# Mud Flow Dynamics at Gas Seeps (Nirano *Salse*, Italy)

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# Abstract

The Nirano *Salse*, known since the Roman Times, are one of the most beautiful and scenic mud volcanoes areas of Italy with thousands of visitors every year. In this work, we apply hydrogeological techniques to characterize mud levels in the *Salse* by means of GPS-RTK positioning and continuous level logging within mud conduits. Our results suggest that different mud levels in mud volcanoes clusters are due to the different gas-liquid ratio in the conduits and not necessarily exclude interconnection at depth, a hypothesis, on the other hand, that seems strengthened by mud level time series correlations. The presence of shallow aquifers at a depth of 5 to 30 m is also supported by our field data. These shallow aquifers may provide a temporary storage for the ascending gas and when fluid pressure in these aquifers exceeds the tensional strength of the sedimentary rock, leakage of fluids to the surface would occur.


# 1. Introduction

Mud volcanoes are broadly distributed throughout the globe, both on land and below the seas (Milkov, 2000, 2005). In the last few decades mud volcanism has been widely investigated from the geological, geophysical, and geochemical points of view with important implications in energy resource exploration, seismicity, geo-hazard and greenhouse gas emissions (Mazzini and Etiope, 2017). Generally, the main driving forces for the mud volcanoes formation is a combination of gravitative instability, due to the overall low density of clay-bearing strata on surrounding units, and fluid overpressures, which can develop both in the same strata or in surrounding sedimentary rocks, shales, and reservoir rocks (Kopf, 2002; Revil, 2002). Hydrofracturing, due to the increase of fluid pressure or tectonic stresses, fault reactivation and seismicity, allows for the pressurised gas-water-sediment motion towards the surface and the brecciation of sedimentary units (Mazzini and Etiope, 2017). The manifestation to the surface can happen via progressive and slow release of mud and fluids, or in violent and explosive forms (Mazzini et al., 2021).

The mud volcanoes of Italy are clustered in four main geographical zones: in northern Apennines (mainly in the Emilia-Romagna Region); in central Apennines (Marche and Abruzzo Regions); in southern Apennines (in Basilicata, Calabria, and Campania Regions), and in Sicily (Gattuso et al., 2020). Italian mud volcanoes are small (area < 500 $m^2$), low (only 5% exceed 2 m in height), and characterized by the continuous, but relatively quiet expulsion of gas, water, and mud. Martinelli and Judd (2004) ascribed most of their formation to tectonic compression in areas with thick sedimentary sequences. The fluids rise from considerable depth within these sedimentary sequences as consequence of overpressures and the tectonic stress, possibly aided by the loss of density associated with gas generation. Specifically, in the northern Apennine foothills near *Fiorano Modenese* a 4-km-long mud volcanoes belt is currently active and located in the Regional Natural Reserve of Nirano *Salse* (Modena, Emilia-Romagna Region) (Bonini, 2012; Borgatti et al., 2019; Capozzi and Picotti, 2002). This area has been widely studied since the Reserve was established in 1982. Several studies focused on the structural geological setting of the area to explain relationships between mud volcanism and active tectonics (Bonini, 2008; Capozzi and

Picotti, 2002), as well as between mud volcanism, fluid venting, and fault/fracture zones (Bonini, 2007). Seismic and geo-electrical investigations were carried out to detect the sub-vertical structures of the superficial outlet of the volcanic conduits and chimneys (Accaino et al., 2007; Lupi et al., 2016). Micropaleontological studies on cones, level-pool mud vents and mud flows were used to identify the fluid source and reservoirs depths (Papazzoni, 2017). Several geochemical studies were carried out to characterize the fluid venting, deep fluid compositions, origin of these fluids, and verify the possible contribution of meteoric water (Boschetti et al., 2011; Conti et al., 2000; Martinelli et al., 2012; Mattavelli et al., 1983; Mattavelli and Novelli, 1988; Minissale et al., 2000; Oppo et al., 2017, 2013); extensive geochemical soil gas survey and exhalation fluxes ($CO_2$ and $CH_4$) were also carried out in the mud volcano field (Sciarra et al., 2019) to show geochemical anomalies that would indicate the presence of high permeability conduits and preferential leakage pathways for the gas migration.

