Tectonic structures vs genesis and activity of mud volcanoes: examples from Emilia and Marche (Northern Apennines, Italy)

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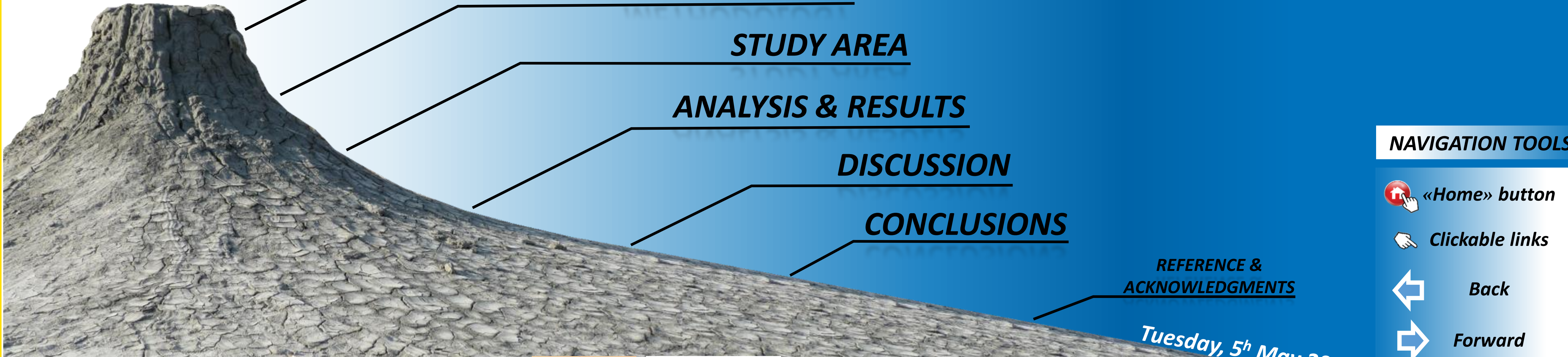

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INTRODUCTION & AIMS

MUD VOLCANOES vs TECTONIC STRUCTURES

- **Although widely studied, mud volcanism remains a debated topic, particularly its tectonic controls and the relationships with seismic activity, which has been shown to occasionally trigger mud volcanoes into eruption.**

- **In general, the activity of MVs 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 MVs.**

- **We aim to analyse the near- and far-structure control. We present structural and geological data in combination with interpretation of available seismic sections from the Northern Appenine, Italy.**

- **We intend to address some research questions:**
  - **are the investigated MVs related to near- and possibly active structures of the Pede–Apennine foothills?**
  - **Can tectonic and seismic activity of far structures influence MVs responses?**

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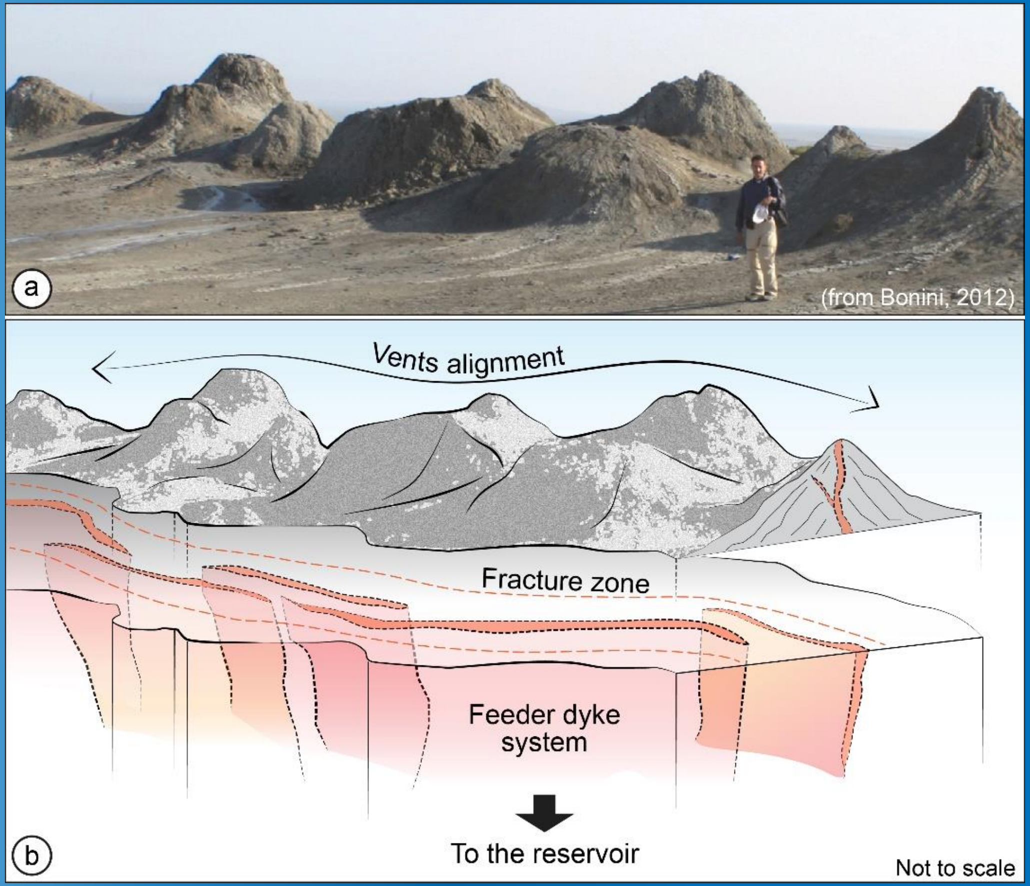
METHODOLOGY

STRUCTURAL AND MORPHOLOGICAL ANALYSIS

- We carried out a fieldwork structural survey with the aim to characterise the fracture arrays, which act as feeder system of MVs.
- The feeder dyke can be defined as a system of faults and fractures, able to channel mud and fluids from a reservoir up to the surface. Its orientation can be estimated from morphological features (i.e. alignment of vents, elongation of MVs and mud calderas; Bonini 2012).
- Sub-orthogonal joint sets associated with fold anticlines (“ac” and “bc” joints, Hancock 1985) are exploited by the rising fluid–mud mix (e.g. Bonini 2012).
- We aimed to map structures in the field and measure fracture orientation around the MVs.
- We used seismic profiles to illuminate the subsurface below the MVs, and to correlate them with the potential fluid reservoir and structures at depth.
- We used aerial photos and satellite images to investigate the recent (historical) activity of target MVs.



Definition of MV feeder dyke system (from Maestrelli, 2018)

STUDY AREA

EMILIA-ROMAGNA AND MARCHE MVs

- **We investigate onshore mud volcano systems from Emilia-Romagna and Marche, in the Northern Appenines (Fig. 1).**
- **MVs in Emilia-Romgna localise along the Pede–Apennine margin, 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. Beside, Marche MVs are more widespread along the broader Marche Apennine foothills.**
- **Both areas have in common the presence mudstone sequences in which the MVs find favourable conditions for their development, due to the sealing characteristics (Bonini, 2007).**
- **MV systems (red areas hihlighted in Fig. 1) are shown from NW to SE in the upcoming slides.**

