Bulletin of Geophysics and Oceanography Vol. 65, n. 2, pp. 165-176; June 2024
DOI 10.4430/bgo00437

The fine structure of seismic emissions from the Nirano mud volcanoes (northern Apennines, Italy): a phenomenological study

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(Received: 17 May 2023; accepted: 3 September 2023; published online: 21 December 2023)

ABSTRACT Seismic signals generated by mud volcanoes could be used to monitor gas emission. To this end, a seismic array of vertical geophones and three-directional velocimeters have been deployed close to major emission cones in the Nirano mud volcano area, in the northern Apennines. A detailed analysis of the resulting time series has been performed both in time and spectral domains, revealing the existence of three distinct kinds of signals: background noise, paroxysmal phases (drumbeats), and regular sequences of identical pulses (drumrolls). Both drumbeats and drumrolls are characterised by higher frequencies than the background seismic noise. Drumbeats show relatively high amplitudes and long durations (in the order of several seconds) but an irregular time pattern, while drumrolls are constituted by very regular sequences of almost identical short (less than 1 s) monochromatic pulses. Both drumbeats and drumrolls appear to be constituted by S waves, originated locally in the same shallow subsoil area, close to the main vents. These seismic signals could be related to the mechanical interaction of shallow solid conduits with a two-phase (mud and gas) slug flow from depth, which is characterised by irregularly spaced long bubbles (drumbeats), alternated with trains of small bubbles (drumrolls).

Key words: mud volcanoes, Nirano, gas emission, passive seismic measurements.

1. Introduction

Mud volcanoes (MVs) are geological structures found all over the world, both in continental and offshore settings, with sizes varying from a few metres to several kilometres of diameter, and up to hundreds of metres in height. Sedimentary volcanism related to mud volcanoes is among the main manifestations related to surface emissions of deep fluids, including mud, saline water and hydrocarbons, and carries important implications in energy resource exploration, seismicity, hazard, and the atmospheric budget of greenhouse gases (Mazzini and Etiope, 2017), especially methane and carbon dioxide. MVs originate from rapid depositional processes, which lead to the genesis of fluid-rich overpressured sediments. This fluid-enrichment causes a reduction of sediment density and viscosity with respect to the surrounding wall rocks, and it initiates the process of material ascent to the surface.

Volcanic activity, which feeds such structures, usually consists in the superficial escape of fluid material, known as mud-breccia, while the sporadic, although present, more energetic phases are usually responsible for the expulsion of mud, ash, and decimetric and metric clasts (Accaino *et al.*, 2007).

There are about 60 inland MVs in Italy, mostly located along the outer Apennine belt and Sicily (Martinelli and Judd, 2004). Among these sites, those known as 'Salse di Nirano' (Fig. 1) are one of the most spectacular, attracting about 2,000 visitors per year. The main vents are located at the bottom of a topographic depression formed within clay sediments of marine origin, and are aligned along a NE-SW direction; the largest vent reaches a height of about 3 m from the surrounding plain, and is surrounded by several secondary vents that include pools, saline muds, and gryphons (Oppo, 2011).

