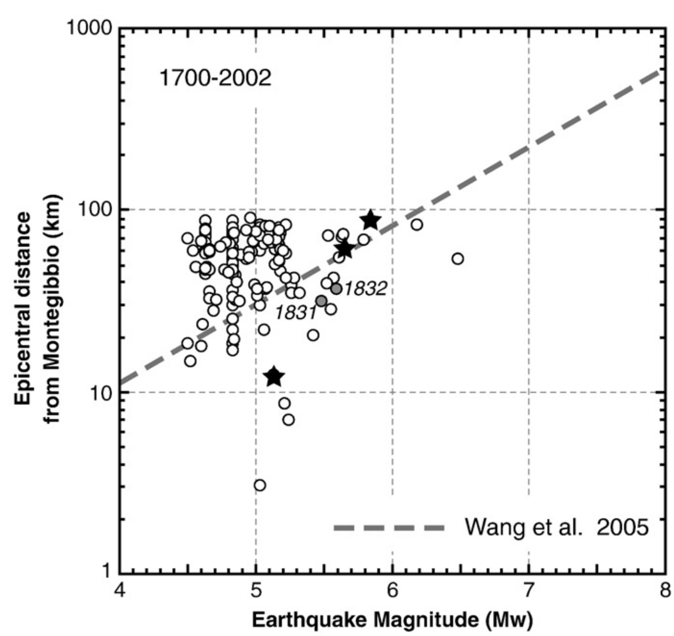

Fig. 5. Earthquakes with magnitude $M\mathrm{w}>4.5$ (highest $M\mathrm{w}=6.48$) versus epicentral distances (<90 km) referred to the Montegibbio mud volcano (Northern Apennines) for the period 01/01/1700–31/12/2002 (earthquake epicentres after CPTI Working Group, 2004). The potentially triggering earthquakes are those below the dashed grey line, which indicates the empirical relation for upper liquefaction boundary of Wang et al. (2005). The black stars indicate earthquakes documented to have triggered mud volcano eruptions at this site. The two grey circles indicate the potentially triggering 1831 and 1832 earthquakes that predated the 1835 Montegibbio eruption (see Fig. 4a–c).

(in press) have shown that the Niikappu mud volcanoes in Japan have consistently shown a couple year repose time for triggering. In other terms, earthquakes can only increase the fluid overpressure resulting from other processes (such as gas expansion, mineral dehydration, tectonic stresses, external fluid input) able to promote the liquefaction and fluidisation of unconsolidated subsurface sediments (Brown, 1990; Maltman and Bolton, 2003).

The critical threshold can be placed when the internal pressure to the mud volcano reservoir exceeds lithostatic magnitudes (plus the tensile strength T_F of depth-to-surface conduits), that is when the pore fluid factor (the ratio of fluid pressure P_F to vertical lithostatic stress P_L; Hubbert and Rubey, 1959) $\lambda_v \geq 1$. In the intervening period between successive eruptions (dormant stage; see Mazzini et al., in press), the surface activity of the mud volcano shows either essentially quiescent flow of fluids, or the system remains inactive. This evolution can be schematically idealised through a pressure–time diagram, in which paroxysmal eruptions are expected to occur at regular time intervals assuming the fluid recharge to be constant (Fig. 6a). The recharge may be however affected by a number of factors, such as the production rate of the driving gas (CH_4 or CO_2), in combination with the presence/efficiency of permeable structures connecting the reservoir to the surface. Intuitively, the presence of permeable fluid conduits would result in the continuous but generally weak fluid emission (for instance, the nowadays activity at the Nirano field), which is expected to prolong the recurrence interval of eruptions. In contrast, impermeable pathways would favour paroxysmal phases (when $P_F \geq P_L + T_F$) to alternate with inactive periods (for example, the activity of the Caltanisetta mud volcano field).