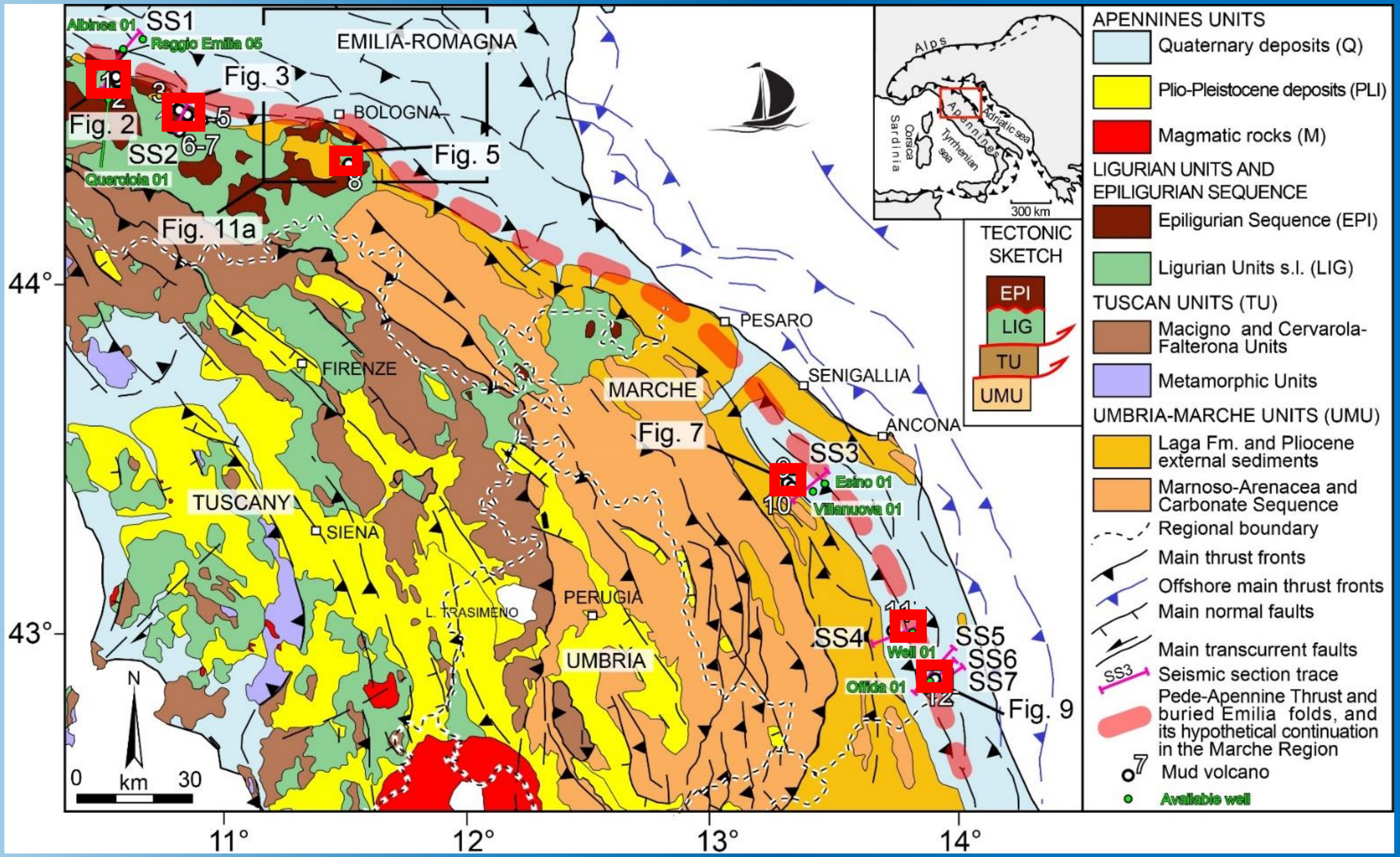


Fig. 1. Simplified geology of the Northern Apennines, showing the position of studied mud volcanos. Red rectangles mark the area of investigated mud volcano systems (from Maestrelli et al., 2019)

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REGNANO AND CASOLA-QUERZOLA MV SYSTEMS

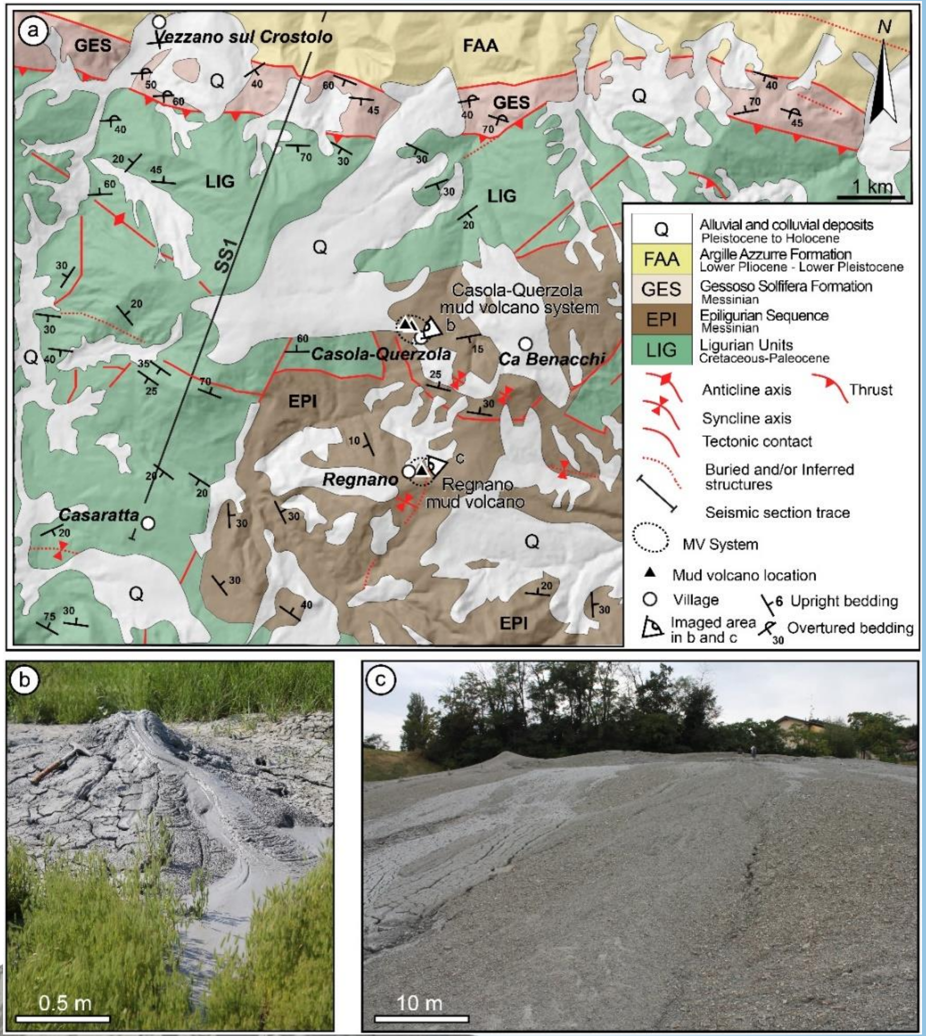

Fig. 2a. Geological setting of Regnano and Casola-Querzola MVs. **(b,c)** Detail of Casola-Querzola and Regnano MVs (from Maestrelli et al., 2019)

- **The Regnano and Casola-Querzola MVs occur SE of Vezzano sul Crostolo village (Fig. 2)**
- **Seismic profile SS1 (Fig.3a), crossing the Pede–Apennine margin, shows 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. The latter structure is interpreted as the Pede–Apennine thrust (PAT, the major and active structure of the Pede-Appening Margin.**
- **The anticline beneath the Casola-Querzola and Regnano Mvs is expected to host fluid reservoir(s) at its core, being sealed by the outcropping Ligurian Units.**