To the best of the authors' knowledge a detailed hydrogeological characterization of the Nirano area is missing. Mud pool levels, as well as conduits connections have been explained so far in terms of overpressured fluids that are periodically expelled from the main deep reservoir by the creation or the reactivation of pre-existing fractures/faults or pipes, without considering the hydrogeological aspects. Bonini (2007) stated that, most likely, the persistent mud extrusion could be due to short-lived escape of overpressured fluids along permeable structures connecting the reservoir(s) to surface. In this contest, our paper aims at understanding the fluid dynamics and the connection of conduits. First, we focus on the review of previous integrated geophysical, morphological, and structural geological studies carried out in the study area (Section 2). Then, insights on hydraulic connectivity and the effect of a variable mix between gas and mud on fluid dynamics are achieved by continuous monitoring of mud levels and chemical-physical parameters in several conduits, measurements of gas bubbles frequency, as well as mud grain size analysis and density determinations (Section 3). Results are then discussed, and a conceptual model related to the presence of shallow small fluid-saturated aquifers in which gas is temporarily stored during its ascent from the deepest reservoirs, before the final emission, is presented (Sections 4 and 5).

# 2. Study Area Characterization

## 2.1. Morphology

The Regional Nature Reserve of the Nirano *Salse* is located at the edge of the Northern Apennines (Modena, Italy), an area that is characterized by several active fluid vents (Figure 1).

With a surface of approximately 75000 m$^2$, Nirano is one of the largest mud volcanoes areas of Italy. It is situated at the bottom of a caldera-like structure within a hilly landscape. The oval depression (caldera) is interpreted to be the result of the gravitational collapse of a mud diapir top, which broke to the surface within the Plio-Pleistocene succession, due to degassing, emissions of mud and fluid, and emptying of mud chambers (Bonini, 2008).

The name Nirano *Salse* is not indicating large mud lakes where gas gently bubbles to the surface as the term *Salse* would imply today in the scientific literature (Tingay et al., 2009), but an area with different fluid emissions. There are several individual active cones and subcircular pools distributed at the feet of gryphons within an area of recently extruded mud that has not been colonized by vegetation yet. The actual number and location of the cones vary over time as the area is in constant evolution. Volcanoes morphology depends mostly on the characteristics of extruded cold muds and persistence of degassing produced by the rising to the surface of salty and muddy water mixed with gas (mostly $CH_4$) and, to a lesser extent, liquid hydrocarbons.

The largest cones have a basal diameter of about 4-5 m, a rim with a diameter of 0.2-2 m and, a height of 2-3 m above ground; they intermittently emit gas bubbles and muddy water in variable flow rates. Generally, there is a continuous supply of small bubbles (about a few centimetres in diameter), but their frequency may vary and every few minutes larger bubbles break the surface. The main Nirano mud volcano emits an estimated 100 to 300 $m^3$ of gas per day (Martinelli and Rabbi, 1998). According to Oppo et al. (2013), the volume of emitted fluids varies significantly from well-developed mud volcanoes to gryphons, and mud pools. In the first case the slow dense mud runs down the sides of the cones, dries out, and increases the steep slopes of the structure; in the second case, mud pools seem to contain less viscous mud and have a more abundant and continuous emission of saline water and gas.

## 2.2. Mud characterization

Fluid venting at the surface consists of a mixture of cold clay mud, brackish water, gas mixtures dominated by methane and sometimes $CO_2$, liquid hydrocarbons, and peat fragments from levels encountered during fluid’s ascent. The mud extrusion is driven by the adiabatic expansion of methane during the ascent and the consequent decrease in the fluid density compared to the surrounding rocks (Martinelli et al., 2012; Mattavelli et al., 1983; Mattavelli and Novelli, 1988), and the increase in overpressure where gas accumulates (bottlenecks in the conduits and reservoirs).

The saline composition, $\delta D$ and $\delta^{18}O$ signatures indicate that part of the waters originates from marine connate pore waters entrapped in the Miocene and Plio-Pleistocene sediments during marine deposition, with no contamination from recent meteoric water (Conti et al., 2000; Heller et al., 2011; Martinelli and Judd, 2004; Minissale et al., 2000; Oppo et al., 2013). Geochemical analyses, both on water and gas samples, show that the gas contained in these reservoirs is mainly a mixture of primary and secondary thermogenic gases (due to thermal cracking of oil), and secondary biogenic methane (due to biodegradation of oils), with minor condensates and oil (Oppo et al., 2017; Tassi et al., 2012). Several authors (Martinelli et al., 2012; Mattavelli et al., 1983, 1993; Riva et al., 1986) recognize that in this region of the Northern Apennines, the hydrocarbons (gas and oil) originate in the turbiditic sequences of the Tertiary *Marnosa Arenacea* Fm. Micropaleontological analysis on cones, level-pool mud vents, and mud flows, however, indicated homogeneous fossil assemblages, all consistent with the Plio-Pleistocene age of the *Argille Azzurre* Fm (FAA) (Papazzoni, 2017) (Figure 1).

More recent data suggest that a common source rock responsible for the generation of these hydrocarbons could be located at greater depth than the Tertiary reservoir units (Bonini, 2009; Capozzi and Picotti, 2010, 2002; Oppo et al., 2013; Picotti et al., 2007).

