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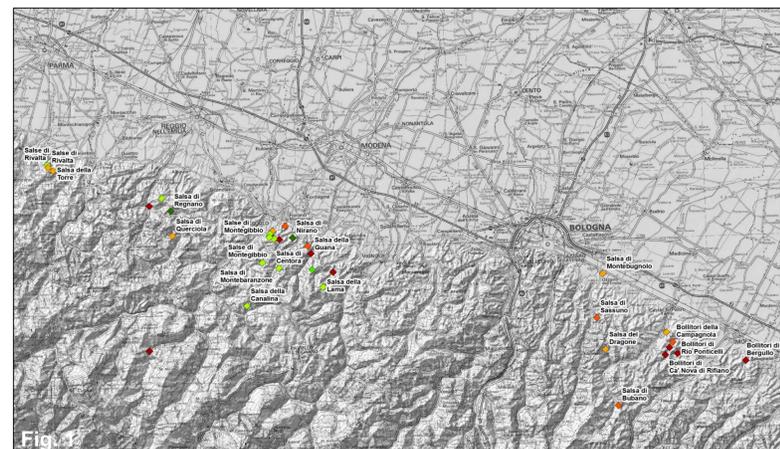
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Mud volcanoes are historically documented geological phenomena. They are also to be found in the Po side of the Northern Apennines (Italy).

Information on positioning of mud volcanoes, years of recorded activations and type of episodes were collected considering historical bibliography. For the first time, these data were analysed by GIS techniques, deriving maps and statistics.

Among references: Biasutti, 1907; Coppi, 1875; Gorgoni, 2003; Govi 1906, 1908; Mucchi, 1966; Scicli, 1972; Spallanzani, 1795; Stöhr, 1867; Stoppani, 1876.

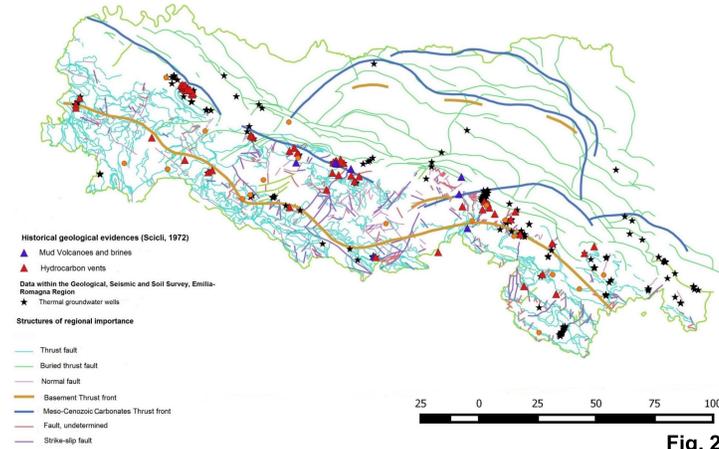
## General setting



**Fig. 1.** Mud volcanoes are mostly to be found near the Emilia Apennine margin, in the Parma, Reggio Emilia, Modena and Bologna provinces. Locally they are known as “Salse” (from the Latin “salsus”, salty) because of brines accompanying their activity. They are made of grouped vents that allow the release of gases (methane) and salty mud, sometimes with lithic debris or even boulders. A few show eruptions accompanied with explosive activity, the majority presents a continuous release of mud. According to historical data and geological field evidences, some of them (i.e. Montegibbio) are dormant, that is temporarily not active, or less active than in the past.

Arrows point-out some of the historically analysed “Salse”, located in the Reggio Emilia and Modena Apennines, where they are more abundant.

## Structural setting

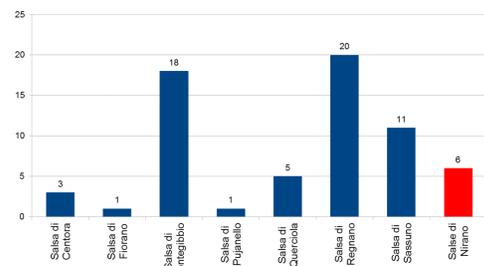


**Fig. 2.** The distribution of vents describes alignments, governed by faults, NW-SE oriented or transverse ones, according to the local structural framework. The Emilia mud volcanoes are to be found nearby Pedeapennine structures, though “dry” gaseous hydrocarbon vents are aligned according to the Basement Thrust Front, an inner and deep-seated fault system. These geological evidences are indicative of the extrusion of fluids: mainly gases originated by deep hydrocarbon reservoirs, with accessory groundwater and fossil salty water. The sketch map is based on historical data on locations (Scicli, 1972) verified by orthophoto imagery, coupled with data on thermal/highly mineralized groundwaters and structures derived from databases in the Geological Survey of Emilia-Romagna Region.