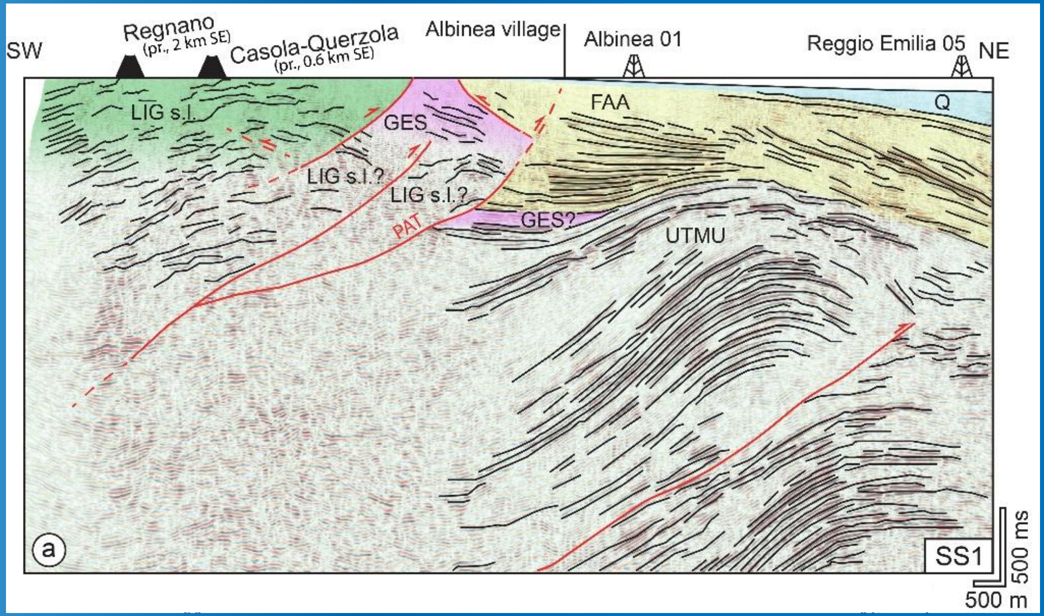

Fig. 4a. Interpretation of seismic line SS1 crossing the Pede-Apennine Margin. (from Maestrelli et al., 2019).

NIRANO AND MONTEGIBBIO MV SYSTEMS

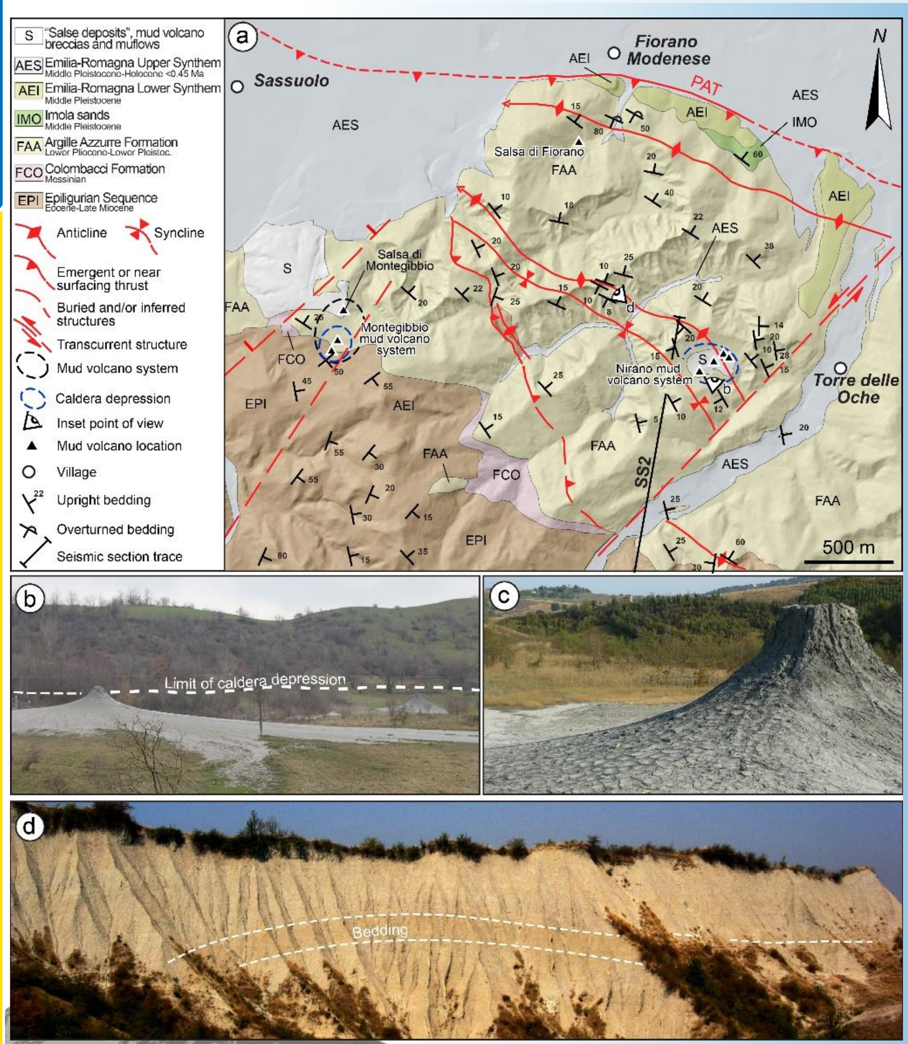

Fig. 3a. Geological setting of Nirano and Montegibbio MVs. **(b,c)** Details of Nirano Mvs and **(d)** the outcropping anticline to which MVs are associated (from Maestrelli et al., 2019).

- **The Nirano MVs occurs within a caldera depression S of Fiorano Modenese (Fig. 3). Vent alignments exploit joints associated with an outcropping anticline. Caldera elongation is inferred to reflect the local stress field (Bonini 2008). (Fig. 3a). The Montegibbio mud volcano is located a few kilometres W of Nirano.**

- **Seismic line SS2 (Fig. 4b) depicts thrusts juxtaposing the Ligurian Units and the Epiligurian Sequence onto the Argille Azzurre sediments (FAA). These are deformed by thrust-related anticlines, and the MVs show connection with these structures.**

- **The two MVs occur above the forelimb of the thrust-related anticline (Fig. 4b).**

- **The thrust generating this anticline is likely the PAT. The outcropping anticline along which the Nirano MVs occur (Fig. 3a,d) is probably a shallower thrust-related fold associated with the main buried structure, which likely hosts the fluid reservoir(s).**

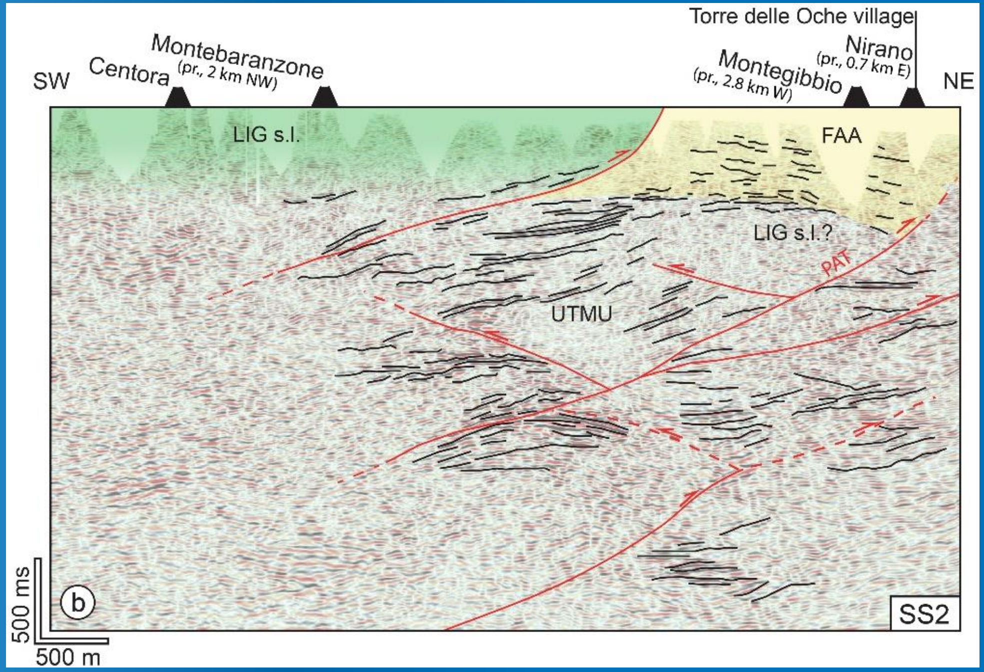

Fig. 4b. Interpretation of seismic line SS2 crossig the Pede-Apennine Margin (from Maestrelli et al., 2019).

