The mud volcanoes at Santa Barbara and Aragona (Sicily, Italy): A contribution to risk assessment

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Abstract

The Santa Barbara and Aragona areas are affected by mud volcanism (MV) phenomena, consisting of continuous or intermittent emission of mud, water, and gases. This activity could be interrupted by paroxysmal events, with an eruptive column composed mainly of clay material, water, and gases. They are the most hazardous phenomena and, nowadays, it is impossible to define the potential parameters for modeling the phenomenon. In 2017, two Digital Surface Models (DSM's) were performed by drone in both areas, thus allowing the mapping of the emission zones and the covered areas by the previous events.

Detailed information about past paroxysms was obtained from historical sources and, with the analysis of the 2017 DSMs, a preliminary hazard assessment was carried out, for the first time at two sites. Two potentially hazardous paroxysm surfaces of 0.12 km2 and 0.20 km2 for Santa Barbara and Aragona respectively, were defined. In May 2020, at Aragona, a new paroxysm covered a surface of 8,721 m^2. After this, a new detailed DSM was collected with the aim to make a comparison with the 2017 one. Since 2017, a seismic station was installed in Santa Barbara. From preliminary results, both seismic events and ambient noise showed a frequency of 5-10 Hz.

Keywords: Mud Volcanism; Macalube; Paroxysm; Hazard assessment; Risk; monitoring.

1.0 Introduction

The mud volcanoes (MV) activity is a typical expression of the sedimentary volcanism mainly occurring in the compressive tectonic regimes, along discontinuities for the presence at depth, of under pressure gases or by diapirism phenomena. It consists mainly of a slow and continuous/intermittent uprising of mud, composed of a mixture of saline water, clay and gases (essentially methane and heavy hydrocarbons), from petroleum seepage (natural gas and oil) at depth, to the Earth's surface (Mazzini et al., 2017). In some cases, a violent and instantaneous explosion ("*paroxysm*") of mud, water and gases could interrupt this activity.
Thousands of mud volcanoes occur globally and they develop in greater numbers in offshore regions than on land (Higgins and Saunders, 1974; Guliyiev and Feizullayev, 1998; Milkov, 2000; Dimitrov, 2002; Kopf, 2002; Deville, 2009).
In the world, within the 42 geographical areas, as well as Alpine-Himalayan, Pacific and Central Asian folding zones, in the deep-water zones of the Caspian, Black and Mediterranean seas and on the passive margins of the continents, a total of 2508 mud volcanoes and mud volcanic manifestations are present (Aliyev et al., 2015).
The largest number of mud volcanoes, including the biggest, most frequently erupting ones and in general, all their known types are located in Eastern Azerbaijan and the adjacent water area of the South Caspian. It is in accordance with these factors, that Azerbaijan region, is considered to be the "Motherland of mud volcanoes". In total, there are 353 mud volcanoes, 199 of which are terrestrial. A complete catalogue of the paroxysm events from 1810 to 2018, for this region, is reported in Baloglanov et al., 2018.
According to a detailed study performed by (Mellors et al., 2007), for the mud volcanoes in Azerbaijan, the temporal correlation between earthquakes and eruptions is most pronounced for nearby earthquakes (within 100 km) and with intensities of Mercalli 6 or greater. According to (Bonini et al., 2009), mud volcanoes of the Pede–Apennine margin in Italy, are intimately connected with rising fluids trapped in the core of anticlines associated with the seismogenic Pede–Apennine thrusts.
Monitoring the activity of the mud volcanoes, in terms of gas outflow, could be helpful to predict a future paroxysmal event. From geochemical point of view, the monitoring is generally carried out by capturing gaseous emissions at the emitting conduits (Kopf et al., 2010). Sciarra et al., 2016, monitoring the soil gas concentration (222Rn, CO2, CH4), have carried different geochemical surveys in 2006 in the Sidoarjo district (Eastern Java Island, Indonesia). However, this approach is not always effective and applicable, due to logistic difficulties, which make this kind of measurement infeasible and expensive in many contexts. For this reason, several multidisciplinary monitoring approaches have been proposed in different MVs in the world. More recently, Mazzini et al., 2021, have estimated the total CH_4 emissions from Lusi using both ground-based and for, the first time, satellite (TROPOMI) measurements; CO_2 emission is additionally measured by ground-based techniques. In May and October 2011, it was documented the activity with high-resolution time-lapse photography, open-path FTIR, and thermal infrared imagery (Vanderkluysen et al., 2014).
In areas characterized by MVs the gas "bubbling" phenomena can be effectively recorded by geophysical monitoring system, as a local seismic network. Low permeability of clays in mud-volcano areas (Kopf, 2002) suggests that, in the lack of large mud outflow (typical of quiescent phases), gas propagation from the reservoir mainly occurs by the uprising of gas bubbles (Etiope and Martinelli, 2002; Albarello, 2005). Recent researches (Albarello et al., 2012) showed that seismic monitoring could provide useful signals to characterize the activity of mud volcanoes. The seismic signals recorded on the Dashgil mud volcano allowed to model of several transients as a surface effect of resonant gas bubbles in a shallow basin just below the volcano (Albarello et al., 2012). The interpretation of transient events in seismic tremor in terms of bubble resonance suggests a new approach to stimulate gas emissions in the mud volcano.
In Italy, the mud volcanoes are clustered in three main geographical zones: in the northern Apennines (mainly in the Emilia Romagna Region); in central Apennines (Marche and Abruzzo Regions); in the southern Apennines (in Basilicata, Calabria and Campania Regions) and in Sicily where 13 mud volcanoes areas are present both in central and western sectors. The sizes and shapes of the Italian mud volcanoes vary considerably. According to (Martinelli et al., 2004), only a small proportion (20%) can be described as 'large' with a surface area >500 m^2, while only 5% exceed 2 m in height.
In Sicily, mud volcanoes are mostly located within Caltanissetta and Agrigento Provinces (S. Barbara and Aragona locations respectively). The name of these phenomena is known as "maccalube" (or macalube), which derives from Arabic and it means, "*overturning*". In some cases, a violent and instantaneous explosion called "*paroxysm*" could occur and, the erupted material, consisting of mud breccias composed of a mud matrix with chaotically distributed angular to rounded rock clasts from a few millimeters to meters diameter, could reach a long distance from the emission point. The volume of the erupted materials is generally in the order of tens cubic meters and covers a big portion of the surface. On 27 September 2014 at Maccalube of Aragona two kids died covered by thick erupted mud deposits, during a violent

paroxysm. At Santa Barbara village, the last paroxysmal episode occurred in August 2008, causing significant damages to houses, roads, electric and water pipelines.

The majority of the mud eruptions occurred in the absence of any earthquake, suggesting that mud volcanoes may erupt in response to a seismic input only if the internal fluid pressure approaches the lithostatic one. A dormancy time is needed for triggering an eruption, related to the production rate of the driving gas to overcome the permeability of the system at depth (Bonini et al., 2009).

In this paper, we have gathered some historical information about the pre and post-paroxysmal events that occurred in the past at both study areas as a starting point for a correct hazard assessment.

In October 2017, a seismic monitoring station was installed at Santa Barbara, in order to collect some seismic information of the site. Moreover, a number of drone surveys were performed both at Santa Barbara and Aragona. Finally, at Aragona a drone survey has been carried out a few days after the last paroxysm event occurred on 19th May 2020, with the aim of mapping the surface of the erupted material and estimating volume and thickness.