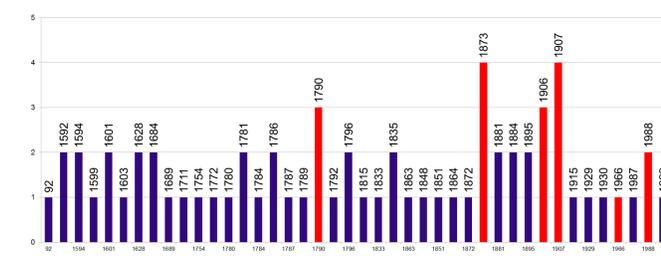
## Historically documented activations, Reggio Emilia and Modena Apennines

Historical naturalistic and geological studies have been collected, analysed and geological information derived from descriptions, sometimes rich of literary details typical of storytelling. The literature was divided into two parts:

1) scientific-historical reports written by Authors from the 18th to the early 20th century. Activations here documented in more ancient times (Roman Age, 16th, 17th centuries) were quoted as well. 2) quasi-historical publications, that is more recent studies carried out from 1966 to 2004.

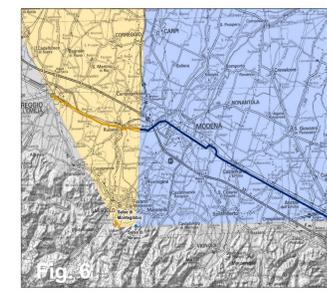
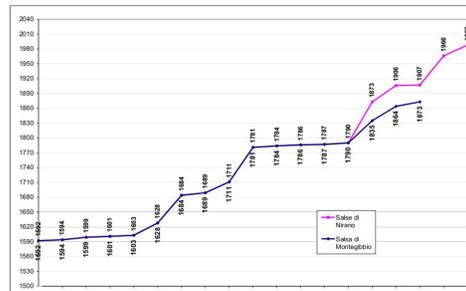


**Fig. 3.** Documented activations (number) of mud volcanoes, mainly located in the Reggio Emilia and Modena Apennines (arrows in Fig. 1). In red, the Salse of Nirano; high values correspond to mud volcanoes characterized by explosive past or present activity.



**Fig. 4.** Number of activations per year, documented for the Modena and Reggio Emilia mud volcanoes. In red, data referred to the Nirano mud volcanoes, the best preserved example of “Salse” in the Emilian sector of the Northern Apennines, thanks to a Regional natural protected area established in 1982.

## Historically documented activations: comparing Montegibbio with Nirano mud volcanoes



**Fig. 5.** Historically documented activations for the Montegibbio and Nirano mud volcanoes. Records for Montegibbio are more numerous, due to the paroxysmal explosions that frightened inhabitants and stir-up the interest of natural observers and local governments. Since the last episodes in the 19th century, Montegibbio is dormant though not extinguished: ephemeral (Salse di Sopra, Fig. 10) and small (Salse di Sotto 10a, 10b) group of vents are present. Nirano presents a continuous activity nowadays.

**Fig. 6.** The most ancient, documented activation in the Montegibbio and Nirano area is the one in 92 BC, described by Plinius the Senior. Explosions and fires captured the attention of Roman chivalry riding along the Via Aemilia, near the town of Mutina (Modena). By GIS simulations, calculating visual angles under the condition of a conservative topography of Nirano, explosions were due to the Montegibbio mud volcano and could be seen from Reggio Emilia to the surroundings of Modena (yellow sector). Otherwise, explosions could be attributed to Nirano, visible from Bologna to Modena (blue sector), if the latter had been 100 meters in elevation higher than nowadays.

