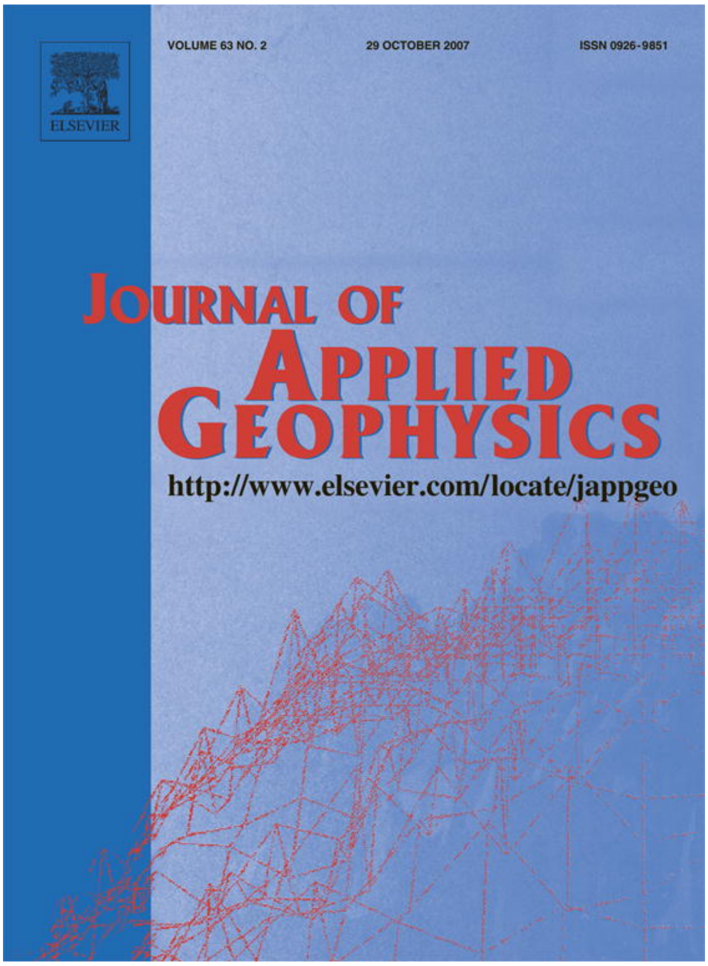
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Fluid seepage in mud volcanoes of the northern Apennines: An integrated geophysical and geological study

Flavio Accaino [a,*], Antonio Bratus [a], Stefano Conti [b], Daniela Fontana [b], Umberta Tinivella [a]

[a] *Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/C, Sgonico, Trieste, Italy*
[b] *University of Modena and Reggio Emilia, Italy*

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Abstract

An integrated geophysical and geological study of small mud volcanoes occurring along the external compressive margin of the chain in the northern Apennines was carried out in order to investigate the fluid pathways and the mud reservoir. Results obtained by tomographic inversion of first arrivals of 3D seismic data, and models obtained by 2D geo-electrical data, allow determination of the geometry of the buried shallow structures, and the details of the fluid seepage down to 50 m below the mud volcano surface.

Seismic and geo-electrical investigations clearly detected the sub-vertical structures of the superficial outlet of the volcanic conduits and chimneys. A mud chamber was identified at a depth of 25 m. This shallow reservoir could represent the last phase of mud accumulation before final emission. Comparison with other mud volcanoes of the northern Apennines suggests a close relationship between extruded materials and substratum typology.

Keywords: Mud volcano; 3D seismic; Seismic tomography; Geo-electric tomography

1. Introduction

Among fluid venting structures, mud volcanoes are the most important phenomena related to natural seepage from the earth's surface (Mazurenko and Soloviev, 2003). Mud volcanoes have variable geometry and size, from one to two meters to several hundred meters in height, and are formed as a result of the emission of argillaceous material and fluids (water, brine, gas, oil) (Milkov, 2000; Dimitrov, 2002; Kopf, 2002). They occur globally in terrestrial and submarine geological settings: most terrestrial mud volcanoes are located in convergent plate margin with thick sedimentary sequences within the Alpine–Himalayan, Carribean and Pacific orogenic belts (Hovland et al., 1997; Kopf et al., 2001; Delisle et al., 2002; Etiope et al., 2002; Deville et al., 2003; Yassir, 2003; Shakirov et al., 2004; Stewart and Davies, 2006). Mud volcanoes and mud diapirs are responsible for the genesis of many chaotic deposits, such as mélanges, chaotic breccias and various deformed sediments (Barber et al., 1986; Barber and Brown, 1988; Orange, 1990; Brown and Orange, 1993).

The normal activity of mud volcanoes consists of gradual and progressive outflows of semi-liquid material called mud breccia or diapiric mélange. Explosive and

* Corresponding author. Tel.: +39 0402140259; fax: +39 040327307.
E-mail address: faccaino@ogs.trieste.it (F. Accaino).

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paroxysmal activities are interpreted as responsible for ejecting mud, ash, and decimetric to metric clasts. Mud volcano breccias are composed of a mud matrix, which supports a variable quantity of chaotically distributed angular to rounded rock clasts, ranging in diameter from a few millimeters to several meters (Camerlenghi et al., 1992; Dimitrov, 2002; Deville et al., 2003). Clasts are of various lithologies and provenances, derived from the rocks through which the mud passed on its way to the surface or to the sea-floor. Slumps, slides and sedimentary flows can also affect the entire structure of mud volcanoes, even if gradients are very low.

The occurrence of mud volcanoes is controlled by several factors, such as tectonic activity, sedimentary loading due to rapid sedimentation, the existence of thick, fine-grained plastic sediments and continuous hydrocarbon accumulation (Treves, 1985; Guliev and Feizullayev, 1996; Ivanov et al., 1996; Limonov et al., 1996; Milkov, 2000; Dimitrov, 2002).

Mud volcanoes in Italy occur along the external compressive margin of the Apennine chain (Pellegrini et al., 1982; Capozzi et al., 1994; Martinelli, 1999; Martinelli and Judd, 2004). They were described far back in history (Spallanzani, 1795; Stoppani, 1908) and listed by Biasutti (1907), Scicli (1972), and Ferrari and Vianello (1985). Italian mud volcanoes are usually small and unspectacular, when compared to other world examples. They rarely exhibit the periodic explosive activity (Capozzi and Picotti, 2002), which is often related to important seismic events. The Nirano mud volcanoes represent one of the best examples of the Bulganaskshi category as reported in the northern Apennines (Martinelli and Rabbi, 1998), even if the fluid pathways are still not well understood. In the framework of co-operation between the Department of Earth Science of the University of Modena and Reggio Emilia and the OGS, a geophysical study recorded geo-electrical profiles and 3D seismic data at Nirano (Italy, Northern Apennine) (Fig. 1). The aim of this study is to investigate the shallow buried structure and associated fluid seepage processes down to 50 m below the mud volcano surface, using information obtained by tomographic inversion of first arrivals of 3D seismic data and models derived from 2D geo-electrical data.