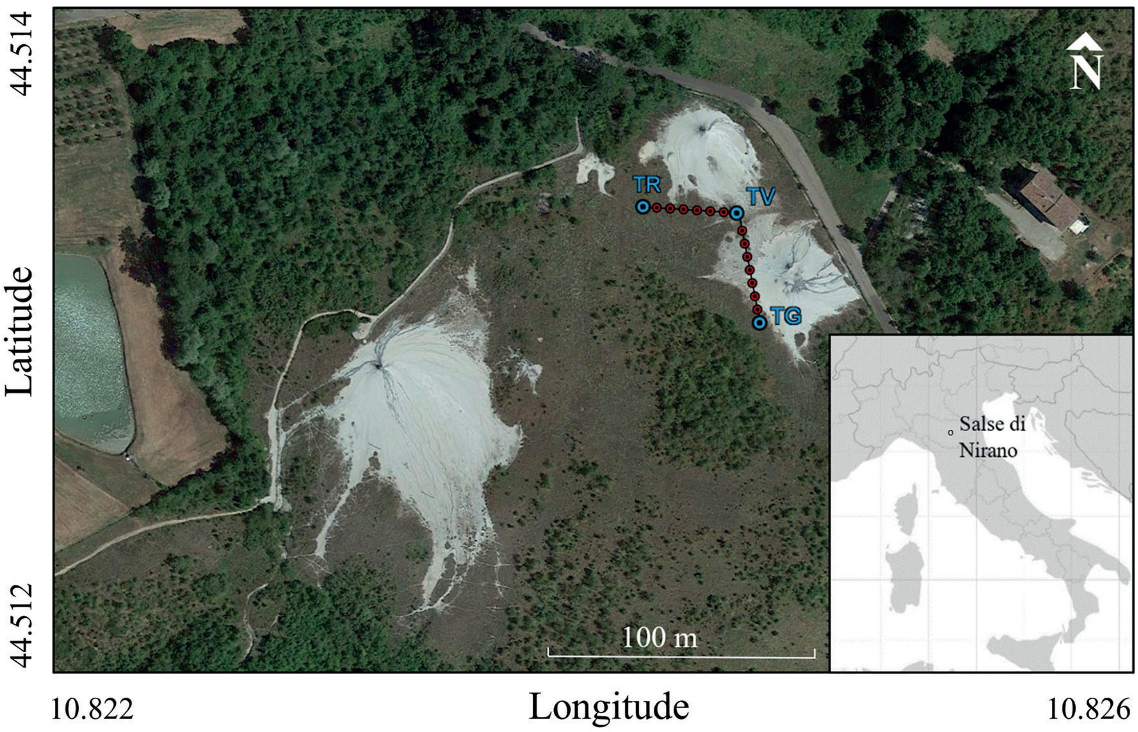


Fig. 1 - Google Earth image of the Nirano MVs, subject of this preliminary study. The figure shows the location of the 16 geophones (red and blue dots) used for computing the Rayleigh wave dispersion curve. The blue dots identify receivers, next to which ambient vibration measurements have been performed with the aid of three-directional single-stations. TR, TV, and TG are the abbreviations used for the three stations.

Nirano MVs, and their volcanic activity have been known for centuries, and they have been the subject of several surveys during the years. Historical studies (Coppi, 1875; Stoppani, 1876; Pantanelli and Santi, 1896; Biasutti, 1907; Barbieri, 1947; Mucchi, 1966, 1968) and researches pertaining to different scientific fields, such as the mineralogical (Ferrari and Vianello, 1985), volcanic (Gorgoni, 1988, 2003; Bonini, 2008, 2009, 2012; Manga and Bonini, 2012; Lupi *et al.*, 2016), geological and geomorphological (Bonazzi and Tosatti, 1999; Castaldini *et al.*, 2003, 2007, 2011, 2017; Castaldini and Coratza, 2017) ones, have contributed to creating an important documentation based on the formation and evolution of the Nirano MVs.

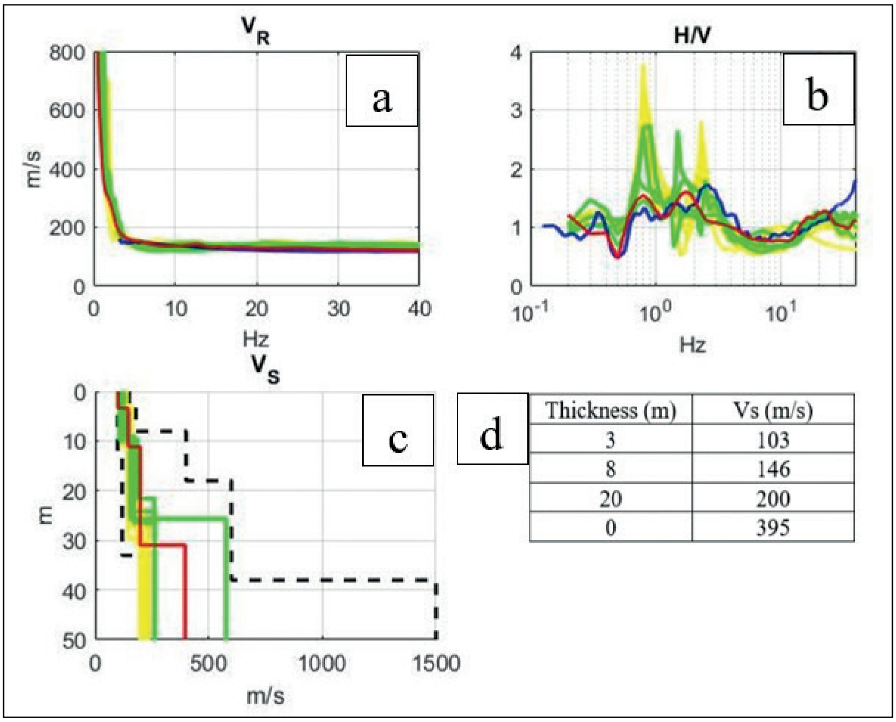
From a geophysical point of view, resistivity and seismic surveys were carried out in the area, with the aim of investigating the configuration of the shallow subsoil (a few tens of metres) below the vents. Accaino *et al*. (2007), Oppo (2011), and Lupi *et al*. (2016) highlighted the possible existence of rich-fluid sub-vertical ducts just below the main vents. Active and passive seismic surveys, performed by Albarello (2005), Albarello *et al*. (2007, 2012), Lupi *et al*. (2016), and Antunes *et al*. (2022), revealed the existence of seismic signals, that originated in the area, and are possibly related to gaseous emissions. These findings are in line with similar outcomes obtained by La Rocca *et al*. (2023) in relation to another site in southern Italy.