ANALYSIS & RESULTS: EMILIA MVs

THE DRAGONE DI SASSUNO MV

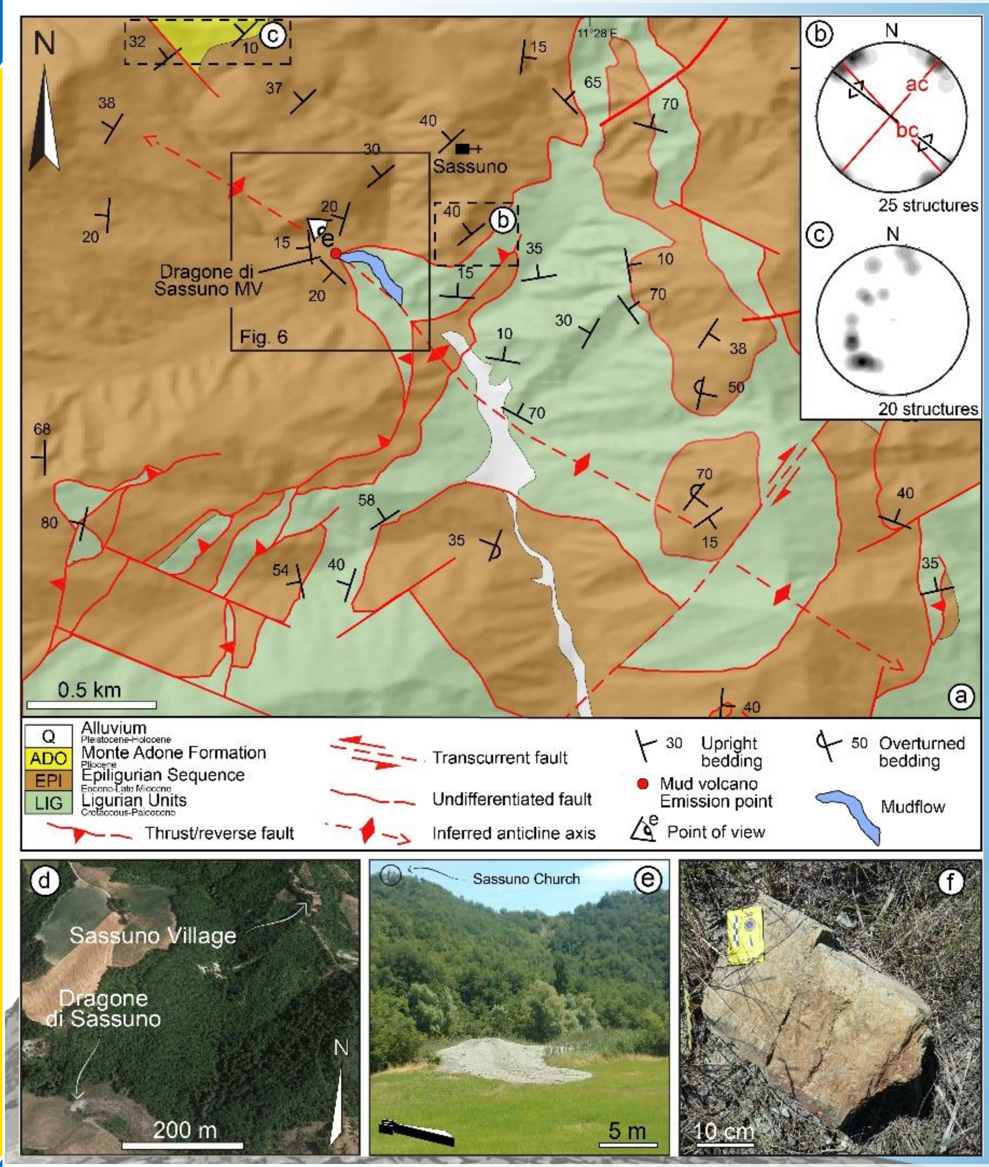

Fig. 5. Structural setting of the Dragone di Sassuno Mv (from Maestrelli et al., 2019).

- The Dragone di Sassuno is a gryphon located in the Pede-Apennine Margin SW of Bologna (Fig. 5a, d).
- Capozzi et al. (1994) documented its recent eruptive activity, and Calindri (1781) described some large eruptions occurred in July 1780 during a period of large earthquakes coccurence.
- The MV lies at the top of Ligurian Units and the Epiligurian Sequence (Fig. 5a). The MV is settled along a ca. N145E°-striking anticline axis.
- Fractures from the Epiligurian outcrop (Fig. 5a,b) are 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’).
- Analysis of historical activity of this MV may provide information about the presence of aligned vents, which can be used to reconstruct the possible orientation of the subsurface feeder dyke.

THE DRAGONE DI SASSUNO MV

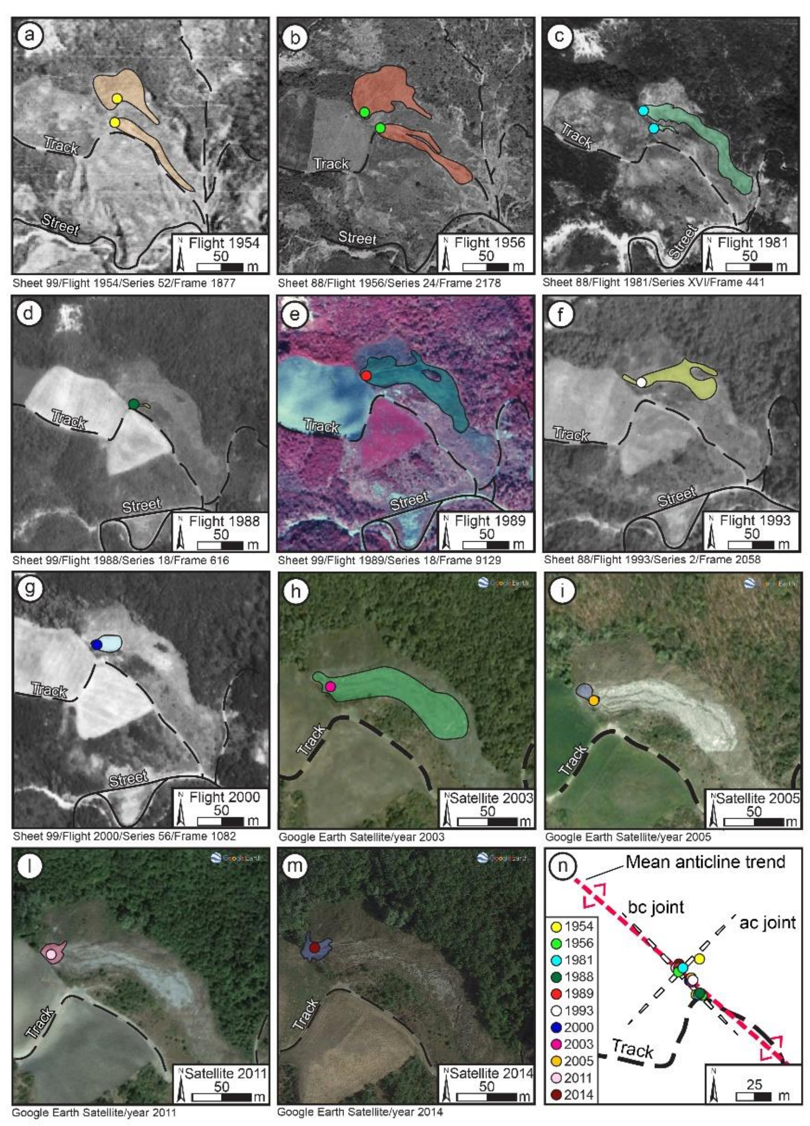

Fig. 6. Aerial photos and satellite images of the Dragone di Sassuno throughout time (from Maestrelli et al., 2019).

- Using aerial photos, we identified periods of activity or inactivity of MV even though the dataset is scattered and a continuous investigation was not possible.
- Photos 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 modest. At the time of the survey, only a single mud cone was visible in the field, with two minor emission points at the cone apex, ligned along a N40°E direction.
- Aerial photos from 1954 to 1981 (Fig. 6a-c) show two distinct vents. Their location varies through time, as shown by emission points collectively plotted on Fig. 6l.
- We interpret vents as located on two different fractures, along which they can migrate. Although their current distribution 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).