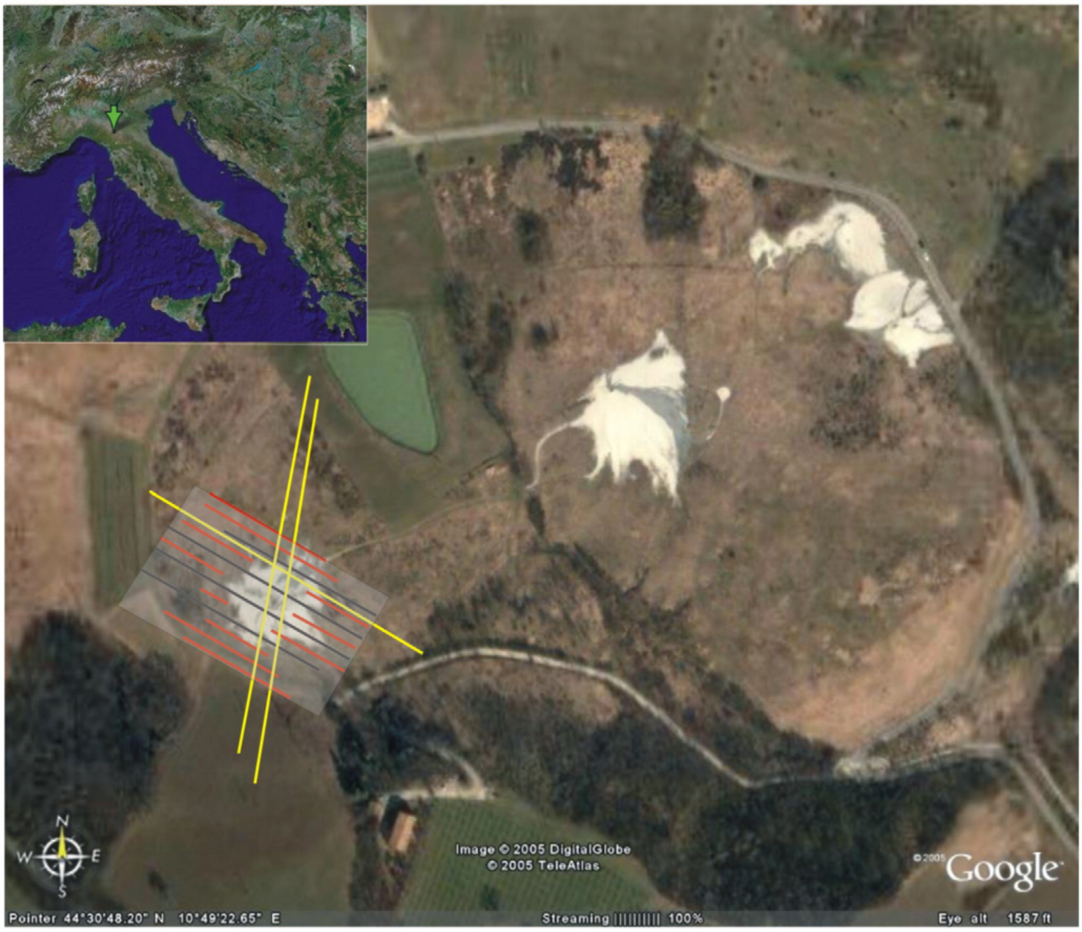

Fig. 1. Location map of the geophysical investigation. The yellow lines are the geo-electric lines; the black lines indicate the shots position; the red lines indicate the receiver lines of the seismic experiment.

2. Geological setting

The northern Apennines are characterized by imbricated thrusts, thrust sheets, and nappes verging towards the NE. These structures bound several tectonic units of oceanic and continental origin. The complex structure of the chain is the result of the convergence and collision between the European and the Adria (a promontory of the Africa) plates from the Mesozoic to the present. Starting from the Early Cretaceous, an intra-oceanic accretionary prism caused the progressive consumption of the Piedmont-Ligurian Ocean, a portion of the Tethys. The complete closure of the ocean during Middle–Late Eocene time caused the rapid uplift and erosion of the Alpine orogenic wedge and the inception of the continental collision. The thrust imbrication includes a Late Cretaceous–Cenozoic polyphase accretionary wedge, which shows evidence of recycling perched basins and is progressively involved in thrusting and folding (Boccaletti et al., 1990; Doglioni et al., 1998; Guegen et al., 1998; Argnani and Ricci Lucchi, 2001).

From top to bottom, and from SW to NE, the nappes and thrust units include: Ligurian nappe, composed of ophiolites and oceanic sediments of Jurassic to Eocene age (Ligurian units) and sub-oceanic sediments of Cretaceous to Oligocene age (sub-Ligurian units); Tuscan nappe and Cervarola unit, made up of Mesozoic to Tertiary carbonate-siliciclastic successions of the outer Adriatic continental margin; Umbria–Romagna and Marche-Adriatic thrust units, constituted by Mesozoic to Pleistocene carbonate-siliciclastic deposits of the inner Adriatic continental margin.

Foredeep basins (Oligocene to Recent) formed in front of the migrating thrust front (NE–E-vergent) on the flexured margin of the Adria plate, and their sedimentary fills were progressively deformed and accreted to the fold-thrust belt. During the migration of the thrust belt-foredeep system, deposition also occurred in smaller basins located on top of the migrating frontal thrust, called wedge-top or satellite basins. The sedimentary succession of these basins, ranging from Eocene to Plio-Pleistocene is named the epi-Ligurian sequence (Ricci Lucchi, 1986).

