International Journal of Earth Sciences (2019) 108:1683–1703
https://doi.org/10.1007/s00531-019-01730-w

ORIGINAL PAPER

Linking structures with the genesis and activity of mud volcanoes: examples from Emilia and Marche (Northern Apennines, Italy)

Daniele Maestrelli[1] · **Marco Bonini**[1] · **Federico Sani**[1,2]

Received: 25 July 2018 / Accepted: 3 May 2019 / Published online: 25 May 2019

Abstract

Mud volcanism is known to be strictly linked to tectonic structures, since they have the ability to trap hydrocarbon and other fluids, and eventually induce them to migrate from a deep reservoir (e.g. sited into an anticline core, where large overpressures may be generated), to the surface. A central theme is how fluids can migrate upward, and which is the role in this process of near structures (i.e. structures directly controlling the mud volcano system) and far structures (i.e. faults located far away from the mud volcano system). In this study, we investigate the role of both types of structures in the genesis and evolution of mud volcanoes. In particular, we investigate six mud volcano case studies from the Emilia-Romagna and Marche Pede–Apennine margin, in Italy, through integration of fieldwork, interpretation of available seismic reflection profiles and aerial photos. The results of these analyses support an intimate link of the investigated mud volcanoes with anticline structures. We discuss two different fluid migration settings, particularly (i) mud volcanoes emplaced on outcropping anticlines, and (ii) mud volcanoes located on top of buried structures, discerning when fluids are likely to exploit anticline-related fracture sets, or secondary structures and porosity. Finally, we speculate on how far structures, via the seismic triggering, may play a role in the occurrence of historical eruption of some of the investigated mud volcanoes.

Keywords Mud volcanism · Anticline structures · Fracture systems · Seismic interpretation · Seismic triggering · Northern Apennines

Introduction and aims

Mud volcanoes are the superficial expression of deep focused fluid flow processes, involving the upward migration of mud breccias, fluids and gases (mostly methane and other heavier hydrocarbon gases) that are typically sourced from deep hydrocarbon reservoirs and driven by gas exolution (Brown 1990; Dimitrov 2002; Kopf 2002). This worldwide diffuse phenomenon is generally associated with the presence of four key geological controlling factors (Dimitrov 2002): (1) recent tectonic activity, (2) sedimentary or tectonic loading, (3) genesis of hydrocarbon, and (4) the existence of thick, fine-grained, soft and plastic sediment layers buried in the stratigraphic succession. These conditions are particularly common in compressional tectonic settings (Kopf and Behrmann 2000; Bonini 2008; Roberts et al. 2011), where the overthrusting leads to the stacking of thick sedimentary sequence and involves the formation of hydrocarbons, that is typically located in the core of thrust folds (Jakubov et al. 1971; Planke et al. 2003). Besides, mud volcanoes may also be associated with different tectonic contexts, such as those observed in strike-slip/transpressive settings (e.g. Mazzini et al. 2009; Medialdea et al. 2009; Hensen et al. 2015), inversion tectonic settings (e.g. Maestrelli et al. 2017a) or associated with extensional faulting (e.g. Slack et al. 1998; Kopf 2002). Nonetheless, these tectonic environments need to be characterised by the presence of high rates of sedimentation, to develop conditions for hydrocarbon and overpressure generation (Dimitrov 2002). An example is the focused fluid flow developed due to sedimentary overloading, occurring in the Nile deep sea fan (Ceramicola et al. 2018), or shallow and deep submarine environments (e.g. Davies 2003; Judd and Hovland 2009; Somoza et al. 2012; De Prunele et al. 2017).

✉ Daniele Maestrelli
daniele.maestrelli@gmail.com; daniele.maestrelli@igg.cnr.it

[1] Consiglio Nazionale delle Ricerche (CNR), Istituto di Geoscienze e Georisorse (IGG), Via G. La Pira 4, 50121 Florence, Italy

[2] Dipartimento di Scienze della Terra, Università di Firenze, Via G. La Pira 4, 50121 Florence, Italy

Beyond the tectonic context, mud volcanoes can be found in various environments, spanning from onshore to near- and deep offshore. Despite this variety of environments, mud volcanism occurrence is invariably linked to fluid overpressuring mechanisms, which drive the migration of the water/mud/hydrocarbon mixture up to the surface. These mechanisms are various and have been widely described (e.g. Kopf 2002; Bonini 2007; Manga et al. 2009; Rudolph and Manga 2012). Overpressure genesis can be related to fluid retention in high-sedimentation rate environments in the presence of sealing horizons, especially when undergoing tectonic loading (e.g. compressive tectonic setting), dewatering of minerals, and biogenic and thermogenic effects involving fluid volume increase due to hydrocarbon production. Whatever the process responsible for it, overpressure—together with mud mixture buoyancy—is generally considered the most valuable mechanism for mud volcano emplacement (Dimitrov 2002; Kopf 2002; Revil 2002; Bonini 2007).

Mud volcano activity is typically characterised by periods of quiescence alternating with periods of quiet effusive eruptions and degassing, which may be related to cycles of "overpressures recharge" due to continuous/scattered reservoir degassing. Occasional paroxysmal activity may interrupt such a background activity, and sometimes the eruptions may be triggered by earthquakes, as a result of the associated perturbation of the local stress field and fluid overpressure increase due to variation induced by static and dynamic stress changes (Mazzini et al. 2007; Mellors et al. 2007; Manga et al. 2009; Wang and Manga 2010; Lupi et al. 2014; Bonini et al. 2016; Maestrelli et al. 2017b; Miller and Mazzini 2018).

Although widely studied, mud volcanism remains an intriguing and debated topic, particularly its tectonic controls and the relationships with seismic activity, which has been shown to occasionally trigger mud volcanoes into eruption (e.g. Mellors et al. 2007; Manga and Bonini 2012). In general, the activity of mud volcanoes may be influenced by both near- and far structures. Near structures may control directly the mud volcano system (i.e. being linked with it), while far structures are settled at several fault lengths away, and their seismic activation can only perturb the stress field around the mud volcanoes. Nonetheless, this perturbation may potentially favour eruptions.

In this study, we aim to analyse the near- and far-structure control, taking as examples six onshore mud volcanoes from Emilia-Romagna and Marche, in central-northern Italy. We present structural and geological data in combination with interpretation of available seismic sections. Specifically, we intend to address some relevant research questions, particularly: are the investigated mud volcano systems related to near- and possibly active structures of the Pede–Apennine foothills? Can tectonic and seismic activity of far structures influence mud volcano responses? We shall attempt to answer these questions, particularly the relationships between shallow and deep-seated structures and mud volcano location, on the basis of available unpublished seismic sections as well as field and historical data.

Tectonics and geological framework

Mud volcanoes of the Emilia-Romagna Apennines have been widely studied (e.g. Capozzi et al. 1994; Martinelli et al. 1995; Minissale et al. 2000; Capozzi and Picotti 2002, 2010; Martinelli and Judd 2004; Bonini 2008; Tassi et al. 2012; Oppo et al. 2013; Lupi et al. 2015; Sciarra et al. 2019), and mostly occur along the so-called Pede–Apennine margin (Fig. 1), a sharp morpho-structural feature that separates the inner and outcropping portion of the fold-and-thrust belt, from the more external, active thrust and folds that are considered seismogenic sources for compressive earthquakes (Boccaletti et al. 1985; Martelli et al. 2017). Thrust folds are characterised by an arcuate shape in plain view (Pieri and Groppi 1981; Barberi and Scandone 1983), and are buried beneath a cover of Quaternary continental deposits, filling of the Po Plain. The Pede–Apennine margin corresponds to the surfacing of the Pede–Apennine Thrust (PAT), which consists of a system of thrusts and thrust-related folds (Fig. 1, e.g. Boccaletti et al. 1985; Doglioni et al. 1999; Maestrelli et al. 2018). Along the Pede–Apennine margin, a series of tectonic units belonging to the Ligurian and Epiligurian domain are widely exposed. Ligurian Units (sensu *latu*) were deposited into the Ligurian-Piedmont basin, a Jurassic ocean closed by the Adria–Europe convergence. The Epiligurian Sequence was deposited into satellite basins located on top of the Ligurian wedge, during its overthrusting (Ricci Lucchi 1987). At present, the Ligurian Units are tectonically overlying the Tuscan and Umbria–Marche stratigraphic series, which were deposited into a marine domain associated with the thinning continental margin of Adria. At the leading edge of the outcropping chain, the Ligurian Units often overthrust the Miocene–Pliocene marine and transitional sequence, which is mainly represented by mudstones (e.g. Argille Azzurre Formation) and sandy to conglomerate deposits marking the progressive costal progradation due to sea level retreat and Apennine margin uplift. Overall, this tectonic pile is the direct result of the Adria–Europe convergence that led to the Northern Apennines build-up (e.g. Molli 2008; Fig. 1).

The geology of the Marche region includes the external structures of the Northern Apennines involving the Umbria–Marche sequence (Fig. 1). This area is of particular interest because makes it possible to observe a portion of the chain that in the Emilia-Romagna region is buried under the Quaternary infill of the Po Plain. The Umbria–Marche Apennine thrust belt is characterised by an arcuate shape,

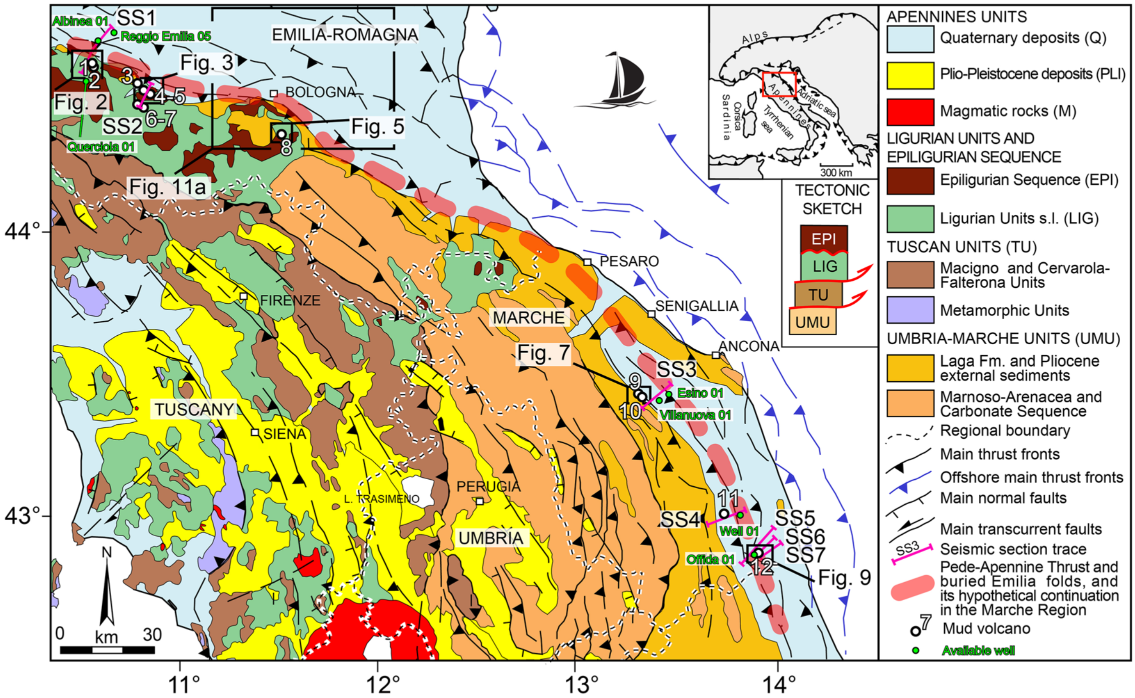

Fig. 1 Simplified geology of the Northern Apennines, showing the position of studied mud volcano systems. Seismic traces SS1 to SS7 are shown. 1: Casola-Querzola mud volcano system; 2: Regnano mud volcano; 3: Salsa di Fiorano mud volcano; 4: Montegibbio mud volcano system; 5: Nirano mud volcano system; 8: Dragone di Sassuno mud volacano; 9: Maiolati Spontini mud volcano system; 10; Bagno mud volcano system; 11: Monteleone di Fermo mud volcanoes; 12: Offida mud volcano system. Exact location of mud volcano and mud volcano systems is indicated in Table 1. *Q* quaternary deposits, *PLI* plio-pleistocene deposits, *M* magmatic rocks, *EPI* epiligurian sequence, *LIG* Ligurian units s.l., *TU* Tuscan units, *UMU* Umbria-Marche units

shows a main northeastern vergence, and has been variously interpreted as the result of thin-skinned and thick-skinned tectonics (Lacombe and Bellahsen 2016, and references therein). This belt involves a Mesozoic–Tertiary sedimentary succession (e.g. Calamita and Deiana 1987), topped by turbidite sediments (e.g. Marnoso Arenacea and Laga formations), marking the advancing foredeep position. A Miocene–Pliocene sequence of marine sediments unconformably overlie the thrust systems, nowadays mainly buried in the Marche foothills. Whereas the Emilia-Romagna Pede–Apennine margin displays a sharp and well-defined morphology, separating the Apennine chain from the buried external thrust arcs, the Marche Pede–Apennine margin consists of a broad and gently deformed area bounding the exhumed chain. Reverse focal mechanisms indicate the occurrence of a regional compressive stress field related to the costal and off-shore continuation of both the PAT and buried arcs beneath the Po Plain (e.g. Bally et al. 1986; Lavecchia et al. 2003; Vannoli et al. 2004, 2015). Extensional tectonics dominates the axial portion of the Apennine chain in the Marche and Abruzzo regions, as demonstrated by strong extensional seismic sequences that have struck this area in the recent past (e.g. the 1997 Colfiorito, the 2009 L'Aquila, and the 2016–2017 Central Italy seismic sequences; e.g. Miller et al. 2004; Chiarabba et al. 2009; Guerrieri et al. 2009; Terakawa et al. 2010; Chiaraluce et al. 2017; Pucci et al. 2017). Consequently, the internal sector of the Marche foothills represents the connection area between the internal extensional domain and the external sectors experiencing compression (e.g. DISS Working Group 2015).