## 2.3. Structural geology

The Nirano area has a typical badland morphology due to the outcrops of the *Argille Azzurre* Fm (Figure 1), made up of fine-grained sediments of Pliocene to Pleistocene age. The study site is 4 km south of the main seismogenic Pedeappennine thrust (Figure 1a) and Bonini (2008, 2009) maps a NW-SE oriented anticline axis dividing in half the geomorphological bowl (caldera) where the gas emissions are active today (Figure 1b). Current seismicity in the area is due mainly to thrust (Magnitudes 3.0 to 4.0) and strike-slip faulting (Magnitudes 3.5-5).

The Nirano mud volcanoes are interpreted to be just above a NW-SE blind thrust anticline (Bonini, 2008, 2009, 2012). The gas emissions would be the surface expression of fluids escaping from a deep leaky reservoir (about 1.5 km) located in the *Marnoso Arenacea* Fm, and eventually from shallower (400-500 m from the topographic surface) reservoirs located in permeable Epiligurian units of Eocene-Miocene Age (Bonini, 2007, 2008).

The mud volcanoes are roughly oriented along a NE-SW trend (Figure 2), which correlates with the maximum horizontal in-situ stress ($S_H$) direction due to Appennine shortening. Bonini (2009, 2008) interprets both the alignment of the mud volcanoes and the shape of the geomorphological bowl as the result of the in-situ stress conditions present in the Nirano area. Any gas accumulation within a subsurface reservoir would increase the pore pressure due to buoyancy (Dasgupta and Mukherjee, 2020); if the sealing unit has not a good quality, the gas may rise towards the surface following faults and fracture zones or simply fingering through poorly consolidated mud sediments.

# 3. Methodology

## 3.1. Mud monitoring and analysis

A total number of 2 mud pools and 2 small gryphons were equipped with level-loggers LTC Solinst for monitoring mud hydrostatic pressure, temperature (T), and electrical conductivity (EC) at different time intervals (every second for a total of 4.5-hour monitoring, and every 5 minutes) (Figure 2). The probes were installed at different depths as reported in Table 1. The time series collected go from July 7, 2020, to January 7, 2021. The hydrostatic pressure data measured by the divers were converted into levels considering the atmospheric pressure data recorded by the weather stations of Vignola (Modena) and available from the Regional Agency for Prevention, Environment, and Energy of Emilia-Romagna (ARPAE website; https://simc.arpae.it/dext3r/), based on the following equations and Figure 3.

$$MC = 9806.65\frac{P_{diver}-P_{baro}}{\rho g} \tag{1}$$

where $MC$ is the mud column above the diver (m), $P_{diver}$ is the pressure exerted by the mud column and recorded by the diver (m $H_20$), $P_{baro}$ is the atmospheric pressure (m $H_2O$), $g$ is the acceleration of gravity (m/$s^2$), and $\rho$ is the mud density (kg/$m^3$).

The mud level ($ML$) in relation to the vertical reference datum (mean sea level, m.s.l.) is as follow:

$$ML = TOC - CL + MC \tag{2}$$

where $TOC$ is the elevation of the mud pool rim in which the diver was installed (m a.s.l., Table 1), and $CL$ is the cable length (m, Table 1).

Electrical conductivity values (mS/cm at 25°C) were converted into salinity (g/L) using the conversion formula of Lewis and Perkin (1981).

To highlight hydraulic connectivity between volcanoes, variance of daily mud level ($ML$) elevation with respect to the mean mud level within the period of data analysis, as well as correlation coefficients between the monitored parameters (such as *ML-Patm*; *ML-EC*; *ML-T*; *Patm-EC*) and between mud volcanoes were calculated.

Mud level measurements were averaged on an hourly base to evaluate the barometric efficiency and describe how levels in the volcanoes fluctuate in response to atmospheric pressure. We used the slope method with mud level change ($\Delta ML$) on the $y$-axis and barometric pressure change ($\Delta B$) on the $x$-axis (Gonthier, 2007; Hare and Morse, 1999). Measurable $\Delta ML$ is the mud level ($ML$) in the volcano at time ($t$ + 1) minus the mud level in the volcano at time (t):

$$\Delta ML = ML(t+1) - ML(t) \tag{3}$$

while $\Delta B$ that causes the mud-level change ($\Delta ML$) is measurable as the barometric pressure at time ($t$) minus the barometric pressure at time ($t$ + 1):

$$\Delta B = B(t) - B(t+1) \tag{4}$$

The order of time ($t$) and time ($t$ + 1) in (3) is inverted with respect to (4) to follow the convention that $\Delta B$ is negative for an increase in barometric pressure during a time interval.

