Mud Volcanoes in the Emilia-Romagna Apennines: Small Landforms of Outstanding Scenic and Scientific Value

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Abstract

Mud volcanoes are emissions of cold mud due to the ascent to the surface of salty and muddy waters mixed with gaseous (methane) and, in minor part, fluid hydrocarbons (petroleum veils) along faults and fractures. In the Emilia-Romagna Apennines (Northern Italy) mud volcanoes are closely linked to the active tectonic compression associated with a thrust of regional importance. They are mostly cone shaped and show variable geometry and size, ranging from one to few metres, and are located in 19 sites in the northwestern part of the Apennines. The mud volcanoes of the region have been known since a long time and have always aroused great interest due to their outstanding scenic value. In the past, the mud volcano emissions have been used in many ways: the mud was applied for cosmetic use and the natural oil was much appreciated for its balsamic and purgative properties. In the last decades, the mud volcanoes have represented relevant tourist attractiveness.

Keywords

Mud volcanoes • Geotourism • Emilia-Romagna Apennines

19.1 Introduction

Mud volcanoes are usually cone-shaped landforms constructed by the extrusion of mud, rock fragments, fluids (such as saline water and fluid hydrocarbons) and gases. The normal activity of mud volcanoes consists of gradual and progressive outflows of semi-liquid material. Explosive and paroxysmal activities are responsible for ejecting mud and decimetric to metric clasts.

The occurrence of mud volcanoes is controlled by several factors, such as tectonic activity, sedimentary loading due to rapid sedimentation, the existence of thick, fine-grained plastic sediments and continuous hydrocarbon accumulation (cf. Dimitrov 2002). Mud volcanoes have variable geometry and size, from one to two metres to several hundred metres in height. These features, expression of a remarkable natural process initiated deep in the sedimentary succession, are distributed worldwide, both inland and offshore. They can be found in a wide variety of tectonic settings, including passive continental margins, continental interiors, as well as transform and convergent plate boundaries. Anyhow they typically predominate at converging plate boundaries and are disseminated all along the Alpine-Himalayan, Pacific and Caribbean mobile belts.

The principal gas emitted by mud volcano eruptions is thermogenic methane, generated within the sediments at depths often greater than 10 km. It is commonly accepted that overpressure generated by methane-rich fluids is one of the main driving mechanisms triggering mud volcanism (Dimitrov 2002). Despite their name, morphology and the resemblance in the activity are the only characteristics of mud volcanoes that link them with magmatic volcanism. They generally exhibit a typical cone form, although of smaller dimension than the magmatic relatives, but other forms, such as sharp cones, flat and plateau cones, dome shapes, calderas, can be distinguished. Mud volcanoes appear to be generally characterised by a gentle activity, but they may occasionally experience impressive explosive

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M. Soldati and M. Marchetti (eds.), *Landscapes and Landforms of Italy*,
World Geomorphological Landscapes, DOI 10.1007/978-3-319-26194-2_19

eruptions, with violent ejection of mud and rock blocks often accompanied by flames produced by self-ignition of the methane contained in the mud.

Mud volcanoes show a high scenic value and are well known from many areas of the world such as Azerbaijan, Mexico, Venezuela, Colombia and Ecuador. In Europe they can be found in Italy, Albania and Romania. They are quite common in Italy, with the most spectacular ones located in Emilia-Romagna and in Sicily. Italian mud volcanoes are generally characterised by relatively small apparatuses, and occur along the external compressive margin of the Apennine chain (Martinelli and Judd 2004). They are clustered in three main geographical groups: northern Apennines (Pede-Apennines margin of Emilia-Romagna), central Apennines (eastern Marche and Abruzzo) and Sicily. Moreover, there are also few mud volcanoes offshore in the central sector of the Adriatic Sea (Fig. 19.1).

The mud volcanoes of Italy have been known for a long time and have always aroused great interest. They were first described by Pliny the Elder, at around 50 AD, in his monumental "Naturalis Historia". Others in the following centuries described the mud volcanoes with fantastic attributes of impressiveness and spectacularity (e.g. the naturalists Spallanzani, at the end of the eighteenth century, and the Abbot Stoppani at the end of nineteenth century).