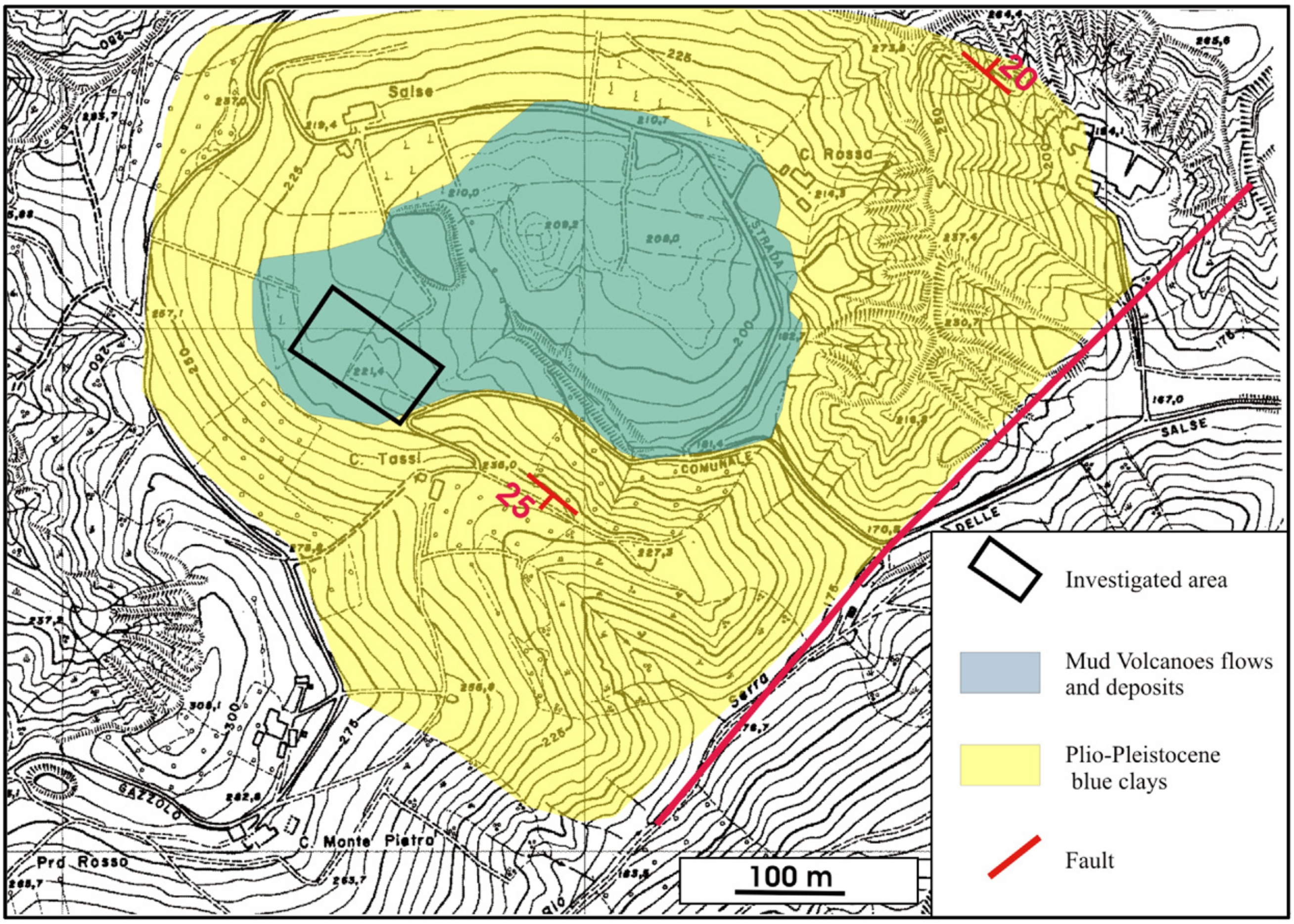

Fig. 2. Geological map of the investigated area.

2.1. The Nirano mud volcanoes

The Nirano mud volcanoes are located in a large oval-shaped depression, about 500 m in size, near an anti-apenninic fault line cutting a little anticline (Gasperi et al., 1989, 2003) deforming the Plio-Pleistocene argillaceous sediments (Rio of Petrolio Clays) of the foredeep (Fig. 2). In the pliocenic mudstones natural emissions of mineral oil are present along the Petroleum Creek, exploited for medical purposes since the XV century A.C. The material expelled is semi-liquid and composed of mud and water, usually of Cl–Na type, associated with methane, carbon dioxide and subordinate liquid hydrocarbons (Martinelli and Rabbi, 1998). Isotope geochemistry of waters expelled from mud volcanoes evidences ancient marine origins and a thermogenic origin of methane bubbling (Mattavelli and Novelli, 1988; Martinelli and Rabbi, 1998). Field investigations reveal that emissions of liquid and bubbling clay form several small cones, 3 main clusters of cones (gryphons), and larger pools called “salses”. The cones range in height from 1 m to 3 m, and are less than 2 m in diameter. Griphon extension varies from 10 to 20 m. Cones have a large flat base passing to steep flanks. The positions and dimensions of cones vary greatly through time. The bubbling activity differs from cone to cone, with small bubbles in low-viscosity mud, and large bubbles in high-viscosity mud. The pools do not have an elevated rim structure and emit liquid mud of low viscosity. Mud flow sheets and lobes depart all around cones and extend to 100 m.

The fluid emissions are mainly represented by mud flows (Bulganakshi category, according to Snjukov et al., 1986), sporadically alternated with flows enriched in a fine-grained debris of pliocenic shell fragments. Eruptive phases are related to seismic activity, as reported in historical chronicles (see Martinelli, 1989). The Nirano fault, probably linked to the Sassuolo fault-scarp line, which is located 2 km North of the Nirano valley, represents the main pathway of fluid expulsion. However, the details of the fluid circulation are still not well known.

3. Seismic experiment

The seismic experiment was performed during the summer 2005 with the purpose of identifying the geometries of the shallower structures below a cluster of mud volcanoes of the area. The energy source was generated by a MiniVib with a sweep of 8 s ranging from 20 Hz to 250 Hz. The choice of source was made in order to limit environmental damage and to have the possibility of generating both P and S energy. Two 3D seismic readings were taken using vertical geophones in the first acquisition with P energy as source, and horizontal geophones in the second acquisition when S energy was generated. The geophone pattern consisted of four lines spaced at 12 m and crossing the largest mud volcano. The outlet of this mud volcano was between the two central geophone lines, where no shots were performed to avoid environmental damage. Along each geophone line the receivers, with a nominal frequency of 10 Hz, were spaced at 6 m with a total for the four lines of 85 three component geophones. 23 shot lines, perpendicular to the geophone lines, were fired as shown in Fig. 3 with a total of 111 shot positions. In Fig. 4 the fold