Moreover, a Digital Surface Model (DSM) has been elaborated and the emission points at the Earth's surface were mapped. Based on the DSM analysis and our historical information, two main hazardous paroxysm areas at Santa Barbara and Aragona have been elaborated, in this paper, for the first time.

2.0 The study areas

Santa Barbara and Aragona MVs areas are located in the central and south-west sector of the Sicily Region respectively, inside the Caltanissetta Basin (locations in Fig. 1). These two areas, consisting of Late Miocene to Pleistocene accretionary prism, have been formed simultaneously with the Tyrrhenian Sea opening, during the convergence between the African and Eurasian plates in the Neogene-Quaternary (Catalano et al., 2000b), reaching a deposit thickness of the order of some km.

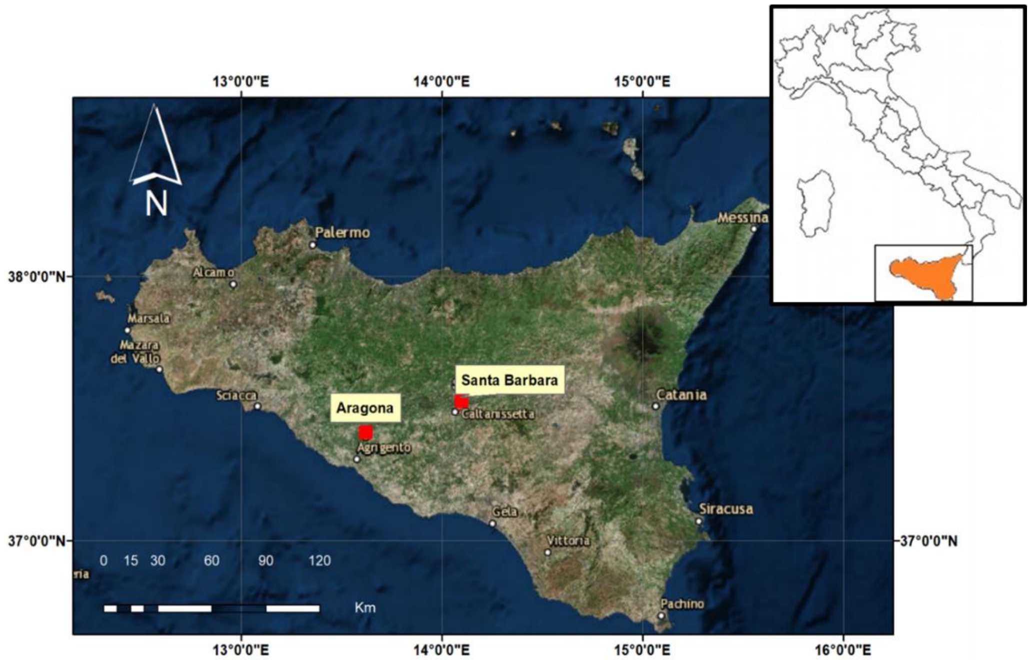

Fig.1. Location of the two investigated mud volcanoes areas: Santa Barbara (Caltanissetta Province) and Aragona (Agrigento Province) (image from ESRI).

At Santa Barbara, the mud volcanism is located eastward of the Caltanissetta town, near the "Santa Barbara village". The composition of its deposits consists essentially of clay, clayey- marly and sandy composed. Around the main mud emission, in the northern sector, different residential buildings are present which were built mainly in the 60's while, in the southern sector, twenty mono-familiar houses (Fig.2a). Several public facilities are present at the western side of the mud volcano and, electric pipelines, roads and services for about 4,000 resident people should be considered for a correct risk assessment of the entire area.

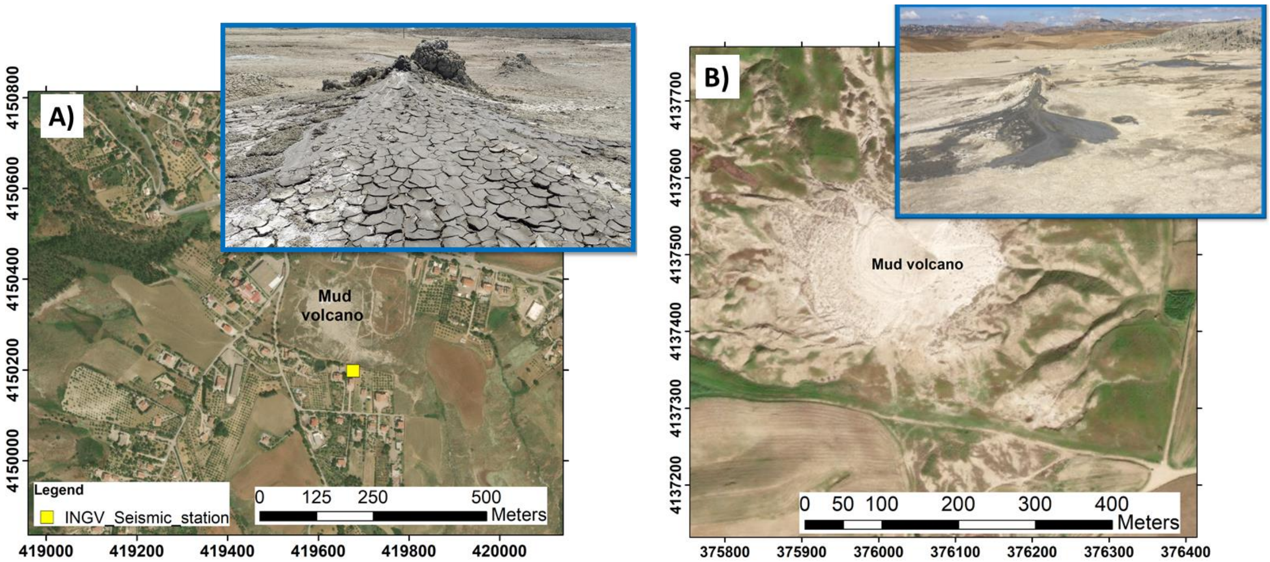

Fig 2. Location of the two mud volcano areas: Santa Barbara (A) and Aragona (B). Image of ArcGis 10.5, ESRI.

The Aragona MV area is located about 3.5 km from the town, in the SW direction. The *Maccalube of Aragona* MV area is a beautiful natural touristic attraction over time and in 1995 has been established Integral Natural Reserve, nowadays managed by Legambiente. The geology of the entire area is mainly characterized by clay deposits, clayey-sands and marls, alternating with sandstone that favour low-relief geomorphology (Fig.2b). No residential buildings and public facilities are present around the main mud emission area but the site represents a naturalistic attraction for tourists. After the 2014 paroxysm, where two kids died, the entire area was closed.

3. The historical background: a tool for the hazard assessment

The Maccalube of Aragona and Santa Barbara have been affected in the past by different paroxysmal events, characterized by violent explosions of gas and mud, which periodically cause the interruption of the normal degassing activity, with a rapid emission of considerable quantities of clayey material and ballistics, accompanied by strong rambles. The paroxysmal activity, reaching a maximum column height of about 20-30 meters is generally, determined by the accumulation and the sudden release of pressurized gases (mainly CH_4 with 95-97% vol.) at depth. The volumes of the expelled mud during these events have reached tens of thousands of cubic meters and consequently, after a paroxysmal event, a drastic variation in the morphology occurs. Sometimes, during historical paroxysmal manifestations, the emitted gas giving rise to suggestive manifestations like burning fountains (Grassa et al., 2012). However, MVs do not represent only a relevant geological phenomenon as they also act as elements of hazard. Therefore, the understanding of the occurrence of historic events, together with the intensities of the pre- and post-evidences associated with this phenomenon, could be a useful tool for the Civil Protection authorities in order to define the most probable hazard scenarios for a correct risk assessment in both study areas.

