Mud volcanoes in onshore Sicily: a short overview

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A short overview on Sicilian mud volcanoes is given. A total of 8 sites are presently known and studied in Sicily, mainly located in central–southern Sicily (Caltanissetta basin). All of these are of small dimension and sometimes associated to water pools. Methane is the main emitted gaseous phase, with the exception of the Paternò site, dominated by CO_2 due to its proximity to Mt. Etna.
Emitted waters are of the chloride–sulphate–alkaline type, due to the dominance of NaCl as the main dissolved salt. Sicilian mud volcanoes represent a potential threat for humans but, at the same time, they are threatened by anthropic activities. The main risks are related to the damages produced by paroxysmal events, while their survival is threatened by illegal discharge of wastes, consumption of rural land and agricultural activities.

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Introduction

Mud volcanoes are geological structures formed as a result of the emission of argillaceous material on the Earth's surface, which are commonly associated with compressive tectonics and sediment accretion at convergent margins (for a review, see Kopf 2002). Overpressured multiphase pore fluids incorporated in this material, mainly water and methane, make it semi-liquid and force it up through fissures in the crust, producing an outflowing mass of mud on the surface.

Mud volcanoes present characteristic isometric to elongated morphological structures, varying both in shape (from plano-conical shapes rising some hundred meters above the adjacent landscape to irregular shapes) and size (from tens of square meters to very large structures up to 100 km^2), composed by "mud breccia" sharply contrasting to the surrounding host sediments (Dimitrov 2002).

Presently more than 1800 mud volcanoes are known from modern accretionary complex areas, with high sedimentation rates originating as a result of rapid overloading caused by structural or tectonic thickening (Dimitrov 2002). Mud volcanoes are normally in a quiescent stage because of the short duration of eruptions, often characterized by vigorous seepage of water, gas, and petroleum.
Mud volcanoes in Sicily occur both onshore (Etiope et al. 2002) and offshore (Holland et al. 2003; Savini et al. 2009; Cangemi et al. 2010) in geological settings characterized

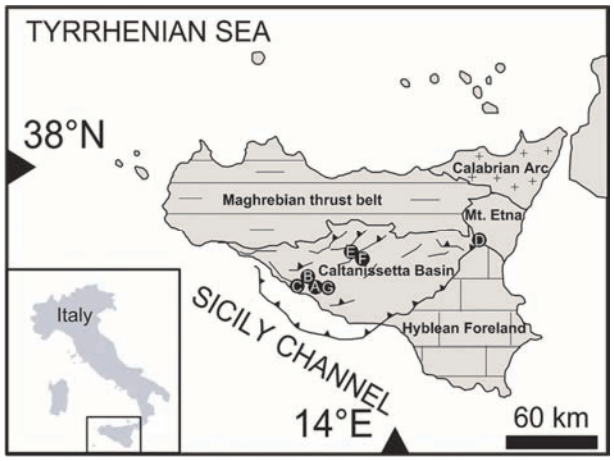

Fig. 1: Geological map of Sicily with locations of mud volcanoes: Bissana (**C**), Comitini (**G**), Fuoco di Censo (**B**), Maccalube (**A**), Marianopoli (**E**), Santa Barbara (**F**), Salinelle San Biagio and Salinelle Stadio at Paternò (**D**).

by a rapid sedimentation since the Late Cenozoic and intense neotectonics. These phenomena have been studied since the second half of the XIX century (Silvestri 1866). Comprehensive lists of Sicilian Mud volcanoes were reported by Etiope et al. (2002; 5 sites) and Martinelli & Judd (2004; 13 sites).

The present paper is aimed to give a short overview on Sicilian mud volcanoes. After the description of the general geological setting of Sicily, we will present the list of the known mud volcanoes together with a short description, and chemical and isotopic data of the emitted fluids, if available. We will complete our overview with the geochemical characterization of the emitted fluids and some considerations about environmental threats originating from or affecting Sicilian mud volcanoes.