This work describes the preliminary results of a seismic survey carried out on the Nirano MVs by using a small-scale seismic array, with the purpose of providing a more detailed characterisation of the seismic emissions detected by the abovementioned authors. In particular, a seismic array was deployed close to the main vents of the Nirano MVs (Fig. 1). The array includes 16 4.5-Hertz vertical geophones, and BrainSpy™, a digital acquisition system produced by Moho S.r.l. (https://moho.world/). The geophones were deployed along two branches (i.e. eight sensors per branch), each 5 m apart. Three three-directional 24-bit digital Tromino™ tromographs, produced by Moho S.r.l., were installed at the two ends and at the central point of the array (Fig. 1). Seismic signals were collected for one hour at 256 sps.

First, the velocity (Vs) profile, below the array, is estimated. Next, a detailed spectral and time domain analysis of the registered signals is described. Lastly, a possible, yet rather preliminary, interpretation of the above findings is provided.

2. Estimating the local Vs profile

Artificial signals generated at both ends of the array, and at the central point, were analysed by following the standard Multichannel Analysis of Surface Waves approach (e.g. Foti *et al*., 2018). To this end, acquisitions at the eight geophones of each of the two branches were considered to retrieve the Rayleigh wave dispersion curve by using the MASWaves software (Olafsdottir *et al*., 2018). Another estimate of the dispersion curve was obtained by considering the registration of the whole array, by using the Extended Spatial AutoCorrelation technique (e.g. Okada, 2003; Foti *et al*., 2011) in the form proposed by Parolai *et al*. (2006). By combining the resulting estimates, a site-representative dispersion curve has been obtained in the frequency range 3-50 Hz. Moreover, ambient vibrations acquired at the three-directional single-stations were analysed using the Horizontal to Vertical Spectral Ratio (HVSR) technique (e.g. Molnar *et al*., 2022) by following Picozzi *et al*. (2005). In particular, the spectra of the single components were computed by averaging 20-second long non-overlapping windows; a baseline correction, and a 5% cosine taper were applied to each window, and the spectra were smoothed using a triangular moving window with a frequency-dependent half width (5% of central frequency). No sharp impedance contrast has been identified by the HVSR curves (Fig. 2). Moreover, the presence of a V/H maximum around 0.5 Hz (see the minima in Fig. 2b), detected by Antunes *et al*. (2022), is confirmed. The local Vs profile has been obtained by jointly inverting Rayleigh wave dispersion and HVSR curves by using a genetic algorithm procedure (e.g. Albarello *et al*., 2011). The inversion procedure was repeated 10 times, and the overall best-fitting profile (red profile in the bottom left panel of Fig. 2) was chosen among all the ten separated inversions (Farrugia *et al*., 2016) as the one characterised by the minimum misfit value. Similar procedures, based on HVSR measurements and surface wave prospecting methods, were performed by Panzera *et al*. (2016, 2018) in different volcanic contexts, to obtain information about the subsoil structure and the presence of a potential reservoir beneath the vents. Unlike the profile obtained by Antunes *et al*. (2022) in the same area (the Nirano MVs), no buried low-velocity layer was found, possibly due to the different location of the respective arrays.