3.1 The Santa Barbara historical paroxysms

The old naturalists and geologists have described the activity of the mud volcano at Santa Barbara, since 1800, reporting some of their major paroxysmal events (Carnemolla, 2017). The first scientific document was produced in 1823 with a manuscript entitled "*Descrizione geologico-mineralogica nei dintorni di Caltanissetta*" by Gregorio Barnabà La Via, who documented one of the paroxysmal eruption reporting: "[….] *on March 5th, 1823 at 5:25 PM, the wind from the north with strong and broken turbines, the sky being clear, a few dense clouds with long stripes appeared. Five earthquakes occurred in 9 seconds without damages at factories. Going to mud volcano with the Villarosa duke, Luigi Barrile and Livolsi abbot, that observed since 1818 the phenomenon, increasing up to 50 cm the width of the cracks at the maccalube (that were 27 cm) and observing an increasing of the height of the mud volcano with a continuous emission of mud, water and hydrogen sulphide at 2.30 m height […]* ".
The Livolsi abbot, in his study entitled *"Sul vulcano aereo di Terrapilata in Caltanissetta"* reported the description of the entire area of the mud volcano: "[…] *Its surface is conical in shape, and at first glance offers the appearance of an*

extinct volcano [...]”. According to this manuscript, different paroxysms occurred in 1783, 1817, 1819 and 1823 (Madonia et al., 2011).
The intense phenomena have occurred continuously over time, and there is evidence of a significant event that occurred between the years 1930 -40.
On August 11th, 2008, near the village of Santa Barbara, a sudden emission of natural gas occurred, accompanied by the expulsion of large quantities of clayey material, gas and water, reaching a maximum height of about 30 meters. From the morning, the village was affected by intense phenomena of soil cracking causing diffuse damages to civil and industrial buildings. A general uplift of the area around the mud volcano, together with the presence of variable fractures with horizontal and vertical rejections were observed (DRPC report, 2008). During the period just before the paroxysmal event, from December 2007 to August 2008, Cigna et al., (2012) recorded up to 3–5 cm of progressive movements accumulating in the direction towards the satellite with the Satellite-based synthetic aperture radar interferometry method.
As a consequence of these phenomena heavy damages to factories, roads, residential buildings and public facilities (water, gas, electricity pipelines) occurred. The Regional Department of Civil Protection forced the evacuation of several buildings both in the southern sector of the mud volcano area at a short distance (hundreds of meters) from the MVs area, as well as at a distance 2.5 km far from the main area, where, a large scale of soil deformations and fracturing occurred (DRPC, 2008).
At 16.52 of the same day (11th August) a paroxysm occurred next to the Santa Barbara village, accompanied by strong rumble and by an about 30 meters column height composed mainly by clayey material, gas and water that covered in seven minutes about 12,000 m^2 of the area with an estimated volume of about 9,550 m^3 (INGV, Report 2008). The maximum width of the deposit was 3.5 meters next to the emission points up to 30 cm in the SE direction reaching a total distance of about 136 m from the main vents. The paroxysmal event lasted several minutes and was anticipated by a telluric event (Madonia et al., 2011) that occurred a few hours before in the whole Terrapelata area and, contemporaneously, in the neighbouring area of St. Anna. According to Madonia et al., 2011, in august 2008, 5 earthquakes occurred with magnitudes ranging from 1.7 to 2.4 in the radius of 10-55 km from the sites. After the end of the paroxysm, an increase in the length of the pre-existing fractures occurred. The main pre- and post-historical observations of these events are shown in table 1.

Table 1. Pre and post observation of the historical paroxysm events at Santa Barbara.

Pre-event observations	**Paroxysm Event**	**Post-event observations**
✓ Large scale soil fractures	1783, 1817,1819	✓ Paroxysm related to large scale fracturing
✓ five earthquakes felt by population in 9 seconds ✓ Increasing of soil fractures from 27 cm to 50 cm	5th March 1823	✓ Erupted clayey material up to 2,30 meters height; ✓ Increasing of the mud volcano surface; ✓ Water and gas bubbles with the H_2S presence;
11th AUGUST 2008 – MORNING: ✓ Soil displacement, decimetric to metric fracturing with damages to civil and industrial buildings, roads and electrical networks ✓ Uplift of the entire area; ✓ Deformations up to 2.5 km far from the mud volcano. ✓ Seismic event	11th August 2008 hours: 16:52	✓ Audible roar up to a few hundred meters; ✓ Maximum height of the column of clay material mixed with water, gas and ballistic = 30 meters; ✓ Cover of 12000 m^2 with a newly formed clay deposits; ✓ Volume of erupted material of about 9500 m^3; ✓ Presence of lithics with a particle size from decimeters to centimeters; ✓ Extent of fractures about 1 km from the eruptive center; ✓ Maximum thickness of the new erupted deposit = 3.5 meters near the mud volcanoes;

		✓ Diffuse methane flux up to 85 gm^2 / day with a NNW-SSE direction; ✓ Maximum distance reached by the erupted material towards SE direction = 136 meters.

3.2 The Aragona historical paroxysms

The activity of the Maccalube of Aragona, according to Greek, Roman and Arab historical evidences, has occurred at least for 2,500 years. The cosmetic and therapeutic use of the mud, emitted from these geological manifestations, has been reported by Platone, Aristotle, Diodoro Siculo and Plinio. In 1777, the first big mud eruption (today called paroxysm) has been documented by Abruzzese (1952), reporting: " […] *In the early hours of September 29^{th}, the inhabitants of the neighbouring felt a strong shaking of the ground and observed a copious mud flow from the craters up to different heights"*.

Furthermore, the Ferrara abbot described the same paroxysm as one of the most violent eruption known: "[…] *On the September 29^{th}they heard before a roaring noise in all the surroundings. The ground shaking around a great chasm formed up a few miles […] an enormous column of mud rose up to almost a hundred feet high, having been abandoned by the force that pushed it upward […] the terrible explosion lasted half an hour, then calmed down, but recovered after a few minutes and intermittently continued all day but the smoke lasted all night. In all the time of the phenomenon the very strong smell of hydrogen sulphide gas was felt at a great distance in all the surroundings.*

An unknown author reports the same eruption on 30^{th} describing: "[….] *on September 30^{th} 1777, after half an hour when the sun had risen, a murmur was heard in the above mentioned place, which, momentarily advancing, surpassed the roar of the strongest thunders. The earth begins to tremble, and shows the deep cracks, which widened more than usual to ten palms, the main crater, from where the clay and the murky water emerged perpetually, like a cloud of smoke, although somewhere it was flame-colored [….]this eruption lasted for half an hour, and, with a quarter*-hour interval, replied three *more times. The next day, the clay material emitted, however, appeared at the natural consistency, in such a way that it allowed the curious to approach the mud volcano. The clay material erupted still retained the smell of sulfur, which more penetrating was felt during the eruption."*

On October 19^{th}, 1936, at 5, some of Aragona and Giancaxio neighbor villages heard two rumbles, like thunders, which had followed one another in a short period of time. A violent explosion destroyed the central part of the Maccalube from where an imposing fountain of mud raised, which in its ascent dragged blocks of marl mixed with sandstones and gypsum. This fountain reached ten to fifteen meters in height.