19.2 Mud Volcanoes in the Emilia-Romagna Apennines

Mud volcanoes of relatively small size (≤ 500 m^2), but of high scientific interest and scenic value, punctuate the northwestern sector of the Pede-Apennine front of Emilia-Romagna, between Parma and Bologna, representing almost 30% of all those present on the Italian territory (Figs. 19.1 and 19.2). They are genetically linked to the ascent of salty and muddy waters mixed with gaseous (methane) to the surface and, in minor part, with circulation of fluid hydrocarbons (petroleum veils) along tectonic discontinuities produced by the overthrusting of the Apennine chain front. Their local name "Salse" results from the high "salt" content of the muddy waters whose origin is related to the presence of the sea that occupied the present Po Plain till about one million years ago and that deposited clays which nowadays outcrop in the hilly sector of the Apennines.

The shape of the mud ejection apparatuses depends on the density of the muddy mixture: if it is dense, cones (single, double or multiple) of height ranging from a few decimetres to some metres may develop; if the muddy mixture is liquid, ground level-pool mud volcanoes (diameters ranging from a few decimetres to some metres) are formed. The cones have the classic shape of a volcano, occupy roughly circular areas, and stand up above the general ground level. They intermittently emit gas bubbles and muddy water from a crater; these vary from a few centimetres to almost a metre in diameter (Fig. 19.3).

Mud volcanoes show a rather discontinuous activity; sometimes old apparatuses become dormant or even extinct whereas new vents can appear in other spots. Therefore, the morphology of mud volcano areas is constantly evolving with the formation of new craters whilst others cease their activity.

The clayey materials ejected from the craters cover the surrounding ground with mudflows; owing to their fluidity, mud flows can cover distances of up to 100 m from the vent. In the hot season, the shrinking of mud deposits creates typical polygonal mud cracks (Fig. 19.4).

From a geological point of view the Emilia-Romagna Apennines are a fold-and-thrust belt, characterised by complex structures and geodynamic evolution. The northern Apennines originated from the consumption of the Liguria-Piedmont oceanic basin, located in the western Tethys, and the consequent collision between the Adria plate and the European plate, which started in the Upper Cretaceous (Bosellini 2017).

The mud volcanoes occur above the hanging wall of the active Pede-Apennine thrust, and thus have their origin in the deformation associated with this regional structure (Manga and Bonini 2012). In this sector of the Apennines, the following main structural and stratigraphic units crop out (Fig. 19.2): (i) Ligurian Units made up of deep-sea sediments, including Jurassic Ophiolites, followed by thick sequences of Cretaceous to Eocene calcareous or terrigeneous turbidites; (ii) mainly terrigenous Epiligurian Succession of Middle Eocene to late Messinian, uncorformably resting on the previously deformed Ligurian Units; (iii) prevalently marly-clayey Late Miocene–Pleistocene marine rocks.

The morphology of this sector of the Apennines is strongly influenced by this sequence of lithotypes. In the surroundings of mud volcanoes, clayey terrains largely outcrop which are characterised by typical and locally spectacular "calanchi" landforms (badlands). They are typically shaped in clayey soils due to concentrated gully erosion. The landscape is also characterised by several landslides of different types, from shallow movements to large-scale displacements.

19.3 The Landscape of Mud Volcanoes in the Emilia Pede-Apennines

The mud volcanoes of the Pede-Apennine front of the Emilia-Romagna Region are mainly located in the Emilia sector (the northwestern one) and are associated with a SSW-dipping thrust.

Fig. 19.1 The geographical distribution of mud volcanoes inland (*red dots*) and offshore (*yellow dots*) in Italy (*data source* Martinelli and Judd 2004). The box refers to the mud volcanoes in Emilia-Romagna Apennines (see Fig. 19.2)

Here below only the mud volcano areas with scenic value (and easily accessible) are described (Fig. 19.2).

