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Mud volcanoes in central Italy: Subsoil characterization through a multidisciplinary approach

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ABSTRACT

Mud volcanoes are common geological phenomenons observed worldwide as in Italy. They are well described in the scientific literature for their morphological, tectonic and hydrogeological features. They represent not only a relevant geological and geomorphological interest but also not negligible elements of hazard and risk associated with the presence of soft and pliable sediments and with the possible unexpected emission of gas and mud. Therefore, the understanding of their structure and hydrogeological circuits in the subsurface is an important key to define hazard and risk conditions in the adjacent areas.

This paper deals with a multidisciplinary study including geophysical and hydrochemical surveys undertaken at the Pineto (central Italy) mud volcano site to achieve an interpretative conceptual model explaining the shallow upward migration of deep mud fluids. Shallow electrical and seismic imaging of the mud volcano was obtained using two dimensional and three dimensional (2D–3D) electrical resistivity tomography and 2D reflection seismic surveys. The hydrochemical properties of the rising fluids were assessed by means of seasonal measurements of the chemical–physical parameters, the concentrations of major ions, and some natural isotopes. This mud volcano or mud lump appears as a dome of about 15 × 10 m in size. The height of the crater is 2 m approximately, while the diameter of the crater is 2.5 m. Emission of fluids and solids (cold brine, mud, gas) occurs from this crater. Upper Pliocene–lower Pleistocene foredeep pelitic deposits (over-compacted clays with silty–sandy levels) overlain by clayey–silty deposits crop out in the area. The survey results seem to reveal that the uprising of deep fluids does not occur exactly below the mud volcano at present. Instead, a high conductivity body is present within a fractured zone in the pelitic deposits at 60 m approximately to the ENE. The probable occurrence of a high permeability layer approximately between 20 and 30 m below ground level, confined by clay deposits, gives rise to an overpressured mud fluids reservoir. Mud fluids appear to be flowing toward the surface from the reservoir up to the mud volcano crater. The interpretative conceptual model proposed by the authors is a first attempt to explain the shallow upward migration of deep mud fluids in this central Italy mud volcano. The results can be used to identify the uprising of fluids with similar chemical–physical properties even in areas where the superficial and morphological evidence of the volcanic bodies have been obliterated or covered.

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1. Introduction

1.1. Mud volcanoes

Mud volcanism is a well-known geological phenomenon, consisting of an eruption or extrusion of mud fluids from a highly pressurized zone to a shallower, lower-pressure zone close to the surface. These features are often associated with gas, mineralized water, and fluidized sediments forming complex structures. The surface morphology of the most common mud volcanoes (MVs) is generally represented by a cone with a diameter ranging from a few metres to hundreds of metres. Emissions can be either continuous or periodic with unexpected events. The complex mechanisms and processes involved (Nanni and Zuppi, 1986; Kopf, 2002) are still not fully understood, in particular for some MVs. The MVs are found onshore and offshore in many places on Earth; and although they occur in various tectonic settings, the majority of these are located in areas subject to compressional tectonics and associated with sediment accretion at convergent margins (Higgins and Saunders, 1974; Brown and Westbrook, 1988; Reed et al., 1990; Di Giulio, 1992; Kopf et al., 1998; Aslan et al., 2001; Kopf, 2002). In Italy, mud volcanoes occur in the western Alps, along the Apennines and in Sicily Island (Martinelli, 1999; Etiope et al., 2007) where fluid-rich, fine-grained sediments ascend within clayey deposits.

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Many MVs are characterized by an origin from thick, rapidly deposited sequences of marine clays; a Tertiary age; a structural association caused by tectonic shortening and/or earthquake activity; sediment over-pressure and fluid emission like gas, brines, gas hydrate, salt water (Nath et al., 2008) or, more rarely, oil (Etiope and Klusman, 2010); and polymictic assemblages of the surrounding rock present in the ejected argillaceous matrix (Ansted, 1866; Higgins and Saunders, 1974; Fertl, 1976; Yassir, 1989; Hovland et al., 1997).

For all these reasons, mud Volcanoes represent not only a significant geological and geomorphological interest but also not negligible elements of hazard and risk associated with the presence of soft and pliable sediments and with the possible immediately and unexpected emission of gas and mud. Therefore, the understanding of their structure and hydrogeological circuits in the subsurface is crucial to define hazard and risk conditions in the adjacent areas. Moreover the reconstruction of the geological subsurface model can be a helpful integration of the geomorphological and geological surveys, usually performed for natural hazard assessment.

1.2. The study area and its previous studies

This article deals with the results obtained from the study of the superficial portion of a MV located in central Italy (Figs. 1 and 4) through a multidisciplinary approach. The study area is located 1 km approximately to the west of the town of Pineto and 1.4 km from the Adriatic Sea on the north bank of the Calvano stream.