Only at the sunrise the people noticed that a large black mass had covered the place where the mud volcanoes are located for about 2 hectares. From the surveys data detected by Prof. Ponte and Prof. Abruzzese, […]*since February 1935 there were the presence of a soil fracture extending for about 400 m to E direction, then distancing 600 m towards the W. In March 1935, at the proximity of the fracture, several mud volcanoes arose, some of which reached a height of one meter.*

The main pre and post observations of these historical paroxysms at Aragona are showed in table 2.

Table 2. Pre and post observation of the historical paroxysm events at Aragona.

Pre-event observations	**Paroxysm Event**	**Post-event observations**
✓ Seismic events felt by population ✓ Large scale soil fractures ✓ Rumbles	✓ September 29^{th} 1777	✓ Mud, ballistics, water and gases column up to 30 m height; ✓ Half an hour duration with intermittent activity for all day; ✓ Presence of Hydrogen Sulphide smell at considerable distance from the mud volcano;

		✓ Presence of lithics of various sizes aligned on the both sides of the mud volcano.
FEBRUARY 1935: ✓ Presence of a soil fracture extending for about 400 m to E direction, then distancing 600 m towards the W MARCH 1935: ✓ Appearance of some mud volcanoes set on the previously fracture, with heights of 1 meter	✓ October 19th 1936	✓ Emission of mud mixed with water, gas and lithics with a column height <= 15 meters; ✓ Cover with newly formed clayey material of 2 hectares of the surface.
AUGUST 2014: ✓ Large scale soil fractures	✓ September 27th 2014	✓ Emission of mud mixed with water and gas with a column height <= 15 meters;

Since 1995, the year of establishment of the Natural Reserve, eight paroxysmal events took place in 1998, 2002, 2005, 2008, 2010, 2012 (Fig.3) 2014 and the last one occurred on 19 May 2020. Grassa et al., (2012) reported the volumes and the covered areas for each of the first six events. The largest event was in 2005, with an estimated volume of about 19,600 m^3 (Fig.3B) covering an area of about 16,350 m^2 (Fig.3A). It is interesting to note that a strong correlation exists between the erupted material and the covered surface areas for the paroxysms that occurred from 1998 to 2012 (no volume data are available for the 2014 paroxysm) as is demonstrated by the high correlation coefficient (R^2=1) and showed in figure 3C. From the same plot, the 2020 paroxysm event falls far from the general trend previously highlighted covering a smaller surface (approximately a half) rather than the expected one. In our opinion, this could be linked to a different location of the main emissive vent, being 2020 the only one eccentric event, and/or to the different nature of the emitted material.

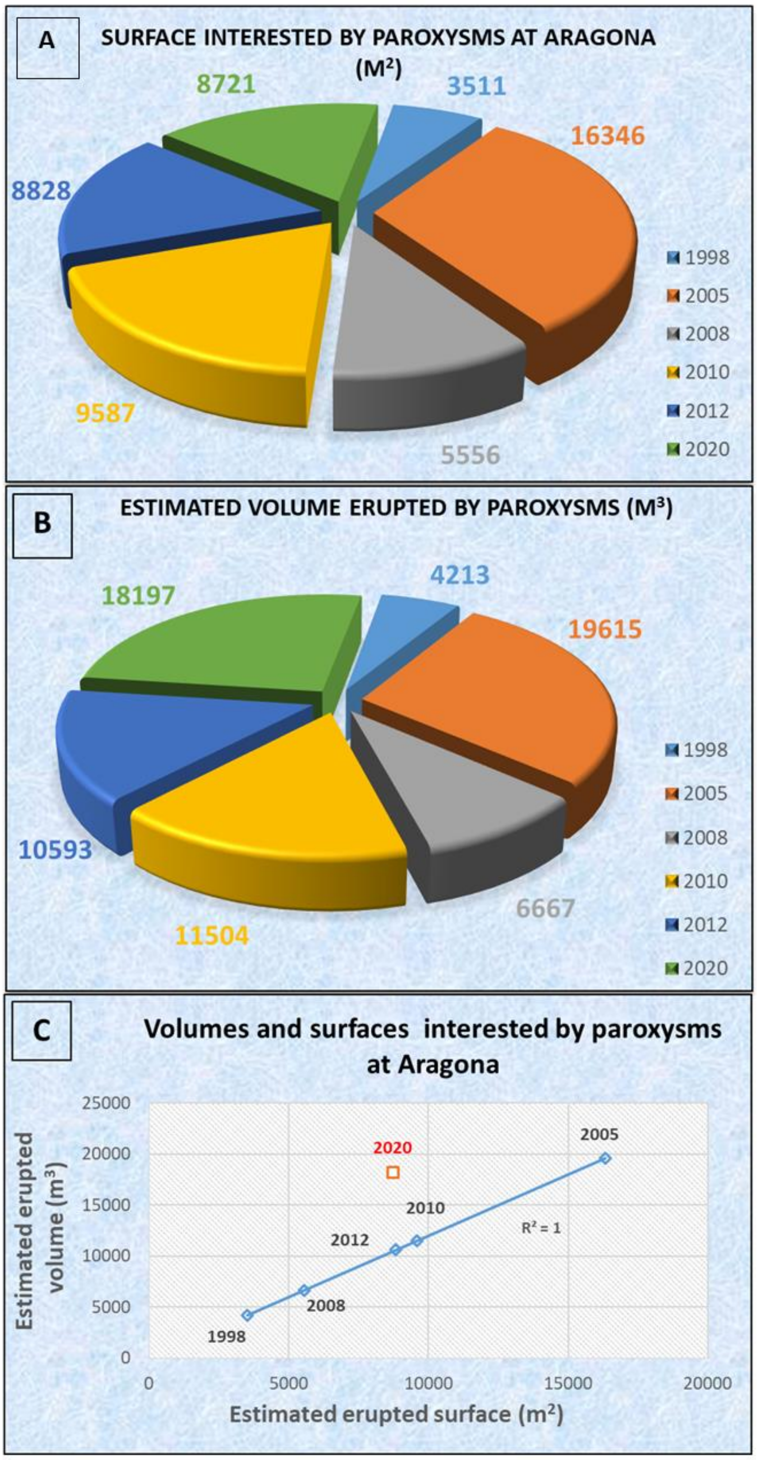

Fig.3. A) Estimated volume and B) interesting surfaces at Aragona mud volcanoes during paroxysmal events. C) Correlation coefficient for erupted volume and interesting surface for the 1998-2012 events (Grassa et al., 2012, modified). In blue the linear correlation with R^2=1. The red square represents the 2020 paroxysm.

4. Associated hazards at Santa Barbara and Aragona mud volcanoes

From the historical information, obtained by the past documentary sources, it is clear and evident that the most hazardous phenomena existing in both areas are the paroxysms.

They are quite common, especially at Aragona, and therefore, it is likely to hypothesize that others hazardous events, with the same magnitude or higher, could repeat in the future.