*Table 1 – Dates and time intervals of mud monitoring. Shown are also logger depths (m below the ground – m b.g.) and altimetry (m a.s.l.). Gray cells mean that data are available in that period; white cells mean that data are not available. Refer to Figure 2 for the mud pools locations.*

| Mud pool or gryphon name | Altimetry (m a.s.l.) | Depth (m b.g) | 1-second interval | 5-minute interval | | |
|---|---|---|---|---|---|---|
| | | | 7/07/2020 | 7/07/2020 – 10/09/2020 | 10/09/2020 – 12/11/2020 | 12/11/2020 – 7/01/2021 |
| N1 | 206.74 | -3.00 | | | | |
| N2 | 207.41 | -0.62 | | | | |
| N3 | 207.41 | -3.00 | | | | |
| N8 | 207.62 | -3.00 | | | | |

# 3.2. Fluid characterization

To characterize the fluid, a total of 22 mud samples (500 ml) were collected in N1, N2, and N3 (Figure 2) and mud densities were measured in laboratory with an electronic scale and graduated beaker.

Mud samples were also analysed for grain size. The samples were wet sieved with a 63 μm clear sieve to separate the muddy from the coarser fraction. The fraction retained by the sieve was dried in a natural convection oven at a temperature of 105°C. The coarse fraction was subjected to analysis by sieving in the dimensional range between 8000 μm (-3 φ, Krumbein φ scale, Krumbein, 1934) and 63 μm (4 φ) using a battery of American Standard Test Sieve Series (ASTM) sieves with a particle size range of 1/2 φ and a vibro-tilting sieve. The passer-through (muddy fraction) was measured by aerometry, which correlates the size and percentage of particles suspended in the liquid with their sedimentation rate, based on specific weights of the liquid and particles themselves. The particle size distribution was reconstructed by software Gradistat v. 8.0.

Topographic surveys were carried out during the monitoring campaigns using a real-time kinematic differential global positioning system (RTK-DGPS, Figure 2) with the aim of referring the rims and the mud level of the main gryphons and mud pools, as wells as the volcano field, to the mean sea level (m a.s.l.). Moreover, the conduit depths of the main mud pools and gryphons were measured by lowering a stainless-steel cylindrical weight down the conduit until progression was stopped.

The frequency and diameter of gas bubbles in several mud pools were visually counted and measured with a stopwatch, by photographs and video recordings; the average gas flow rates and hydraulic heads were compared with the aim of identifying the presence of gas bearing aquifers at different depth.

Finally, all data were discussed with regard to the geological information available for the area, such as penetrometer, cores, and well logs data available from the archive of the ViDEPI project database (https://www.videpi.com/videpi/videpi.asp) concerning Italian oil exploration within the National Mining Service for Hydrocarbons and geothermal energy of the Italian Ministry for Economic Development (UNMIG). The well logs considered for the present study are: Levizzano 1, Levizzano 2, and Maranello 1 (Figure 1a), which were drilled in the 1960s by former Agip S.p.A. (now Eni S.p.A.), the Italian multinational energy company.

# 4. Results

Figure 4 reports the time series measured with a 5-minute interval in four different locations: N1 (a), N2 (b), N3 (c) and N8 (d). For N2, only the data acquired in the largest time window are shown (see Table 1).

To better understand the behavior of the signals (Figure 4) on long (weeks - months) time scale, we removed the high frequency noise by applying a Gaussian moving average filter on the raw time series of *ML*, *T*, and *EC*. In order to have a uniform dataset, the time series of atmospheric pressure (1 data point per hour) were re-sampled, with a linear interpolation, at the same time-step of the measured time-series (1 data point per 5 minutes). The noise filtered out from Figure 4 is shown in Figure 5. The *EC* sensor in the divers takes a few days to adjust to an *EC* value with a precision of 0.1 mS/cm as apparent in Figure 4c. A sudden drop in mud level (about 0.2 m) occurs at N3 (Figure 4c) around 10/27/2020 without any change in $P_{atm}$, *T*, and *EC*. At N8 Figure 4d), the mud level and *EC* drop at the beginning of December (-0.2 m and 7 mS/cm, respectively); no correlation is shown in N3.

The high frequency noise (Figure 5) is due to bubble activity (the bubble flowing next to the sensor causes a change in pressure; the more bubbles, the more activity) and it is the largest in N1 (± 0.3 m), which has always been one of the most active (in terms of gas bubble emissions) gryphons during the monitored interval. In general, the noise is low at N1, N2, and N3 until September and it is high in the period September-October (Figure 5).

The correlation coefficients of mud level, EC, T, Patm of monitored volcanoes are listed in Table 2. Within the 1-second dataset, the highest value is between N1 and N2 (0.8), while the lowest is for N2 and N3 (0.54), which are the closest pools. Correlation values decrease if the 5-minute dataset is considered, with no correlation for N2-N3 (0.06) and good correlation for N1-N3 (0.5).