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ANALYSIS & RESULTS: MARCHE MVs

S. PAOLO DI JESI AND MAIOLATI SPONTINI MV SYSTEMS

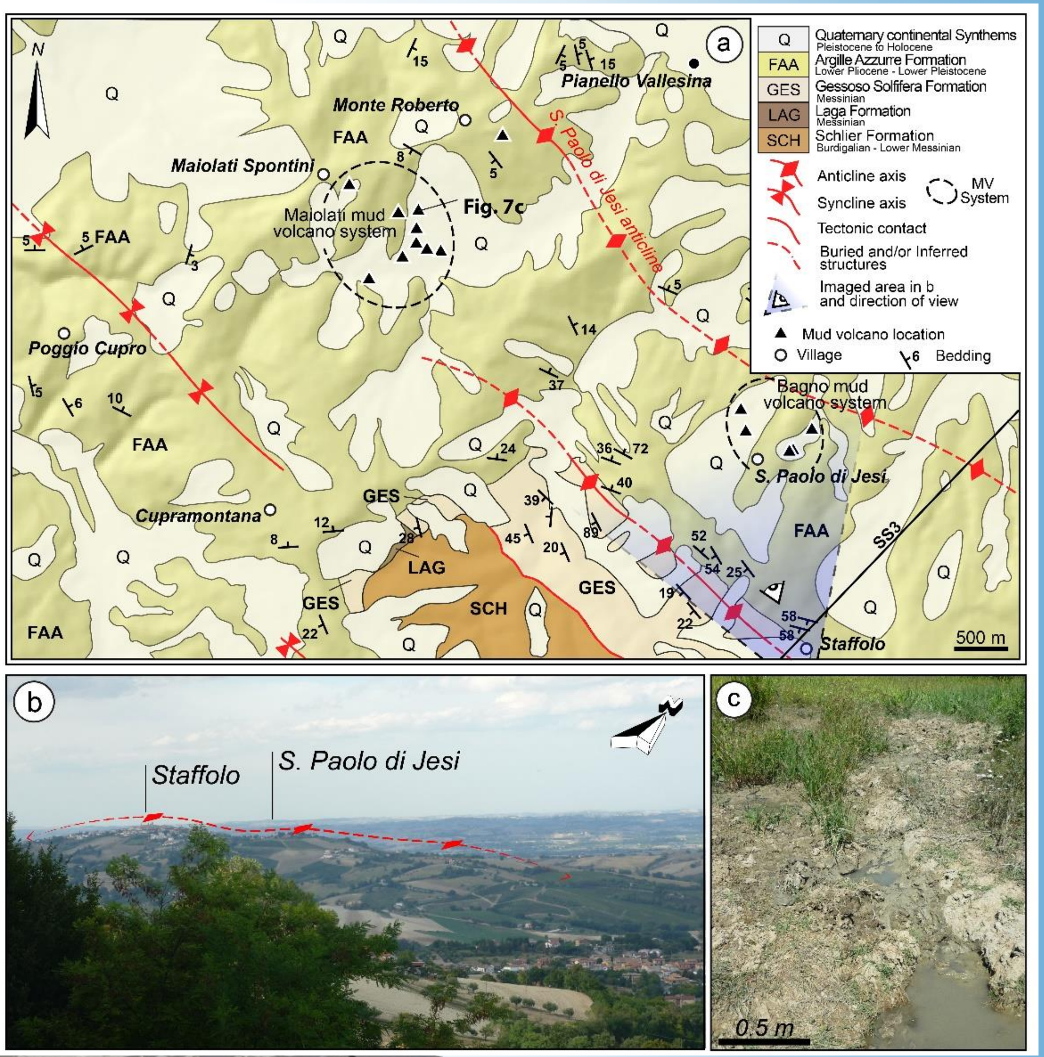

Fig. 7. (a) Geological setting of S. Paolo di Jesi and Maiolati MVs. (b) The S. Paolo di Jesi anticline. (c) The Maiolati Mv (from Maestrelli et al., 2019).

- Bonasera (1952) reported MVs at Maiolati Spontini and S. Paolo di Jesi, along the Marche foothills (**Fig. 7a**), nowadays not visible anymore. Only one (a mud pool), here called Maiolati, is still preserved.
- The pool is about 15×5 m, and the major axis corresponds to a vent alignment oriented ca. N150°E, consistent with the trend of an anticline axis, (San Paolo anticline), striking N140°E. Mud pool elongation and vent alignment correspond to "bc" joints related to the anticline.
- A similar case is represented by the San Paolo di Jesi MVs. In the Bagno locality (close to San Paolo di Jesi), Bonasera (1952) described a particularly active mud volcano. Serpieri (1888) reported that this MV experienced a small eruption in 1873 after the Mw 5.85 San Ginesio earthquake (Marche region) on 12th March 1873.
- Inhabitants indicate that the MV (active during past decades) has changed the position. A ground fracture, locus of a diffuse water flux (oriented N55°-60°E) connects the Bagno MV position reported in Bonasera (1952) with the current MV location.
- The MV may change its position along this fracture. The fracture trendcorresponds to the orientation of a hypothetical "ac" joint system associated with the NW–SE trending San Paolo anticline (**Fig. 7a,b**).

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S. PAOLO DI JESI AND MAIOLATI SPONTINI MV SYSTEMS

- Seismic profile SS3, image a thrust system buried below the Pliocene marine succession, located few kilometres forward from the outcropping anticline (**Fig. 8a**).
- We interpret the Bagno MV as settled at the top of a minor back-thrust associated with the major thrust-related anticline corresponding to the exposed San Paolo anticline.
- The Bagno MV is apparently connected to a secondary structure of the outcropping San Paolo anticline (**Fig. 8a**).
- The Maiolati Spontini MV 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**).