Thickness (m)	Vs (m/s)
3	103
8	146
20	200
0	395

Fig. 2 - Results of the Rayleigh wave joint inversion procedure (a), dispersion curves and HVSR (b). In panel c, the best fitting profiles relative to 10 runs of the procedure are reported. The overall best fitting profile is reported in red; green curves represent models characterised by misfit values lower than 50% of the overall minimum, and the yellow curves correspond to the remaining best fitting models; dashed lines delimit the overall constraints of the inversion procedure. In panel d, the overall best fitting model is reported.

3. Seismic activity patterns

In Fig. 3, the 16 traces recorded at the array are shown, ordered from north to south. At first glance, all the traces show similar patterns.

Amplitude variations have been estimated by considering the ratios between the average amplitude (in absolute value) of the signal within a sliding 10-second moving window with respect to the one relative to the whole trace [the Real-time Seismic Amplitude Measurement (RSAM) parameter by Endo and Murray (1991)]. The Fourier spectrogram has also been computed by considering a 2-second moving window overlapping for 0.85 s. To highlight the shape variations of the Fourier spectra, the spectrum obtained for each window has been normalised to the respective maximum.

Outcomes (Fig. 4) show the clear non-stationarity of the seismic signal over time, with phases of intense activity (lasting tens of seconds) occurring several times during the recordings. In addition, the spectrogram shows that different spectral structures emerge during monitoring. Identical patterns have been determined for all the vertical sensors of the array

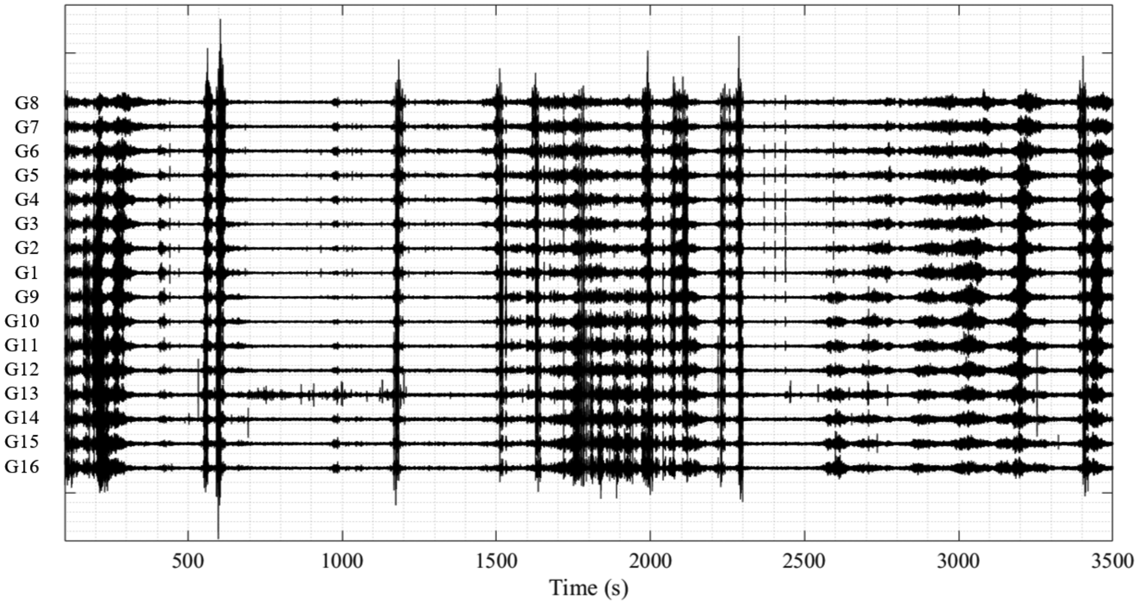


Fig. 3 - Plot of the 16 recorded traces of the array, ordered from the northernmost (at the top) to the southernmost (at the bottom).