19.3.1 Mud Volcanoes of the Parma Apennines

The mud volcanoes of the Parma Apennines are located in three sites in which the formations of the Epiligurian Succession outcrop. In detail, in the hills of Parma Apennines the mud volcanoes of Rivalta, Torre and S. Polo d'Enza (n. 1, 2, 3 in Fig. 19.2) can be found. All these sites are modest in size and have no volcanoes with height of over 50 cm. Noteworthy are the first two mud volcano fields which occur in elliptical depressions (approximately coincident with the axis of an WNW–ESE trending anticline) interpreted as mud calderas (Bonini 2012). The Rivalta field is hosted in a sub-tabular mud-filled depression at an altitude between 320 and 325 m a.s.l.; active vents occur as small cones and bubbling pools in the depression central sector (Fig. 19.3a). The Torre field depression exhibits comparatively steeper scarps that connect to a gentler zone likely to represent the residual caldera floor. Fluid venting, consisting of bubbling mud pots, occurs in two zones corresponding to the apical part of small creeks entering the amphitheatre at about 330 m a.s.l.

In Rivalta and Torre sites, agricultural activity interferes with muddy emissions, with varying effects in space and time; in fact owing to their high fluidity, the ejected mud flows tend to create small swamps, which can disappear as a result of agricultural activity.

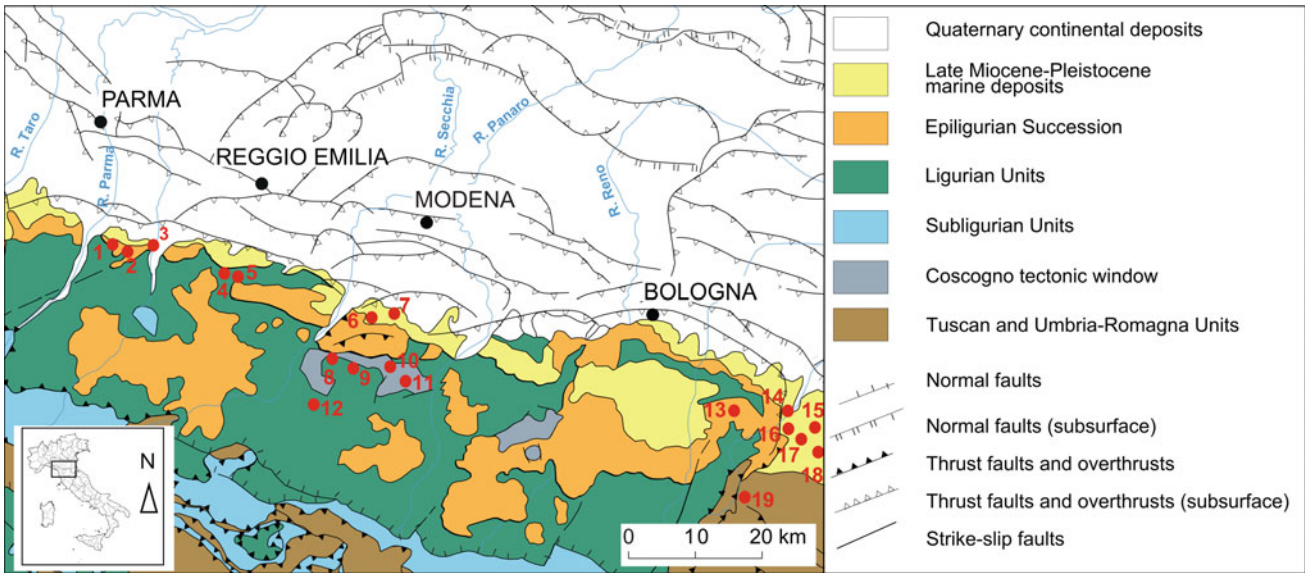

Fig. 19.2 Geological sketch map of the Emilia Apennines (modified after Remitti et al. 2012). Areas of mud volcanism (*red dots*): *1* Rivalta; *2* Torre; *3* San Polo d'Enza; *4* Casola-Querciola; *5* Regnano; *6* Montegibbio; *7* Nirano; *8* Montebaranzone; *9* Centora; *10* Madonna di Puianello; *11* Ospitaletto; *12* Canalina; *13* Sassuno; *14* San Martino in Pedriolo; *15* Bergullo; *16* Sallustra Valley; *17* Pedriaga; *18* Casalfiumanese; *19* Cà Rubano