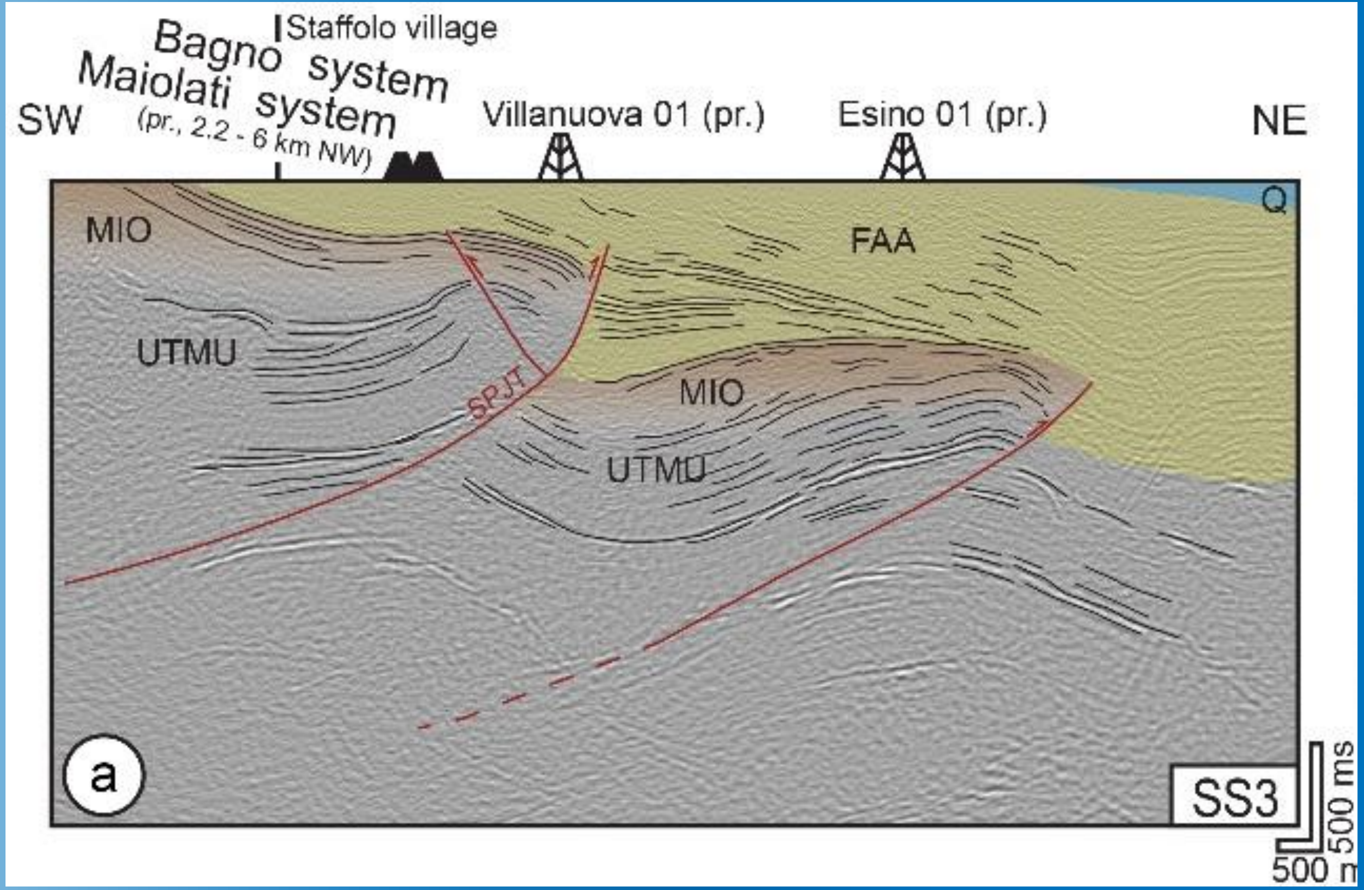
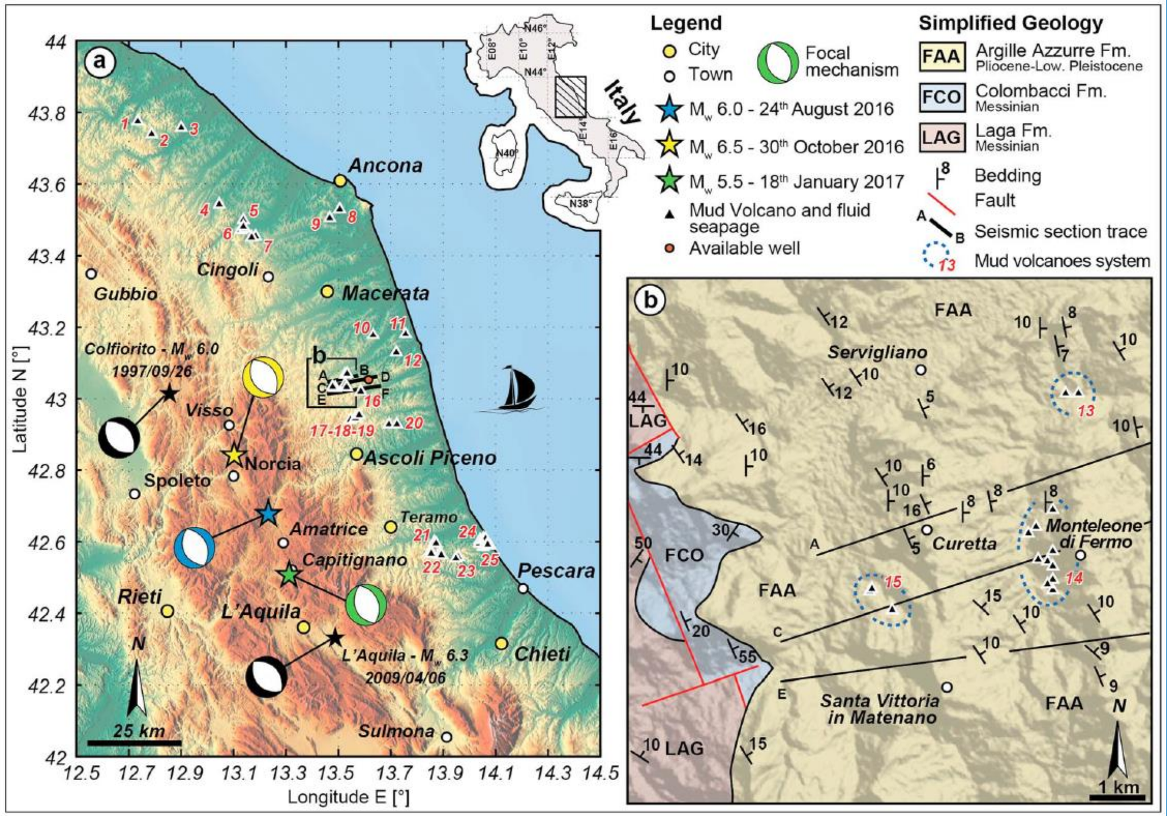


Fig. 8a. Section SS3 showing the structural setting of S. Paolo di Jesi MVs (from Maestrelli et al., 2019).

MONTELEONE DI FERMO MV SYSTEM



Geological setting of the Monteleone di Fermo MV systems (from Maestrelli et al., 2017).

- **The Monteleone di Fermo MVs are located on a NE-dipping monocline of Miocene–Pliocene deposits which cover a series of thrust faults and thrust-related folds.**

- **Structural survey and seismic lines (SS4; Fig. 8b) revealed that the MVs lie above buried ramp anticlines, which likely act as reservoirs for the fluids sourcing the MV. The feeder dyke system 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. 2017).**