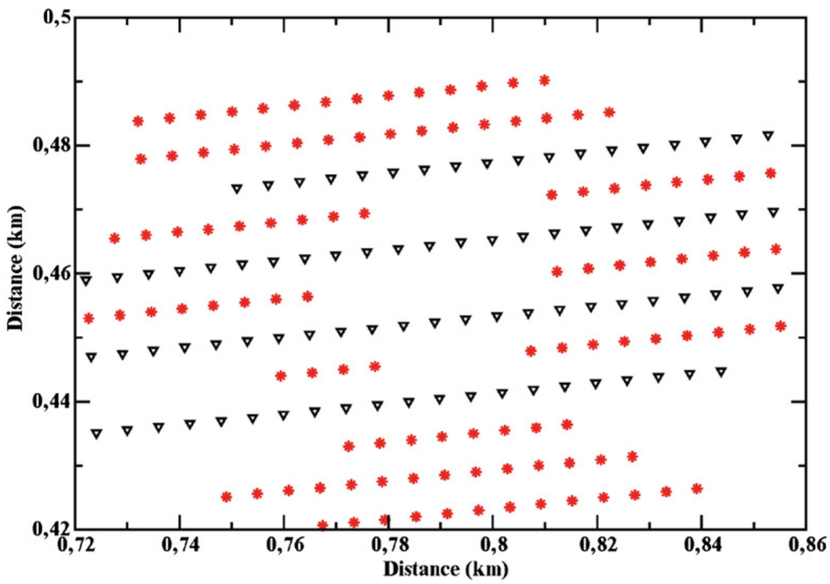

Fig. 3. Coverage of the seismic experiment considering pixels of 2.5 × 2.5.

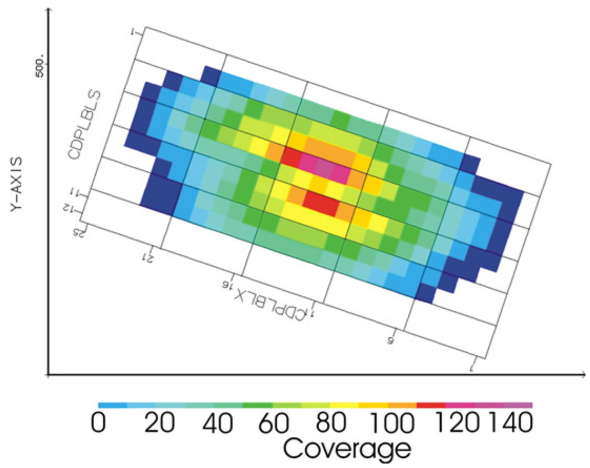

Fig. 4. Scheme of the 3D seismic acquisition. The stars are the shots and the triangles are the receivers.

of the investigated area is shown considering a binning of 6 × 6 m. It can be observed that a high areal coverage (in the central part of the investigated area more than 100) is obtained.

The quality of the P data is high and the identification of the first arrivals is clearly detected (Fig. 5; top). On the other hand, the quality of the S-wave data is poor, as shown in Fig. 5 (bottom). The S data was rotated to enhance the energy response. In the Fig. 5 the in-line component is shown. The poor quality of the S data could be due to various factors imputable either to acquisition difficulties or to the nature of the sub-soil. In fact, if the S-wave data does not permit a reliable velocity analysis, the comparison of the different responses between P and S energy can provide information on the presence of fluid phases in the subsurface, which hinder the transition of the S energy.

3.1. Tomographic inversion

To obtain detailed information about the shallow structures under the studied mud volcano, picking of the first arrivals of all the shots was performed. A total of more that 8000 picks was used simultaneously to perform the tomographic inversion. To avoid errors in picking, the analysis of the apparent velocity of the pick was performed, and the picks with anomalous apparent velocity were not considered (see Fig. 6).

The initial velocity model was composed of the topographic surface and deeper surfaces, spaced every 8 m in depth, that smooth the topography until reaching

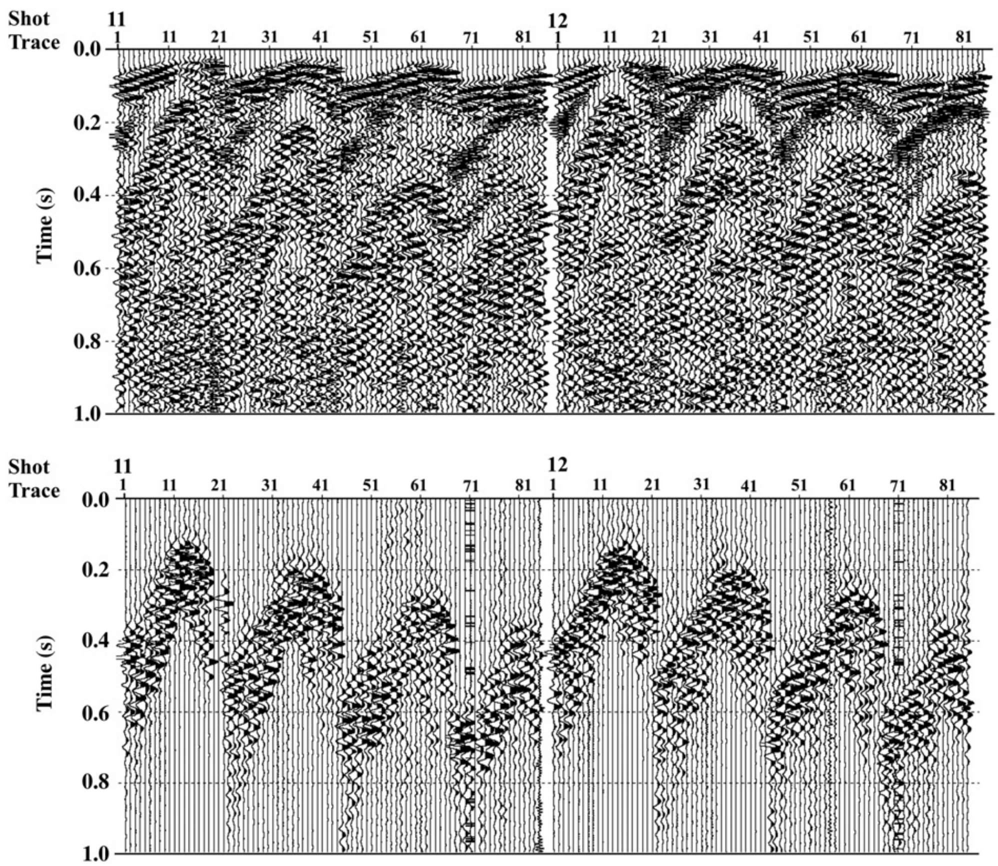

Fig. 5. Example of a shot record in the vertical (top) and horizontal in-line component (bottom), using P and S energy respectively.