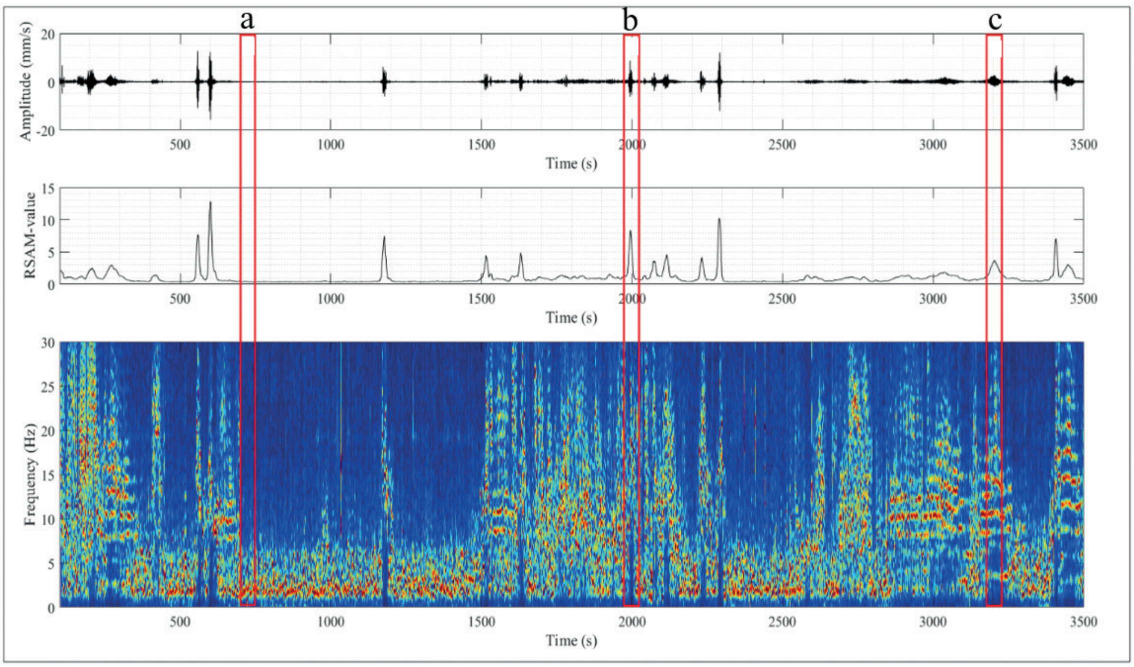


Fig. 4 - The top panel shows the recorded signal at one of the receivers. The central panel shows the RSAM values and the bottom panel illustrates the spectrogram computed for the entire trace. Spectral amplitudes computed for each window have been normalised with respect to the highest value. The red rectangles represent three 40-second time windows, representative of the three different patterns: background ambient vibration (a), drumbeat (b) and drumroll (c).

and three-component stations. Based on these outcomes, this study proposes a classification of the observed activity by considering three patterns: quiescent phases, drumbeat activity, and drumroll activity.

Quiescent phases are characterised by relatively low RSAM values (between 0.5 and 1) and low frequency contents (below 10 Hz). In Fig. 5, the time pattern, typical of these phases, is shown. No evident correlation can be detected by comparing the signals of the surrounding sensors. In these phases, it is apparently reasonable to identify background noise relative to ambient vibrations generated by distributed remote sources (Nakata *et al.*, 2019).

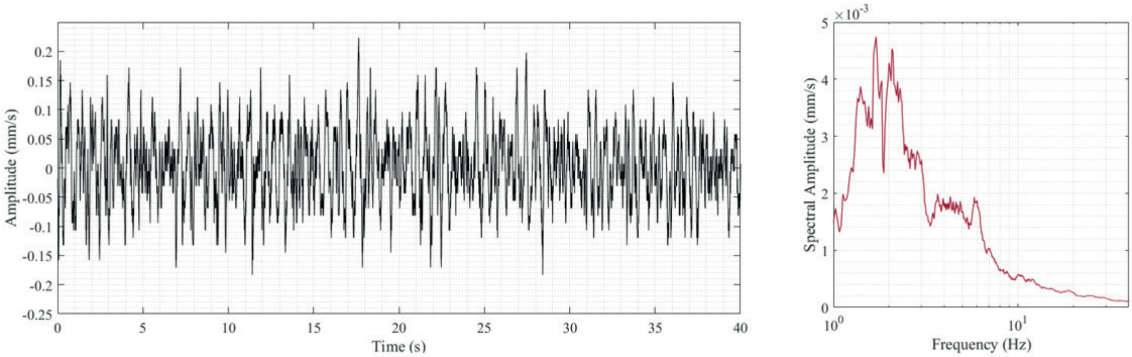


Fig. 5 - The left panel shows a 40-second long time window of background ambient noise (window a in Fig. 4); the right panel represents the corresponding Fourier spectrum.