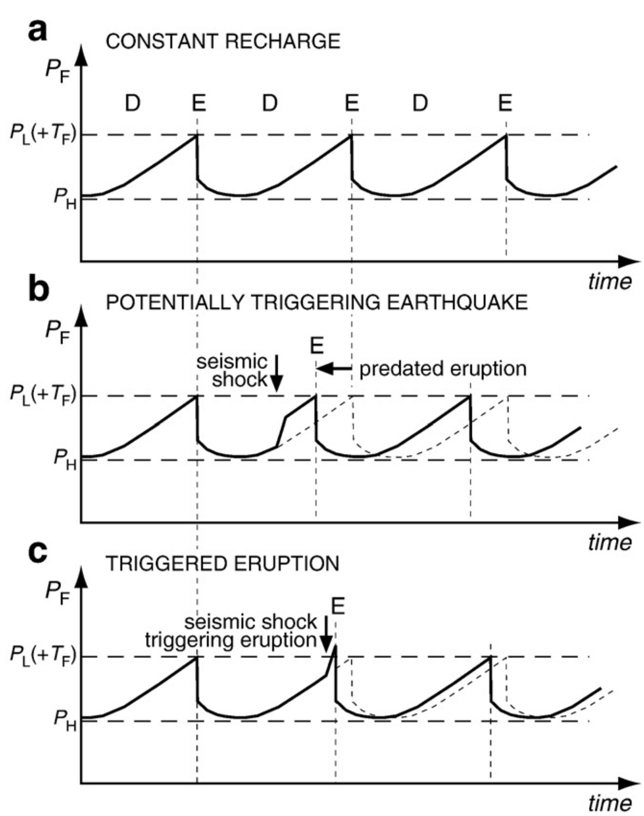

Fig. 6. Schematic cartoons showing the recurrence time of mud volcano eruptions as a function of seismic events and the level of fluid pressure internal to the fluid reservoir (P_F). Eruptions are expected when the critical pressure P_{crit} $(=P_F) \approx (P_L + T_F)$, where P_L is the lithostatic fluid pressure and T_F the tensile strength of fault/fracture-controlled mud/fluid conduits. (a) Hypothetical steady state system driven by constant fluid recharge, resulting in regular inter-eruption intervals. (b) Earthquake-induced P_F increase; at the moment of the earthquake P_F is not sufficiently close to critical to trigger the system into eruption, but the seismic-induced pressure increase is expected to predate the next eruption. (c) Earthquake-induced eruption. The system is on the edge of eruption, and a triggering earthquake is capable to increase P_F to exceed the lithostatic load. P_H, hydrostatic fluid pressure; E, Eruption; D, dormant period.

Besides magnitude and epicentral distance, the efficiency of earthquakes as eruption trigger will obviously depend upon the reservoir pressure at the moment of the seismic shock. In systems distant from eruption, pre-eruptive seismic events would increase the internal fluid pressure, so that even relatively small pressure increases produced by the regular gas recharge can prime the system into eruption (Fig. 6b). Analysis of Azerbaijan mud volcanoes suggests however a weak correlation between large earthquakes and delayed mud volcano eruptions in the months to years after an earthquake (Mellors et al., 2007). Even so, the occurrence of reiterated potentially triggering earthquakes is expected to raise the system closer to the threshold. For instance, the violent earthquakes that struck the Reggio Emilia area in 1831 and 1832 fall both in the "triggering" field (see Fig. 5), and hence they are suspected to have prepared the following 1835 Montegibbio eruption that started independently from seismicity (Table 3). This theory could also explain the strong activity described by Calindri (1781–1783) at the Sassuno mud volcano field on July 1780, which was predated by earthquakes that struck the Bologna region (see data points 16a and 16b in Fig. 3a and Table 1).

In the same way, systems on the edge of eruption may erupt even in reaction to distant triggering earthquakes occurring at approximately 1–2 ruptured fault lengths away (Fig. 6c; Mellors et al., 2007). For example, the Caltanisetta mud volcano showed strong paroxysmal activity in 1783 (Li Volsi, 1828) most likely in response to the destructive Calabria seismic swarm, which yields a ~190 km triggering distance (data point 27; Fig. 3a, and Table 1).

4.2.2. Earthquake-responding and poorly earthquake-responding mud volcanoes

The observation that some mud volcanoes are apparently more susceptible to earthquake triggering than others suggests a broad classification in "responding" and "poorly responding" types. Such a different evolution is obviously dependant upon the mutual relationships between the production/recharge rate of the driving gas and the frequency of triggering earthquakes. At a first approximation, mud volcanoes with low gas input falling in areas with frequent strong seismicity are expected to respond less to earthquakes than mud volcanoes with high gas production settled in regions with lower frequency of triggering earthquakes. This consideration highlights once more the site and time-specific propensity of a mud volcano system to respond to earthquakes. In other terms, in order eruptions to occur earthquake triggering is required to be in-phase with near-critical conditions of the mud volcano systems.

On this basis, the eruptive history and the susceptivity of mud volcanoes to erupt in reaction to earthquakes could be fully defined by the following ratios: (1) triggered eruptions/total eruptions, and (2) triggered eruptions/potentially-triggering earthquakes. The Montegibbio and Paternó mud volcanoes in Northern Apennines and Sicily are taken to exemplify different mud volcano responses.