Mud volcanoes basically localise along the Pede–Apennine margin of the Emilia-Romagna sector, while they are more widespread along the broad and gentle Marche Apennine foothills (Fig. 1). Both areas have in common the presence of the Argille Azzurre formation (FAA), a thick (mainly marine) mudstone sequence, in which—as for the Ligurian Units and Epiligurian Sequence—the mud volcanoes find favourable conditions for their development, due to the sealing characteristics of these lithologies that allow fluid overpressure build-up (e.g. Bonini 2007).

Methods: structural and morphological analysis

We have performed a structural analysis of mud volcanoes in order to determine their structural setting. A fieldwork structural survey was carried out with the aim to characterise the fracture arrays, which generally act as feeder system of the mud volcanoes (from now on referred to as “feeder dyke system” as in analogue magmatic volcanoes). The subsurface feeder dyke of mud volcanoes can be defined as a system of various faults and fractures, able to channel mud and fluids from a reservoir up to the surface, whose orientation can be estimated from morphological features of mud volcanoes (i.e. alignment of vents, elongation of mud volcanoes and mud calderas; Bonini 2012). In some cases, sub-orthogonal joint sets associated with fold anticlines (“ac” joints, Hancock 1985) have been inferred to represent the main structures exploited by the rising fluid–mud mix, although also joints parallel to the fold axis (“bc” joints, Hancock 1985) may play the same role (e.g. Bonini 2012). During the survey, we aimed to map the large structures and measure fracture orientation around the mud volcanoes. When available, we used the seismic profiles to illuminate the subsurface below the considered mud volcano system, and to correlate the superficial structural setting with the potential fluid reservoir and structures at depth. It is important to note that the scale of the available seismic sections allows one to image only the large-scale setting of subsurface structures potentially controlling mud volcanoes. Furthermore, we used aerial photos and satellite images to investigate the recent (historical) activity of target mud volcanoes. These were particularly useful to identify mud volcano features (e.g. emission points) no longer visible in the field.

Structural controls on fluid migration

To characterise the structural controls on mud volcanoes systems, and to investigate the relationships between tectonic structures and fluid migration, we interpreted 7 seismic lines (SS1–SS7) oriented sub-orthogonally to the main thrust structures, and located close to mud volcano systems in the Emilia-Romagna and Marche regions (Fig. 1). Some of these mud volcanoes have already been investigated from a structural point of view (e.g. the Nirano caldera; Bonini 2008, or the Monteleone di Fermo mud volcano system; Maestrelli et al. 2017b). Other mud volcano systems deserve further investigation and therefore have been surveyed in the field. Mud volcanoes systems are described from Northwest to Southeast.

Emilia-Romagna Pede–Apennine Margin mud volcanoes

Regnano and Casola-Querzola mud volcano systems

The Regnano and Casola-Querzola mud volcanoes occur southeast of Vezzano sul Crostolo village (Fig. 2, Table 1), about 15 km northwest of Nirano and Montegibbio mud volcano systems (Fig. 3). The interpretation of seismic profile SS1, crossing the Pede–Apennine margin, allows us to image that both the Casola-Querzola and Regnano mud volcanoes, when projected on the seismic section, are located above a main thrust-related anticline (Fig. 4a). This fold is related to a major SSW-dipping thrust, from which splays another thrust that possibly surfaces in correspondence of the Albinea village. The latter structure is interpreted as the Pede–Apennine thrust (PAT). The anticline beneath the Casola-Querzola and Regnano mud volcano systems is expected to host fluid reservoir(s) at its core. In particular, the methane and heavier hydrocarbons are expected to be sourced from the Miocene siliclastic deposits (basically the Marnoso Arenacea Fm; Tassi et al. 2012), which is sealed by the outcropping Ligurian Units. The deep well Querciola 1, settled ca. 3 km south-southwest from the Regnano mud volcano (Fig. 1), has drilled the backlimb of this fold for about 4 km without encountering the Marnoso Arenacea Formation.

Nirano and Montegibbio mud volcano systems

The Nirano mud volcano occurs within a caldera depression located south of Fiorano Modenese (Fig. 3, Table 1). Several emission points erupt a muddy mixture, building up four main gryphons inside a caldera depression elongated in a ca. ESE direction (Bonini 2008; Fig. 3a). Here, vent alignments have been inferred to exploit a system of joints associated with an outcropping anticline, and caldera elongation is inferred to reflect the local stress field, the long caldera axis being orthogonal to regional S_{Hmax} (Bonini 2008) (Fig. 3a).

The well-known Montegibbio mud volcano is located a few kilometres west of Nirano, while the Montebaranzone and Centora (also known as Bomba della Centora) mud volcanoes occur further to the south. The subsurface structural setting of these mud volcano systems has been investigated through seismic profile SS2 (Fig. 4b). The interpretation of this seismic line depicts a series of stacked thrusts juxtaposing the Ligurian Units and the Epiligurian Sequence onto the Argille Azzurre marine sediments (FAA). These sediments are deformed by thrust-related anticlines, and the mud volcanoes of the area show some connection with these structures. In particular, the Montegibbio and Nirano mud volcano systems occur approximately above the forelimb of the thrust-related anticline imaged in the seismic line SS2 (Fig. 4b). The thrust generating this anticline—likely the PAT—propagates upsection toward the NE (unfortunately, this thrust is not completely captured by the seismic section SS2). The outcropping anticline along which the Nirano mud volcano occurs (Fig. 3a, d) is probably a shallower thrust-related fold associated with the main buried anticlinal structure, which most likely hosts the subsurface

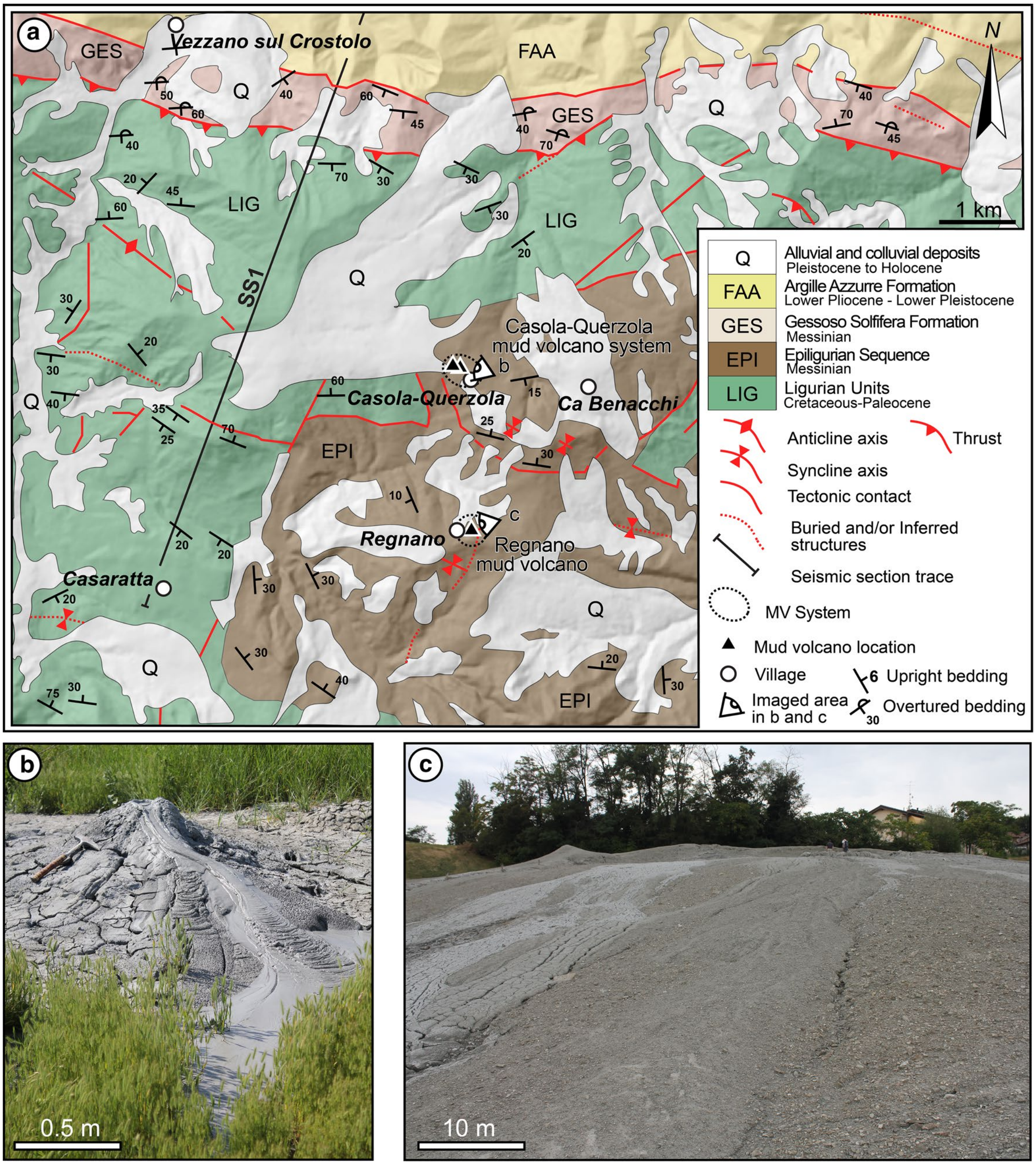

Fig. 2 **a** Simplified geology of the Regnano and Casola-Qurzola area (modified from sheet 2018, CARG Project; Papani et al. 2002). The two mud volcano systems are indicated, as well as the location of seismic line SS1. **b** View of one of the gryphons at Casola-Querzola, (photo taken on 24th May 2012 at 44°34’27.14″N, 10°34′0.18″E looking toward Northwest). **c** The Regnano mud volcano, south of Casola-Querzola (photo taken on August 2013 at the base of the mud volcano, looking toward East). Inset points of view are reported in (a)

reservoir(s) of fluids sourcing these mud volcanoes. The Montebaranzone and Centora mud volcanoes are located more to southwest along the margin. In this area the seismic reflection data are of poor quality and a clear structural interpretation is not possible. This is due to the presence of a thick sequence of Ligurian Units, which is frequently responsible for a considerable absorption of the seismic signal.

The Dragone di Sassuno mud volcano

The so-called “Dragone di Sassuno” is a small mud volcano classified as a gryphon (e.g. Kopf 2002), located in the Pede–Apennine Margin, 4 km west of Monterenzio (southwest of Bologna), and close to the rural Sassuno village (Fig. 5a, d, e, Table 1). This gryphon is known since historical times, and has been mostly studied from a geochemical

Table 1 Positioning of mud volcano (single emission point) and mud volcano systems (multiple emission points) investigated in this work

Mud volcano no.	Name	Lat (°)	Long (°)
1	Casola-Querzola	44°34′26.77″N	10°33′59.53″E
2	Regnano	44°33′28.95″N	44°33′28.95″N
3	Slasa di Fiorano	44°31′55.51″N	10°48′32.23″E
4	Montegibbio	44°31′7.47″N	10°46′45.63″E
5	Nirano	44°30′49.27″N	10°49′22.18″E
6	Montebaranzone	44°29′0.70″N	10°46′21.37″E
7	Centora	44°28′9.44″N	10°47′40.92″E
8	Dragone di Sassuno	44°20′9.51″N	11°27′16.24″E
9	Maiolati Spontini	43°28′23.28″N	13° 7′55.47″E
10	Bagno	43°27′19.53″N	13°10′37.83″E
11	S. Maria in Paganico	43°4′27.87″N	13°31′42.88″E
12	Contrada S. Lazzaro (Offida)	42°55′56.65″N	13°42′55.91″E

Mud volcano numbers refer to Fig. 1

point of view (e.g. Minissale et al. 2000; Capozzi and Picotti 2010; Tassi et al. 2012). Capozzi et al. (1994) documented the recent eruptive activity of this mud volcano, and Calindri (1781) described in extreme detail some large eruptions that occurred in July 1780 during a period characterised by the occurrence of large earthquakes (Table 2). We have investigated the Dragone di Sassuno mud volcano integrating the field analysis of its structural setting with interpretation of aerial photo time series to track its past activity (Fig. 6). In periods of high activity, the mud volcano is able to erupt large rock blocks up to considerable distance. Interestingly, Sassuno inhabitants report that during the 70s, a large eruption threw mud up to the Sassuno village (see Fig. 5e) that is placed on top of the hill, about 100 metres higher than the mud volcano. We could not verify this fact, but information about eruption energy of this mud volcano can be somehow gained by the considerably large dimensions of the erupted rock clasts preserved in old mud flows, which are sub-angular and often exceed 40 cm in length (Fig. 5f). On the basis of the analytical solution of Manga and Bonini (2012), one can argue that, to bring clasts $>$ 40 cm to the surface, ascent speeds should be greater than 3 ms^{-1}, thereby suggesting that past eruptions of the Dragone di Sassuno were very energetic.