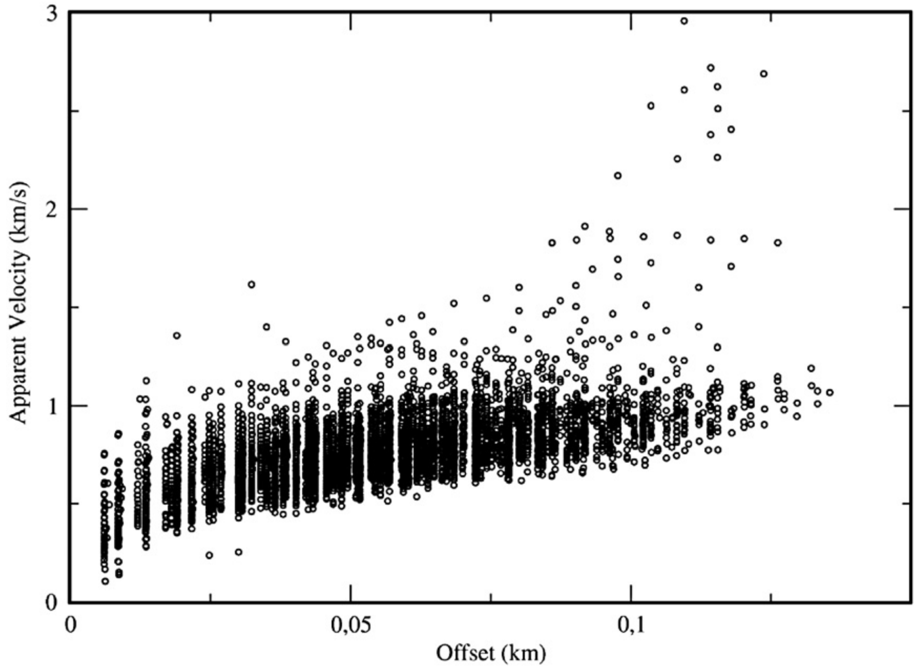

Fig. 6. Apparent velocities of the first breaks picked in the shot domain.

a horizontal surface. Each layer is composed of 20 × 10 pixels with a size of 10 m, so the lateral and depth resolutions are comparable.

The initial model was performed using a constant velocity of 500 m/s.

The inversion was performed with tomographic software (CAT3D), using a modified version of the minimum time ray tracing (Böhm et al., 1999), and an iterative procedure for the inversion, based on the SIRT algorithm. The ray tracing algorithm starts from an initial hypothesis for its path and converges to a final geometry through an iterative procedure by using the analytical solution of Snell's law (Böhm and Petronio, 2003).

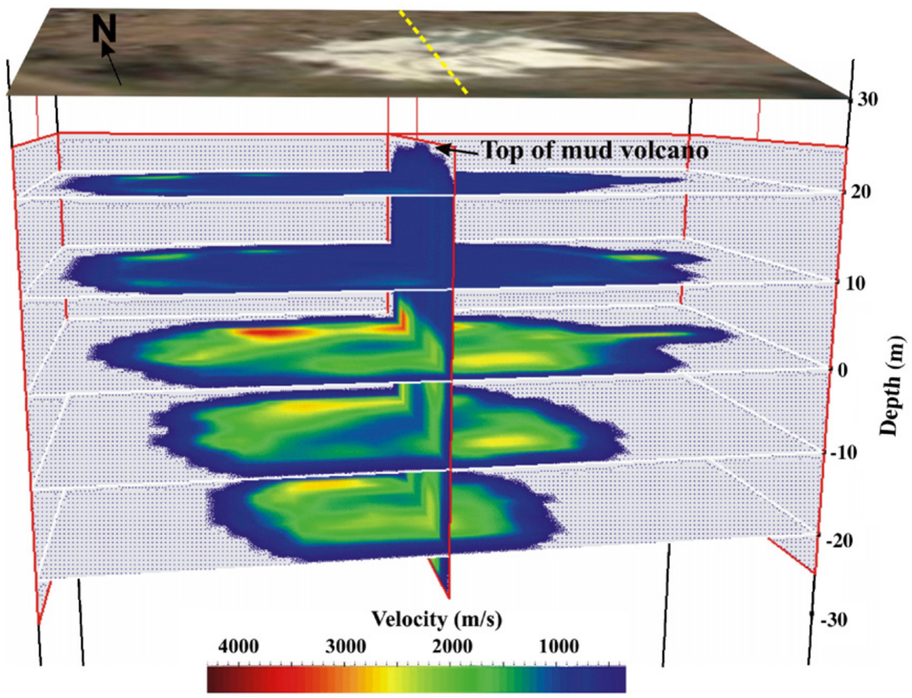

Fig. 7. Depth slices of the velocity model obtained by the inversion of the first breaks. The top of the mud volcano is 22 m.

Initially, the first arrivals were inverted using the circular travel of the rays to obtain an initial model close to a real model. Then, using the results obtained in the previous inversion, the arrivals were inverted assuming a ray path of diving waves. Subsequently, to improve the lateral resolution of the velocity model, inversion was performed using the staggered grid method. This technique provides a better resolution of the inversion without increasing the null space energy of the tomographic system (Vesnaver and Böhm, 2000).

In order to verify the reliability of the final velocity field we calculated a normalized chi square, obtaining a value equal to 1.785. The result confirms the reliability of the final data of the tomographic inversion.

The normalized chi square was computed using the formula:

$$\chi^2 = 1/(N-1)\sum_{i=1}^{N}\left[(t_{\mathrm{obs}i} - t_{\mathrm{calc}i})/t_{\mathrm{err}i}\right]^2$$

where N is the picks number, t_{obs} is the picked first arrival, t_{calc} is the calculated travel times of the first arrivals of diving waves in the final tomographic velocity field, and t_{err} is the estimated error in the first arrivals analysis. Considering the sample interval, the quality of the data and the diameter of the vibrating plate we estimate that t_{err} is equal to 2 ms. This time error, considering the average travel path of 55 m and an average velocity of 1000 m/s, can be translated into a velocity error of 3.5%.

The results obtained in the tomographic approach are shown in Figs. 7 and 8. The velocities vary from 450 m/s in shallow structures to 2000–2500 m/s at a depth of about 20–30 m with respect to the top of the mud volcano. In the two figures only the volume included in the ray paths is shown.

Particularly interesting is the resolution of the vertical conduit, representing the outlet leading to the surface vents of the mud volcanoes, clearly evidenced by the low velocity in the last three in-plane sections in Fig. 7. Note the presence of an area with low velocity in the fourth in-plane section in the same figure. Fig. 8 shows clearly that the low velocity area is absent in panel 2.