For the Montegibbio mud volcano (period 1700–2002), the triggered eruptions/potentially triggering earthquakes ratio is ca. 0.1 (3/31; see Fig. 5), while (for the same period) the ratio triggered eruptions/total eruptions increases to 0.25 (3/12) (see Table 3). These results indicate that only a limited part (10%) of the potentially triggering earthquakes did activate mud volcano eruptions, but earthquakes triggered a considerable fraction (25%) of the eruptions. The ratio triggered eruptions/total eruptions decreases to 0.19 (4/21) when considering also the older events reported in Table 3. Despite the relative smallness of the fraction of triggered eruptions, the number is apparently greater than that inferred for the Azerbaijan mud volcanoes (Mellors et al., 2007). The Paternó mud volcano (though its historical record is seemingly less robust than that of Montegibbio) provides a substantially different evolution. For the same period (1700–2002), the triggered eruptions/potentially triggering earthquakes ratio is ca. 0.18 6/33; see Fig. 7 and Table 3), but this ratio increases

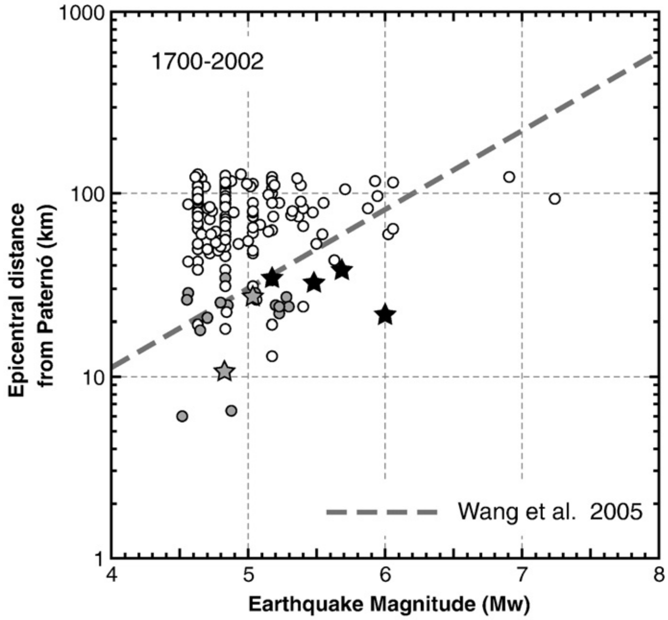

Fig. 7. Earthquakes with magnitude $Mw>4.5$ (highest Mw = 7.24) versus epicentral distances (<130 km) referred to the Paternó mud volcano (Sicily) for the period 01/01/1700–31/12/2002 (earthquake epicentres after CPTI Working Group, 2004). The 130 km distance was chosen to include the epicentre of the 1783 Calabria earthquake that likely triggered the eruption of the more distant Caltanisetta mud volcano. The potentially triggering earthquakes are those below the dashed grey line, which indicates the empirical relation for upper liquefaction boundary of Wang et al. (2005). Stars indicate earthquakes documented to have triggered mud volcano eruptions: black, tectonic origin; grey, volcanic origin (Mount Etna). The grey circles indicate earthquakes presumably associated with the activity of the nearby Mount Etna volcano. The 24/12/1878 seismic event (triggering the synchronous eruption) mentioned in Silvestri (1879) does not appear since it is not reported in the CPTI Working Group (2004) catalogue.

to 0.22 when considering only the earthquakes (and the associated eruptions) of tectonic origin (18 events), and neglecting those presumably related to the activity of the Mount Etna volcano (15 events). The ratio triggered eruptions/total eruptions is difficult to estimate, but likely it is very high (i.e., close to 1). For instance, in the 19th century nearly all the eruptions were apparently triggered by seismic events generated by either tectonics or volcanic activity of the Mount Etna (see Table 3). On the other hand, a relevant number of recent eruptions was apparently not triggered by earthquakes (see Table 3). The consideration of the whole dataset still yields a very high triggered eruptions/total eruptions ratio of 0.58 (7/12).