The Dragone di Sassuno lies at the top of Ligurian Units and the Epiligurian Sequence (Fig. 5a). Particularly, the mud volcano is settled along the trace of a ca. N145E°-striking anticline axis, and near the tectonic contact between the Epiligurian Sequence (mainly composed of sandstones, marls and argillaceous breccias), and the varicolored shales and limestones belonging to the underlying Ligurian Units. We measured joints and faults in the Epiligurian unit outcrops, close to the Dragone di Sassuno mud volcano, as well as in the Monte Adone Formation (see Fig. 5a and stereoplots in Fig. 5b,c). Whereas the structural data collected in the Monte Adone Formation do not relate to the anticline trend, fractures from the Epiligurian outcrop are coherently organised with respect to the main anticline, with a system of joints oriented along-strike (set 'bc') and a system of joints orthogonal to the anticline axis (set 'ac'). In this regard, the analysis of historical activity of this mud volcano may provide some information about the presence of aligned vents, which can be used to reconstruct the possible orientation of the subsurface feeder dyke (e.g. Bonini 2012). Using aerial photos, we identified periods of activity or inactivity of the mud volcano during the last decades, even though the aerial photo dataset is scattered and therefore a continuous investigation was not possible. Nevertheless, the photos clearly image periods of high activity, such as for 1954, 1956, 1981 (Fig. 6a–c), 1989, and 1993 (Fig. 6e, f), and 2003 (Fig. 6); in contrast, in recent years (Fig. 6i–k), the activity was of modest intensity, as shown by the small amount of erupted mud.

At the time of the survey (May 2017), only a single mud cone was visible in the field, showing two minor emission points at the cone apex, roughly aligned along a N40°E direction. The analysis of aerial photos from 1954 to 1981 (Fig. 6a–c) allows the recognition of two distinct vents. Interestingly, the location of vents varies through time, as shown by emission points collectively plotted on Fig. 6l. On this basis, we interpret such vents as being located on two different fractures, along which they can migrate. More specifically, although the current distribution of vents suggests a N40°E alignment, sub-orthogonal to the anticline axis ('ac' set), we cannot exclude the possibility that another feeder dyke is aligned along with the average direction of "bc" joints (N145°E). In other words, both 'ac' and 'bc' trends represent potential feeder dyke systems that may be exploited by fluids.

Mud volcanoes of Marche foothills

Paolo di Jesi and Maiolati Spontini mud volcano systems

Bonasera (1952) reported a series of mud volcanoes at Maiolati Spontini and S. Paolo di Jesi, along the Marche foothills (Fig. 7, Table 1), and described their morphology and activity. Geological maps (Guerrera et al. 2014) report two anticline structures near the Maiolati Spontini and S. Paolo di Jesi mud volcano systems, which possibly occur over the forelimb and the backlimb of such anticlines, respectively (Fig. 7a, b). At Maiolati Spontini, many mud volcanoes were not visible anymore in the field due to cultivation and anthropic influence; only one, here called Maiolati, is still preserved and active. This mud volcano, formally a mud pool (e.g. Kopf 2002), is

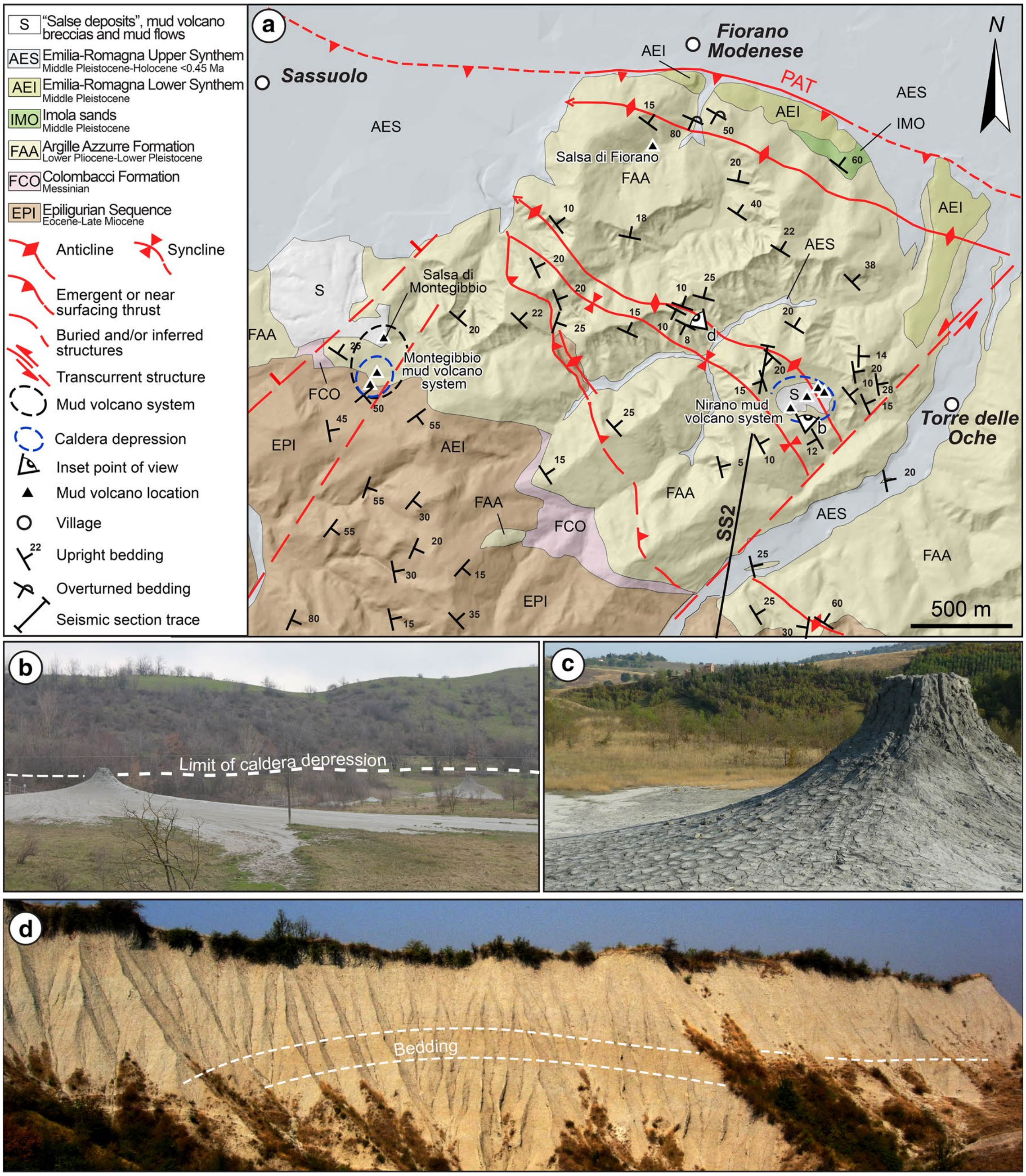

Fig. 3 **a** Geological map of the Nirano–Montegibbio area, showing the location of the two mud volcano systems (Geology is modified from sheet 219, CARG Project; Gasperi et al. 2005). Structures are modified from Bonini (2012). **b** View of the Nirano caldera depression, hosting four main mud cone edifices and several gryphons. **c** Example of a mud cone from the Nirano mud volcano system. **d** Closure of the gentle anticline whose axis is passing through the Nirano mud volcano field; photograph taken at 44°31′9.42″N, 10°48′42.01″E, looking Northwest (see point of view in **a**)

composed of a series of emission points gently erupting water and mud (Fig. 7c). The pool dimension is about 15 × 5 m, and the major axis corresponds to a vent alignment oriented ca. N150°E. Interestingly, this orientation roughly corresponds to the trend of the anticline axis, referred hereinafter to as San Paolo anticline, which strikes around N140°E. Mud pool elongation and vent alignment might possibly correspond to "bc" joints related to the anticline structure.

A similar case is represented by the San Paolo di Jesi mud volcano system. We have surveyed the area, collecting information about the mud volcano activity by local inhabitants. Particularly, we focused on the Bagno locality (a small village close to San Paolo di Jesi), where Bonasera

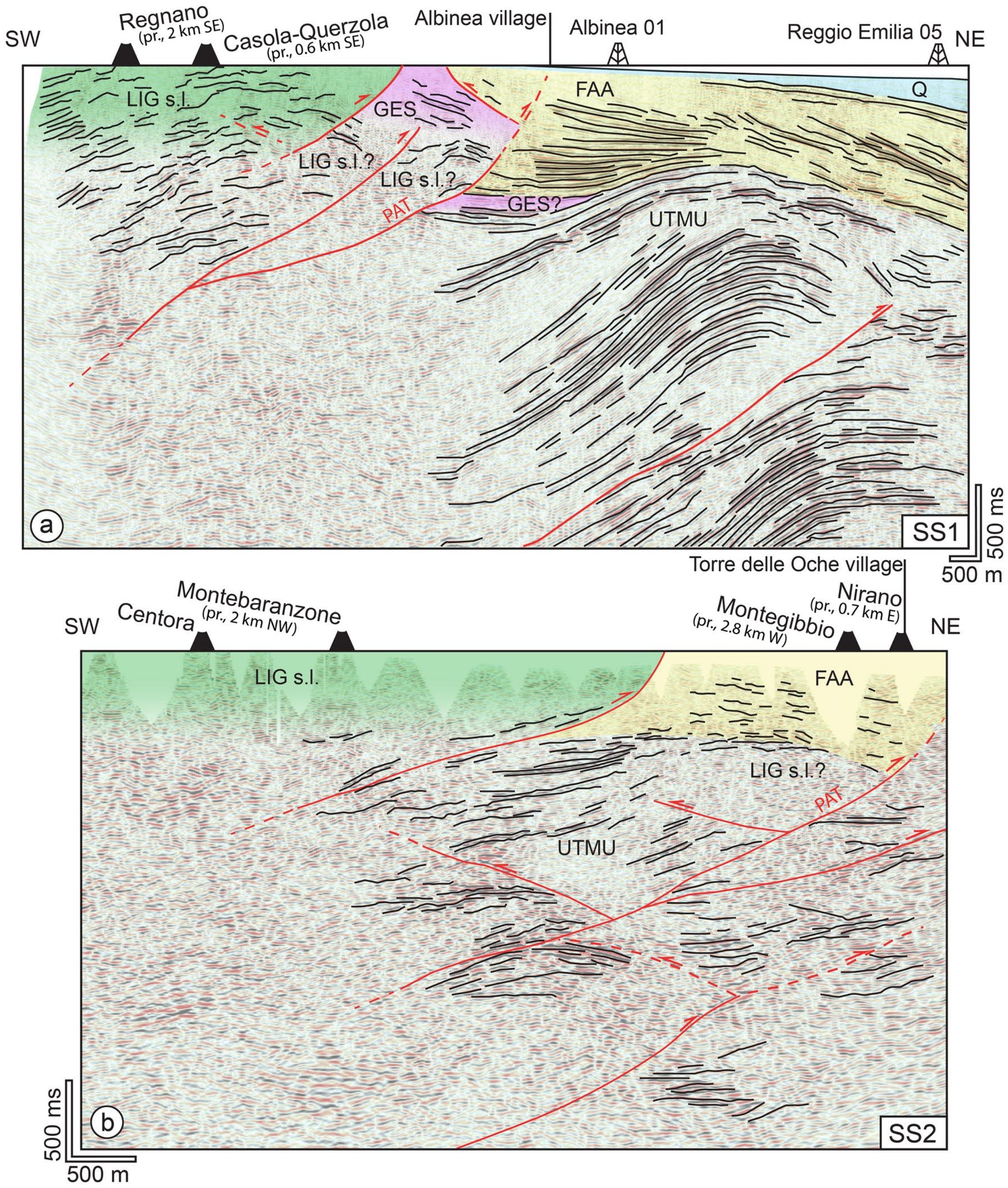

Fig. 4 Seismic lines **a** SS1 and **b** SS2 (trace reported in Figs. 1, 2, 3). **a** The interpreted seismic section SS1 depicts the structural setting beneath the Pede–Apennine margin and the associated mud volcano systems; the more external splay thrust is the PAT and is likely emergent near the Albinea village. The Regnano and Casola Querzola mud volcano systems are associated with the ramp anticline probably acting as fluid structural trap. **b** The interpreted seismic section SS2 depicts thrust-related anticlines beneath the Pede–Apennine margin. The Montegibbio and Nirano mud volcano systems are approximately located above the forelimb of the major ramp anticline, while the Centora and Baranzone mud volcano systems cannot be characterised due to the very poor definition of the seismic signal. *Q* quaternary deposits, *FAA* Argille Azzurre Formation, *LIG s.l.* Ligurian units s.l. (including Ligurian Units s.s. and Epiligurian Sequence), *UTMU* undifferentiated Tertiary and Mesozoic units, *PAT* Pede–Apennine Thrust

(1952) described a particularly active mud volcano. Serpieri (1888) reported that this mud volcano experienced a small eruption in 1873 after the M_w 5.85 San Ginesio earthquake (Marche region), which struck on 12th March 1873 (Table 2; see also the CPTI15 database for earthquake details; Rovida et al. 2016). The Bagno mud volcano position is nowadays