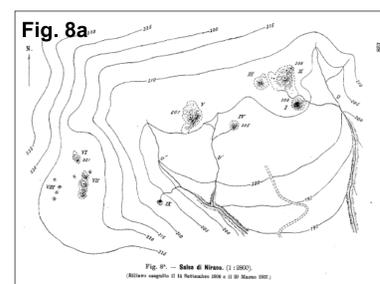
## The Nirano mud volcanoes, nowadays and in historical mapping



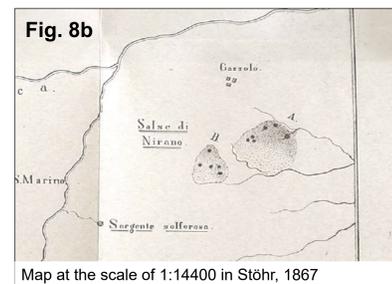
**Fig. 7.** The Nirano mud volcanoes, in a recent ortophoto imagery (Agea, 2011). The vents are distributed in seven cone-shaped groups. In grey, bare and active mud deposits. They describe a N64 azimuth (dotted) alignment, matching nearby transverse structures documented in local geological maps, interpreted as sinistral strike-slip faults (in: Castaldini *et alii*, 2017, «Studi interdisciplinari in Scienze della Terra per la fruizione in sicurezza della Riserva Naturale delle Salse di Nirano» *cum bibl.*). a) and b) mark the point of view of photos 7a and 7b respectively.



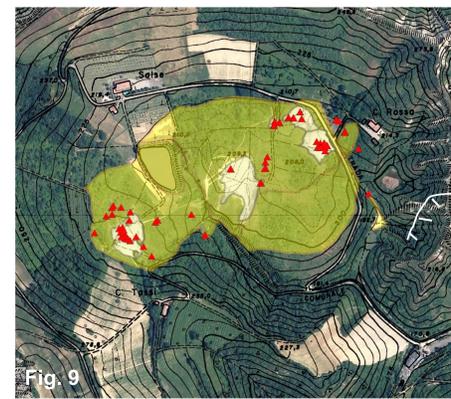
7a, Historical, general view of the Nirano mud volcanoes; photo taken in the '70s. «Delfino Insolera» collection  
7b, View of the north-eastern cones, as they appear nowadays



**Figs. 8a.** Sketch-map of the Nirano groups of vents, drawn by Biasutti in 1907 and derived from field notes of the Author, a vivid portrait suitable for a comparison with present days evidences. **8b.** Map published by Stöhr, 1867, detail on Nirano, active deposits in dotted areas. Both maps point out the subdivision between the more elevated western group of vents, the so called “Salsa Alta” and the other groups.



Map at the scale of 1:14400 in Stöhr, 1867



**Fig. 9.** GIS map with bare, muddy active deposits (in grey), superposed on older ones colonized by halophyte vegetation (yellow area). Vents (red triangles) were surveyed in 2014-2016, for an interdisciplinary study promoted by Modena University, Fiorano Municipality and the Geological Survey of Emilia-Romagna Region

(Castaldini *et alii*, 2017). Older deposits were made up by the superposition of past mud flows; the more elevated “Salsa Alta” and the presence of a scarp suggest the existence of different phases of accretion.

## The Montegibbio mud volcanoes, nowadays and in historical mapping



**Fig. 10.**

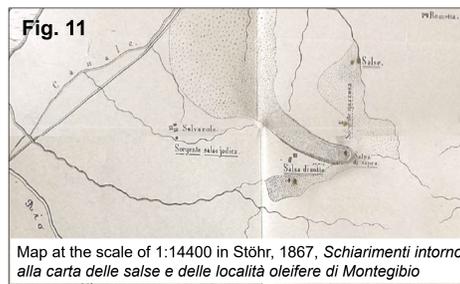


**10a**



**10b**

**Fig. 12.** GIS map with deposits mapped by Stöhr in 1867 (blue polygons) matched with field evidences of debris deposits built up by past emissions. The area is now urbanized. If compared to Nirano, where muds are widespread, Montegibbio deposits are made up of



**Fig. 11.** Biasutti (1907) did not draw any map of Montegibbio, though Stöhr (1867) published a report on historically documented eruptions, completed by a map of the deposits in the second half of 19th century (dotted areas) based on field surveying.



**Fig. 12**

muds, blocks and boulders of limestones and sandstones. The vents crop out in proximity of the tectonized contact between the pelitic Pliocene “Argille Azzurre” and older chaotic units, made up of shales with limestone blocks. Red triangles symbolize the Salse di Sotto (10a and 10b) active vents.