Correlation coefficients calculated on 1-second mud level dataset (Table 2) show high values due also to the short interval (about 0.5-1 second) between sampling frequency and gas bubble frequency in the conduit. The correlation coefficients for the 5-minutes mud level dataset show good correlation between N1 and N3, while it is lower between N2 and N3.

Mud in all volcanoes show no correlation between *ML* and *EC* except in N1, which has good correlation (0.58). In the whole database, EC ranges between 9 and 20 mS/cm, with average values of 14.2 mS/cm.

*Table 2 – Correlation coefficients of mud level (ML), electrical conductivity (EC), temperature (T) and atmospheric pressure (Patm) between the monitored volcanoes (N1, N2, and N3) at different time intervals (1-second, and 5-minute). ‘n.a.’ is for ‘not available data’.*

| | *ML* | | | |
|---|---|---|---|---|
| | 1-second interval | 5-minute interval | | |
| N1-N2 | 0.80 | n.a. | | |
| N1-N3 | 0.70 | 0.50 | | |
| N2-N3 | 0.54 | 0.06 | | |
| | | | | |
| | *ML-Patm* | *ML-EC* | *ML-T* | *Patm-EC* |
| | 5-minute interval | | | |
| N1 | -0.002 | 0.58 | 0.60 | 0.11 |
| N2 | -0.01 | 0.15 | -0.26 | -0.26 |
| N3 | 0.12 | 0.37 | -0.12 | 0.33 |

The daily mud level variance within the periods of data analysis in N1, N2, and N3 is shown in Figure 6. The graphs show variance peaks in different dates for each monitored mud pool. In N1 the maximum variance values are on 09/21 and 10/23, with *ML* variance values of 0.01 and 0.005 $m^2$, respectively (6a). In N2, the maximum variance values are 0.0015 and 0.0005 $m^2$ on 07/21 and 07/31, respectively (Figure 6b). In N3, the maximum variance values are recorded on 08/10 (0.0005 $m^2$, Figure 6c), and on 10/27 (0.009 $m^2$, Figure 6d).

Figure 7 shows the barometric efficiency calculated for N1, N2, N3 and N8. Figure 8 and Figure 9 show gas flow rates and mud level in all gryphons and mud pools presenting gas emission. In Figure 8, mud level and gas flow are grouped based on their location (refer to Figure 2). The highest flow rate is recorded in N14 with 0.0013 $m^3$/sec, followed by N1 and N2 (0.0012 and 0.0010 $m^3$/sec, respectively), while N4 and N5 present no gas bubbles (Table 1 in Supplementary Material). In Figure 9, mud level and gas flow data highlight two main groups: N1-N14 on the Eastern, and N15-N18 on the Western side of the Nirano *Salse*.

Regarding fluid characterization, the results of mud densities analysis are listed in Table 3. Mud density ranges from 1145 to 1350 g/l. To convert the hydrostatic pressure data measured by level-loggers into mud levels (1), we used the mud density value (1265.3 g/l), which was measured in N2 and it is consistent with an average value measured in N1, N2, N3, and N4.

The particle size distributions of mud samples are shown in Figure 10. All samples show similar grain size distribution and consist of clayey silt, with average values of 55.4 and 36.4% of silt and clay, respectively.

*Table 3 - Mud density values collected in N1, N2, N3 and N4.*

| | N1 | N2 | N3 | N4 |
|---|---|---|---|---|
| | $\rho$ (g/l) | | | |
| | 1152 | 1220 | 1173 | 1350 |
| | 1152 | 1221 | 1160 | |
| | 1150 | 1251 | 1167 | |
| | 1156 | 1261 | 1165 | |
| | 1147 | 1264 | 1153 | |
| | 1147 | 1265 | 1160 | |
| | 1146 | # | 1166 | |
| | 1145 | # | 1156 | |
| Min | 1145 | 1220 | 1153 | |
| Max | 1156 | 1265 | 1173 | |
| Mean | 1149 | 1247 | 1163 | |

# 5. Discussion

Based on the results above, a conceptual model of flow dynamics is shown in Figure 11 and justified in the following discussion section.

Bonini (2008) presents a geological model where pressurized fluids move up through discontinuities in the Ligurian Units, and accumulate in shallower reservoirs controlled by the lithological boundary between the impermeable claystone *FAA* and the underlying, more permeable, Epi-Ligurian Units and *Colombacci* Fm deposits. Bonini (2007) stated that anticlines in combination with the brittle structures associated with folding provide an efficient system for trapping and transferring fluids to the surface, where overpressured fluids are periodically expelled from the main reservoir (*Marnosa-Arenacea* Fm) through the creation or the reactivation of pre-existing fractures/faults (Figure 11d). Permeability contrasts, tectonic loading and gas generation likely represent the main factors triggering fluid overpressures (Bonini, 2007). Vannoli et al. (2021) suggest that a seal-bypass system, such as extrados fracture corridors developed along the fold crest, is needed to allow fluids to reach the surface. Furthermore, they claim that mud volcanoes can persist if they are connected by a network of deep long-lived structures possibly associated with background seismicity.