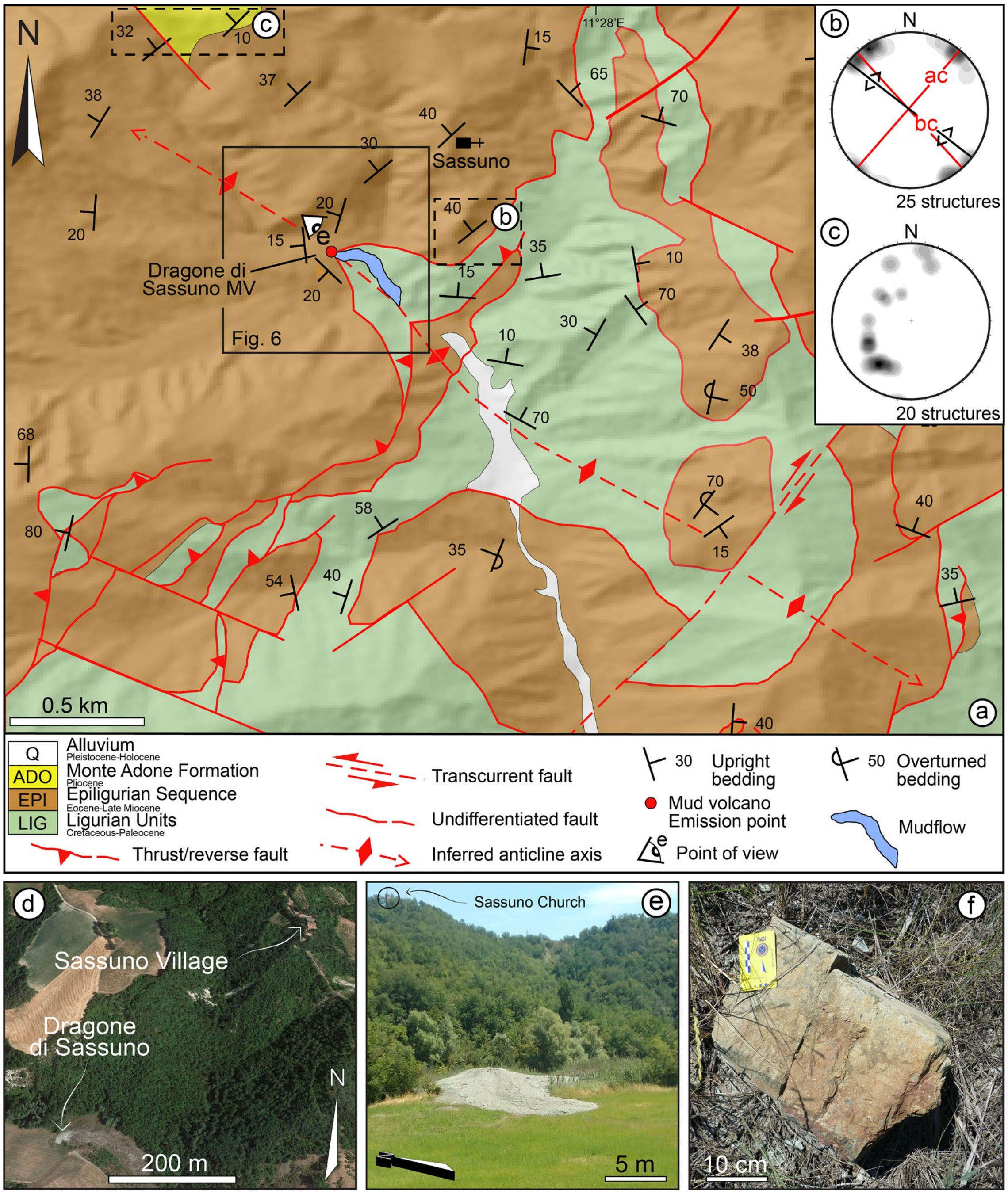

Fig. 5 **a** Geological map of the Sassuno area. The mud volcano is settled along the axis of an inferred anticline and near the tectonic contact between Ligurian Units and Epiligurian Sequence. **b**, **c** Stereoplot showing distribution of poles of joints. **d**, **e** The Dragone di Sassuno mud volcano and the Sassuno village. The bell tower of the Sassuno Church is visible in the background behind the trees in **e**. Sassuno inhabitants report that a strong eruption in the 70s was able to throw mud up to the village and to the Church. **f** A large clast erupted by the Dragone di Sassuno mud volcano

marked only by vegetation, growing stronger at the emission point. During the survey, a farmer (who indicated the position of the mud volcano, Table 1) reported that it has been largely active during the past decades, and it may occasionally build up a well-structured mud cone. He also reported that after usual tillage work the mud volcano was able to re-build up the mud cone in a few days. At the time of the survey (August 2015) it was completely inactive, except for the water flow. Furthermore, the inhabitants indicate that the mud volcano has changed the position through years.

This justifies the different (yet approximate) position of mud volcanoes reported by Bonasera (1952). We cannot

Table 2 Coordinates of macroseismic epicentre, magnitude and epicentral distance (from the specified mud volcano) for selected seismic events discussed in the text

Mud volcano	Earthquake date	Epicentre locality	Lat. (°)	Long. (°)	M_w	Epicentral distance (km)
Dragone di Sassuno	06/02/1780	Longara	44.567	11.310	5.06	27.95
	23/11/1779	Osteria Grande	44.424	11.529	4.7	11.35
	20/08/1779	Villa Bianca	44.459	11.390	4.16	14.6
	04/06/1779	Ozzano nell'Emilia	44.443	11.479	5.22	12.01
Bagno (S.Paolo di Jesi)	12/03/1873	San Ginesio	43.089	13.244	5.85	40.9
Contrada S. Lazzaro (Offida)	03/10/1943	Offida	42.940	13.626	5.67	4.1
S. Maria in Paganico (Monteleone di fermo)	06/04/2009	Aquilano	42.320	13.449	6.1	71.5

These earthquakes might have played a role in the triggering of mud volcano eruptions

exclude that this discrepancy is due to errors in the positioning of a mud volcano from the Bonasera's (1952) map, but it is interesting to note that a ground fracture dissecting the hill slope is the locus of a large and diffuse water flux. This fracture is oriented N55°–60°E, and apparently connects the Bagno mud volcano position reported in Bonasera (1952) with the current mud volcano location. We speculate that the mud volcano may change its position along this fracture set. Interestingly, the fracture trend roughly corresponds to the orientation of a hypothetical "ac" joint system associated with the NW–SE trending San Paolo anticline (Fig. 7a, b). The analysis of seismic reflection profile SS3, running near S. Paolo di Jesi, allows us to image a thrust system buried below the Pliocene marine succession and located few kilometres forward from the outcropping anticline (Fig. 8a). On this basis, we interpret the Bagno mud volcano system as settled at the top of a minor back-thrust associated with the major thrust-related anticline corresponding to the exposed San Paolo anticline. Therefore, the Bagno mud volcano system is apparently connected to a secondary structure of the outcropping San Paolo anticline (Fig. 8a). The Maiolati Spontini mud volcano is located at a greater distance from the San Paolo anticline axis, and its position is likely still controlled by the buried backthrust associated with the main ramp anticline (Fig. 8a).

Monteleone di Fermo mud volcano system

The Monteleone di Fermo mud volcanoes (Fig. 1, Table 1) are located on a NE-dipping monocline of Miocene–Pliocene deposits which cover a series of thrust faults and thrust-related folds. Structural analysis of the mud volcano systems was carried out to implement numerical modelling that was performed to evaluate the role of static and dynamic stress on the coseismic triggering of mud volcanoes during the 2016–2017 Central Italy seismic sequence (Maestrelli et al. 2017b). Among the results of this investigations, the structural survey and the interpretation of available seismic lines (seismic section SS4 is reported in Fig. 8b, cf. Figure 4 in Maestrelli et al. 2017b) revealed that the mud volcanoes lie above buried ramp anticlines, which likely act as reservoirs for the fluids sourcing the mud volcano features (gryphons and mud pools). The feeder dyke system controlling the uprising of fluids shows an average trend of N355°E ± 5°. This orientation has been inferred from vent alignments, elongated extrusive mud cones and fractures (Maestrelli et al. 2017b). The mud volcanoes have been surveyed in 2015, and presented a fracture trend oriented similarly to what observed after the 2016–2017 seismic sequence. Therefore, this orientation can be considered as constant.

The Contrada S. Lazzaro (Offida) mud volcano

A number of small mud volcanoes occur around Offida, in southern Marche. Among them, the most interesting is the Contrada S. Lazzaro mud volcano (Fig. 9, Table 1), which is not visible in the field anymore, but it is reported to have erupted violently in 1959 (Fig. 9b, c). In particular, Damiani (1964) describes the effects of the 15th December 1959 eruption, reporting (as witnessed by local inhabitants) that this mud volcano had been inactive for a long time, except the small eruptions of 1956 or 1957 that preceded the large one. Damiani (1964) describes the strong paroxysmal eruption of the December 1959 with a detailed morphological and geological study, furnishing interesting details that are useful for our investigation (Fig. 9b).

During our August 2015 survey, we found the area where the mud volcano is supposed to lie completely covered by vegetation. Therefore, the description provided by Damiani (1964) is particularly useful to reconstruct the mud volcano setting. The author reports three original emission points, one of which (labelled "C" in Fig. 9b) was responsible for the major mud extrusion that flowed down slope toward the

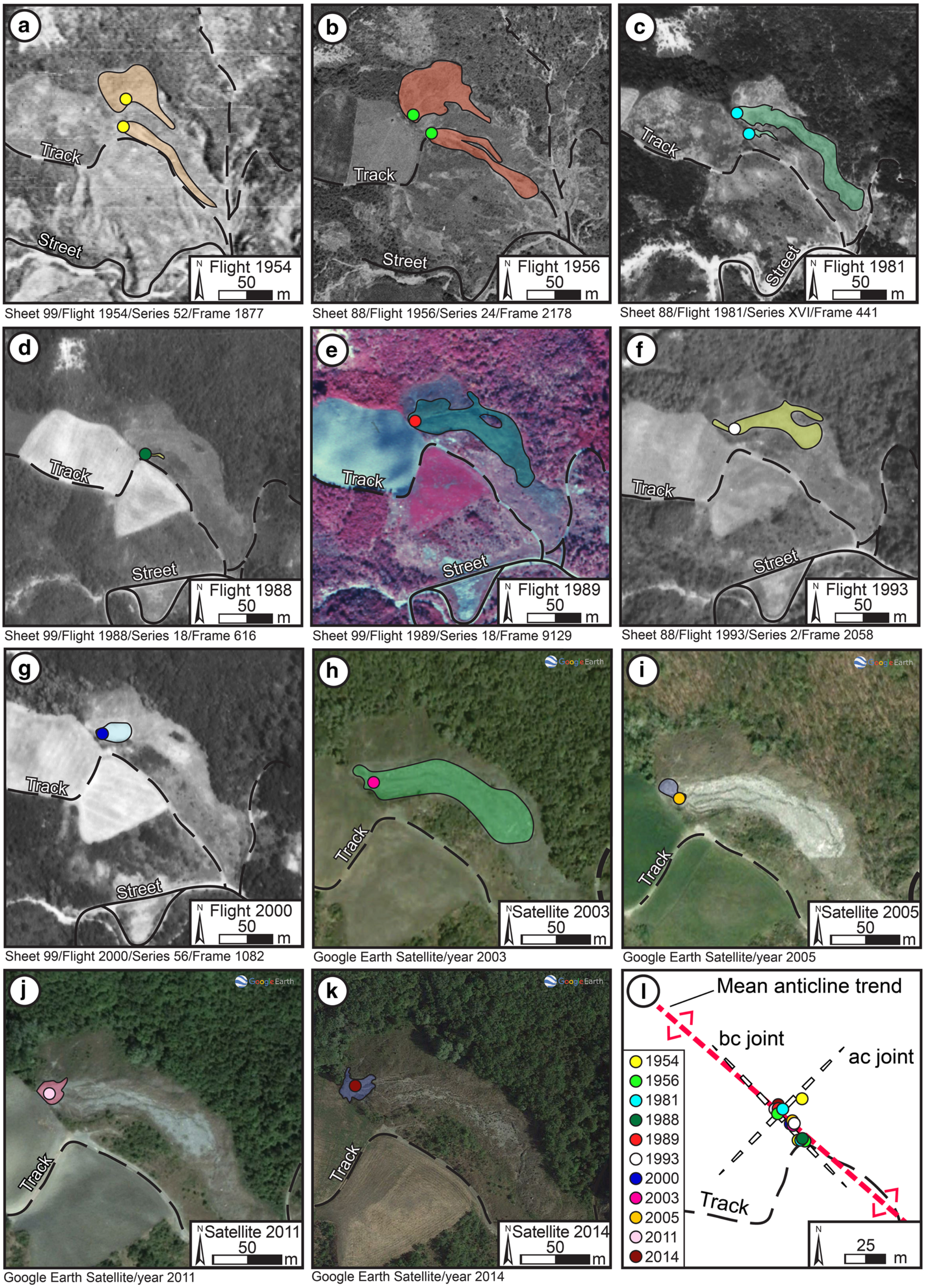

Fig. 6 **a**–**g** Interpretation of IGM aerial photos acquired in years 1954, 1956, 1981, 1988, 1989, 1993, and 2000 in the Sassuno area. Notable is the presence of multiple emission points (**a**–**c**), which are not visible in more recent photos, nor currently in the field. **h**–**k** Interpretation of satellite images (from Google Earth©) acquired in years 2003, 2005, 2011, and 2014. **l** Schematic sketch showing the position of emission points through years as interpreted from **a** to **k**, and the inferred fracture pattern. Geometry of the feeder dyke system (joints "ac" and "bc") derives from the joint data plotted in Fig. 5b, as well as the mean trend of the anticline axis