In all of the paroxysmal events that occurred in the past, both at Santa Barbara and Aragona (Tables 1-2), diffuse soil fractures and deformations, even at considerable distances from the mud volcanism area, occurred during a pre-paroxysm period. In particular, at Santa Barbara the population has felt several seismic events before the 2008 paroxysm.
Another important element that emerges from historical descriptions is that, following the paroxysms, people approaching the mud volcano areas, usually detected a strong acrid smell of gas, reasonably being H_2S. It could be lethal to human life if breathed in high concentrations; It is a toxic, corrosive, irritant and colorless gas with the characteristic unpleasant smell of rotten eggs. It can cause chronic diseases of the respiratory organs through prolonged exposure even at very low concentrations; at concentrations of 200-250 ppm it can cause pulmonary edema and risk of death, while at 1,000 ppm it is immediately lethal (NIOSH, 1981).

5. Methods

5.1 Digital Surface Model (DSM)

High-resolution DSM maps of both study areas have been performed in 2017 while, in 2020 only at Aragona MV, with a range of 0.1-0.15 m. For these surveys, we used a DJI Phantom III Professional drone (quadcopter) with a mounted 12 Mega Pixel digital camera (Lens FOV 94° - 20 mm, Sony Sensor EXMOR 1/2.3", effective pixels resolution of 12.4 M). Before conducting drone mapping, we planned the flight paths and areas for each flight mission. The drone was set to take aerial photographs using "autopilot mode" with a camera facing directly downwards for hilly terrain. The surveys were conducted with the camera mounted 90° sideways. We selected 75% forward and sideways overlap of images.
The acquisition of field data requires the determination of several control points on the ground, known as GCPs (Ground Control Points). Therefore, 11 points distributed within the defined area, were recorded using a GPS NAVCOM SF-3040 with angular accuracy of 1 cm.
The images were processed with a Structure-from-Motion (SfM) and multi-view stereo approach, in order to produce a high-resolution DSM (Digital Surface Model) and to identify the morphological structures linked to the sedimentary volcanic activity. These approaches allow the geometric constraints of camera position, orientation and GCPs from many overlapping images to be solved simultaneously through an automatic workflow. The image datasets were processed with the software Agisoft Photoscan (Agisoft, 2016). The post-processing of the acquired data merged in GIS software (ArcGIS 10.5), allowed to extrapolate the thickness and the volume of the erupted material, with its reached distance.

5.2 Hazard assessment

In order to define the potential paroxysm hazardous scenarios for both areas, in this paper, we consider the maximum real distances reached by the erupted material over time through the analysis of the high-resolution (12x12 cm) DSM acquired by the drone during the 2017 surveys at Aragona and Santa Barbara areas.
At Santa Barbara mud volcano, the erupted material, has reached a total distance along its major axis in the main event of 2008, of about 136 meters while at Aragona, it has reached a total distance of 150 meters. In the 2014 paroxysm event at Aragona, the distance reached by the erupted material was 111 m (Fig.4).

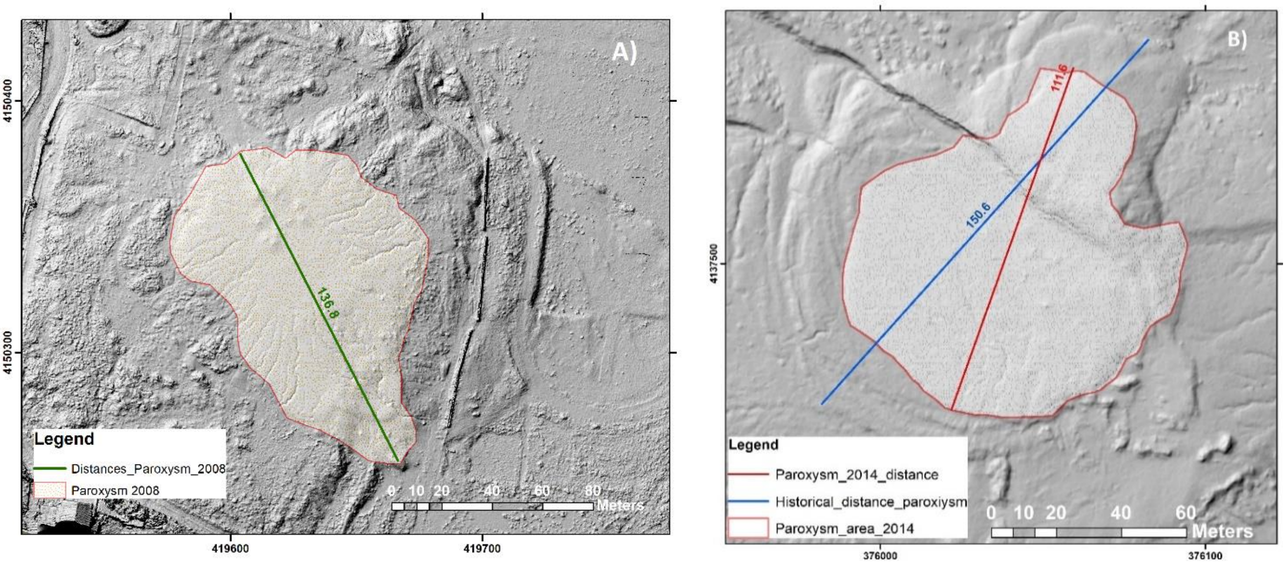

Fig.4. Historical distances reached by the erupted paroxysm material: A) Santa Barbara; B) Aragona. (Source: 2017 DSM's in ArcGIS 10.5)

In both areas, according to the historical sources, the maximum estimated erupted column height, is in the range of about 20-30 meters. During the 2008 paroxysm, the erupted clay material fallout at Santa Barbara covered an area of about 9,000 m^2 with a maximum thickness of about 3.5 meters next to the emission points (INGV, 2008 report) while at Aragona, during the 2014 ones, the affected surface was 7,525 m^2.

In this preliminary phase, in order to model the potential hazard scenarios, we assumed that both areas, in the next future, will be affected by similar erupted fallout deposits that reaches a maximum distances of 136 m and 150 m for Santa Barbara and Aragona area respectively.

For these reasons, starting from our 2017 DSM, we identified the mud volcanoes and bubbling pools in both areas (Fig.5) as the potential emission points for generating a future paroxysmal event. By using the kernel density tool in ArcGIS 10.5, we defined different clusters maps (Fig.4), with two main directions, appeared mostly highlighting NW-SE and NE-SW directions at Aragona (Fig.5b) while, at Santa Barbara, the distribution at the surface seems to be inhomogeneous (Fig.5a).

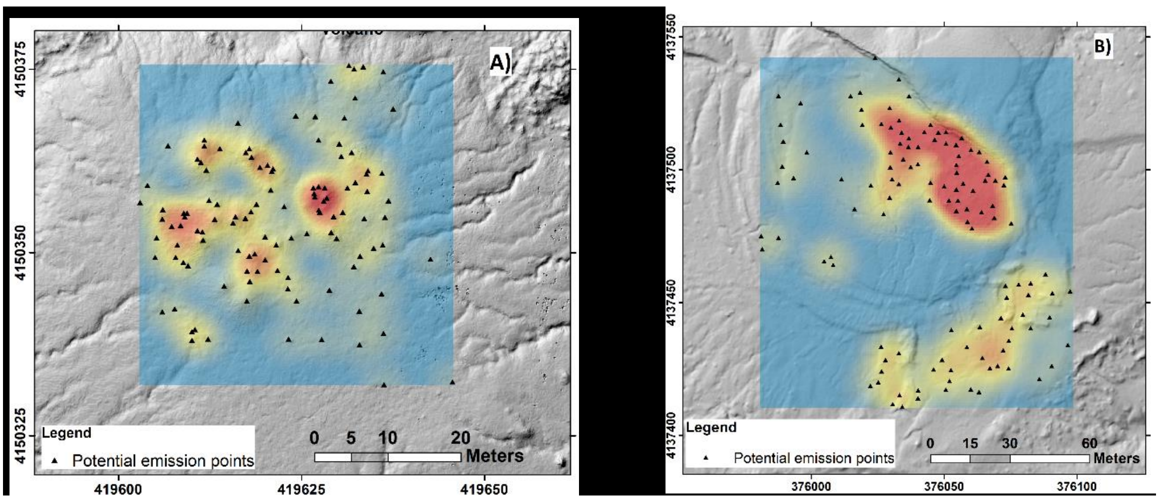

Fig.5. Density maps of the potential emission points investigated. Red: high-density values; Yellow: low-density values. A) Santa Barbara MV area and at B) Maccalube of Aragona. (Source: 2017 DSM's in ArcGIS 10.5)