Our data suggest the presence of small shallow aquifers between 4-20 m depth where rising gas, from deep structures in the Epi-Ligurian units (Capozzi and Picotti, 2010), is trapped and temporarily stored. The impermeable *FAA* (in which the shallow aquifers are encased) allows pore fluid pressure to build up till this overcomes the tensional strength of the rock, so that gas can escape along fractures or fractures-aligned pipe conduits, reaching the surface and dragging and fluidifying solid material along the way up (Figure 11d). This flow dynamics allows both clay particles, gas, and eventually some silt (from the shallow aquifers) to rise to the surface with formation of gryphons and mud pools. As most of the mud pools are located around the gryphons, it is suggested that the overburden of the tall gryphons causes collapse and fracturing through which the fluids migrate, mixing with shallow meteoric waters (Mazzini, 2009; Mazzini and Etiope, 2017). Most of the gas is rising from deep reservoirs (gas dominated fluid) and, perhaps, some deep connate water is carried along with the gas. The fluids reaching the surface may also mix with brackish water, which is present in the shallow aquifers and this justifies the EC values measures in the field.

The presence of local shallow aquifers is confirmed by particle size distribution of mud samples collected in the field (Figure 10) showing coarser granulometry than clay sediments. The presence of coarse sediments (sand and silt) within *FFA* is also confirmed by the AGIP S.p.A. core logs near the study area (Maranello 001, Levizzano 001 and 002, refer to Figure 1a for location) and the explanatory notes of the Geological Maps of Italy (Scale 1:50000, Sassuolo sheet, RER, 1999). Here, the *FAA* is described as consisting of silty and slightly marly clays, with a thin to medium stratification marked by intercalations of fine sands in flat, isolated, or connected lenses. On the right of the Secchia River, where Nirano is located, the sandy levels become thicker, laterally continuous and the stratification more powerful. Core logs show clays with frequent sandy and silty intercalations within the first 100 m of the *FAA* sequence.

Sciarra et al. (2019), who carried out extensive geochemical soil gas and exhalation fluxes ($CO_2$ and $CH_4$) surveys, indicate the presence of high permeability areas that act as preferential leakage pathways for gas migration. These areas positively correlate with the dome-shaped conductive anomalies mapped by Lupi et al. (2016) at 20 m depth. We suppose that these permeable areas are none other than shallow aquifers with variable size and thickness possibly leaking to the surface along circular faults formed during the collapse of the area and the formation of the caldera-like morphology (bowl). The salinity of the muds is low (around 7 g/l) and well-correlates with the salinity of formation waters recovered during DST tests in the Levizzano 1 and 2 wells, as well as Maranello 1 from sandy layers within the *FAA*. The mud reaching the surface also does not contain any microfossil older that the age of the FAA, suggesting no direct mass transport from below them (Papazzoni, 2017).

The connection between shallow aquifers is variable in time and depends on the gas flow activity. The measurement of conduits depths indicates that they range varies from 0.5 to 5 m with a mode around 1.5 m; at N2, however, we measured a depth of 8 m and 15 m in two distinct occasions. Our observations suggest that conduits opening is variable through time, some conduits may close and then reactivate; the whole conduit network appear to be in a state of continuous change and individual conduits are temporary features. Furthermore, the observations of Kopf (2002) that mud pools conduits are larger than those of gryphons is also confirmed by our observations. The N2 mud pool, in fact, is the only one where we could lower our sounding line in several points without any impediment and it is the one where we have reached the largest depth (15 m).

Correlation coefficients of mud levels variations between volcanoes depend on the conduit geometry, type, as well as their connection (i.e., direct connection and degree of tortuosity). High correlation coefficients between *ML* vents (Table 2 and Figure 4) could be explained by the connection to the same source whereas low correlation coefficients may represent separation of the conduits feeding the different pools and mud vents.

In the Nirano system, *ML* and $P_{atm}$ are not correlated (Table 2, Figure 4) and this is further confirmed by the barometric efficiency analysis in Figure 7. The influence of barometric pressure on a groundwater surface can follow several scenarios. In confined aquifers, the change in water level is caused by a change in the force applied to the Earth's surface by the atmospheric pressure—higher atmospheric pressure causes a greater load, which is transferred to water at depth, causing the water pressure within the aquifer to rise (Rasmussen, 2005). The unconfined aquifers show delayed responses due to the delay in transmitting the atmospheric pressure signal through the vadose zone to the water table surface (Spane, 2002). If the system were affected by barometric-pressure change, the slopes of the fitted linear curves in Figure 7 would be positive. As it can be seen, the coefficients of determination (R-squared values) are all small, indicating no significant barometric efficiency (Figure 7). Gas storage and overpressure in small shallow aquifers and flow from those to the surface seems more important than the barometric pressure change.