The frequency of eruptions provides additional clues about the dynamics of the mud volcano systems. The eruptive history of the Montegibbio mud volcano shows four main clusters of activity, respectively around 1600 (1592–1628), 1690 (1684–1711), 1780 (1772–1790), and 1850 (1835–1873) (see Fig. 8a and Table 3). This denotes rather regular cycles with periods of 70–90 years, which could reflect the long-term reloading period of the system. The great majority of eruptions were not triggered by seismicity, and triggered eruptions occurred essentially at the end of the last period of mud volcano activity (see Fig. 8a). The Paternó mud volcano shows an opposite scenario, as all the eruptions in the period 1818–1878 were triggered by earthquakes, and showed a rather constant 12–18 years cycle (Fig. 8b and Table 3). This evolutionary trend may suggest a direct correlation with tectonic structures, but the triggering earthquakes are dispersed around the Paternó mud volcano field and cannot be ascribed to a specific structure controlling its fluid reservoir (see Fig. 2b). Such a straightforward correspondence between eruptions and earthquakes is however surprising and enigmatic.

The reason of such a dissimilar behaviour may simply be that triggering earthquakes and critical state of the mud volcano systems were in phase at Paternó and out-of-phase at Montegibbio. Another explanation may concern the permeability of the conduits connecting the fluid reservoir to the surface. In the Montegibbio, the depth-to-surface fluid pathways may be expected to have been relatively permeable, and thus have allowed the fluid discharge as soon the system reached the critical state. The fluid conduits at Paternó may be instead expected to have been comparatively impermeable, and opened only in response to a sudden and strong fluid pressure pulse produced by earthquakes (see also Vecchioni P.E., as cited in Mucchi, 1966). This evolution is consistent with mineral precipitation (calcite) and cementation of conduits following the post-seismic decrease of CO_2 partial pressure. The Paternó mud volcano is in fact massively supplied by CO_2-rich fluids derived from the activity of the near Mount Etna volcano (Silvestri, 1866; Chiodini et al., 1996). Such a strong gas input also accords with the pronounced propensity of this mud volcano to respond to the recurrent earthquakes that struck the area.

4.2.3. Hypothetical relations with seismogenic faults controlling reservoirs

The mud volcanoes of the Pede–Apennine margin invariably occur above the hanging wall of the active Pede–Apennine thrust, and are thus strictly associated with this structure (Figs. 2a and 4a). Specifically, mud volcanoes often lie along the crest of thrust anticlines, and the related fluid reservoirs are inferred to develop preferentially at the fold core where rising fluids can be easily trapped and overpressured below sealing layers; in this setting, fluids may be expelled via fracture sets associated with the fold (Bonini, 2007, 2008).