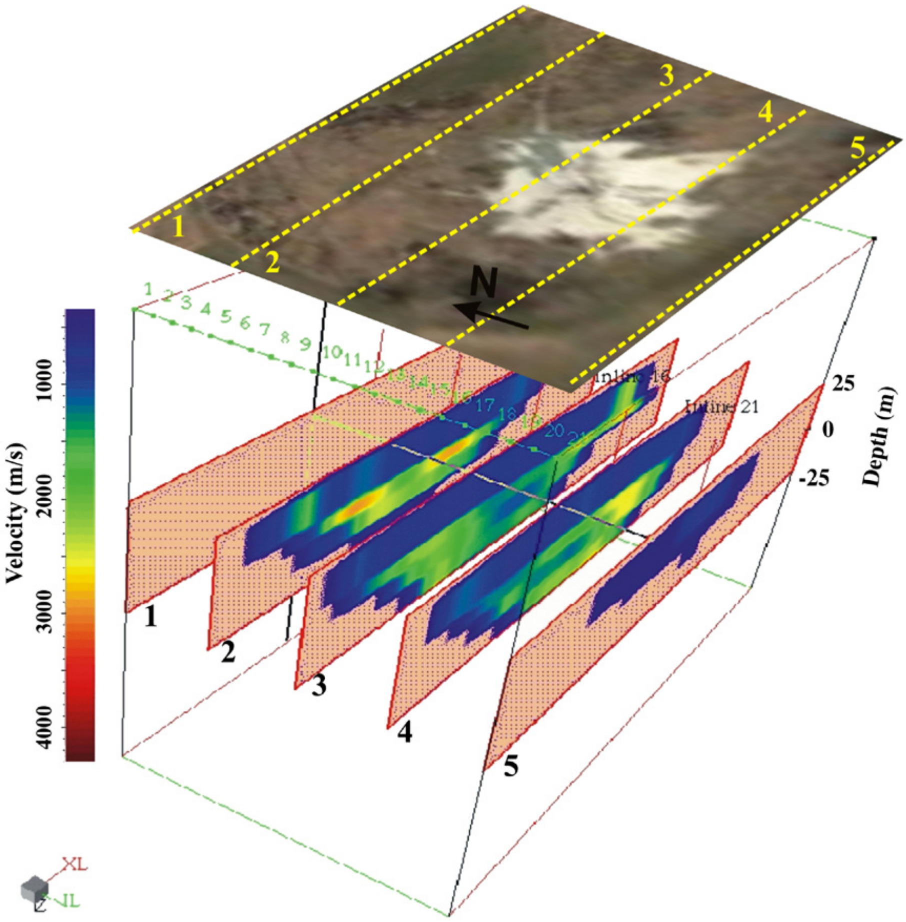

Fig. 8. Vertical slices of the velocity model obtained by the inversion of the first breaks. The top of the mud volcano is 22 m.

4. Geo-electric experiment

In the same area of the seismic experiment, three geo-electric lines were measured.

Data acquisition was performed using 64 electrodes spaced at 3 m. Fig. 1 shows the position of the geo-electrical lines in comparison with the seismic experiment.

A preliminary test was performed by comparing the results of the dipole–dipole to the Wenner–Schlumberger geometries. The acquisition test was performed with the aim (i) verifying the possibility of acquiring the data with the dipole–dipole geometry to obtain information on vertical structures in the presence of ambient noise, and (ii) investigating with the Wenner–Schlumberger method the possibility of detecting vertical structures. As shown in Fig. 9, the test indicates that the best method is the dipole–dipole geometry. In fact, even if the root mean-squared (RMS) error is lower in the Wenner–Schlumberger method (1.69%) with respect to the dipole–dipole method (7.4%) the latter approach better resolves the vertical structures, which are the main targets of the study. The RMS error given in the figures of the resistivity models measures the difference between the calculated and measured apparent resistivity by adjusting the resistivity of the model blocks during the inversion of the acquired data (Loke, 1999). This difference is essentially due to the inversion of the data, while the field measurements errors are not significant. Data was inverted using the RES2DINV software, which uses a forward modelling sub-routine to calculate the apparent resistivity values and a non-linear least-squares optimisation technique for the inversion (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). The inversion considers the effect of the topography (Loke, 2000). The spatial resolution is a function of electrode spacing, and so pixels with a width of 3 m are used during the inversion procedure.

The results obtained by the tomographic inversion of the three geo-electrical lines are shown in Fig. 10. The resistivity values are low: the maximum resistivity is 40 Ω m, detectable away from the mud volcano. The Nirano mud volcanoes are mainly salt mud associated with water; this means that the lower resistivity volumes described by the models could be related to the mud volcano features, such as rising conduits and buried