The mud level variance (Figure 6) is an indicator of gas activity in the monitored mud pools. Peaks appear following periods of quiescence during which gas accumulates and overpressure increases in the small aquifers system. The trend of these values indicates a chaotic system characterized by non-constant gas flow rates, with an alternation of quiescence and extrusion activity periods (Figure 4 and Figure 6). This is further confirmed by some drawdown tests carried out on site (by emptying the N3 mud pool), during which no linear recovery of mud level was observed, testifying the presence of a non-continuous and constant flow in the conduits.

The different mud levels measured at the vents seem to be controlled by the variable gas-liquid ratio in the mud conduit (Figure 8 and Figure 9). Low mud levels correspond to the vents that do not allow gas accumulation (fast continuous degassing) in their conducts and their pressure head is dominated by mud density (low gas-liquid ratio) whereas volcanoes whose conduits are occupied by many gas bubbles that move slowly (high gas-liquid ratio) have a higher mud level dominated by the gas volume. The latter are more likely to erupt mud suddenly and unexpectedly than the former type. In Figure 9, mud level and gas flow data highlight two main groups (N1-N14 on the Eastern side, and N15-N18 on the Western side of the Nirano *Salse*), which could indicate two different shallow aquifers at different depths (Figure 11d). Neighbouring volcanoes have comparable but not equal mud level values. The mud viscosity is variable and heterogeneous, depending on climatic conditions, depth of measurements along the conduits, and, more importantly, gas flow. Also mud density is heterogenous and as gas flow increases, density will decrease along with viscosity. However, as shown in Table 2, gas flow is not the only cause. Dilution with rainwater and evaporation during hot and dry periods could contribute to density variability.

One other issue important for discussion is the source of fluids (gas and water) at the Nirano *Salse*. According to Kopf (2002) the possible fluid sources for overpressuring and mud extrusion can be summarized as: (1) pore fluids from compaction; (2) biogenic methane from degradation of organic matter; (3) fluid migration along deep-seated thrusts; (4) thermogenic methane; (5) fluids from mineral dehydration; (6) hydrothermal fluids, and alteration of crustal rock; (7) fluid expulsion from internal deformation within the diapiric intrusion. By reviewing the mechanisms above on the basis of what we know for the Nirano *Salse* and our observations, we can argue that: (1) fluid expulsion during compaction has already occurred at Nirano, because the *FAA* already went through primary compaction; (2) biogenic methane from degradation of organic matter is not supported by the geochemical isotopic characteristics of the gas analyzed (Martinelli et al., 2012); (3) fluid migration along deep-seated thrusts is possible for the gas (deep source of Martinelli et al., 2012); furthermore, there might have been mixing between deep connate and shallower aquifer waters; 4) the methane is of thermogenic origin as suggested by Oppo et al. (2017), Martinelli et al. (2012), and Tassi et al. (2012); (5) there are only traces of smectite in the Nirano mud suggesting no dehydration reactions involving opal-smectite reactions to cause overpressures (Vezzalini et al., 2017); (6) fluids in Nirano do not have hydrothermal characteristics (Martinelli et al., 2012); (7) fluid expulsion from internal deformation within the diapiric intrusion does not fit well Nirano *Salse* dynamics and formation given that the gas source is below the *FAA*. Furthermore, mud diapirs are interpreted today as areas of seismic attenuation caused by intrusion of mud dike swarms formed by hydrofracturing due to overpressures (Figure 11d) and not by the density driven phenomena of viscous flow that are typical of salt diapirs (Tingay et al., 2009).

By considering the possible fluid sources that we discussed above and our observations, we suggest that the reason for fluid release at the Nirano *Salse* is leakage of a hydrocarbon seal (Figure 11d). Abnormal overpressure in a deep reservoir (*Marnoso-Arenacea* Fm) would be generated by gas accumulation following secondary migration. Fluids could escape from a seal broken by a fault, or gas may leak from the spill-point of a faulted reservoir layer. The seal could also have a valve behavior and fail when the overpressure in the gas reservoir increases due to the continuous gas migration from below. Gas following upward migration routes, such as faults and fractures (Figure 11d), would accumulate in shallow aquifers confined within the *FAA* and then be released when the fluids overpressure would exceed the tensional strength of the seal (Gibson, 1994). In this way, the conduits forming the mud volcanoes would start at the depth of this shallow aquifers (5 to 30 m from the surface) as also measured by our soundings. Conduits may have different shapes (cylindrical to fracture-like) and may be interconnected where mud volcanoes are in proximity as also suggested by our mud level correlations. The system of fractures and conduits feeding from the deep source into the shallow aquifers cannot be assessed by our work and is better addressed by geophysical methodologies.