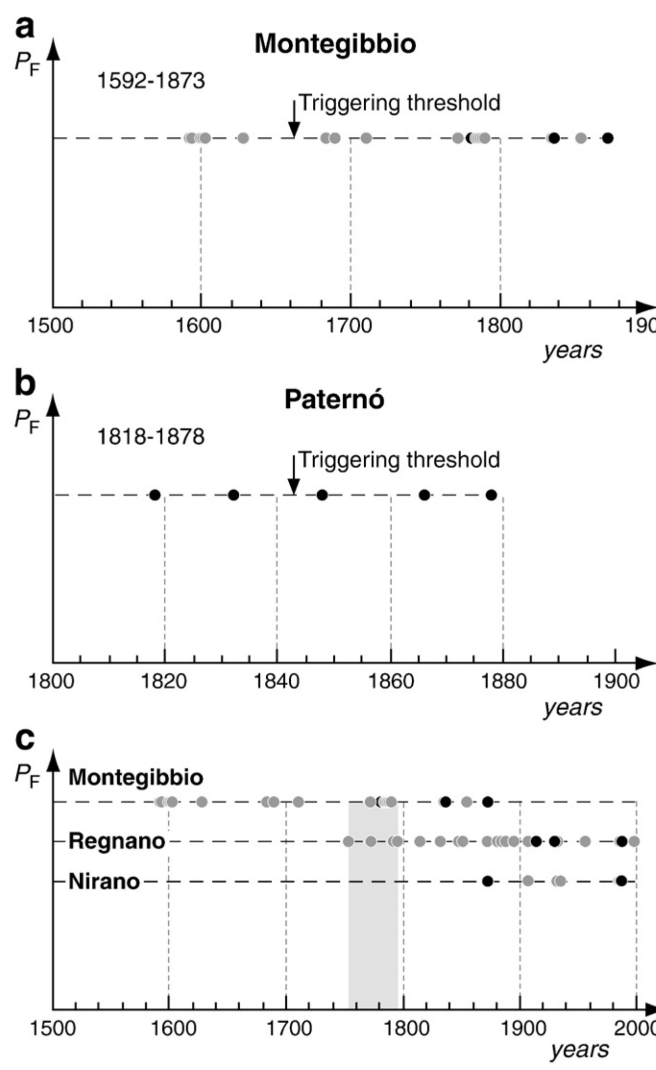

Fig. 8. Eruptions at (a) Montegibbio, and (b) Paternó mud volcanoes. The black and grey circles indicate earthquake-triggered and not-triggered eruptions, respectively. (c) Eruptive history of some Pede–Apennine mud volcanoes (data from Table 3). The grey shading indicates the coincidence between an apex of Montegibbio mud volcano activity and the onset/renewal of activity at the Regnano mud volcano.

Therefore, the Pede–Apennine mud volcano reservoirs lie very close to potentially seismogenic structures (say <5 km distance), and some may even rest along the same active thrust. Impulsive and static stresses generated by earthquakes along the Pede–Apennine thrust fault (and/or related splays) may be large at these small distances from the earthquake focus, and are thus expected to perturb largely the overlying mud volcano reservoirs (see Fig. 9a).

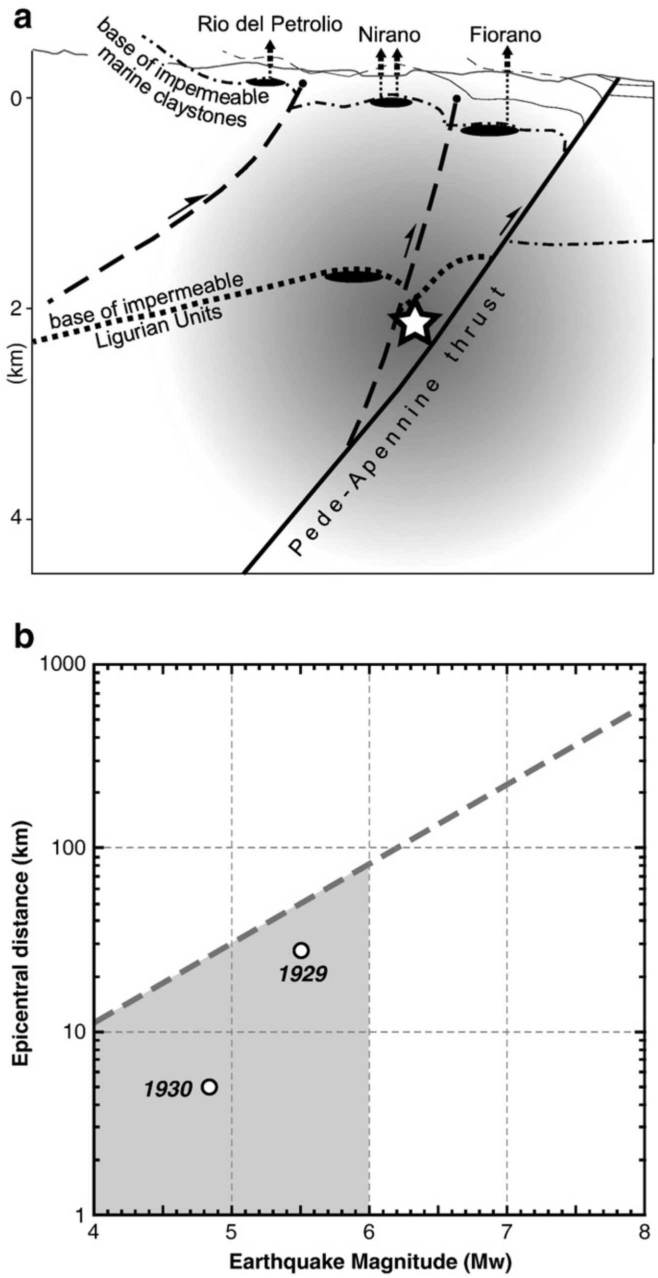

Fig. 9. (a) Idealised cross section through the Pede–Apennine margin (modified from Bonini, 2008). The black ellipses schematise the mud volcano fluid reservoirs coring the thrust-related folds associated with the active Pede–Apennine thrust. The reservoirs are inferred to localise at the base of impermeable units, such as the shale-dominated Ligurian Units (deep reservoirs), and the Pliocene–Early Pleistocene marine claystones (shallow reservoirs). The white star symbolises the focus of a hypothetical earthquake generated by slip along the Pede–Apennine thrust, and the shading schematises the associated radial stress transfer perturbing the surrounding reservoirs. (b) Earthquake magnitude–distance diagram showing data points of triggering earthquakes (1929 and 1930 events) potentially generated by the seismogenic Pede–Apennine thrust. Although the focal depth is normally undetermined in the examined catalogues of historical seismicity, the position of these earthquakes on the thrust hanging wall is compatible with this scenario (see Fig. 2a). A potential field of eruptions triggered by the Pede–Apennine thrust (gray shading) is outlined on the basis of such seismic events.