Geological setting of Sicily

Sicily is a segment of the Alpine collisional belt along the Africa-Europe plate boundary that links the African Maghrebides to the west and southwest with the Calabria and the Appennines to the East and Northeast (Catalano et al. 1996, 2000; Avellone et al. 2010). The geological setting of Sicily (Fig. 1) is characterized by three main structural elements: (i) the Hyblean Plateau foreland in southeastern Sicily, constituted by Triassic–Liassic platform and scarp-basin carbonates overlain by Jurassic–Eocene pelagic carbonates and Tertiary open-shelf clastic deposits; (ii) the northwest-dipping foredeep north of the foreland, consisting of Plio–Pleistocene pelagic marly limestones, silty mudstones, and sandy clays overlying Messinian evaporites; and (iii) the complex chain composed of several imbricate units geometrically arranged in a thrust pile verging toward the east and the southeast, including the Calabro-Peloritani Units, located in northeastern Sicily, formed of Hercynian crystalline units with a Mesozoic terrigenous cover and Plio–Pleistocene clastic and pelagic sediments and the Sicilian Maghrebian Units consisting of Meso–Cenozoic siliceous rocks, basin pelagic turbiditic carbonates, and platform and pelagic carbonates.

These units are tectonically overlain by a roof thrust formed of Oligo–Miocene turbiditic successions, or Lower–Middle Miocene glauconitic calcarenites and pelagic mudstones, or Lower Pleistocene foreland or satellite basin deposits, deformed and detached from the substratum (Catalano et al. 1996, 2000). The Maghrebian Units crop out along the northern Sicily belt in the Madonie, Palermo, and Trapani Mountains and in the western and southwestern sectors of the island. Southern and central Sicily are characterized by the presence of Cretaceous–Lower Pleistocene clastic-terrigenous deposits and Messinian evaporites.

Distribution and description of mud volcanoes in Sicily

Mud volcanoes are located in central-southern Sicily (Caltanissetta basin), with the only exception of the Paternò site, that lies at the contact between the eastern margin of the Sicilian foredeep and the volcanic edifice of Mt. Etna (Fig. 1). A total of 8 sites showing volcano-sedimentary activity are presently known and studied from the geochemical viewpoint (Table 1; with indication of the bibliographic sources used in the following descriptions).

All of these mud volcanoes are typically smaller than those generally occurring in other hydrocarbon-prone areas; some are characterized by water pools of several meters in diameter, where gases bubble vigorously (Etiope et al. 2002).

The **Bissana site** rises at the top of a hill and shows intermittent degassing activity, characterized by long periods of quiescence interrupted by violent emissions of mud and associated fluids (hereafter referred as "paroxysmal events"), that caused damages to local roads. A big pool (10 m of diameter and 20 m of depth) with gurgling gases and vents discharging mud and salty water is also present.

The **Comitini site** is located at the end of a hill and characterized by the presence of several active vents.

The **Fuoco di Censo** at Bivona is characterized by gas vents producing charming everlasting fires that occasionally burn with metre-high flames. No mud is emitted, causing the absence of cone-shaped structures.

Maccalube at Aragona is the biggest mud volcanism site in Sicily. It covers an area of about 1.4 km^2, where mud volcanoes are characterized by heights ranging from few centimeters to half a meter. Their eruptive style alternates during non-periodical paroxysmal episodes, not related to seismic activity, with expulsion of blast and burning of gases.

Table 1: Name, location (city and province), latitude and longitude (degrees and decimals, WGS84), elevation (m a.s.l.) of the presently known mud volcano sites in Sicily. Source of data are indicated in the last column. The Ids between brackets in the Name column refer to the locations reported in Fig. 1.

Name (Id)	Location	Latitude	Longitude	Elevation [m]	Reference
Bissana (C)	Cianciana (AG)	37.4833	13.3881	172	Etiope et al. (2002)
Comitini (G)	Comitini (AG)	37.4429	13.6519	210	Martinelli and Judd (2004), Heller (2011)
Fuoco di Censo (B)	Bivona (AG)	37.6250	13.3878	737	Etiope et al. (2002)
Maccalube (A)	Aragona (AG)	37.3757	13.5999	282	Etiope et al. (2002), Heller (2011)
Marianopoli (E)	Caltanissetta (CL)	37.6264	13.8936	374	Graziano (2009)
Santa Barbara (F)	Caltanissetta (CL)	37.4966	14.0907	528	INGV (2008), Madonia et al. (2011)
Salinelle S. Biagio (D)	Paternò (CT)	37.5449	14.9195	217	Etiope et al. (2002)
Salinelle Stadio (D)	Paternò (CT)	37.5726	14.8902	210	Etiope et al. (2002) Heller (2011)

In the Maccalube area there are also two main pools (about 3 m in diameter) with water and gurgling gases.