19.3.2 Mud Volcanoes of the Reggio Emilia Apennines

The mud volcanoes of the Reggio Emilia Apennines are located in the Ligurian Units outcropping in the Viano district close to Regnano and Casola-Querciola hamlets (n. 4 and 5 in Fig. 19.2). The Regnano mud volcano is the second mud volcano field in size, surpassed in all Emilia-Romagna Apennines only by that of Nirano (Modena Apennines); it consists of mud breccias and mud flows spreading over an area of about 1 ha. The Regnano mud volcano field is found at an altitude between 420 and 430 m a.s.l., on the top of a slope which faces eastward. The apparatuses are aligned along normal faults which allow surface leakage of fluid derived from sources located at a depth between 3 and 6 km. The fault system associated with the Regnano mud volcanoes drains a Miocene reservoir which supplies formation water and thermogenic methane (Capozzi and Picotti 2002). The activity sometimes is quite remarkable and occurs in several vents. So much that the main mud ejection mouths assume a cone trunk shape and the relative mud flows remain as higher ground than the surrounding terrain (Figs. 19.3b and 19.4). The Casola-Querciola mud volcanoes are located in an almost flat zone (at about 440 m a.s.l.), a few kilometres far to northwest of Regnano and they are mainly level-pool mud volcanoes. A new mud ejection point, which was formed in July 2014, affects a secondary road causing problems to the local traffic. For both Regnano and Casola-Querciola areas, educational footpaths with panels were built in July 2015.

19.3.3 Mud Volcanoes of the Modena Apennines

In the Modena Apennines, mud volcanism occurs in a wide area (diameter of about 20 km) in which formations belonging to Ligurian Units, Epiligurian Succession and Late Miocene–Pleistocene marine deposits outcrop. In detail, mud volcanoes are found in six areas: Montegibbio, Nirano, Montebaranzone, Centora, Madonna di Puianello, Ospitaletto and Canalina (n. 6 to 12 in Fig. 19.2).

The Montegibbio mud volcano field, in the Sassuolo district (n. 6 in Fig. 19.2), is currently represented by few small pools of salty waters, with limited gas bubbling, rather than true mud volcanoes; such pools occur within a moderately elongated depression at an altitude of about 230 m a.s.l. Historical records report an extremely intense activity, characterised by emissions accompanied by explosions and by a large cone approximately 10 m tall, described by several authors. Even the eruption of 91 BC mentioned by Pliny is believed to have caused extensive damage to historical Roman settlements. Extensive clay deposits widespread downstream the Montegibbio mud volcanoes are evidence of this eruptive event. The decreased activity could be partly explained by the exploitation of subsurface fluids for supplying the adjacent Salvarola spa (Bonini 2009). The mud volcano that caused the large 1835 eruption (described in detail and mapped by nineteenth century authors) is now extinct and looks like a small hill which has its top at 281 m a.s.l. The 1835 eruption was accompanied by a seismic tremor that was perceived by the population up to several