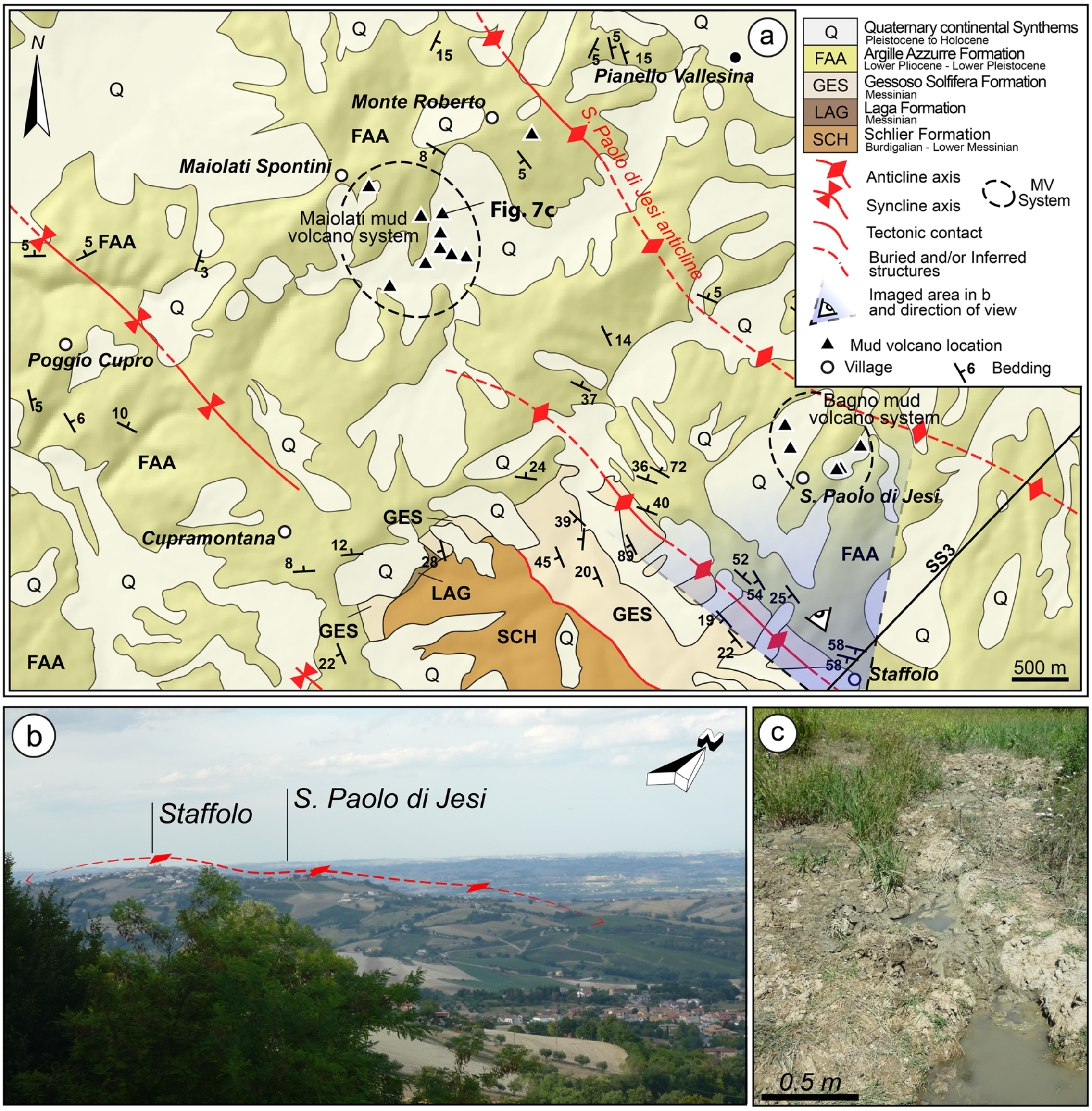

Fig. 7 **a** Simplified sketch map illustrating the geology in the S. Paolo di Jesi and Maiolati Spontini area. At this location, two mud volcano systems are identified as associated with anticline structures (geology is modified from Sheet 292, CARG Project; Guerrera et al. 2014). **b** View of the Staffolo anticline looking North-Northwest. **c** The Bagno mud volcano

so-called "Fosso del Lago", a small creek at the hill base. The alignment of these three vents, as measured from the morphological survey of Damiani (1964) indicates a N100°E trending direction, an orientation similar to the average trend of fractures located close to the emission point "C". These fractures (marked by the author with numbers 5 and 6, see Fig. 9b) seem unrelated to slope collapse, as instead may be the case of other mapped discontinuities (e.g. fractures sets n. 2, reported in Fig. 9b). Of the three emission points, only "C" can be tentatively associated with an area of current water ponding, but with no evidence of mud extrusion. Emission points "A" and "B" as well as ground fractures are completely obliterated by vegetation and anthropic effects. Interpretation of aerial photos, covering a time span (yet scattered) of almost 70 years, does not show any other evidence of activity, but were useful to locate exactly the structural features of the mud volcano described by Damiani (1964).

A correlation of the mud volcano with subsurface structures is attempted using a set of seismic sections crossing the area. In particular, seismic sections SS5, SS6 and SS7(Fig. 8c–e) have allowed us to trace an anticline axis striking N345°E and passing only ca. 500 m west of the Contrada S. Lazzaro mud volcano (Fig. 9a). This structure has been already imaged on other seismic profiles (e.g. Bally et al. 1986). The Contrada S. Lazzaro mud volcano may be,

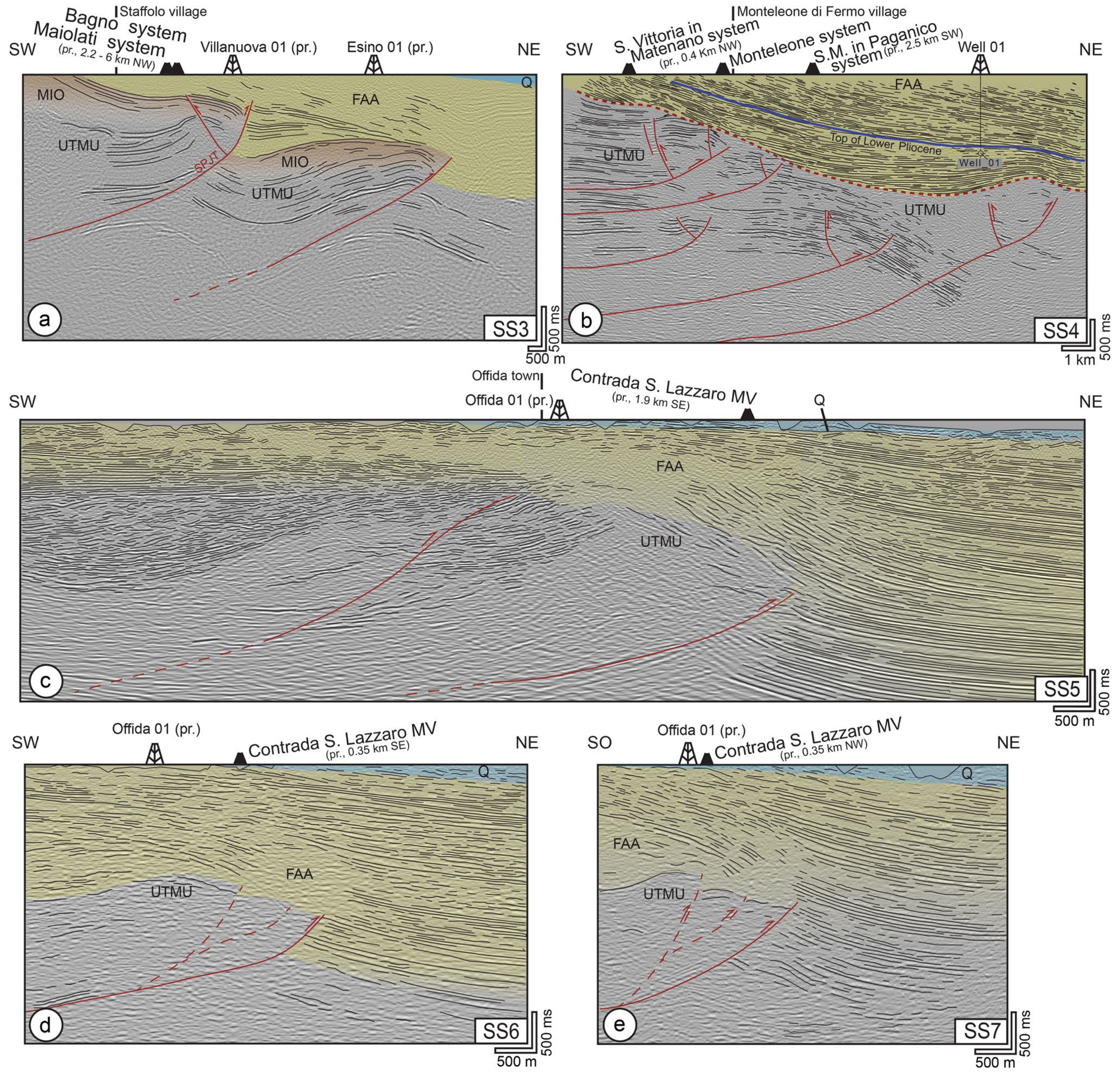

Fig. 8 **a** Seismic line SS3, running close to the S. Paolo di Jesi Village. **b** Seismic line SS4, crossing the Apennine foothills close to Monteloene di Fermo (modified after Maestrelli et al. 2017b). The mud volcanoes basically coincide with thrust-related folds at depth. **c**–**e** Seismic sections SS4, SS5 and SS6 crossing the Offida area. Thrust-related fold anticlines are interpreted in the seismic profiles. The Contrada S. Lazzaro mud volcano is projected on the seismic line along strike of the trend of structures, and lies above the interpreted anticline crest. *Q* quaternary deposits, *PLI* pliocene sediments, *MIO* miocene deposits, *UTMU* undifferentiated Tertiary and Mesozoic units, *SPJT* S. Paolo di Jesi Thrust

therefore, associated with such a buried anticline. Nevertheless, no evidence of the mentioned structure is visible at surface, the outcropping structural setting being a gently NE-dipping monocline. We, therefore, exclude the idea of a main shallow reservoir and we infer the presence of a subsurface reservoir associated with the interpreted thrust-related anticline structures. This hypothesis is in agreement with the attribution of the erupted mud to geological units deeper than the Pliocene sediments, an attribution based on the foraminifera contained in the extruded mud. In addition, Damiani (1964) suggests that the fluids may migrate from a hydrocarbon reservoir settled within turbidite deposits (possibly the Laga Formation), a location suggested by the presence of saline (mainly NaCl) minerals, which are likely

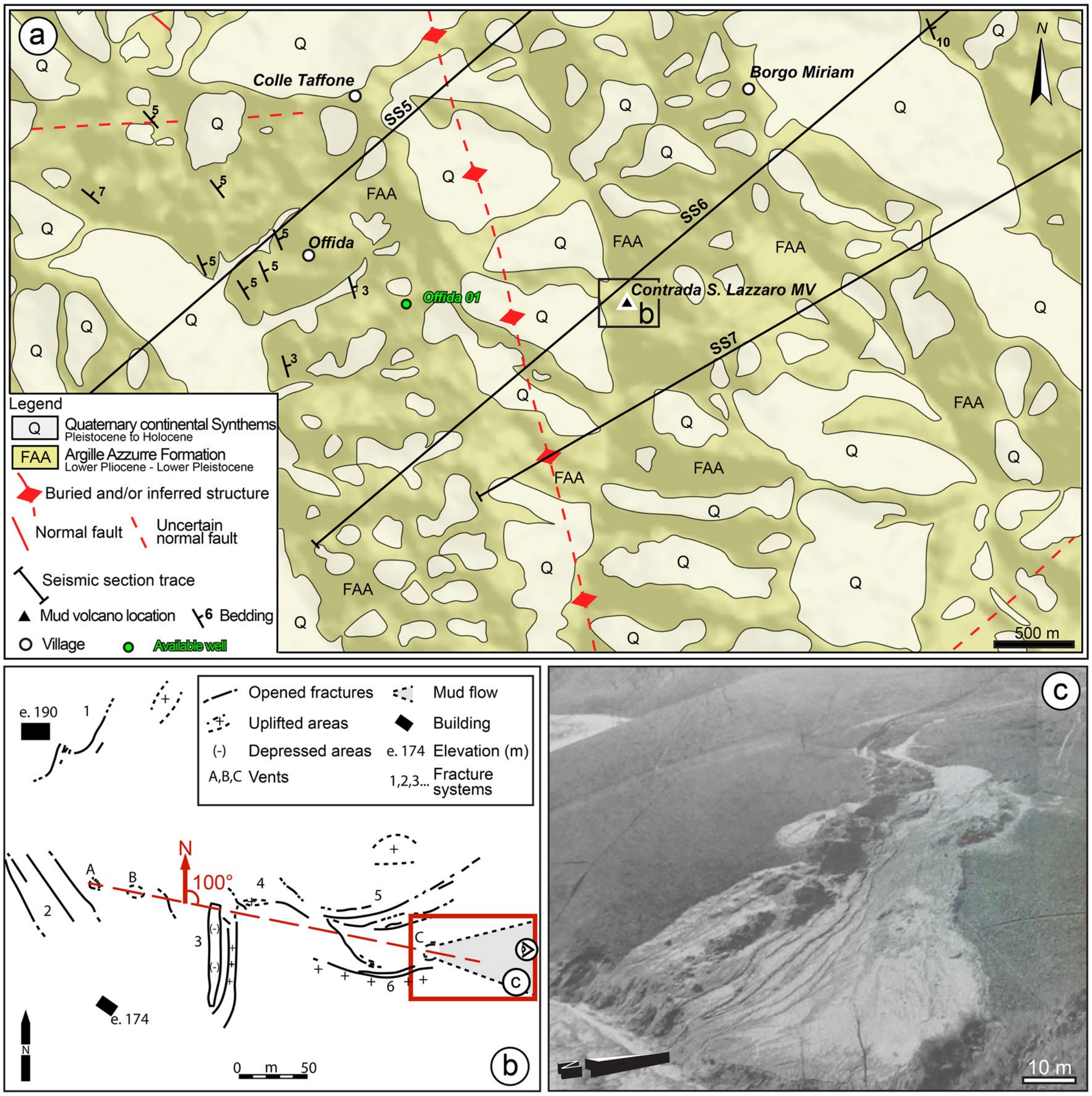

Fig. 9 **a** Simplified geological map of the Offida area (geology and structures are modified from the 1:10,000 CARG maps, available at http://www.ambiente.marche.it/Territorio/Cartografiaeinformazioniterritoriali/Archiviocartograficoeinformazioniterritoriali/Cartografie/CARTAGEOLOGICAREGIONALE110000.aspx). The Contrada S. Lazzaro mud volcano, close to the Offida village, is likely related to the inferred buried anticline interpreted from the available seismic section (see Fig. 8c–e). **b** Topographic survey from Damiani (1964); redrawn and modified): the author reports the fracture array and the emission points (A, B, C). Emission points are aligned along a N100°E trend. The same average trend is visible in the fracture array. We do not consider the slope-parallel fractures which are probably the result of the slope collapse due to subsidence after mud emission and reservoir depletion (e.g. similarly to calderas collapse). **c** Panorama of the 1959 Contrada San Lazzaro mud volcano eruption (from Damiani 1964)

mostly originated from Messinian evaporitic sediments or from connate waters of the Laga Formation.