# Conclusion

The present work has permitted to improve the conceptual model of mud flow dynamics in the shallow subsurface of the Nirano *Salse* area. Geological observations, monitoring of mud levels in several gryphons and mud pools, granulometric analysis of mud samples, topographic surveys, as well as measurement of gas flow have increased our insights into the hydrogeology and hydraulic connectivity of the area.

One first conclusion is that mud level in the different mud pools and mud volcanoes depends on the gas-liquid ratio within the mud of the individual conduits, and it depends also on the geometric characteristics of the conduits. For this reason, different mud levels at mud volcanoes clusters do not exclude a connection of the conduits at depth. Mud levels time series in a cluster of mud volcanoes, in fact, suggests that they are somehow connected at depth.

Geologic data indicate the presence of shallow aquifers located in the first 30 m below the ground. These units could be distal turbidite lobes with coarser grain size than the surrounding clay that act as small local temporary storage reservoirs where gas, raising from the main deep reservoir in the *Marnoso-Arenacea* Fm and Epi-Ligurian Units, accumulates generating fluid overpressures. The gas alimentation from the depth is not constant over time, and as the pressure in the aquifers increases and overcomes the tensional strength of the seal, it comes to the surface following new or pre-set conduits depending on the pressure in the aquifer. The gas liquefies and drags solid material from the conduit walls carrying along to the surface clay, silt, and peat fragments.

The presented conceptual model integrates the geological and structural models already existing for the area and completes the understanding of processes of mud extrusions and gas seepage at Nirano. More work, however, is required to understand at what stage of development the Nirano *Salse* are today. Is this phenomenon fading in time or is it dormant and preparing for new temperamental activity phases? This is an important issue for the Nirano geotourism, which attracts every year tens of thousands school students and visitors.

## Declarations

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### Statement

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Giambastiani BMS, Antonellini M, Nespoli M, Bacchetti M, Calafato A, Venturoli S, and Piombo A. The first draft of the manuscript was written by Giambastiani BMS, Antonellini M, Nespoli M, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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# Figures

### Figure 1

Location of the Nirano Salse study area. a) The geological phenomena and historical hydrocarbons vents occurred in the surrounding area; b) surface drainage basin of Nirano, contour lines, and the surface geology modified from the Emilia-Romagna survey geology map, scale 1:10000. (Coordinate reference system: WGS 1984 UTM Zone 32N). Blue lines with arrows indicate the drainage network in the Nirano area.

### Figure 2

Nirano Salse area and location of gryphons and mud pools. Shown are also some pictures of the field activities (GPS surveys and installation of level-loggers). The dashed red line is the blind thrust anticline axis (as interpreted by Bonini 2007).

### Figure 3

*Schematic representation of the diver installation in a mud pool (a) and in a gryphon (b).*

### Figure 4

Time series measured with a 5-minute interval in four different locations: N1 (a), N2 (b), N3 (c) and N8 (d). For N2, only the data acquired in the largest time window are shown (see Table 1). The time series of ML (black line), atmospheric pressure (magenta line), measured temperature T (green line) and electrical conductivity, EC (orange line) are reported in each panel.

### Figure 5

Plot of the noise of the ML time series, computed as N = ML(raw)-ML(filtered) for the 4 different locations, N1, N2, N3, and N8.

**Figure 6**

Variance of daily mud level (ML) within the periods of data analysis for pools N1 (a), N2 (b), and N3 (c-d).

**Figure 7**

Mud level change ($\Delta$ML in m) as a function of barometric-pressure change ($\Delta$B in m of mud column) in volcanoes N1, N2, N3, and N8.

**Figure 8**

Average gas flow rate and mud level (ML) in the mud pools of the three main zones of Nirano Salse: N1-N7 in the Eastern, N8-N11 in the Northern, N12-N14 in the central, and N15-N18 in the Western part of the study area (refer to Figure 2 for locations).

**Figure 9**

ML values (m a.s.l.) and gas flow rate ($m^3$/sec, log scale) distribution in all vents.

**Figure 10**

Particle size distributions of mud samples collected in N1 (a), N2 (b), and N3 (c).

**Figure 11**

Simplified conceptual model for flow dynamics at Nirano's gas seeps: a) geological sketch map modified from Bonini (2007); b) zoom of the Eastern part of the field, related topographic profile with mud levels (c), and (d) conceptual model; gas migrates through a leaky seal following initially open fractures in the damage zone of the fault and then moving along open fractures aligned in the maximum compressional stress direction ($s_1$) – once the fractures intersect an aquifer, gas accumulates and it is released when overpressure exceeds the tensional strength of the sediment.

# Supplementary Files

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