The Marianopoli site is presently characterized by a very residual activity, with few little mud pools (some square centimeters) and gas vents.

The Santa Barbara site at Caltanissetta occupies an area of about 12 km^2 and is characterized by cone-shaped structures tens of centimeters high, emitting mud and gases. Paroxysmal eruptions are not uncommon. The most recent one, preceded by a strong gas blast, occurred in August 2008 and caused severe damages to the surrounding roads and buildings.

The Salinelle S. Biagio and the Salinelle Stadio at Paternò strongly interact with anthropogenic activities that perturb their morphology and fluid emissions. Their activity is strongly influenced by seismic events and changes of volcanic degassing from Mt. Etna.

Geochemistry of fluid emissions from Sicilian mud volcanoes

In the following discussion we will give a summary of the geochemical data available for fluids emitted from Sicilian mud volcanoes from different bibliographic sources (Etiope et al. 2002 (sites A, B, C, D - gas), Graziano (2009; previously unpublished, site E - gas), Heller (2011; sites A, D, G - water and G - gas), INGV (2008; site F, gas), Madonia et al. 2011 (site F, water).

Sicilian mud volcanoes are characterized by a highly diffuse soil degassing. The emitted gaseous phase is normally dominated by CH_4. Carbon dioxide is subjected to dissolution in the underground aquifers underlying the emitting vents. However, due to the proximity of the Mt. Etna volcanic system (Chiodini et al. 1996; D'Alessandro et al. 1997; Giammanco et al. 1998) the main emitted gas at Paternò is CO_2, along with a significant amount of H_2 and a mantle-derived helium signature that suggests a possible seismogenetic control on mud volcanoes (Etiope et al. 2002, Guliyev & Feizullayev 1995). The chemical compositions of venting gases from the different Sicilian mud volcanoes sites are summarized in Table 2 and in the ternary diagram CO_2–C H_4–N_2 illustrated in Fig. 2.

Chemical data of water emitted by Sicilian mud volcanoes are summarized in the Langelier–Ludwig diagram reported in Fig. 3. All the points decline in the chloride–sulphate–alkaline quadrant, due to the dominance of NaCl as the main dissolved salt. In particular for Santa Barbara (Madonia et al. 2011), the water has a salinity around 28 g l^{-1} and shows circumneutral pH values. Its chemical composition resembles that of seawater, with some modifications induced by both mixing with a low-Cl component (meteoric water) and water-clay interaction processes.

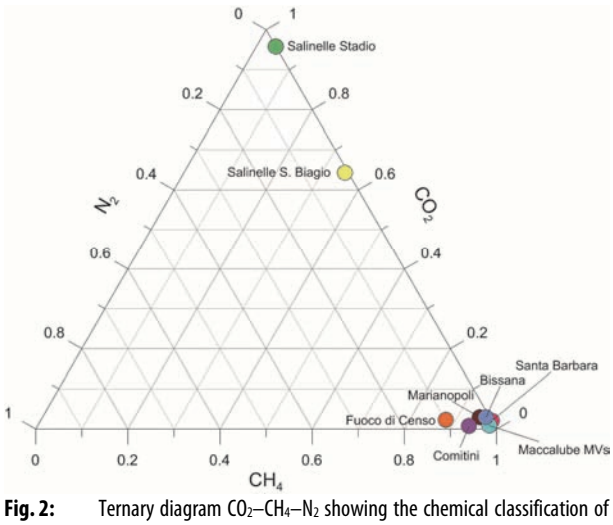

Fig. 2: Ternary diagram CO_2–CH_4–N_2 showing the chemical classification of gases emitted from Sicilian mud volcanoes.

Table 2: Chemical data of venting gases from mud volcanoes and ponds (b.d.l. = below detection limit). Data sources are listed in Table 1.