Secondly, through the elaboration in ArcGis 10.5, we created from each emission point checked in 2017, different omni-directional buffer circumferences, considering an increase in distance of + 30% with respect to the greatest historical distance reached, due to the creation of the safety limits in both areas. For the hazard assessment, we elaborated 117 and

165 buffer circumferences with a radius of 180 m and 195 m at Santa Barbara and at Aragona respectively (Fig.6a and b).

The final potential paroxysmal hazardous areas, in both areas, are considered as the envelope among the entire buffer circumferences elaborated (Fig.7).

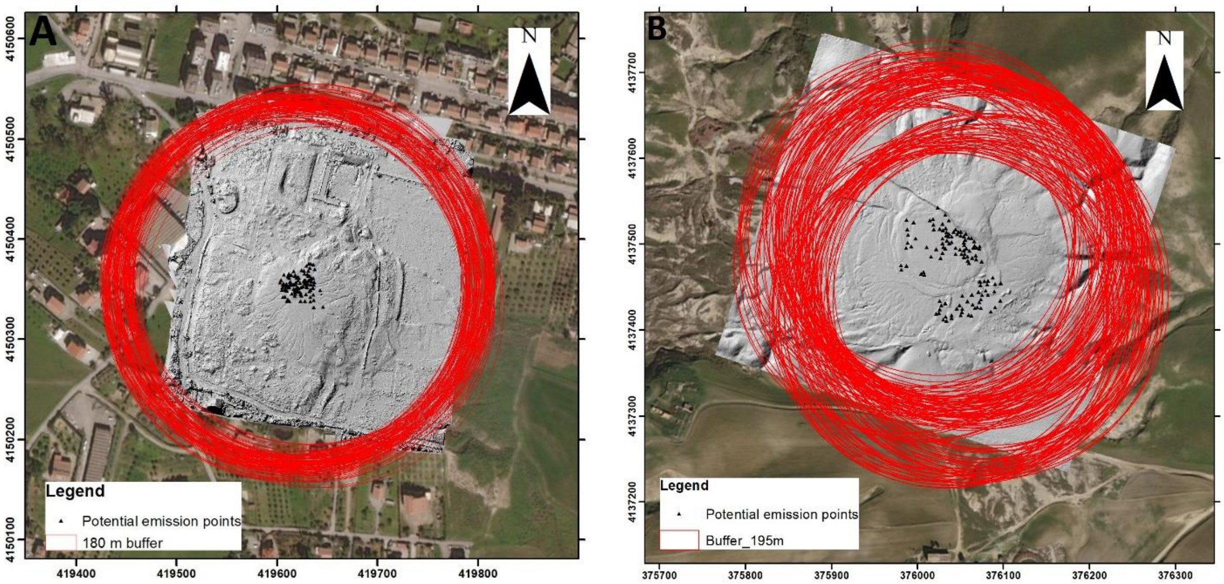

Fig.6. Buffer circumferences in ArcGIS 10.5 at Santa Barbara (A) and Aragona (B) mud volcanoes areas. (Source: 2017 DSM's in ArcGIS 10.5)

5.3 Uncertainties

The application of the methodology for the hazard assessement in both study areas, inevitably, is based on assumptions which could give us some uncertainties. At the same time, the absence of a modelling approach for the paroxysm events at both study areas and, the poor availability of data from all the past events, follow a semi-quantitative approach for the hazard definition. The Digital Surface Model elaborated on 2017 was used to calculate, with some uncertainties, in ArcGis 10.5 the maximum distance reached by the erupted fallout materials. The emission points checked in 2017 at S.Barbara and Aragona may change the location over time due to their constantly evolving, also depending on the seasonality, on the weather conditions or to a new deposition of the erupted clay materials.

5.4 Seismic monitoring activity at Santa Barbara

Since October 2017, a seismic INGV station was installed at Santa Barbara (see Fig.2 for location). It was equipped with a Lennartz 3D-LITE/1s short period velocimeter, with flat response in the bandwidth 1-80 Hz, and a 24-bit seismic data logger RefTek 130 model. To take full advantage of the sensor frequency band, the sampling frequency was set at 200 Hz, while the signals were synchronized via GPS.

6.0 Results

6.1 Paroxysm hazard assessment

The hazardous paroxysm areas for both areas were created through the envelope of all buffer circumferences of Fig.6. An area of 0.12 km^2 and 0.20 km^2, potentially exposed to possible paroxysmal events was calculated for the Santa Barbara and Aragona site respectively (Fig.7). In these two hazardous paroxysm areas, different geophysical phenomena as well as deformation, fracturing and seismic events together with geochemical ones could occur. For that reason, these two exposed areas should be interdicted to visitors, residential or public activities, due to their correlated hazardous phenomena that could occur before, during and after a paroxysm event. In both areas, a dedicated safe path, outside the hazardous paroxysm areas of Fig.7 should be created in order to permit the safety observations of these geological phenomena to visitors.

The decreasing of the gas output in the central area of the Maccalube of Aragona before the paroxysmal events could be an important parameter. It may occur, according to Grassa et al., (2012), due to the increasing of the tectonic stress field in the compression regime, generating an overpressure of the interstitial pores fluids at depth while, on the surface, it reduces the permeability of the structural discontinuities along which the gases migrate, thus reducing the outgassing at the surface. The paroxysmal event would occur, according to these deductions, when the gas pressure at depth exceeds the lithostatic pressure resistance opposed by the overlying rocks.