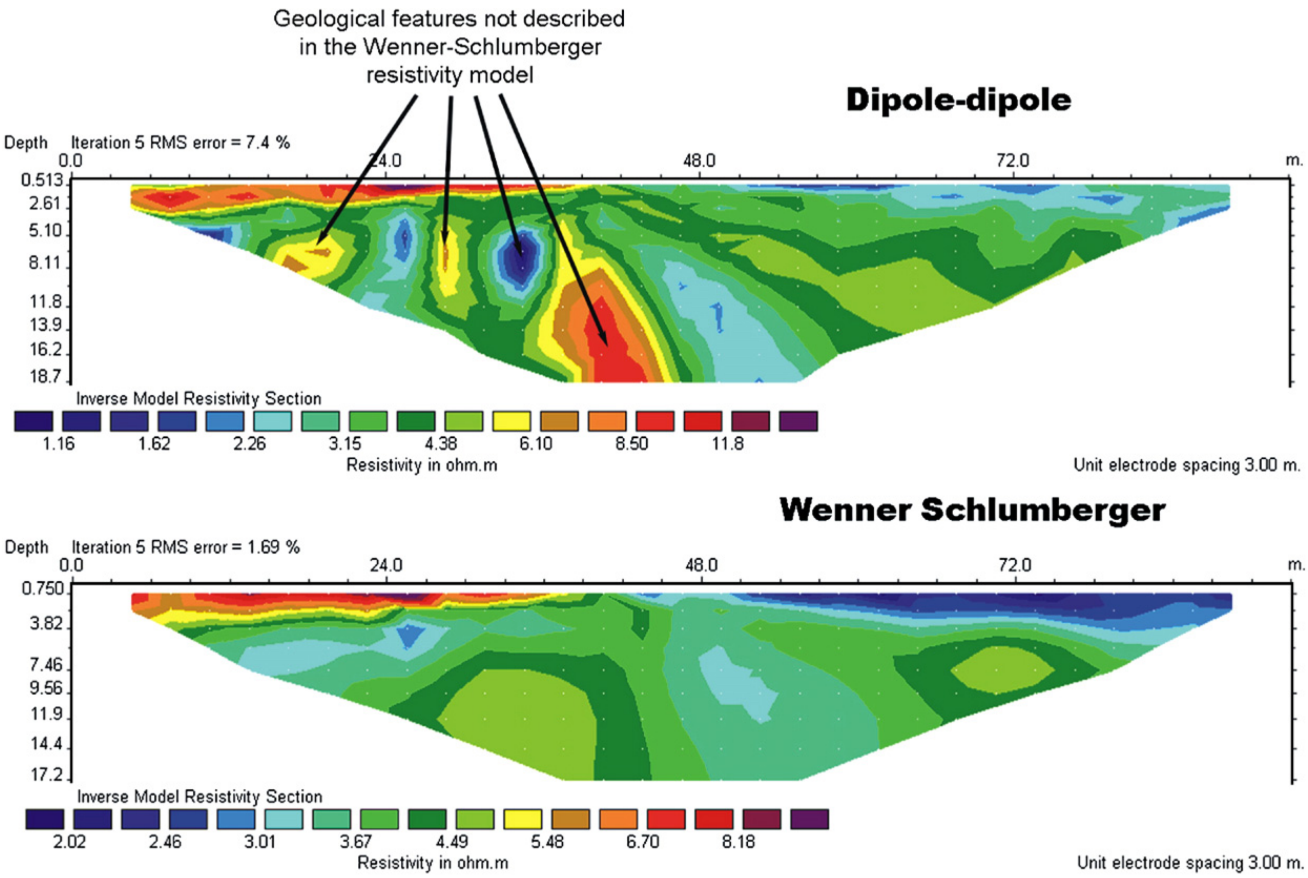

Fig. 9. Results of the preliminary geo-electrical test. The upper resistivity model represents the dipole–dipole data. The lower resistivity model represents the Wenner–Schlumberger data. Note the better detail of the dipole–dipole geometry.

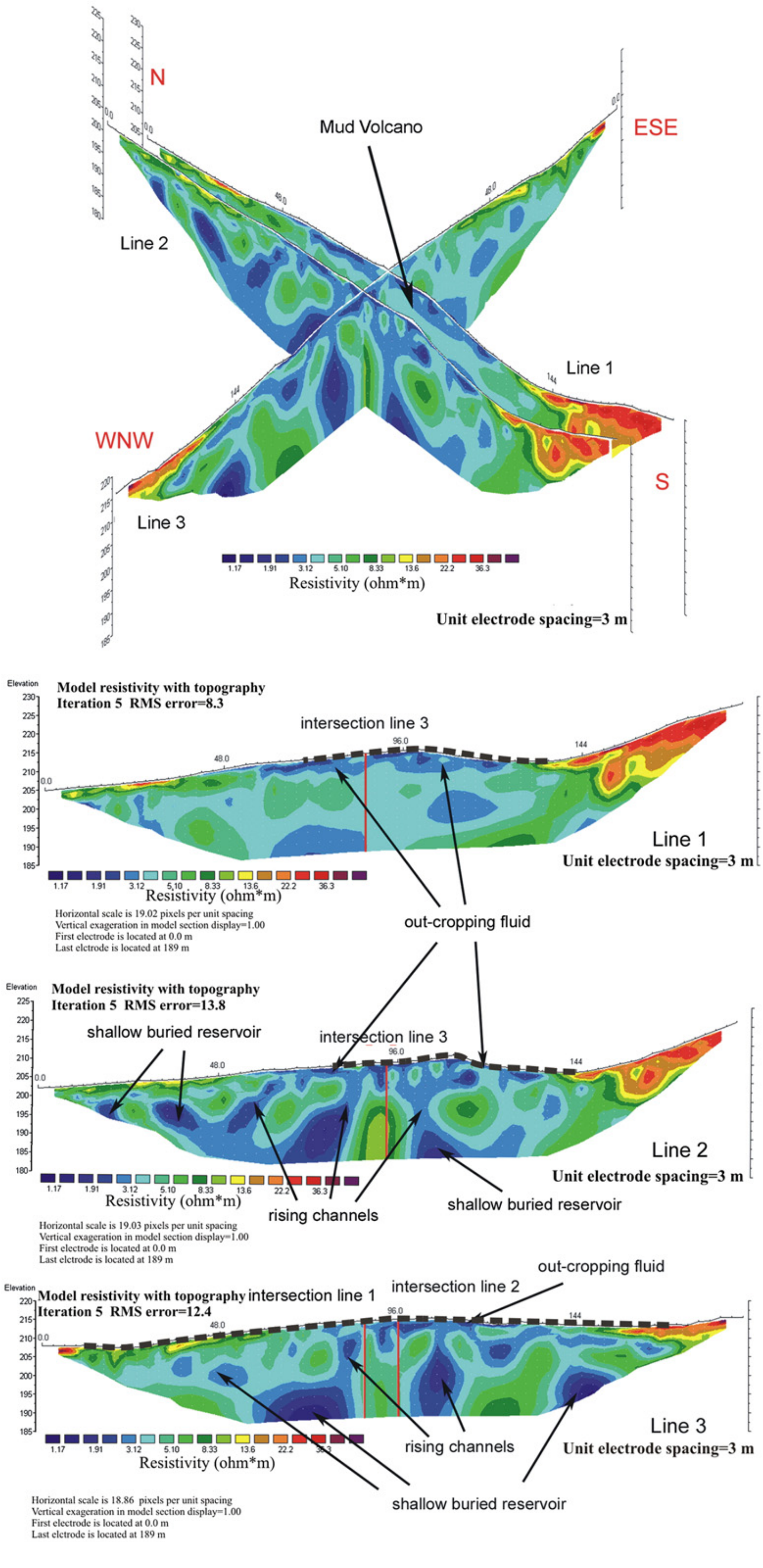

Fig. 10. Result of the tomographic inversion of the geo-electric lines. In the top a 3D view of the lines is shown. The broken grey lines indicate the seismic coverage.

reservoir. This relation is confirmed by the relationship between the geological situation of the surface and the resistivity models. In fact, higher resistivity values are observed in the pelitic sediments surrounding the mud volcano apparatus, whereas, lower resistivity values are observed in fluid-pervaded sediments occurring in the mud volcano area. Line 1, oriented north–south and located east with respect to the mud volcano, clearly identifies the presence of an area of high resistivity in the southern part, and probably corresponds to the southern border of the mud volcano apparatus. In the northern part, the presence of a volume of about 5 m in depth not affected by the presence of fluids is detected. In the central part of the line, where the mud volcano is present, the resistivity values range from 3 to 5 Ωm, showing an area characterized by a high presence of fluids.