During the recordings, phases of intense seismic activity occurred (Fig. 6) and these are characterised by an evident increase of the RSAM parameter (between 2 and 12), and by the Fourier high frequency spectra (>10 Hz). During these phases, there is a good coherence between the signals of the 16 sensors. Similar signals (drumbeats in the literature) have been detected in many volcanic contexts (Iverson *et al*., 2006; Kendrick *et al*., 2014; Lupi *et al*., 2016; Giovani *et al*., 2017; Lin, 2017; Antunes *et al*., 2022; La Rocca *et al*., 2023). Each drumbeat lasts for several seconds (usually between 5 and 30 s), and shows a good coherence between the 16 receivers. During these phases, single high-energy events, with varying amplitude and time duration (generally in the range of 0.2-0.3 s), randomly occur.

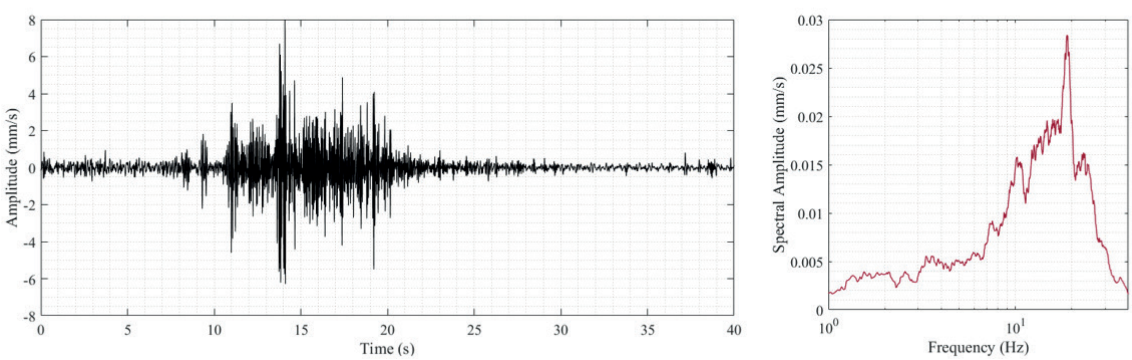


Fig. 6 - In the left panel, a common drumbeat phase with a duration of 40 s is shown (window b in Fig. 4); the right panel represents the corresponding Fourier spectrum.

A peculiar pattern (drumroll, hereinafter) has also been identified (Fig. 7). It is characterised by sequences of tens to hundreds of almost identical short pulses regularly distributed in time, and lasting for several seconds (10 to 50 s). Hereafter, these signals will be referred to as pulses within drumrolls in order to distinguish them from the isolated events detected within drumbeat phases, which do not show the same periodicity. However, similarly to drumbeats, drumrolls are characterised by high frequency content (above 10 Hz), but show a peculiar spectral pattern characterised by sharp peaks around single frequencies (Fig. 7).