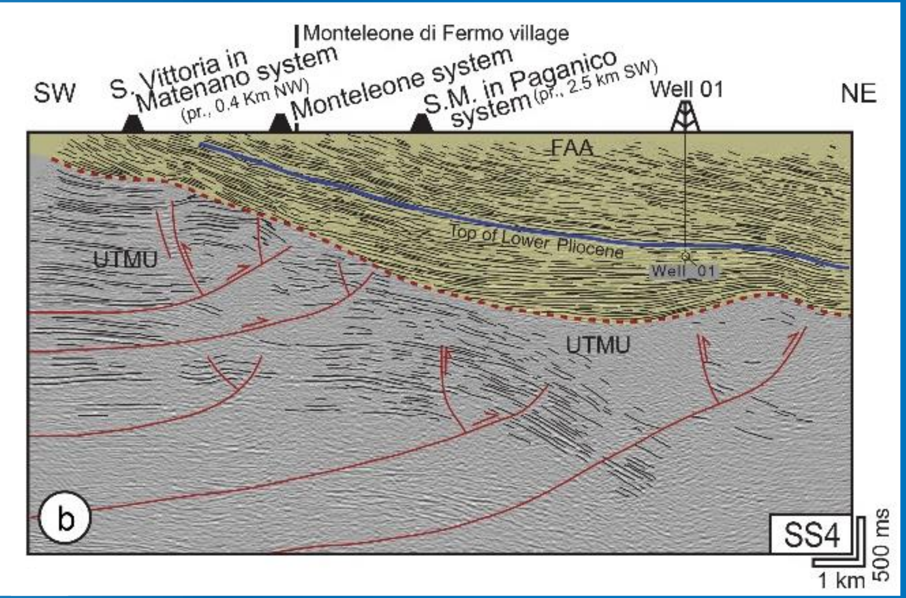
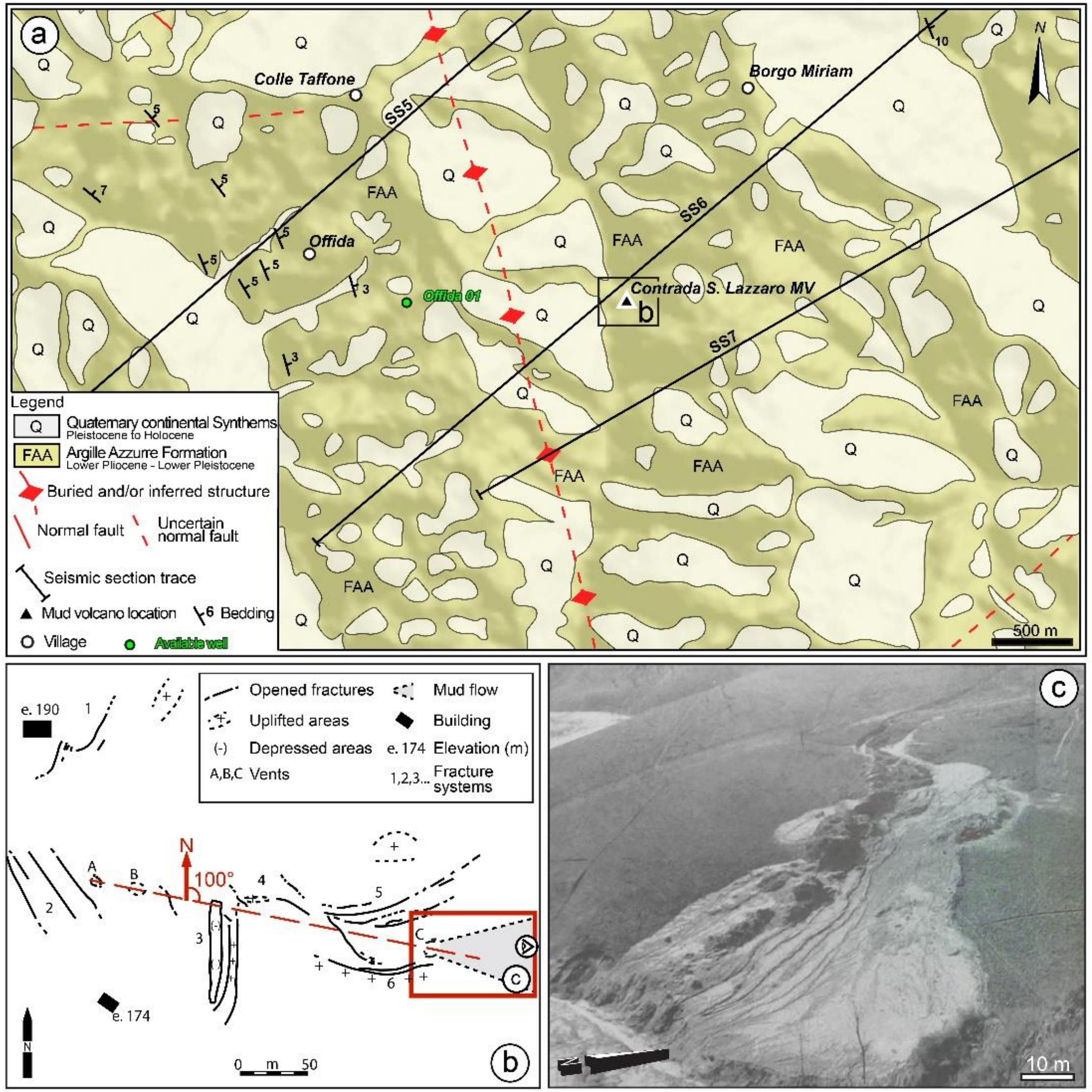


Fig. 8b. Section SS4 showing the structural setting of Monteleone di Fermo MVs (from Maestrelli et al., 2019).

- **These MVs were proven to have been influenced by dynamic stress changes induced by the 2016-2017 Central Italy seismic sequence.**

THE CONTRADA S. LAZZARO (OFFIDA) MV SYSTEM



- Many small MVs occur around Offida, in southern Marche. Among them, the most interesting is the Contrada S. Lazzaro MV (Fig. 9), not visible in the field anymore. It is reported to have erupted violently in 1959 (Fig. 9b, c).
- Damiani (1964) describes the effects of the 15th December 1959 eruption, reporting that this MV had been inactive for a long time, except the small eruptions of 1956 or 1957 that preceded the large one.
- Alignment of 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.
- Interpretation of aerial photos, covering a time span (yet scattered) of almost 70 years, does not show any other evidence of activity.

Fig. 9. (a) Geological setting of the Contrada S. Lazzaro MVs. **(b)** The morphological survey by Damiani, 1964 **(c)** Photo of 1959 eruption from Damiani 1964 (from Maestrelli et al., 2019).

THE CONTRADA S. LAZZARO (OFFIDA) MV SYSTEM

ANALYSIS & RESULTS: MARCHE MVs

- **Seismic sections SS5, SS6 and SS7 (Fig. 8c-e) show the Contrada S. Lazzaro MV as associated with a buried, ca. N345°E trending thrust anticline hosting a ca. 1–2-km-deep fluid reservoir.**

- **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.**

- **The anticline corresponds to the compressive structure hinted to have generated the *M*w ≈ 5.7 earthquake of 3rd October 1943. The N100°E oriented vent alignment trends at high angle to the anticline axis and may represent the feeder dyke system of MV.**

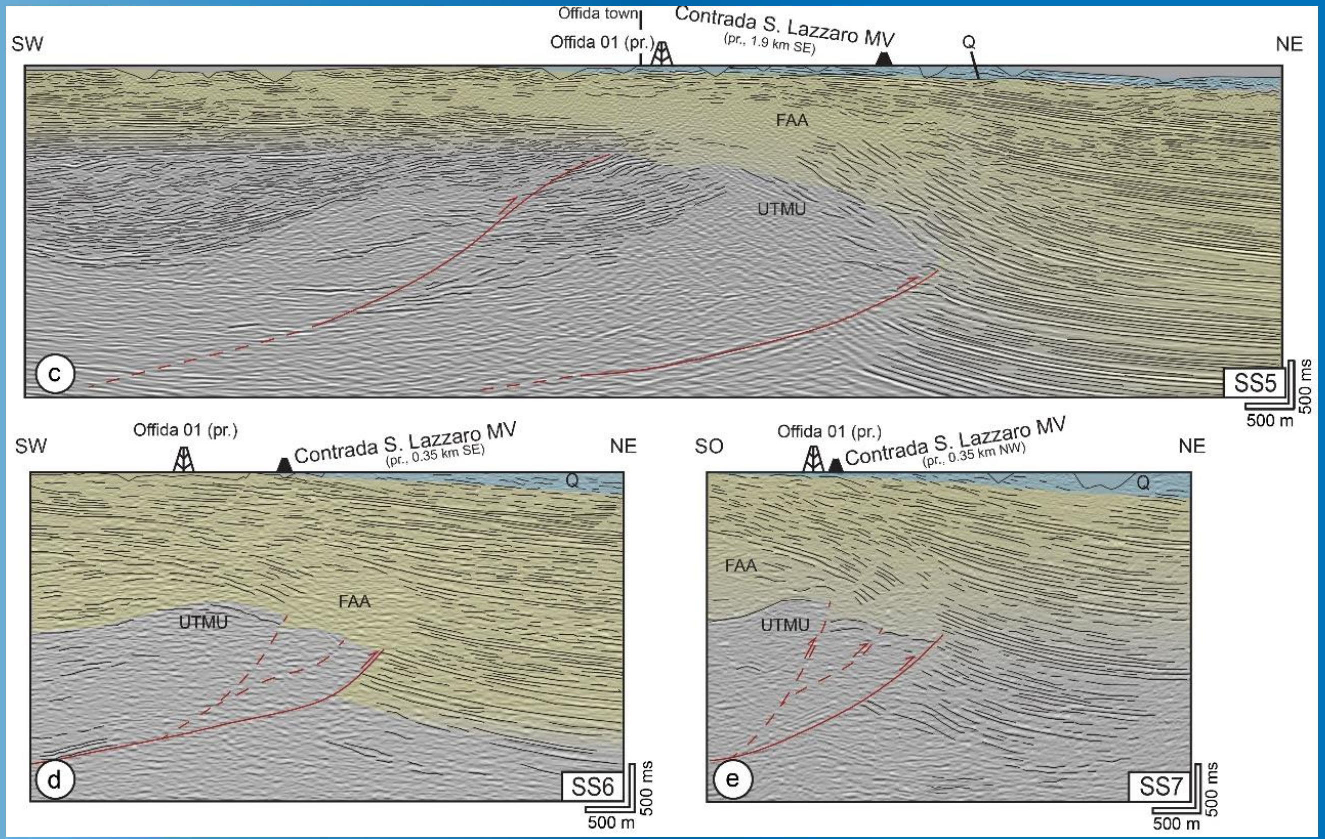


Fig. 8c,d,e. Sections SS5, SS6 AND SS7 showing the structural setting of the Contrada S. Lazzaro MV (from Maestrelli et al., 2019).