Based on the interpretation literature data (e.g. Damiani 1964) and seismic profiles, we interpret the Contrada S. Lazzaro mud volcano as associated with a buried, ca. N345°E-trending thrust anticline hosting a ca. 1–2-km-deep fluid reservoir. It is worth noting here that this anticline presumably corresponds to the compressive structure that is hinted to have generated the $M_w \approx 5.7$ earthquake of 3rd October 1943 (DISS Working Group 2015). The N100°E oriented vent alignment trends at high angle to the anticline axis and may represent the feeder dyke system of mud volcano.

Discussing the role of near- and far structures

Inferences on fluid migration patterns sourcing mud volcanoes

Seismic lines interpretation, together with structural field data, allowed us to support the existence of a close relationship between the investigated mud volcanoes and anticline structures. We have shown that the geometry and orientation of the feeder dyke systems can be inferred from mud volcano features (i.e. alignment of vents). The fracture systems are generally connected to the anticline structures, and may channel fluids from a deep reservoir up to the surface. In all the investigated cases, the mud volcanoes are located at the top of an anticline, suggesting that reservoirs located into the anticline core are the most probable candidates for the source of fluids. Therefore, the results from the analysis of the key areas collectively indicate that the buried thrust system of the Pede–Apennine margin invariably influences the distribution of mud volcanoes. Also fossil thrust-related anticlines may play a similar role, such as those in the axial zone of the Northern Apennines that are found to act as efficient reservoirs of CO_2-rich fluids (Bicocchi et al. 2013).

Despite this first-order correlation between mud volcano location and ramp anticlines, mud volcanoes can be sited in correspondence of the forelimb (e.g. the Monteggibbio and Nirano mud volcanoes), the backlimb (e.g. the Regnano mud volcano), or the hinge (e.g. the Contrada S. Lazzaro mud volcano) of anticlines. Therefore, one may raise the question of how can fluid migration paths be explained according to this variability. Furthermore, Emilia-Romagna and Marche mud volcanoes differ in that the former are located on top of nearly emergent or outcropping anticlines, and the latter on top of buried compressive structures, which, however, do not generally fold the shallowest deposits (mostly the Argille Azzure mudstones). On the other hand, if mud volcanoes are expected to exploit systematic fractures related to folding (as happens for emergent anticlines), how do they interact with the overlaying, undeformed sediments? In other terms, how mud volcanoes lying on top of an unfolded package of sediments are structurally connected with their deep reservoirs?

According to some literature (Kopf 2002; Martinelli and Judd 2004; Etiope et al. 2007; Evans et al. 2007, 2008; Bonini 2008) the main mud volcano reservoir is generally located on top of anticlines, which have a sealing unit able to trap fluids. This is in agreement with the setting of mud volcanoes examined in this study. Nonetheless, a seal bypass system (e.g. Cartwright et al. 2007) is required to transport fluids up to surface, and in our view it is at least partly represented by the systematic fracture array developed during folding (i.e. 'ac' and 'bc' fractures). These fractures are orthogonal and parallel to the anticline axis, but in cross section 'ac' joints develop radially from the anticline core and perpendicular to the anticline surface. In case of an outcropping anticline, this might explain why mud volcanoes can emerge exactly on top of the anticline crest (following fractures located along the anticline hinge), or be located in the forelimb and/or backlimb of the fold. Furthermore, secondary structures associated with the main thrust anticline may interact with the fracture array, deviating the fluid migration pathways (e.g. the back-thrust imaged in seismic section SS3, observed below the Bagno and Maiolati mud volcano systems; Fig. 8a). In this hypothesis, the local state of sealing/opening of faults and fractures plays a primary role in controlling which path the fluids can exploit in their upward migration. This end member model is summarised in Fig. 10a, and well applies to many mud volcano systems of the Emilia-Romagna Pede–Apennine margin. Nevertheless, it does not satisfactorily fit with the setting of the Marche foothills, where the mud volcanoes are located above an almost undeformed monocline of Pliocene Argille Azzurre mudstones that overlie deeply buried anticline structures. A link between surface and the deep reservoir must exist, but joints related to folding are not expected to develop in the Pliocene overburden, and therefore cannot explain the migration of fluid through these sediments. A clear example of this situation is the Contrada S.Lazzaro (Offida) mud volcano that is related to a N345°E trending buried anticline, and displays an inferred feeder dyke system oriented approximately N100°E. The degree of permeability (primary and secondary, but independent from the folding phase that formed the anticline fluid traps) is essential to understand the modalities through which these fluids can migrate. On this basis, it is proposed that once the fluid has migrated from a main reservoir through joints in the anticline, they reach sealing layers that may act again as shallower fluid traps (see Fig. 10b). At this stage, fluids may stop their ascent or find secondary fractures or faults to continue their upward migration. A further possibility is that these sealing horizons may act as fluid barrier increasing overpressure, which in turn may favour hydrofracturing of the overburden (e.g. Bons and van Milligen 2001). This condition is realised when fluid overpressure exceeds the least principal horizontal stress and tensile strength of the sediments (Stewart and Davies 2006; Karstens and Berndt 2015). In a compressive stress fields, the horizontal σ_1 does not allow the formation of vertical hydrofractures that would instead form subhorizontal, even though stress reorientation processes may permit vertical fracturing (e.g. Bonini

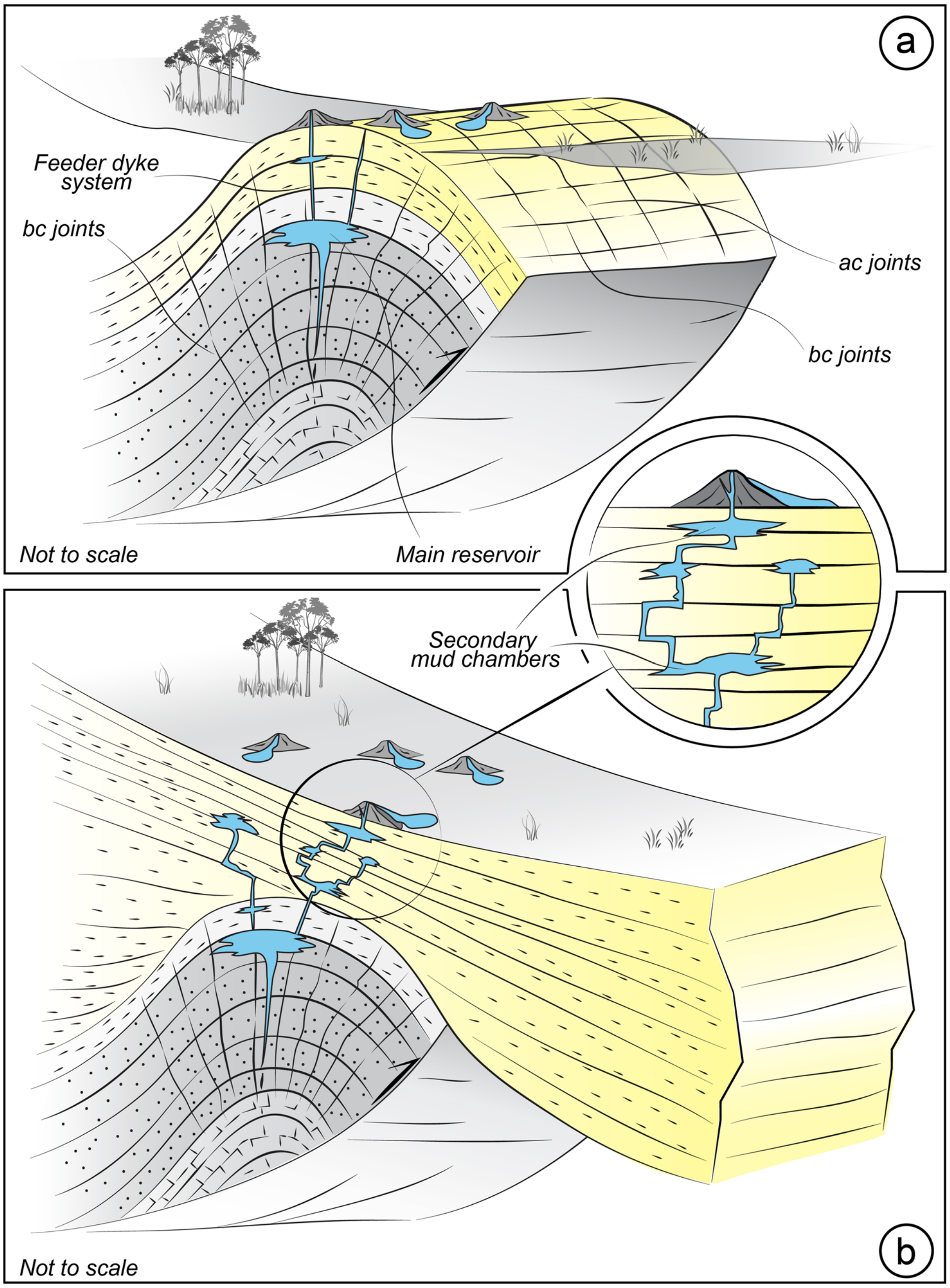

Fig. 10 Cartoon illustrating two possible end-members of fluid migration above outcropping and buried anticlines, respectively. **a** Sketch showing the fluid exploitation of systematic joints ("ac" and "bc" sets) for their upward migration and creation of mud volcanoes at surface in case of outcropping anticlines. Depending of the state of fracture (i.e. opening/sealing), fluids can migrate straight upward or may choose another radial systematic fracture(s). **b** Sketch showing the fluid migration above a buried anticline sealed by unfolded sediments. Once fluids reach the overlaying sedimentary cover, they are forced to crack the rock by hydrofracturing (if overpressure is large enough) or to exploit previously formed fractures (unrelated to anticline growth) or primary porosity

2012). Pliocene sediments draping the buried Marche foothills anticlines were likely not affected by significant compression, and vertical hydrofractures transporting the deep-sourced fluids upward would have formed under an extensional stress field. Nonetheless, hydrofracturing may not be the primary mechanism transporting fluids from the buried anticlines of the Marche foothills up to the surface due to the high overpressures necessary to break up such a thick stratigraphic sequence. It is, therefore, more likely that fluids exploit porosity and previously formed joints and fault networks, rather than creating their own fluid escape conduits. For this reason, fluid pathways above the buried anticline might not be strictly positioned over the anticline crest due to non-uniform migration of fluids in the overburden, as sketched in the close-up of Fig. 10b.

Inferences on mud volcano eruptions versus near- and far-structures activity

We have shown that tectonic structures may play an important role on the upward migration of fluids sourcing the considered mud volcano systems. This link is direct, in that the structures may actively act as fluid reservoirs (e.g. ramp anticlines) and eventually facilitate the upward fluid migration through anticline-related fracture systems. These prospected cases are evidently relative to structures located in the near-field of mud volcano systems. Nevertheless, this is not the unique link between structures and mud volcanism, as also far structures may influence mud volcano systems. Specifically, stresses released from rupture of seismogenic faults may promote the triggering of mud volcanoes into eruptions. Triggering may be immediate (few hours to few days after the earthquake) or delayed (from a few weeks up to several months) (Bonini et al. 2016). The latter mode is possibly the case of some of the investigated mud volcanoes, which erupted a few months after potentially triggering earthquakes. As an example, we speculate a role of stress changes in the long-term response of some mud volcano eruptions, such as for the S. Maria in Paganico mud volcano that erupted 2 months after the L'Aquila earthquake of 6th April 2009 (Table 2). In other cases, seismic triggering, although delayed, may have also been influenced by dynamic stresses induced by earthquakes, such as for the eruptions of the Bagno (S. Paolo di Jesi) mud volcano that erupted in 1873 after the S. Ginesio earthquake (Table 2) as well as the eruptions of July 1780 of the Dragone di Sassuno mud volcano reported by Calindri (1781). With regard to the Dragone di Sassuno, we identify four significant seismic events that hit the region (within a radius of 30 km from the mud volcano) about one year to few months before the 1780 eruptions (Catalogo parametrico dei terremoti Italiani, CPTI15, Rovida et al. 2016, Table 2, Fig. 11a). At a larger distance, no relevant seismic events are reported in the catalogue, apart from an M_w 4.4 earthquake that occurred on 25th May 1780 at an epicentral distance of 80 km. The magnitude, compared to the distance, is too small to have produced effects on the considered mud volcano.