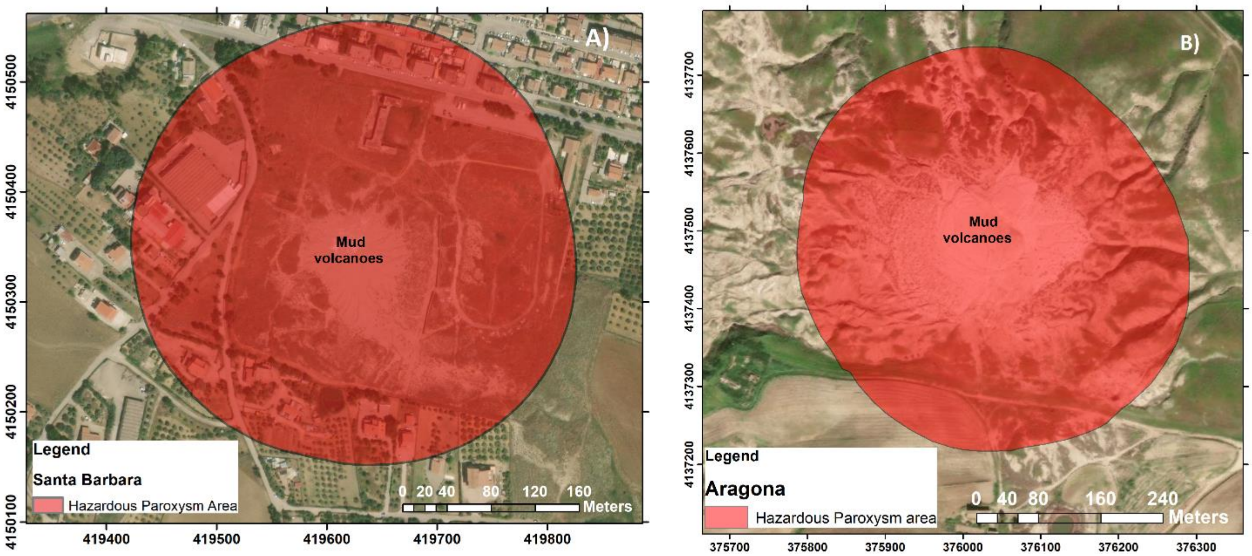

Fig.7. Hazardous Paroxysm areas in ArcGis 10.5 for Santa Barbara (A) and Aragona (B) mud volcanoes area. (Source image from ArcGIS 10.5, ESRI)

6.2 The 2020 paroxysm at Aragona

On 19 may 2020 at around 2 p.m. a new paroxysmal event occurred at the Aragona MVs area. This violent paroxysm occurred in the south-eastern part of the main emission area, emitting a mud volume of 18,196 m^3 and covering a surface of 8,721 m^2 with a maximum thickness of 3.7 m (Fig.8).

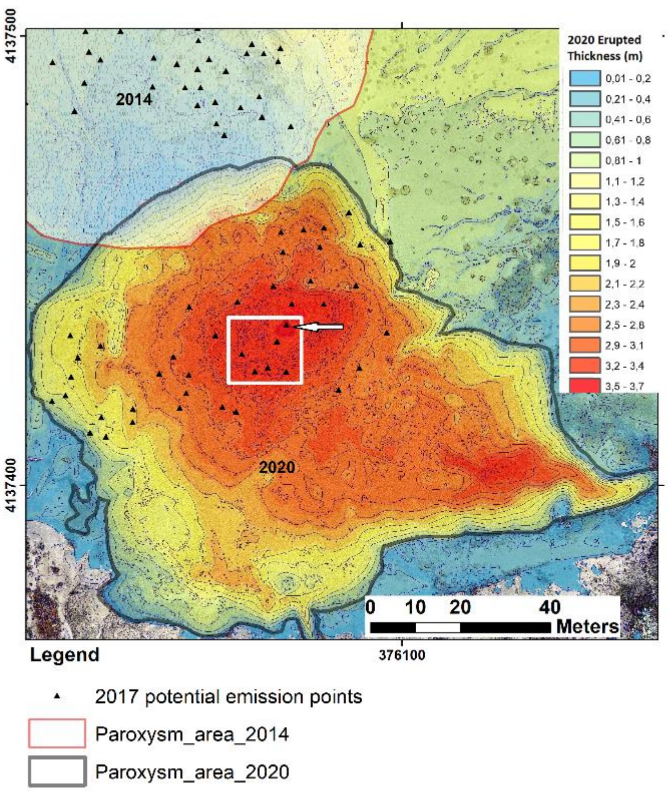

Fig.8. 2020 Thickness map for the erupted materials, due to the paroxysm event of May 19^th^. Inside the white square, the emission point detected in 2017, corresponding to the main centre for the 2020 paroxysm. (Source: 2020 contour map in ArcGIS 10.5)

The maximum distance reached by the erupted materials, according to our analysis is around 130 meters. The 2020 paroxysm occurred in a medium–high density area of emission points detected from our 2017 survey, where a NE-SW structural lineament has been highlighted (Fig. 5 and Fig. 9). In particular, the eruptive centre for the 2020 event is located, according to our thickness map of Fig 8, where the maximum is recorded (arrow in Fig.8) and where, in 2017, the emission points were mapped. Nowadays, the 2017 emission points have been buried by the 2020 new erupted material.

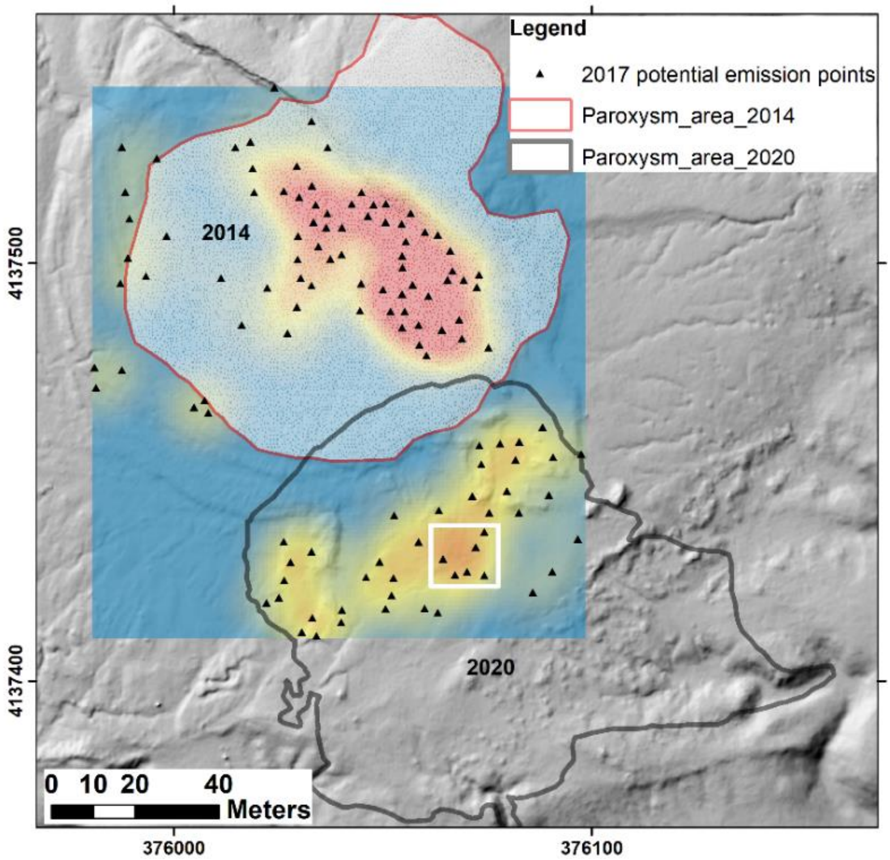

Fig.9. Density maps for the 2017 emission points (Red: High density; yellow: low density). The covered surface area for the 2014 and 2020 paroxysms is shown with red and grey lines respectively. In the white square, the 2017 emission points, likely responsible for the new 2020 paroxysm event. (Source: 2017 DTM's in ArcGIS 10.5)

6.3 The seismic monitoring at Santa Barbara

Preliminary analysis of the continuous recordings allowed to identify variations in the power of the ambient vibrations, mainly in the frequency range 5-10 Hz, which could be due to changes in the emissions activity. Periods of intense activity have also been observed as shown in Fig.10. These periods are characterized by numerous micro-events with high-frequency content (several tens of Hz). This micro-seismicity, of clear local origin, appears to have energy/temporal characteristics similar to a swarm, that is comparable energy of events and stable temporal interdistance from seconds to several minutes. Both ambient noise and seismic events show energy in the frequency range 5-10 Hz, with some possible overtones, that could be generated from local resonance phenomena. This activity could be related to the surface effect of resonant gas bubbles, but we cannot rule out the possibility of a deep origin connected to gas flows at the root of the "volcanic" system.