Site	He [ppm$_v$]	H_2 [ppm$_v$]	O_2 [%]	N_2 [%]	CH_4 [%]	CO_2 [%]	References
Bissana	501	15	b.d.l.	0.83	96.2	2.9	Etiope et al. (2002)
Comitini			2.12	5.47	91.62	0.68	Heller (2011)
Fuoco di Censo	367	59	2.03	9.66	86	2.2	Etiope et al. (2002)
Maccalube ponds	147	10	0.34	0.78	98.9	1.7	Etiope et al. (2002)
Maccalube MVs	71	10	0.29	1.15	98.8	0.9	Etiope et al. (2002)
Marianopoli	300	b.d.l.	0.48	2.12	93.39	2.93	Graziano (2009)
Santa Barbara					>95	<2	INGV (2008)
Salinelle S. Biagio	151	b.d.l.	b.d.l.	0.78	35.1	64.6	Etiope et al. (2002)
Salinelle Stadio	42	3	0.35	b.d.l.	4.2	95.5	Etiope et al. (2002)

Environmental threats affecting and/or originating from mud volcanoes

Mud volcanoes are a source of risks for anthropogenic activities but, at the same time, can be seriously threatened by these. The necessary condition for triggering this "two-ways" environmental treat, e.g., the close proximity between mud volcanoes and anthropized areas, is often found in Sicily.

The main risks for the population living close to mud volcanoes concern their paroxysmal events, during which strong gas blasts can produce seismic shocks able to damage buildings, roads and other facilities. Secondarily, the sudden expulsion and fallout of huge amounts of mud, mixed with soil and clay clots, can seriously injure persons present in their vicinity.

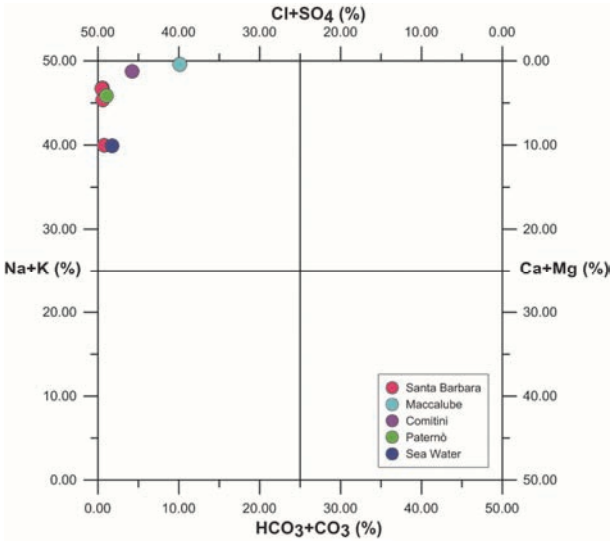

Fig. 3: Langelier–Ludwig diagram reporting the chemical data of waters emitted by Sicilian mud volcanoes. Composition of Mediterranean Sea Water is also given for comparison.

During the last paroxysm from Santa Barbara mud volcanoes, dated August 2008 and described by Madonia et al. (2011), damages of millions of Euros were caused by a near-surface seismic shock induced by the strong gas blast that shortly preceded the eruption. Within a radius of several hundreds of meters around the mud volcanoes, the walls of several buildings were damaged by the opening of wide cracks and many roads were interrupted by deep fractures. Similar problems were reported in 1999 at Bissana, where a paroxysm caused the damage of the local roads (Etiope et al. 2002).

Fortunately, no victims or injured people were reported during mud volcanoes paroxysms in Sicily, even if this potential risk is very high in some sites. Santa Barbara and Salinelle Stadio are located within heavily urbanized areas, and the immediate surroundings of these mud volcanoes are used as occasional playgrounds by children. Moreover, the Aragona site is the core of a natural reserve frequented by ecological tourism, especially during the warm season. On the opposite, the proximity to inhabited areas represents a serious problem for the survival of these geosites, threatened by the illegal discharge of wastes (Santa Barbara, Salinelle Stadio), the concreting of rural land due to the expansion of the city suburbs (Salinelle Stadio) and, when mud volcanoes are located in cultivated fields (Marianopoli), by the periodic plowing of the soil.

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