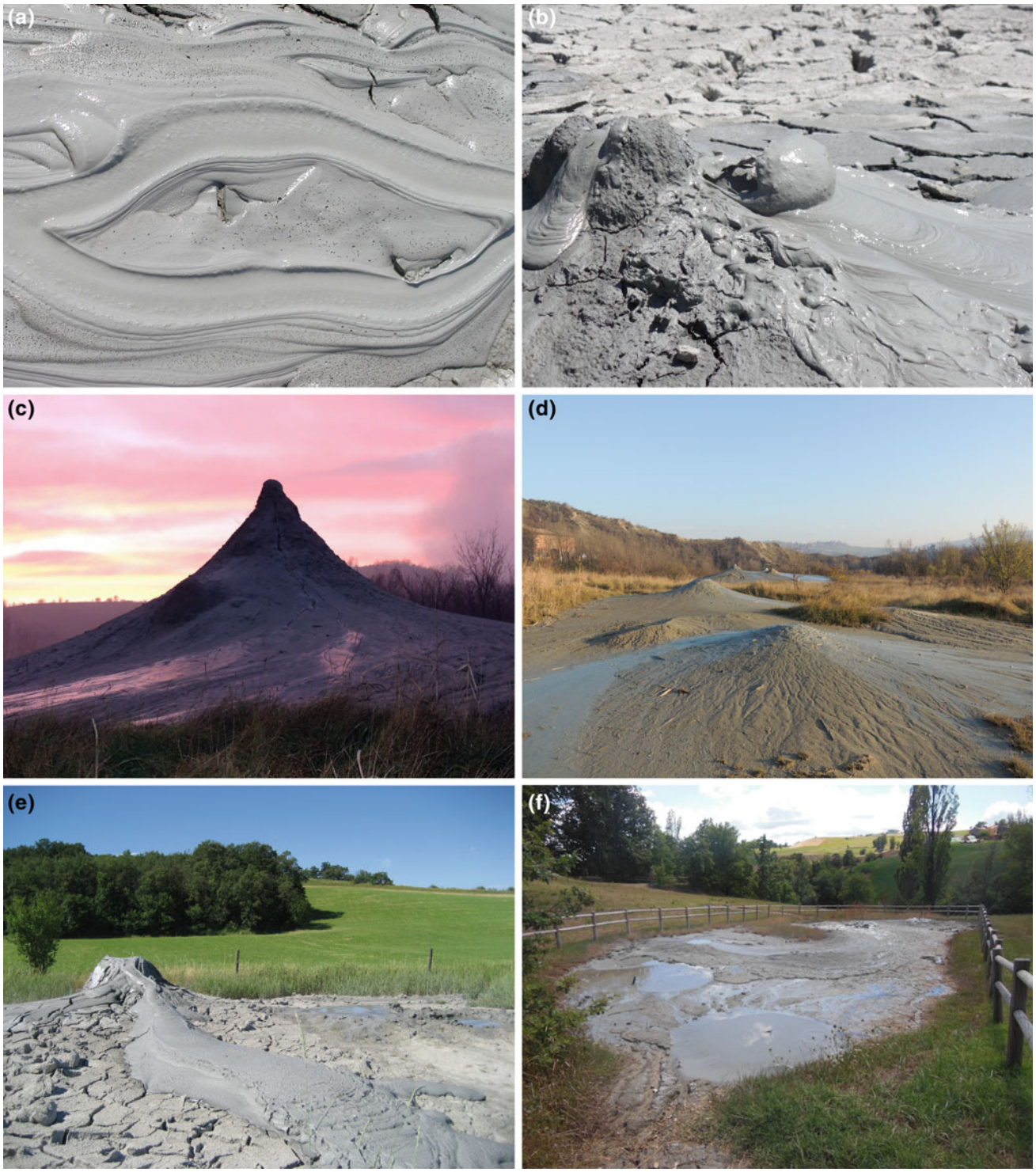

Fig. 19.3 Mud volcanoes in the Emilia Pede-Apennines: **a** close-up of ducted high-velocity flow at Torre mud volcanoes (Parma Apennines) (*photo* J. Valdati); **b** close-up of the main mud ejection mouth of the Regnano mud volcanism area (Reggio Emilia Apennines) (*photo* N. Borghi); **c** cone of the Nirano Natural Reserve mud volcanoes field at sunset (Modena Apennines) (*photo* L. Callegari); **d** panoramic view over some of the mud cones of Nirano Natural Reserve (Modena Apennines) (*photo* L. Callegari); **e** cone and mudflow in the Madonna di Puianello area (Modena Apennines) (*photo* C. Rebecchi); **f** level-pool mud volcanoes of Ospitaletto (Modena Apennines) (*photo* D. Castaldini)

Fig. 19.4 Main mud ejection mouths of the Regnano mud volcanism area in the Reggio Emilia Apennines (*photo* D. Castaldini)

kilometres away; the volume of mud emitted was estimated at 500,000 m^3, whereas the spout of ejection reached a height of 40 m and the eruptive deposit was distributed over an area of 30,000 m^2.

Particularly noteworthy is the Nirano mud volcano field (n. 7 in Fig. 19.2), located in the Fiorano Modenese district, which, with a surface area of approximately 75,000 m^2, is one of the best developed and largest mud volcano field of the entire Italian territory and among the largest in Europe; it is thus protected as natural reserve (Salse di Nirano) since 1982. The Nirano mud volcanoes are found at the bottom of an elliptical depression (Fig. 19.5), interpreted as a collapse-like structure (caldera) that may have developed in response to the emptying of a shallow mud chamber triggered by several ejections and evacuation of fluid sediments (Castaldini et al. 2005); the bottom of the depression is at *ca.* 200 m and the rim at 250 m a.s.l. The Nirano field is characterised by the presence of two main systems of faults/fractures, SW–NE and NW–SE oriented, respectively. They are highlighted by the arrangements of mud volcanoes, which show clear alignments, and by the elongated shape of the caldera (Castaldini et al. 2005; Bonini 2008).