Three of the four mentioned seismic events have an epicentre located near the Pede–Appenine thrust (PAT) (DISS Working Group 2015), which seemingly represents the causative seismogenic structure (Fig. 11a; Table 2). The other event (the M_w 5.22 occurred on 4th June 1779) is located further to the Nord, and it is possibly associated with a more external buried thrust of the Romagna folds (Fig. 11a; Table 2). The eruptions, thus, appear as long-term responses to the earthquakes that preceded the eruptions of July 1780. These paroxysmal events may have been influenced by dynamic stresses related to the instantaneous (and transient) passage of the seismic waves (e.g. Mellors et al. 2007). The role of dynamic stress changes

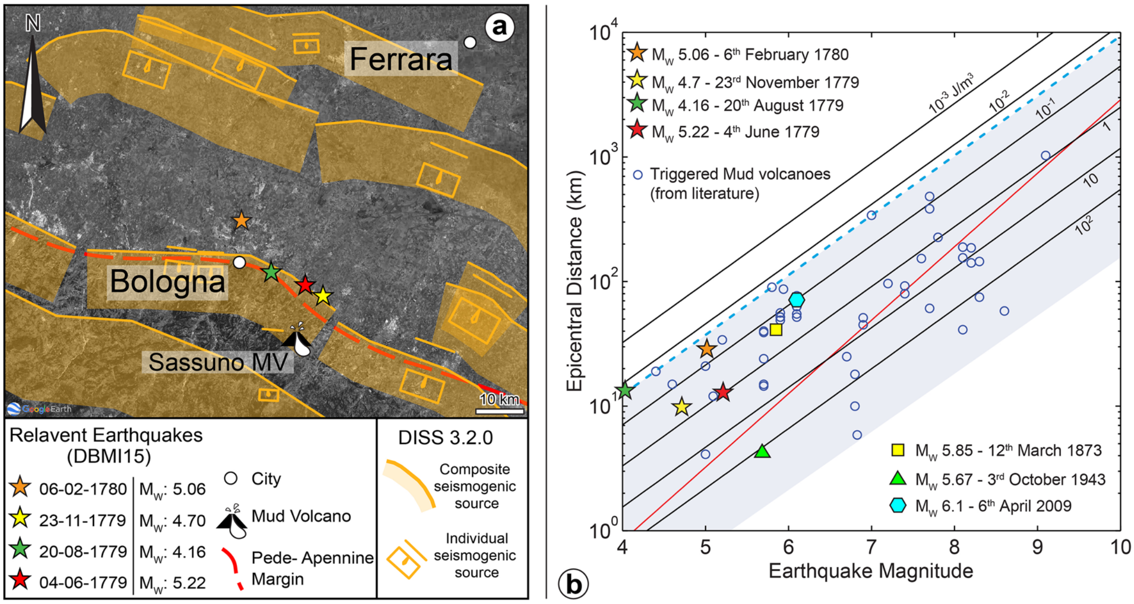

Fig. 11 **a** Location of the Dragone di Sassuno mud volcano, and epicentres of historical earthquakes (with M > 4) within a radius of 30 km from the mud volcano (DBMI15, Rovida et al. 2016, available at https://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm). Composite and individual seismogenic sources from the DISS catalogue are also reported (http://diss.rm.ingv.it/diss/). Satellite image is extracted from Google Earth©. Coloured stars indicate the epicentre location of the mentioned seismic events. **b** Earthquake magnitude versus epicentral distance graph for documented seismically triggered mud volcanoes (modified from Maestrelli et al. 2017b); data are plotted from literature (see Appendix in Maestrelli et al. 2017b, and reference therein). Coloured symbols indicate the epicentral distance versus earthquake magnitude for the various mud volcanoes cited in this study, namely: Dragone di Sassuno (stars), Bagno (square), S. Maria in Paganico (hexagon) and Contrada S. Lazzaro (triangle). Epicentre location, magnitude and epicentral distance from the respective mud volcanoes are reported in Table 2. Black lines indicate constant seismic energy density (Wang and Manga 2010). The blue dashed line represents the threshold energy for the most sensitive mud volcano eruptions, while the solid red line is one fault length (applying the empirical relation of Wells and Coppersmith 1994)

on these eruptions can be evaluated through empirical relationships linking earthquake magnitude and epicentral distance. Following Wang and Manga (2010), we have plotted the epicentral distance of each seismic event from the mud volcano versus the earthquake magnitude (Fig. 11b) to compare our mud volcano eruption–earthquake pairs with literature data. Seismically triggered mud volcanoes (blue empty dots in Fig. 11b) suggest a triggering threshold of ca. 10^{-2} J/m^3 (Wang and Manga 2010). Notably, the 'Dragone di Sassuno' mud volcano falls in the existence field (10^{-2}–10^3 J/m^3) of triggering for each considered earthquake. Nonetheless, since the mud volcano response to earthquakes is delayed (from about 6 to 11 months depending on the considered seismic event), a short-term effect of the transient dynamic stresses is unlikely. These considerations may suggest that the delayed mud volcano response was possibly favoured by the repeated fluid pressure variations originated during the passage of the seismic waves, which may have collectively shifted forward the "clock" of the natural eruptive cycle of this mud volcano. The eruption of the Offida mud volcano is even more controversial in that the eruption took place 14–16 years after the the Offida $M_w \approx 5.7$ earthquake of 3rd October 1943 (Table 2). Dynamic stresses, yet large enough to trigger the mud volcano (Fig. 11b) did not induce an immediate eruption, most likely because the mud volcano was not sufficiently close to eruption (i.e. it was not in critical state). In this case, permanent static stress changes might have played a role in the triggering, but to date this possibility remains uncertain and deserves further investigation.

In general, dynamic stresses released by the activation of far structures may influence mud volcano eruptions by shaking the fluid reservoirs and promoting the exolution of gases that expectedly increases overpressure and therefore the likelihood of eruption triggering. A similar mechanism has been proposed for magmatic volcanoes (e.g. Walter et al. 2007), and has also been proposed for mud volcanoes (Manga et al. 2009; Wang and Manga 2010; Bonini et al. 2016; Maestrelli et al. 2017b). In this process, the effects of stress variations induced by far structures may be combined with those produced by near structures. In particular, it is worth mentioning here that anticlinal structures, which have been shown to control mud volcano location, are very sensitive to dynamic stress perturbations, for the reason that parabolic lithologies with varying acoustic impedance can effectively amplify incoming seismic energy (Lupi et al. 2013). This may provide further explanation about the tendency of some mud volcanoes to respond to distant earthquakes, and testify the existence of a link between the activation of far structures and the eruption of mud volcanoes.

Final remarks

Structures of the Emilia-Romagna and Marche Pede–Apennine foothills have geometrically and genetically influenced fluid migration processes, whose most obvious outcome is the development of mud volcano systems. Generally, mud volcanoes tend to localise on top of thrust-related anticlines with a specific location (e.g. backlimb, hinge or forelimb) that can be controlled by systematic joints in the case of outcropping anticlines, or secondary discontinuities, when anticlines hosting the main reservoir are buried beneath a shallow/thick sedimentary sequence not affected by the folding phase. Thrust faults along the Emilia Romagna and Marche foothills are hinted to have the potential to indirectly influence mud volcano activity through stress perturbations created by earthquakes.

In our case studies, we have investigated the influence of near- and far structures on the genesis and activity of mud volcanoes. When the seismogenic structure is relatively "close" to a mud volcano system but it is not geometrically connected to the reservoir, the activation of the mud volcano can only follow the stress release generated during the rupture of this structure. When a mud volcano system is linked to a seismogenic structure, the fluid reservoir lies close to the seismogenic fault (e.g., the PAT in Emilia-Romagna; Bonini 2008). Stress may then accumulate along the fault plane before an earthquake, and the activity of mud volcanoes could be influenced by such a pre-seismic phase. Considering the possible implications, the study of precursory mud volcanism (yet never documented, except for a possible case represented by the eruption of the Nirano mud volcanoes before a M_w 4.7 occurred in June 2013; Lupi et al. 2015) would be of paramount importance for seismic hazard assessment.

Acknowledgements We kindly thank Luis Somoza and an anonymous Reviewer for their careful and constructive revisions. We thank ENI S.p.A., particularly Dr. Alessandro Fattorini, for providing us the seismic sections shown in this study. We are also grateful to the Osservatorio Geologico di Coldigioco and to Dr. Alessandro Montanari for hosting one of us (D.M.) during the fieldwork. Finally, we kindly thank Olivier Lacombe for the constructive discussion about the structural setting of the Marche mud volcanoes. This study has been partly funded by the Tuscany Ph.D. Regional program [Grant Number POR ICO FSE 2014/2020-Asse C] and by University of Florence ordinary funds 2014-2016.

References

Bally AW, Burbi L, Cooper C, Ghelardoni R (1986) Balanced sections and seismic reflection profiles across the central Apennines. Mem Soc Geol Ital 35:257–310

Barberi F, Scandone P (1983) Structural model of Italy, scale 1: 500,000, Progetto Finalizzato Geodin. Cons. Naz. delle Ric., Rome

Bicocchi G, Tassi F, Bonini M, Capecchiacci F, Ruggieri G, Buccianti A, Burgassi P, Vaselli O (2013) The high pCO_2 Caprese Reservoir (Northern Apennines, Italy): relationships between present- and paleo-fluid geochemistry and structural setting. Chem Geol 351:40–56. https://doi.org/10.1016/j.chemgeo.2013.05.001

Boccaletti M, Coli M, Eva C, Ferrari G, Giglia G, Lazzarotto A, Merlanti F, Nicolich R, Papani G, Postpischl D (1985) Consideration on the seismotectonics of the Northern Apennines. Tectonophysics 117:7–38. https://doi.org/10.1016/0040-1951(85)90234-3

Bonasera F (1952) I vulcanelli di Fango del Preappennino Marchigiano. Rivista Geografica Italiana 59:16–26

Bonini M (2007) Interrelations of mud volcanism, fluid venting, and thrust-anticline folding: examples from the external northern Apennines (Emilia-Romagna, Italy). J Geophys Res 112(B8) https://doi.org/10.1029/2006JB004859

Bonini M (2008) Elliptical mud volcano caldera as stress indicator in an active compressional setting (Nirano, Pede-Apennine Margin, northern Italy). Geology 36(2):131–134. https://doi.org/10.1130/g24158a.1

Bonini M (2012) Mud volcanoes: indicators of stress orientation and tectonic controls. Earth Sci Rev 115:121–152. https://doi.org/10.1016/j.earscirev.2012.09.002

Bonini M, Rudolph ML, Manga M (2016) Long- and short-term triggering and modulation of mud volcano eruptions by earthquakes. Tectonophysics 672–673:190–211. https://doi.org/10.1016/j.tecto.2016.01.037

Bons PD, van Milligen BP (2001) New experiment to model self-organized critical transport and accumulation of melt and hydrocarbons from their source rocks. Geology 29(10):919–922

Brown KM (1990) The nature and hydrological significance of mud diapirism and diatremes for accretionary systems. J Geophys Res 95:8969–8982

Calamita F, Deiana G (1987) The arcuate shape of the Umbria-Marche-Sabina Apennines (central Italy). Tectonophysics 146:139–147

Calindri S (1781) Dizionario Corografico, Geografico, Orittologico, Storico ec. ec. ec. della Italia, Bologna

Capozzi R, Picotti V (2002) Fluid migration and origin of a mud volcano in the Northern Apennines (Italy): the role of deeply rooted normal faults. Terra Nova 14(5):363–370

Capozzi R, Picotti V (2010) Spontaneous fluid emissions in the Northern Apennines: geochemistry, structures and implications for the petroleum system. Geol Soc Lond Spec Publ 348(1):115–135

Capozzi R, Menato V, Rabbi E (1994) Manifestazioni superficiali di fluidi ed evoluzione tettonica recente del margine Appenninico Emiliano-Romagnolo: indagine preliminare. Atti Ticinensi di Scienze della Terra 1(247):e254

Cartwright J, Huuse M, Aplin A (2007) Seal bypass systems. AAPG Bull 91(8):1141–1166. https://doi.org/10.1306/04090705181

Ceramicola S, Dupré S, Somoza L, Woodside J (2018) Cold seep systems. In: Submarine geomorphology. Springer, Cham, pp 367–387

Chiarabba C, Amato A, Anselmi M, Baccheschi P, Bianchi I, Cattaneo M, Cecere G, Chiaraluce L, Ciaccio MG, De Gori P, De Luca G, Di Bona M, Di Stefano R, Faenza L, Govoni A, Improta L, Lucente FP, Marchetti A, Margheriti L, Mele F, Michelini A, Monachesi G, Moretti M, Pastori M, Piana Agostinetti N, Piccinini D, Roselli P, Seccia D, Valoro L (2009) The 2009 L'Aquila (central Italy) M_W6.3 earthquake: Main shock and aftershocks. Geophys Res Lett 36:L18308. https://doi.org/10.1029/2009gl039627

Chiaraluce L, Di Stefano R, Tinti E, Scognamiglio L, Michele M, Casarotti E, Lombardi A (2017) The 2016 Central Italy seismic sequence: a first look at the mainshocks, aftershocks, and source models. Seismol Res Lett 88(3):757–771. https://doi.org/10.1785/0220160221

Damiani AV (1964) Studio della salsa di Offida (Ascoli Piceno-Marche). L'Universo 3:473–487

Davies RJ (2003) Kilometer-scale fluidization structures formed during early burial of a deep-water slope channel on the Niger Delta. Geology 31(11):949–952. https://doi.org/10.1130/G19835.1

De Prunele A, Ruffine L, Riboulot V, Peters CA, Croguennec C, Guyader V, Germain Y (2017) Focused hydrocarbon-migration in shallow sediments of a pockmark cluster in the Niger Delta (Off Nigeria). Geochem Geophys Geosyst 18(1):93–112. https://doi.org/10.1002/2016GC006554