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DISCUSSING THE ROLE OF NEAR-STRUCTURES

DISCUSSION

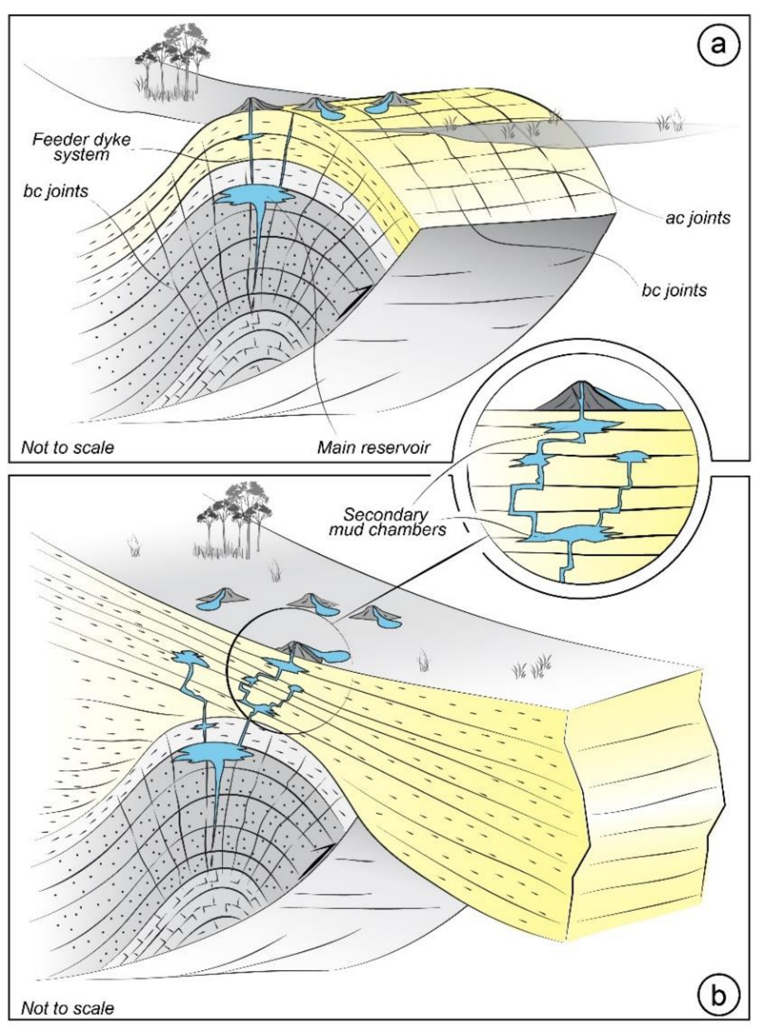

Fig. 10. Structural model explaining fluid migration and MVs localization on top of outcropping (a) and buried (b) anticlines. (from Maestrelli et al., 2019).

- **Our MVs are located at the top of an anticline, indicating that the thrust system of the Pede-Apennine margin drive the distribution of MVs and that systematic joints can act as feeder dyke systems (Fig. 10a).**

- **MVs are located in the forelimb, the backlimb or the hinge of anticlines, so how can fluid migration paths be explained according to this variability? If MVs are expected to exploit systematic fractures related to folding (as happens for emergent anticlines), how MVs lying on top of an unfolded sediments are connected with their deep reservoirs?**

- **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 MVs can emerge exactly on top of the anticline crest or be located in the forelimb and/or backlimb of the fold.**

- **Nevertheless, this does not fit with the setting of the Marche foothills, where the MVs are located above undeformed monocline of mudstones overlaying anticline structures. Joints related to folding are not expected to develop in the overburden, and therefore cannot explain fluid migration.**

- **We propose that once the fluid has migrated through joints in the anticline, they reach sealing layers that act as shallower traps (Fig. 10b). Fluids stop their ascent or find secondary fractures or faults to continue their migration. Therefore MVs might not be strictly positioned over the anticline crest.**

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DISCUSSION

DISCUSSING THE ROLE OF FAR- STRUCTURES

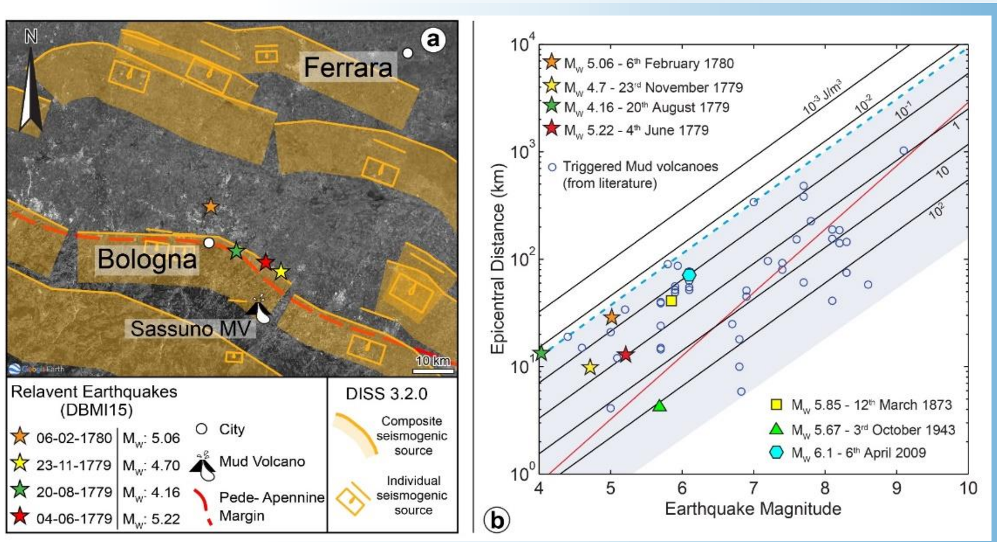

Fig. 10. (a) Epicentres of 1780-1790 earthquakes near the Dragone di Sassuno MV. (b) Magnitude vs Epicentral distance analysis (from Maestrelli et al., 2019).

- **Structures may play an important role on the upward migration of fluids sourcing the MVs. This link is direct, since structures actively act as fluid reservoirs and facilitate the upward fluid migration through anticline-related fracture systems.**

- **Nevertheless, this is not the unique link between structures and MVs, as also far-structures may influence mud volcano systems as, far seismogenic faults may promote the triggering of MVs into eruptions.**

- **E.g., the Bagno MV erupted in 1873 after the S. Ginesio earthquake and the Dragone di Sassuno MV erupted on July 1780, as reported by Calindri (1781).**

- **With regard to the Dragone di Sassuno, we identify four significant seismic events that hit the region (about one year to few months before the 1780 eruptions, Fig. 11a)**

- **Three seismic events have an epicentre near the Pede–Appenine thrust (PAT) which seemingly represents the seismogenic structure (Fig. 11a). The eruptions, appear as long-term responses to the earthquakes that preceded the eruptions of July 1780.**

- **Following Wang & Manga (2010) we have plotted the epicentral distance of each seismic event from the MV versus the earthquake magnitude (Fig. 11b). The Dragone di Sassuno MV falls in the existence field (10^{-2} -10^{3} J/m^3) of triggering. Nonetheless, since the MV response to earthquakes is delayed a short-term effect of the transient dynamic stresses is unlikely. These considerations suggest that the delayed response was possibly favoured by the repeated fluid pressure variations.**

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CONCLUSIONS

…SOME 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 also the potential to indirectly influence mud volcano activity through stress perturbations created by earthquakes.

- In this way we define a direct link, represented by the role exterted by near- structures in localizing and driving the evolution of MVs, and an indirect one, represented by the potential role of far-structures in triggering MVs.

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