There are several individual or multiple cones within the field of the mud volcanoes of Nirano (Fig. 19.3c, d), but it is not possible to provide the exact number of mud-ejecting points, because the morphology of this area is constantly evolving. In fact, they have a rather discontinuous activity; apparatuses become dormant or even extinct whereas new vents can appear in other spots. Nowadays, mud emission occurs clustered into five main venting areas constituted by cones as well as level-pool mud volcanoes. A mud chamber was identified at a depth of 25 m; this mud chamber could represent the last phase of mud accumulation before the final emission, not excluding the existence of deeper larger reservoirs (Accaino et al. 2007).

Other geomorphological features in the Natural Reserve of Salse di Nirano are badlands which are quite evident on many slopes (Fig. 19.5). The numerous facilities, excursion and educational footpaths with panels, equipped trails (one for people with disabilities), the Cà Tassi visitor centre and the Cà Rossa eco-museum, make the area accessible to all, supporting environmental education initiatives.

The Madonna di Puianello vents (n. 10 in Fig. 19.2) occur in two areas located in the Maranello district. The most important mud volcanism site is found near Casa Possessione, in a flat depression at the altitude of 440 m a.s.l. that probably represents a caldera-like feature (Bonini 2012). Actually, it is characterised by three main cones aligned in a WNW–ESE direction and three main bubbling mud level-pools. The mud ejection apparatuses (Fig. 19.3e) are located in a private property affected by agricultural activity from which are protected by wire mesh.

The Ospitaletto mud volcanism area (n. 11 in Fig. 19.2) is located in the Marano sul Panaro district at the bottom of a south-facing gentle concave depression at an altitude of about 525 m a.s.l. It is currently constituted by about a dozen of eruptive apparatuses with moderate activity: most of them are bubbling mud level-pools with diameter ranging

Fig. 19.5 Aerial view of the mud volcanoes of the Nirano Natural Reserve (Modena Apennines). The mud volcanoes (*grey spots*) are located at the *bottom* of an elliptical depression surrounded by badlands (*photo* G. Bertolini)

from about 0.1 to 1 m (Fig. 19.3f). The area is easy to reach by road and is outlined by educational panels.

The Centora, Montebaranzone and Canalina mud volcanoes (n. 8, 9 and 12, respectively, in Fig. 19.2) are nice examples of mud volcanism. Anyhow, they are difficult to be reached, and therefore less known and visited than the others sites.

19.3.4 Mud Volcanoes of the Bologna Apennines

In the Bologna Apennine front, seven mud volcano sites are located in the Umbria-Romagna Units, in the Epiligurian Succession and in the Late Miocene–Pleistocene marine deposits (n. 13 to 19 in Fig. 19.2) at altitudes ranging from *ca.* 50–500 m a.s.l. The most part of them have surface area <5 m^2 and are scarcely known. They are level-pool mud volcanoes with rather discontinuous activity. The only two Bologna Apennines mud volcanism areas described by previous authors are currently inaccessible as located in areas affected by landslides and badlands (mud volcanoes of Sassuno, n. 13 in Fig. 19.2) or hidden by the dense vegetation which covers the site where they are located (mud volcanoes of Bergullo, n. 15 in Fig. 19.2). One of the Bergullo vents is a 3 m diameter bubbling mud level-pools from which fluid is periodically exploited for supplying the near Riolo Terme spa.

19.4 Mud Volcano Eruptions and Earthquakes

From a general point of view, earthquakes have been considered to be a potentially important trigger for mud volcano eruptions (e.g. Martinelli and Panahi 2005; Bonini 2012), but mud volcanoes also erupt independently of seismicity.

Noteworthy is the occurrence of the above-mentioned giant mud volcano eruption, associated with the contemporaneous destructive earthquake of 91 BC that struck the Modena Pede-Apennine margin.