Dimitrov LI (2002) Mud volcanoes—the most important pathway for degassing deeply buried sediments. Earth Sci Rev 59(1–4):49–76. https://doi.org/10.1016/S0012-8252(02)00069-7

Doglioni C, Gueguen E, Harabaglia P, Mongelli F (1999) On the origin of west-directed subduction zones and applications to the western Mediterranean. In: Durand B, Jolivet L, Horváth F, Séranne M (eds) The Mediterranean Basins: tertiary extension within the Alpine Orogen 156. Geological Society, London, Special Publications, pp 541–561. https://doi.org/10.1144/GSL.SP.1999.156.01.24

Etiope G, Martinelli G, Caracausi A, Italiano F (2007) Methane seeps and mud volcanoes in Italy: gas origin, fractionation and emission to the atmosphere. Geophys Res Lett. https://doi.org/10.1029/2007gl030341

Evans RJ, Davies RJ, Stewart SA (2007) Internal structure and eruptive history of a kilometre scale mud volcano system, South Caspian Sea. Basin Res 19(1):153–163. https://doi.org/10.1111/j.1365-2117.2007.00315.x

Evans RJ, Stewart SA, Davies RJ (2008) The structure and formation of mud volcano summit calderas. J Geol Soc 165(4):769–780. https://doi.org/10.1144/0016-76492007-118

DISS Working Group (2015) Database of Individual Seismogenic Sources (DISS), Version 3.2.0: a compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. http://diss.rm.ingv.it/diss/, Istituto Nazionale di Geofisica e Vulcanologia, https://doi.org/10.6092/ingv.it-diss3.2.0

Gasperi G, Bettelli G, Panini F, Pizziolo M, Bonazzi U, Fioroni C, Fregni P, Vaiani, SC (2005) Note illustrative della carta geologica d'Italia alla scala 1:50.000, Foglio 219, Sassuolo. Servizio Geologico d'Italia, p 196

Guerrieri L, Blumetti AM, Esposito E, Michetti AM, Porfido S, Serva L, Vittori E (2009) Capable faulting, environmental effects and seismic landscape in the area affected by the 1997 Umbria–Marche (Central Italy) seismic sequence. Tectonophysics 476(1):269–281

Hancock PL (1985) Brittle microtectonics: principles and practice. J Struct Geol 7(3–4):437–457

Hensen C, Scholz F, Nuzzo M, Valadares V, Gràcia E, Terrinha P, Bartolome R (2015) Strike-slip faults mediate the rise of crustal-derived fluids and mud volcanism in the deep sea. Geology 43(4):339–342. https://doi.org/10.1130/G36359.1

Jakubov AA, Ali-Zade AA, Zeinalov MM (1971) Mud Volcanoes of the Azerbaijan SSR, Atlas. Azerbaijan Academy of Sciences, Baku, p 257 **(in Russian)**

Judd A, Hovland M (2009) Seabed fluid flow: the impact on geology, biology and the marine environment. Cambridge University Press, Cambridge

Karstens J, Berndt C (2015) Seismic chimneys in the Southern Viking Graben-implications for palaeo fluid migration and overpressure evolution. Earth Planet Sci Lett 412:88–100. https://doi.org/10.1016/j.epsl.2014.12.017

Kopf AJ (2002) Significance of mud volcanism. Rev Geophys 40(2):1005. https://doi.org/10.1029/2000rg000093

Kopf A, Behrmann JH (2000) Extrusion dynamics of mud volcanoes on the Mediterranean Ridge accretionary complex. Geol Soc Lond Spec Publ 174(1):169–204

Lacombe O, Bellahsen N (2016) Thick-skinned tectonics and basement-involved fold–thrust belts: insights from selected Cenozoic orogens. Geol Mag 153(5–6):763–810

Lavecchia G, Boncio P, Creati N (2003) A lithospheric-scale seismogenic thrust in central Italy. J Geodyn 36(1):79–94

Lupi M, Saenger EH, Fuchs F, Miller SA (2013) Lusi mud eruption triggered by geometric focusing of seismic waves. Nat Geosci 6:642–646. https://doi.org/10.1038/ngeo1884

Lupi M, Saenger EH, Fuchs F, Miller SA (2014) Corrigendum: Lusi mud eruption triggered by geometric focusing of seismic waves. Nat Geosci 7(9):687. https://doi.org/10.1038/NGEO2239

Lupi M, Ricci BS, Kenkel J, Ricci T, Fuchs F, Miller SA, Kemna A (2015) Subsurface fluid distribution and possible seismic precursory signal at the Salse di Nirano mud volcanic field, Italy. Geophys J Int 204:907–917

Maestrelli D, Iacopini D, Jihad AA, Bond CE, Bonini M (2017a) Seismic and structural characterization of fluid escape pipes using 3D and partial stack seismic from the Loyal Field (Scotland, UK): a multiphase and repeated intrusive mechanism. Mar Pet Geol 88:489–510. https://doi.org/10.1016/j.marpetgeo.2017.08.016

Maestrelli D, Bonini M, Delle Donne D, Manga M, Piccardi L, Sani F (2017b) Dynamic triggering of mud volcano eruptions during the 2016–2017 Central Italy seismic sequence. J Geophys Res Solid Earth 122:9149–9165. https://doi.org/10.1002/2017JB014777

Maestrelli D, Benvenuti M, Bonini M, Carnicelli S, Piccardi L, Sani F (2018) The structural hinge of a chain-foreland basin: quaternary activity of the Pede-Apennine Thrust front (Northern Italy). Tectonophysics 723:117–135. https://doi.org/10.1016/j.tecto.2017.12.006

Manga M, Bonini M (2012) Large historical eruptions at subaerial mud volcanoes, Italy. Nat Hazards Earth Syst Sci 12(11):3377. https://doi.org/10.5194/nhess-12-3377-2012

Manga M, Brumm M, Rudolph ML (2009) Earthquake triggering of mud volcanoes. Mar Pet Geol 26(9):1785–1798. https://doi.org/10.1016/j.marpetgeo.2009.01.019

Martelli L, Bonini M, Calabrese L, Corti G, Ercolessi G, Molinari FC, Piccardi L, Pondrelli S, Sani F, Severi P (2017) Seismotectonic Map of the Emilia-Romagna Region and Surrounding Areas, Scale 1:250,000, 2nd edn. D.R.E.AM, Firenze

Martinelli G, Judd A (2004) Mud volcanoes of Italy. Geol J 39(1):49–61. https://doi.org/10.1002/gj.943

Martinelli G, Albarello D, Mucciarelli M (1995) Radon emissions from mud volcanoes in northern Italy: possible connection with local seismicity. Geophys Res Lett 22:1989–1992

Mazzini A, Svensen H, Akhmanov GG, Aloisi G, Planke S, Malthe-Sørenssen A, Istadi B (2007) Triggering and dynamic evolution of the LUSI mud volcano, Indonesia. Earth Planet Sci Lett 261(3–4):375–388

Mazzini A, Nermoen A, Krotkiewski M, Podladchikov Y, Planke S, Svensen H (2009) Strike-slip faulting as a trigger mechanism for overpressure release through piercement structures. Implications for the Lusi mud volcano, Indonesia. Mar Pet Geol 26(9):1751–1765. https://doi.org/10.1016/j.marpetgeo.2009.03.001

Medialdea T, Somoza L, Pinheiro LM, Fernández-Puga MC, Vázquez JT, León R, Vegas R (2009) Tectonics and mud volcano development in the Gulf of Cádiz. Mar Geol 261(1–4):48–63. https://doi.org/10.1016/j.margeo.2008.10.007

Mellors R, Kilb D, Aliyev A, Gasanov A, Yetirmishli G (2007) Correlations between earthquakes and large mud volcano eruptions. J Geophys Res-Solid Earth 112:B04304. https://doi.org/10.1029/2006JB004489

Miller SA, Mazzini A (2018) More than ten years of Lusi: a review of facts, coincidences, and past and future studies. Mar Pet Geol 90:10–25. https://doi.org/10.1016/j.marpetgeo.2017.06.019

Miller SA, Collettini C, Chiaraluce L, Cocco M, Barchi M, Kaus BJ (2004) Aftershocks driven by a high-pressure CO_2 source at depth. Nature 427(6976):724

Minissale A, Magro G, Martinelli G, Vaselli O, Tassi GF (2000) Fluid geochemical transect in the Northern Apennines (central-northern Italy): fluid genesis and migration and tectonic implications. Tectonophysics 319(3):199–222

Molli G (2008) Northern Apennine–Corsica orogenic system: an updated overview. Geol Soc Lond Spec Publ 298–1:413–442. https://doi.org/10.1144/SP298.19

Oppo D, Capozzi R, Picotti V (2013) A new model of the petroleum system in the Northern Apennines, Italy. Mar Pet Geol 48:57–76. https://doi.org/10.1016/j.marpetgeo.2013.06.005

Papani G, De Nardo MT, Bettelli G, Rio D, Tellini C, Vernia L (2002) Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 218, Castelnuovo ne' Monti. Servizio Geologico. d'Italia, p 140

Guerrera F, Tramontana M, Mattioli M, Pieruccini P, Cardellini Galdenzi S, Pennacchioni, E, Piergiovanni A, Sandroni P, Tosti S, (2014) Note illustrative alla carta geologica d'Italia alla scala 1:50.000, Foglio 292, Jesi. Ispra, Servizio Geologico d'Italia, p 122

Pieri M, Groppi G (1981) Subsurface geological structure of the Po Plain, CNR, Progetto Finalizzato Publication 414, pp 1–13

Planke S, Svensen H, Hovland M, Banks DA, Jamtveit B (2003) Mud and fluid migration in active mud volcanoes in Azerbaijan. Geo-Mar Lett 23(3–4):258–268. https://doi.org/10.1007/s00367-003-0152-z

Pucci S, De Martini PM, Civico R, Villani F, Nappi R, Ricci T, Azzaro R, Pantosti D (2017) Coseismic ruptures of the 24 August 2016, Mw 6.0 Amatrice earthquake (central Italy). Geophys Res Lett 44:2138–2147. https://doi.org/10.1002/2016GL071859

Revil A (2002) Genesis of mud volcanoes in sedimentary basins: a solitary wave-based mechanism. Geophys Res Lett. https://doi.org/10.1029/2001GL014465

Ricci Lucchi F (1987) Semi-allochthonous sedimentation in the Apenninic thrust belt. Sed Geol 50(1–3):119–134

Roberts KS, Davies RJ, Stewart SA, Tingay M (2011) Structural controls on mud volcano vent distributions: examples from Azerbaijan and Lusi, east Java. J Geol Soc 168(4):1013–1030. https://doi.org/10.1144/0016-76492010-158

Rovida A, Locati M, Camassi R, Lolli B, Gasperini P (eds) (2016) CPTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia. http://doi.org/10.6092/INGV.IT-CPTI15

Rudolph ML, Manga M (2012) Frequency dependence of mud volcano response to earthquakes. Geophys Res Lett. https://doi.org/10.1029/2012GL052383

Sciarra A, Cantucci B, Ricci T, Tomonaga Y, Mazzini A (2019) Geochemical characterization of the Nirano mud volcano, Italy. Appl Geochem 102:77–87

Serpieri A (1888) Scritti di sismologia nuovamente raccolti e pubblicati da G. Giovannozzi. Parte I, Il terremoto del 12 Marzo 1873. Casa Editrice Calasanziana, Firenze, p 232

Slack JF, Turner RJ, Ware PL (1998) Boron-rich mud volcanoes of the Black Sea region: modern analogues to ancient sea-floor tourmalinites associated with Sullivan-type Pb–Zn deposits? Geology 26(5):439–442. https://doi.org/10.1130/0091-7613(1998)026%3c0439:BRMVOT%3e2.3.CO;2

Somoza L, Medialdea T, León R, Ercilla G, Vázquez JT, Hernández-Molina J, Fernández-Puga MC (2012) Structure of mud volcano systems and pockmarks in the region of the Ceuta Contourite

Depositional System (Western Alborán Sea). Mar Geol 332:4–26. https://doi.org/10.1016/j.margeo.2012.06.002

Stewart SA, Davies RJ (2006) Structure and emplacement of mud volcano systems in the South Caspian Basin. AAPG Bull 90(5):771–786. https://doi.org/10.1306/11220505045

Tassi F, Bonini M, Montegrossi G, Capecchiacci F, Capaccioni B, Vaselli O (2012) Origin of light hydrocarbons in gases from mud volcanoes and CH4-rich emissions. Chem Geol 294–295:113–126

Terakawa T, Zoporowski A, Galvan B, Miller SA (2010) High-pressure fluid at hypocentral depths in the L'Aquila region inferred from earthquake focal mechanisms. Geology 38(11):995–998. https://doi.org/10.1130/G31457.1

Vannoli P, Basili R, Valensise G (2004) New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy). J Seismol 8(3):297–312

Vannoli P, Vannucci G, Bernardi F, Palombo B, Ferrari G (2015) The source of the 30 October 1930 Mw 5.8 Senigallia (Central Italy) earthquake: a convergent solution from instrumental, macroseismic, and geological data. Bull Seismol Soc Am 105(3):1548–1561

Walter TR, Wang R, Zimmer M, Grosser H, Lühr B, Ratdomopurbo A (2007) Volcanic activity influenced by tectonic earthquakes: static and dynamic stress triggering at Mt. Merapi. Geophys Res Lett 34(5):L05304. https://doi.org/10.1029/2006gl028710

Wang C-Y, Manga M (2010) Hydrologic responses to earthquakes and a general metric. Geofluids 10:206–216. https://doi.org/10.1111/j.1468-8123.2009.00270.x

Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull Seismol Soc Am 84:974–1002