Line 2, parallel to the previous line and passing west of the mud volcano, provides a similar image of the sub-soil. In the centre of the profile, the vertical structures are more evident with respect to the previous line. In fact, the lateral variations in the resistivity values are related to the rising channels (blue colour in the Fig. 10). Line 3, crossing the two previous lines in the area of the mud volcano, is oriented ESE–WNW, and shows that the beginning and the end of the line are not affected by the presence of the mud, while, in the central part, vertical chimneys are present. The main features are in agreement with the results obtained on line 2.

5. Discussion of results

The combination of different geophysical methods on the Nirano mud volcanoes in the external compressional front of the northern Apenninic chain, and the geological study of the substratum, provided a detailed reconstruction of the buried structures in the first 30–50 m from the sub-surface. This is the first study focused on the fluid flow pathways and the configuration of sub-surface structures in terrestrial mud volcanoes of the northern Apennines.

The sub-vertical structures and the superficial outlet of the volcanic chimney are clearly detected by the tomographic inversion of the first arrivals of the seismic experiment in the Nirano site. A mud chamber is also recognized, probably representing a superficial reservoir located at about 25 m below the mud volcano surface (see Fig. 11). In fact, the velocity value of the blue area in Fig. 7 in the in-plane 4 is about 1100 m/s, while, at the same depth, the surrounding area has a compressional seismic velocity that ranges from 1700 m/s to 2300 m/s. Considering that the water–mud mixture has a compressional velocity of about 1475 m/s (see for example Schon, 1996), and in the presence of a water and gas–mud mixture the compressional velocity drops, the compressional velocity values (1100 m/s) obtained with the tomographic inversion can be reached considering about 10% gas volume. So, the low velocity observed just below the top of the mud volcano can be explained by the uplift of a mixture of gas, water and mud.

Data provided by the geo-electrical inversion confirm the seismic results and show the sub-surface morphology of conduits and chimneys of the examined griphon. Geo-electrical investigations permit a detailed imaging of the shallower structures down to 15 m in depth. The resistivity models show that all the diapiric phenomena, within an area of about 50–70 m, are related to the same shallow mud reservoir.

It is also important to note the presence of the shallow buried reservoirs detected in the northern part of line 2, unfortunately where no seismic data is available. These low resistivity volumes are covered by a high resistivity area, where no mud volcano phenomena are observed on the surface. This feature may suggest that in the future this area could see the formation of new cones.

In the light of a preliminary investigation on mud volcanoes of northern Italy, the comparison with other similar mud volcanoes of the Modena-Reggio Apennines,

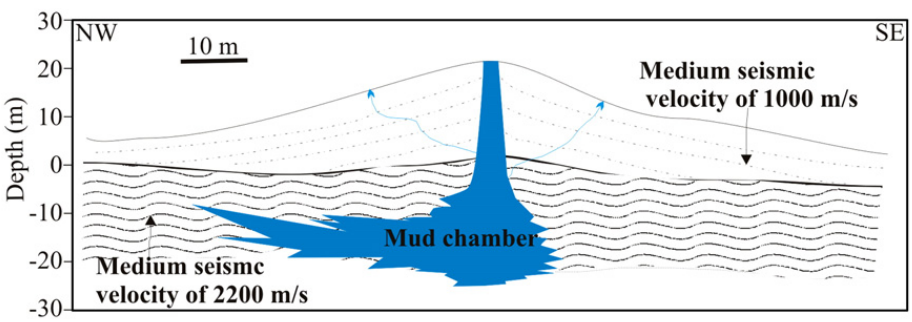

Fig. 11. Schematic geological section across the mud volcano.

such as the Regnano structure, are of particular interest because of the typology of the material extruded (Conti et al., 2003). Both the Nirano and Regnano volcanoes show a similar morphology and the same pattern of activity, but the Regnano structure alternates quiescent periods characterized by the emission of fluid mud with short eruptive periods with emission of chaotic breccias floating in a viscous mud, thus producing debris flows. An accurate field investigation on geologic units of the substratum, suggests a relationship between extruded sediments and substratum typology. In the Regnano mud volcano clast provenances indicate that breccia originates from the base of the epi-Ligurian sequence which encloses intercalations of sedimentary mélanges with chaotic polygenic breccias in a mud matrix. The volcano occurs on top of these chaotic deposits, thus suggesting a relationship between extruded sediments and substratum typology. In the case of the Nirano structure, the substratum is represented by Pliocenic pelitic sediments, and the extruded material, even during paroxysmal activity, does not include clasts but only a fine-grained shell debris.

Compared with other examples in literature (Martinelli and Dadomo, 2005) generally characterized by deeper reservoirs, the mud chamber observed in the Nirano area could represent the last phase of mud accumulation before the final emission. This confirms geochemical data indicating the origin of ejected liquid phase at a depth <50 m, during paroxystic periods (Martinelli and Dadomo, 2005).

However, in literature, the internal structures of mud volcanoes are usually only schematically reconstructed and represented on a larger scale (Daville et al., 2003; Stewart and Davies, 2006) making a comparative analysis difficult.

6. Conclusion

The integrated geological study and different geophysical methods applied on the Nirano mud volcanoes, located in the external compressional front of the Apenninic chain, represents the first attempt to show the fluid flow pathway and the configuration of buried structures in terrestrial mud volcanoes of the northern Apennines.

Seismic and geo-electrical investigations clearly detect the sub-vertical structures of the superficial outlet of the volcanic conduits and chimney. A mud chamber is also identified, probably representing a superficial reservoir located at about 25 m below the mud volcano surface.

All the diapiric phenomena, within an area of about 50–70 m, are related to the same mud reservoir. This mud chamber could represent the last phase of mud accumulation before the final emission, not excluding the existence of deeper larger reservoirs.

The comparison with other mud volcanoes of the northern Apennines suggests a close relationship between extruded sediments and substratum typology. Near-surface fractionation processes and the presence of a shallow reservoir affect fluid emissions by the contamination of fluid with surrounding sediments.

The increasing interest of the scientific community in mud volcanoes, mainly because of their potential contribution to climate change, makes our approach useful for future studies in other areas.

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