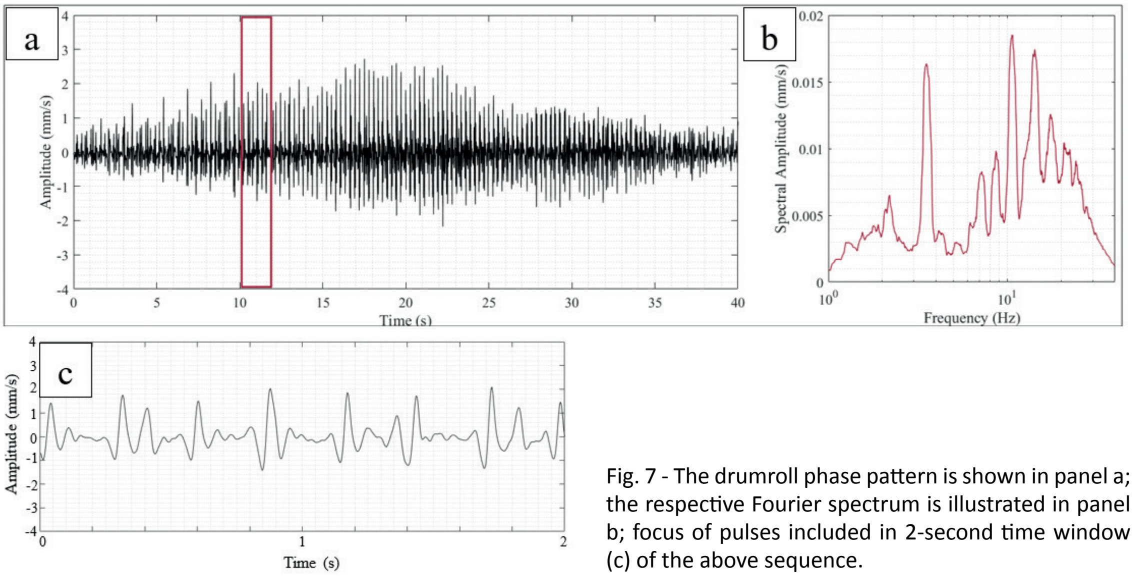


Fig. 7 - The drumroll phase pattern is shown in panel a; the respective Fourier spectrum is illustrated in panel b; focus of pulses included in 2-second time window (c) of the above sequence.

A total of 30 drumrolls were identified throughout the recording, each of which with a different duration and number of pulses (Fig. 8). These pulses show a marked correlation between the traces at the array sensors. It is interesting to note that drumrolls occasionally develop at the end of high intensity drumbeats (Fig. 11), thus suggesting the possible presence of a physical interaction between the processes causing both phenomenologies.

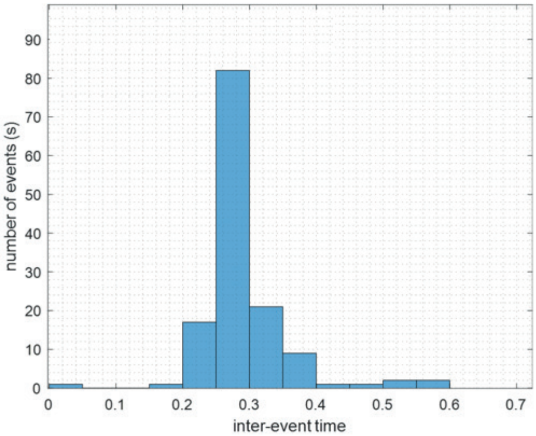


Fig. 8 - Histogram of the inter-event time distribution within a drumroll sequence composed of 137 pulses.

4. Provisional source identification

As noted above, unlike background noise, both drumbeats and drumrolls show a high correlation between the signals registered at the array sensors (Fig. 9). This offers the possibility of provisionally locating the respective sources. To this purpose, time arrivals of single events (within drumbeats) and pulses (within drumrolls) at the array sensors have been picked, and the approximate approach by Pujol and Smalley (1990) has been used for the preliminary identification of the respective sources and determination of the signal phase velocities.

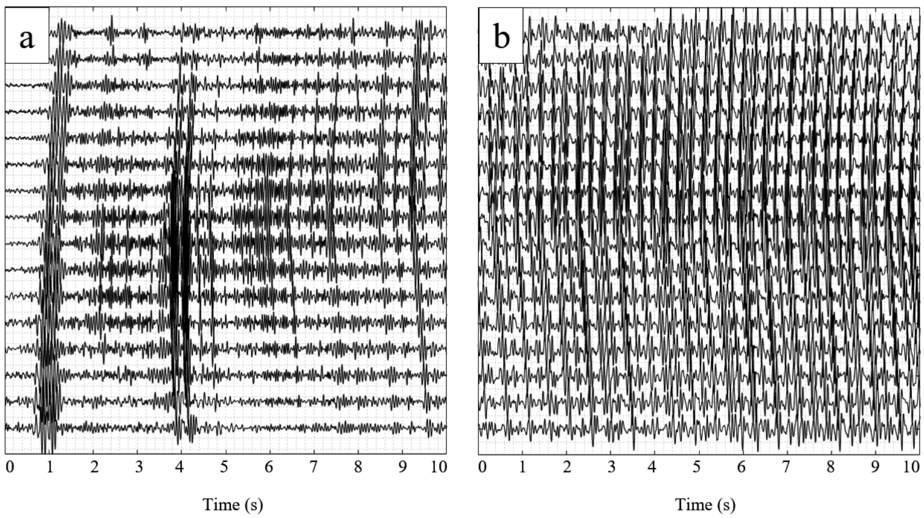


Fig. 9 - Panels a and b show 10 seconds of recorded seismic signals, respectively of drumbeat and drumroll phases over all the 16 traces of the array. It should be noted that drumbeat amplitudes are scaled by a factor of five compared to drumroll amplitudes.