Previous scientific studies on this MV only focused on the hydrochemical aspects (Desiderio and Rusi, 2004; Desiderio et al., 2007, 2010) and the environmental aspects (Buccolini et al., 2003; Colli and De Ascentiis, 2003; Scalella and Di Francesco, 2004). Geochemical data relating to MVs in Italy, including the Pineto MV, particularly in relation to gas emissions, are discussed by Etiope et al. (2003, 2007) and Etiope and Klusman (2010). The authors found that the gas emissions are related to N_2, CO_2, and CH_4 with percentages of 5.4%, 0.36%, and 94.13%, respectively, of the total of the gas emissions. The CH_4 flux has been estimated to be 480 mg/d m^2. The methane emissions can be connected to a microfiltration from hydrocarbons of biogenic origin according to the authors. Etiope et al. (2007) measured a helium concentration of about 16,000 ppb from the gas emissions. This value, compared with the average value of the area (146 ppb from Scalella and Di Francesco, 2004), could indicate the occurrence of deep fractures. The Pineto MV is referred to in the database for Italian MVs compiled by Martinelli and Judd (2004).

1.3. The multidisciplinary approach

The study has been undertaken with a multidisciplinary approach that includes geology, hydrogeology, and particularly geophysics and hydrochemistry (Figs. 1 and 2).

Two dimensional and three dimensional (2D–3D) electrical resistivity tomography (ERT) and 2D reflection seismic surveys were undertaken. The ERT surveys employ a direct current and measure the variation of spatial potential fields to explore the distribution of the subsoil's apparent resistivity. Real resistivity values are obtained through an inversion problem solving including forward and inverse modelling processes. The ERT surveys have been successfully used for environmental purposes because of the technique's abilities to identify resistivity changes stemming from water-content variation (Torrese et al., 2013, 2014), migration of contaminants (Kean et al., 1987; Van et al., 1991) or caused by MVs occurrence (Accaino et al., 2007; Chang et al., 2010; Torrese et al., 2012). The ERT surveys are suitable for the study of the Pineto MV because of the large gap (more than 4.5 times) occurring between the electrical conductivity of the typical groundwater and the waters that emerge from the MV.

Geoelectric assessments (e.g., 3D ERT) of MVs in New Zealand are discussed in Zeyen et al. (2011), while electromagnetic applications (VLF-EM) undertaken in Taiwan have been discussed by Lin and Jeng (2010). In particular, Zeyen et al. (2011) obtained a 3D resistivity imaging for the uppermost 25–30 m of depth from the inversion of densely spaced profiles. They found a more complex structure than one would expect. Furthermore, the deeper areas of rising mud are not well correlated to the distribution of the vents: between 8 and 20 m of depth, the smallest resistivities do not correspond to the areas of vent concentration and, surprisingly, certainly not to the position of the main vent. Especially below the main vent, they found no connection between the upper and the lower mud reservoir. Nevertheless, their data do not allow us to exclude a narrow, up to 3-m-wide, mud conduit at this place, since data were not acquired in a real 3D configuration (differently than in this study). This means loss of resolution with depth.

An energy source is used in seismic reflection surveys to send elastic waves into the subsoil, where each layer reflects a portion of the wave's energy back. These reflected energy waves are recorded by receivers that detect the motion of the ground in which they are placed. Typically, the recorded signals are subjected to significant amounts of signal processing before they are ready to be interpreted. The MVs are poorly resolved using conventional P-wave seismic imaging because these

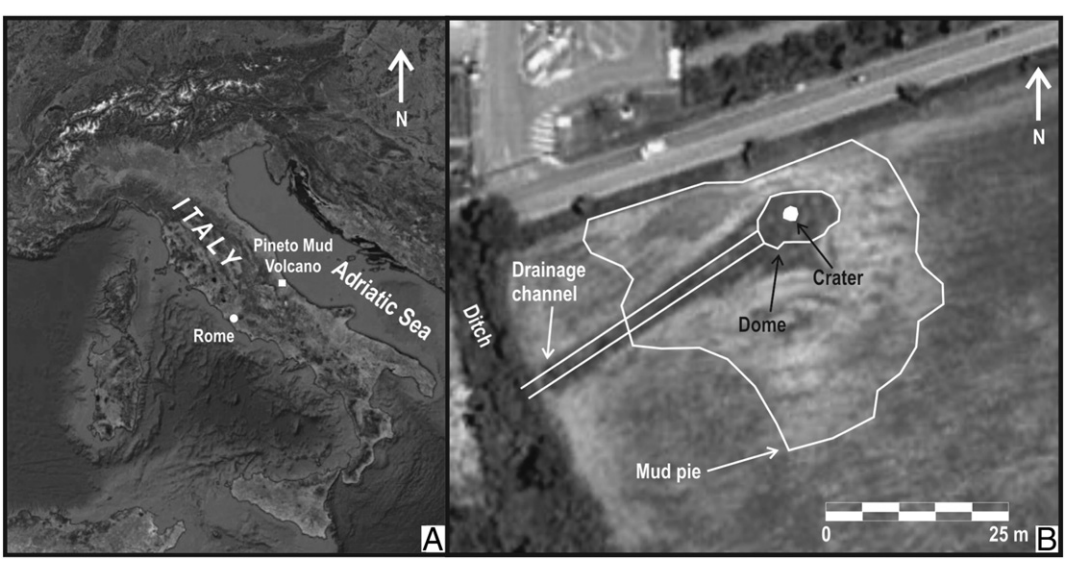

Fig. 1. Geographical setting of the Cenerone-Pineto mud volcano (from Google Earth™).

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