The relationships between seismicity and mud volcano activity have been testified by the strong seismic events that occurred in 2012 in northern Italy. In detail, in May 2012 a seismic sequence struck the lower central part of the Po Plain, located about 50 km NE of the Modena and Reggio Emilia Pede-Apennine front. The main shocks occurred on 20 and 29 May, with local magnitude 5.9 and 5.8,

respectively. The seismic sequence, due to buried Apennine faulted folds, caused a number of fatalities and significant damage as well as many ground effects such as cracks, liquefaction-type phenomena and hydrological anomalies (Emergeo Working Group 2013). A few days before the onset of the seismic sequence, an anomalous activity was observed in some mud volcanism areas. In particular in Nirano, Ospitaletto, Puianello, Regnano and Casola-Querciola areas (Modena and Reggio Emilia Apennines), normally inactive or poorly active mud volcanoes became active or showed increased activity and new small vents formed (Manga and Bonini 2012).

19.5 Cultural Value and Tourism Attractiveness

The peculiar geological phenomenon of mud volcanoes makes this sector of the Emilia-Romagna Apennines a site of worship and interest since the Roman period. In particular the field of Nirano has been known since ancient times and has been studied by historians, scientists and travellers. The area where the Nirano mud volcanoes are located was called "the beautiful place", due to the high aesthetic value of hilly landscapes forming the foothills of the Apennines. Since the Roman period, the Nirano area was a dwelling place of organised groups that worked with ceramics and bricks, as testified by many historical sources and proved by the discovery of an ancient crockery furnace. Probably, as in other cults and places, the area of the Nirano mud volcanoes had represented in the past an ideal place where the phenomenon of leakage of water and mud was interpreted as a prodigy. In his "Naturalis Historia", Pliny the Elder, as other scientists later from the seventeenth century, described the *salse* with apocalyptic and spectacular attributes. In particular, he described the eruption of a mud volcano in the Modena district, with skyscraping flames and smoke, seen from a distance of about 10 km, during which the violent ejection of overpressured mud was accompanied by methane combustion. At the end of the nineteenth century, the abbot Stoppani compared the *salse*'s phenomenon to molehills out of which noises similar to "retching" came out, giving them the epithet of "cesspool volcanoes" (Stoppani 1876) (Fig. 19.6).

Mud volcanoes are interesting owing also to the ecological changes induced by the widespread deposition of sodium chlorine. Indeed, the herbaceous plants which colonise the soil around mud volcanoes make up the most complete example of halophilous vegetation.

In addition to arouse interest and curiosity, the mud volcanoes between Nirano and Sassuolo (Modena Apennines), were used in many ways in the past. The mud from the *salse* was applied for cosmetic use as mud masks and for mud baths at the ancient Salvarola Spa, near Sassuolo. Also, natural oil of the *salse* was much appreciated for its balsamic and purgative properties and sold by monks of San Pietro in Modena. Nowadays, the mud is used only in veterinary science to blaze up articulations of horses.

Besides their cultural value, the Emilia-Romagna mud volcanoes represent a tourist attraction as testified by an increasing number of visitors (about 70,000 visitors in 2015