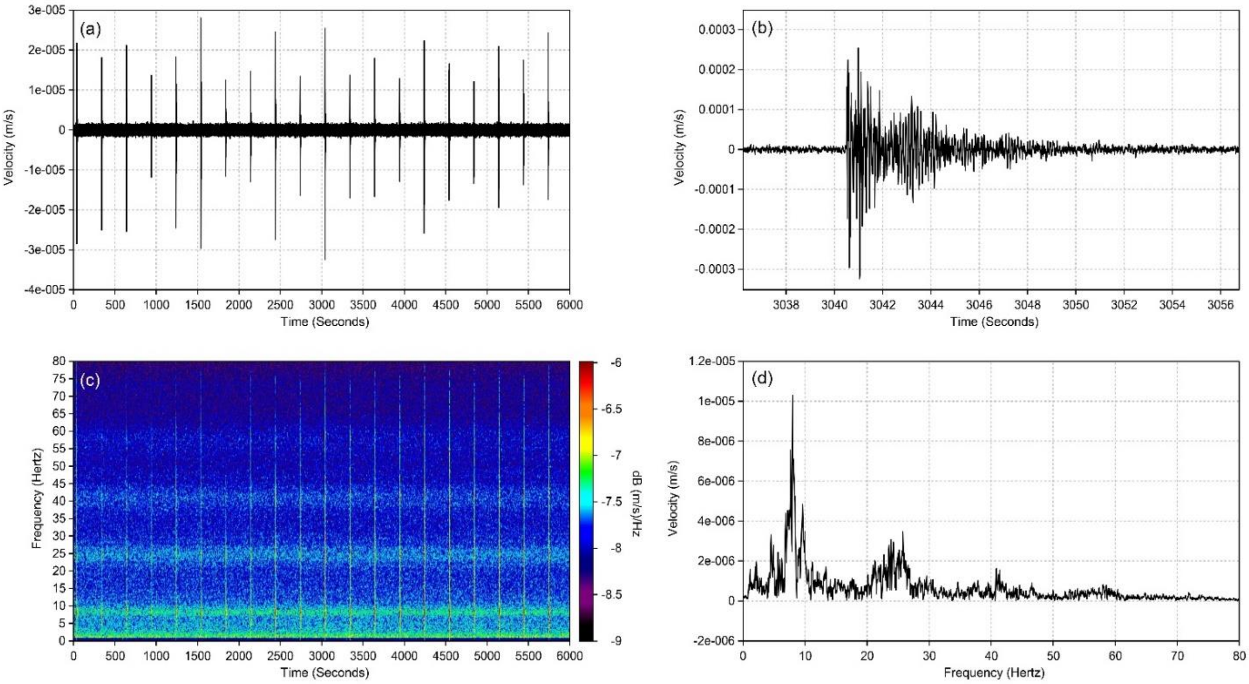

Fig.10. Example of micro-seismicity record by the seismic station installed at Santa Barbara: (a) time signal relative of some minutes of the vertical component (velocity) record and (b) zoom on a single waveform with relative spectrogram (c) and amplitude spectrum (d). The spectrogram allows highlighting the presence in the ambient noise of a continuous energy band in the frequency range 5-10 Hz and some possible overtones. The same frequencies can be identified in the amplitude spectra of the micro-events, suggesting a possible link to local resonance phenomena.

7. Discussion and conclusions

In this paper, for the first time, a preliminary hazard assessment of two main mud volcanoes area of Sicily was evaluated. We calculated the hazard scenarios based on the most recent paroxysm events at Santa Barbara and Aragona, in order to define a realistic dimension for a correct risk assessment. It is evident that the hazardous paroxysm areas that we have computed, should be implemented with a probabilistic modelling approach, deriving from the real measured parameters on both areas. For these reasons, it should be important to implement in terms of acquisition frequency as well as the number of parameters, the actual discrete multidisciplinary surveys, with a new technological geochemical and geophysical observatory, in order to minimize the knowledge gaps in these two areas. In light of this, therefore, it is appropriate to realize and maintain a high-frequency multidisciplinary data acquisition system to allow the construction of a forecast model able to best represent the real conditions and, on the basis of which, a monitoring system should be implemented.

Nowadays, it is impossible to define "*when*" the next paroxysm will occur and how much will be intensity. This is because currently there are not enough information to recognize the parameters that could potentially change before a paroxysm as well as a modelling approach of the phenomenon does not exist.

In this work, our hazard assessment for the Santa Barbara and Aragona areas, represent a picture of the 2017 survey. The emission points, checked in 2017, could change their location over time. It is therefore appropriate, in the light of this, to monitor the new emission points and fractures in both sites, as potential sources of future paroxysmal events, as demonstrated in 2020 at Aragona where the paroxysm occurred in an emissive point, mapped in our 2017 survey.

It is important to underline that we cannot exclude that these paroxysmal events, could occur out of the restricted area in which most of the emission points are located at the surface. At the same time, an update of the actual hazard maps for the two areas must be implemented. However, a better comprehension of the sedimentary volcanism paroxysmal processes is needed, with particular reference to their hazard assessment; it is certainly important in a next future, to build a paroxysmal events catalog in order to be able to apply advanced assessment approaches such as the one proposed by Mellors et al, (2007).

From hystorical informations, we know that different phenomena could occur before a paroxysm in the mud volcanoes areas, in particular deformations, soil fractures and increasing of seismicity.
After the paroxismal event, according to the hystorical descrisptions, a strong smell of acrid gas reasonably H_2S is recorded. H_2S, if breathed in high concentrations, could be lethal to human life. It is a toxic, corrosive, irritant and colorless gas with the characteristic unpleasant smell of rotten eggs. It can cause chronic diseases of the respiratory organs through prolonged exposure even at very low concentrations; at concentrations of 200-250 ppm it can cause pulmonary edema and risk of death, while at 1,000 ppm it is immediately lethal (NIOSH, 1981).
Since October 2017, a short period seismic station was installed in Santa Barbara site. The continuous monitoring and the preliminary analysis of the acquired signals allowed to highlight variations in the power of environmental vibrations. Moreover, the presence of periodic micro-seismicity, likely due to linked variation in emissions and bubbling activity, was detected. However, the use of a single station does not allow a complete characterization of the seismic activity, for which the creation of a micro-network would be desirable. Continuous monitoring of local microtremor and micro-seismicity, in particular before and during a paroxysmal event, could allow us to understand the source mechanisms of these events and propose useful predictive models for risk reduction.
Only with the installation of a multidisciplinary geochemical and geophysical observatory at the two study areas, we could speculate to discriminate the "potential" phenomena that could occur before, during and after a paroxysm event. For these reasons, different geochemical and geophysical parameters will have to be analysed, verified and validated in the next future.
It could be a useful tool for Civil Protection Authorities in order to take the appropriate risk mitigation measurements for the exposed people. A safety path outside our hazardous detected areas should be considered by the local administrations, in order to reduce the risk. Our hazardous paroxysm areas, in both sites, finally should be forbidden to visitors, expecially during the period where high deformation, fractures and seismicity occur.

Competing interests

The authors declare that they have no conflict of interest.

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