Nevertheless, the epicentres of triggering earthquakes have been mostly positioned in the Po Plain, thus ahead of the Pede–Apennine thrust and only seldom over its hanging wall, near the mud volcanoes (see Figs. 2a and 9b). This suggests that the great majority of the identified triggering earthquakes, including the 91 BC event, was associated with the buried structures in the Po Plain, and thus structurally unrelated to the fluid reservoirs. This behaviour may hypothetically indicate an aseismic component in the movement of the Pede–Apennine thrust, but past and several recent earthquakes (period 1981–2003) seem to be associated with this structure (Benedetti et al., 2003; Boccaletti et al., 2004). In addition, despite the apexes of Montegibbio mud volcano activity were essentially not induced by earthquakes, the apparent coincidence of the third peak of activity with the onset or renewed activity of the Regnano mud volcano may suggest that they share a causal mechanism, which may be envisaged in the activity of the Pede–Apennine thrust that structurally controls their deep fluid reservoirs (see Fig. 8c).

In this scenario, long-term monitoring of mud volcanism could offer a great potential for understanding the relations between the current and past tectonic activity of the neighbouring Pede–Apennine thrust. However, crucial information is lacking, such as the age of mud volcanism onset, and the frequency and magnitude of fluid emissions. In addition, many questions are still open, for example the age and evolution through time of the large depressions that host some of the main mud volcano fields (i.e, Rivalta, Biasutti, 1907; Nirano, Bonini, 2008; Fig. 2a), which most likely resulted from the evacuation of a large amount of fluids (see Section 4.1.3). The magnitude of expelled material is, in fact, apparently not in equilibrium with the mostly quiet and limited fluid discharge that has been characterising some of these depressions in the last centuries, such as the Nirano ones (Bianconi, 1840; Biasutti, 1907). One may thus speculate that the development of these collapse structures was linked to paroxysmal phases possibly related to the tectonic activity of the nearby seismogenic Pede–Apennine thrust.

In the same way, the Paternó mud volcano system is likely controlled by the neighbouring thrust-anticlines of Late Quaternary age associated with the external chain thrust front (La Manna and Carnazzo, 2000; Catalano et al., 2007, 2008). The structural setting of this mud volcano field is however more complicated than the Montegibbio case, since it is potentially influenced/perturbed by additional active tectonic and volcanic elements, such as the Mount Etna, and the normal-transtensive faults composing the Siculo–Calabrian Rift Zone (see Fig. 2b; e.g., Catalano et al., 2008).

5. Concluding remarks

The relations between earthquakes and paroxysmal activity of mud volcanoes have been explored at the Pede–Apennine margin of the Northern Apennines and in Sicily. The main conclusions are summarized as follows:

1. Magnitude of the earthquakes inferred to have triggered historical mud volcano eruptions and epicentral distance of the eruptive (or anomalous activity) events are in good agreement with the empirical relations determined for observed earthquake-induced liquefaction (e.g., Wang et al., 2005). These findings support seismic triggering of mud volcano eruptions by distant earthquakes, and imply that the triggering thresholds may be extrapolated also to mud volcano systems discharging fluids from depths up to several hundreds of meters.
2. With a few exceptions (i.e., the Paternó mud volcano), the majority of eruptions occurred in the absence of earthquakes, suggesting that mud volcanoes may erupt in response to potentially triggering earthquakes only if the system is near critical (i.e., when internal fluid pressure approaches lithostatic magnitudes). This confirms the concept that a repose time is needed for triggering, as well as that the production rate of the driving gas and the permeability of the depth-to-surface fluid

pathways may be also expected to control the susceptibly of the system to respond to triggering earthquakes.

3. Mud volcanoes of the Pede–Apennine margin are intimately connected with rising fluids trapped in the core of anticlines associated with the seismogenic Pede–Apennine thrust. Fluid reservoirs are thus susceptible to the perturbations generated by near-field earthquakes associated with this fault system. From this follows that the historical and ongoing eruptive activity of the mud volcanoes may hint also for the tectonic activity of such a structure.

Acknowledgments

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