Fig. 10 shows the location of 10 detected pulses within drumroll sequences, and the location of five events identified within different drumbeat phases. All the sources are local, and shallow

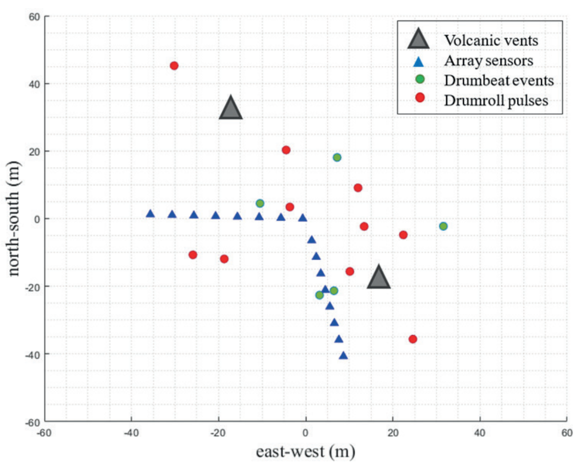


Fig. 10 - Final sources of the 10 pulses and five events selected. The grey triangles represent the main north-eastern volcanic vents in the Nirano mud volcanic field.

(mostly below 5 m of depth). No systematic difference results between drumbeat and drumroll locations. By accounting for the preliminary character of this analysis, these findings are in line with source locations detected by Antunes *et al*. (2022). Regarding the apparent phase velocity of the signals, pulses and events are in the approximate range of 110-180 m/s. These values suggest that most of the wave energy is carried by the S seismic phases.

5. Concluding remarks

Deploying a small aperture seismic array close to the main vents of the Nirano mud volcano system enables the detection of different activity phases, each characterised by distinct patterns: background seismic noise, drumbeat, and drumroll. A careful analysis of time and spectral patterns, along with the correlation between the signals registered at the array sensors, makes a clear distinction of these activity phases possible. The respective markers could be of considerable help in the future in evaluating the underlying dynamics of these signals, most probably related to gas emission. Whole drumbeats were detected by previous authors (e.g. Antunes *et al*., 2022; La Rocca *et al*., 2023), whereas drumrolls have been detected and characterised for the first time. These show a slight similarity with seismic events detected in magmatic volcanic contexts by Lin (2017). This suggests that such kind of signals could be ubiquitous in degassing environments, and representative of peculiar dynamics.

As observed, drumbeats and drumrolls occasionally follow each other, and are possibly generated by local sources. A possible and useful model to interpret these features may be represented by the interaction of conduit walls with an ascending two-phase (mud and gas) fluid. This could be a ‘slug flow’ (Fabre, 1994; Fabre and Line, 2006) characterised by the intermittent sequence of mud slugs with dispersed small bubbles (possibly responsible for drumrolls), and long gas bubbles (possibly responsible for drumbeats) flowing through the conduits (Fig. 11). Apparently, this model roughly captures the features of the observed signals, and could be of great help in interpreting gas emissions at mud volcanoes.

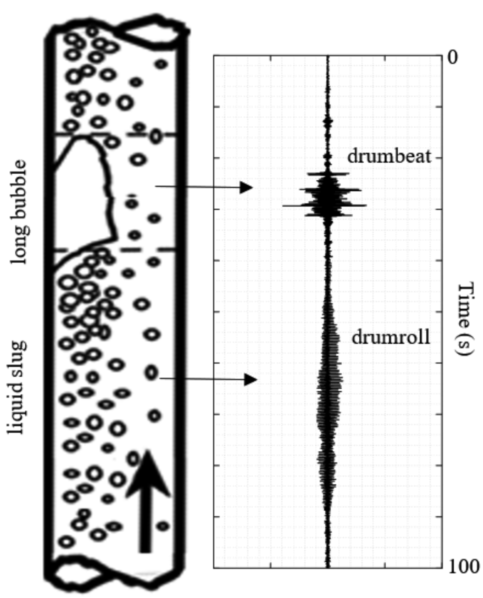


Fig. 11 - Schematic picture of slug flow. The figure shows a sequence of liquid slugs containing dispersed bubbles, alternating with sections of separated flow (modified from Fabre and Line, 2006).

Acknowledgments. We would like to thank the Municipality of Fiorano Modenese for supporting our experimental activities. This work was presented at the GNGTS 2023 conference.

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