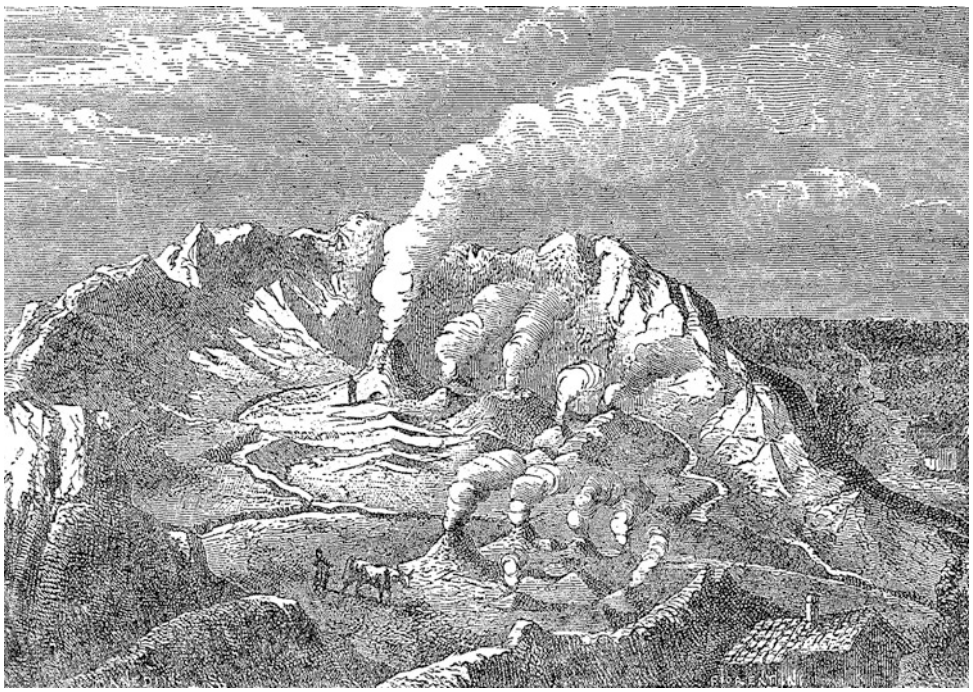

Fig. 19.6 The Salse di Nirano as illustrated in famous book "Il Bel Paese" by Abbot Antonio Stoppani (1876)

in the Salse di Nirano Natural Reserve). Numerous initiatives to improve access and enhance understanding have been developed in the last decades. In particular, tourist environmental maps, geotourism maps, books in hard copy and digital format, videos, virtual flights, multimedia and audio CDs have been implemented (e.g. Castaldini et al. 2011). These activities are targeted at various potential users, tourists, local residents, young people, schools, etc., and are aimed at the enhancement of geological and geomorphological aspects of the natural heritage making it available to the public.

Worthy of note is the 2015 initiative called the "Mud Volcanoes Route" for the promotion of the environment, art, wellness, tastes, technology and talent of the territory of districts of Viano (Reggio Emilia Apennines), Sassuolo, Fiorano Modenese and Maranello (Modena Apennines), in which part of the Emilia-Romagna mud volcano fields are located. The Mud Volcanoes Route is an emotional journey that connects places and excellences through the geological phenomenon of mud volcanoes.

19.6 Conclusions

Mud volcanoes are landforms of outstanding scenic value that are expression of a remarkable natural process initiated deep in the sedimentary succession. Although these features have a long history of investigation, in recent years interest in mud volcanism has increased for several reasons. A considerable impulse to investigations on this topic has been recorded in part because of petroleum exploration but also due to the role that mud volcanoes play in the global methane budget, a potent greenhouse gas.

Moreover, thanks to their scenic value, mud volcanoes generate tourist attraction; for example, the natural reserves of Northern Apennines of Nirano or the "vulcanii noroiosi" of Buzau (Eastern Carpathian foredeep, Romania) are relevant examples in Europe. Recently a growing interest in the heritage value of mud volcanoes has been observed in Emilia-Romagna, in relation to geoconservation and geotourism issues. In this context, in 2015 the above-mentioned Mud Volcanoes Route has been developed. The itinerary is outlined in a leaflet containing short explanation, photos and a map in which are located areas with mud volcanoes, castles, archaeological sites, historic and holy buildings and represents an initiative for the promotion of environment, art, wellness, tastes, technology and talent of the territory of these districts. Although the hazard from mud volcanoes is generally low, sometimes they may lead to sudden and violent eruptions and isolated casualties have been reported. Very notable cases in this regard are those of the Offida mud volcanoes (Ascoli Piceno, Marche Region), which at the end of 1959 exploded with a deafening roar, associated with a small earthquake and damaging some houses of the areas; or the most recent event that occurred in September 2014 in the Natural Reserve of Macalube di Aragona in Sicily where a mud volcano erupted, with an ejection of mud up to about 20 m above the ground and causing the burial of an adult and two children killing them. When a given geological site acquires a tourism value, it is necessary to assess the possible natural hazard processes which might threaten the safety of visitors (Soldati et al. 2008). In particular, fast-occurring processes might directly involve tourists in proximity of the site of interest or along access roads and footpaths. In this context, interdisciplinary research aiming at analysing the causes and understanding triggering mechanisms of paroxysmal and dangerous phenomena in the Natural Reserve of Nirano, are in progress, funded by the local municipality.

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