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Reply

Reply to comment by G. Etiope and G. Martinelli: “Pieve Santo Stefano” is not a mud volcano: Comment on Structural controls on a carbon dioxide-driven mud volcano field in the Northern Apennines

1. Introduction

I welcome the criticism raised by Etiope and Martinelli concerning my use of the term “mud volcano” in Bonini (2009, this issue). I do also appreciate their recommendation to use my work “as reference for studies on the relationships between seismicity and surface gas manifestations in general”, even if they conclude “but absolutely not as an example of mud volcanism”. The central aim of the paper was a discussion of the relationships between surface seepage, tectonic features (pre-existing brittle discontinuities and rheological stratification at upper crustal levels) and seismicity. I am aware that the Pieve Santo Stefano vents are not strictly equivalent to the mud volcanoes punctuating the compressive Po Plain margin of the Northern Apennines. However, I employed (Bonini, 2009) the term “mud volcano” to emphasise the increase in fluid flow and surface mud extrusion that followed the $M_w = 4.74$ earthquake (and subsequent seismic sequence) that struck the Upper Tiber Basin, in the Northern Apennines, on the 26th November 2001.

2. Discussion

2.1. Mud volcano definitions

The validity of using the term “mud volcano” for the Pieve Santo Stefano (referred hereinafter to as PSS) vents is, in my opinion, a mere matter of definition. Following the review by Kopf (2002), cited by Etiope and Martinelli (this issue), a mud volcano is defined as the “surface expression of mud that originated from depth. Depending on the geometry of the conduit and the physical properties of the extrusive, the feature may be a dome (cone) or a pie with low topographic relief.” This definition is general, and doesn’t refer to the amount of extruded mud, nor to the depth of the source layer, or to the presence of a specific driving gas. According to this definition, some of the PSS vents retain the characteristics necessary to be defined as mud volcanoes, at least for a specific time period.

Etiope and Martinelli (this issue) suggest that the amount of mud released is relatively low and that the major gas is not related to a catagenetic hydrocarbon production system. Mud pools dominate the PSS venting area, but mud extrusion has been observed at some vents of Mount Fungaia and Covivoli (see Figs. 2 and 3 in Bonini, 2009). As shown in Heinicke et al. (2006), a well-developed conical extrusive feature developed 18 months after the main shock at the Covivoli vent as a consequence of the seismically-triggered increase in fluid flow. Though very limited, surface mud extrusion was still taking place at some vents during 2006–2007.

The definition provided by Etiope and Martinelli (this issue) for what a mud volcano should be is in my opinion representative of the mud volcanoes that classically develop in the frontal regions of thrust-and-fold belts and accretionary prisms, which may be typified respectively by examples from Azerbaijan and the Mediterranean Ridge. However, this definition is restrictive, ignores some other natural cases, and contains a number of potential problems. I address only some of these issues in the section below.

2.2. Mud volcano characteristics: distinctive or elusive?

2.2.1. The involvement of sedimentary rocks with gravitational instability resulting from rapid sedimentation

Etiope and Martinelli (this issue) refer to regions like Azerbaijan, where mud volcanoes are best expressed and are favoured by the extremely rapid rates of sedimentation of the latest Miocene–Quaternary siliciclastics (e.g. Stewart and Davies, 2006). In particular, Etiope and Martinelli (this issue) state that “the PSS substratum is characterized by a sequence of continental Pleistocene alluvium (only 66 m), flysch, sandstones and carbonate rocks typical of the Appennine orogenic nappes; the basin is not characterized by long-lasting or rapid sedimentation or subsidence leading to horizons with gravitational instabilities, i.e. less dense sediment layers buried under denser units, as required in mud volcanism”. This statement is evidently contradicted by the observation that the substratum of the PSS venting areas is characterized by a rock sequence and rheological stratification very similar to that of the “genuine” mud volcanoes of the Northern Apennines, specifically a major sealing layer (Ligurian Units) overlies Tertiary turbiditic sandstones (i.e. the Falterona sandstones below the PSS vents and the Marnoso Arenacea sandstones below the external mud volcanoes) and carbonates. The majority of Northern Apennine mud volcanoes rest in fact directly over the

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pre-Pliocene substratum rocks forming the Apennine foothills, and rarely in the Po Basin where long-lasting rapid sedimentation and subsidence continued up until Holocene times (see distribution in Bonini, 2007). Therefore, the regional geological framework cannot be used to reject a priori the use of the term "mud volcano".

2.2.2. Discharge of a three-phase system (gas, water and sediments)

The discharge of gas and sediments at the PSS vents is obvious (see the point below). It is suggested that fossil water in the PSS deep pool exists only as a minor component with a content of less than 0.5% in weight and that the surface water in the crater is practically meteoric. The deep pool corresponds to the CO_2 reservoir unlocked by the well for hydrocarbon research ("Pieve Santo Stefano 1"). However, significant pockets of saline water (with NaCl varying between ~2 and 90 g/l) have been encountered during the drilling of this well during 1983–1984 (well log available at http://unmig.sviluppoeconomico.gov.it/unmig/pozzi/disponibili.asp). I assumed that fossil water took part in the process, and that this was possibly trapped in small reservoirs controlled by rheological boundaries and mobilised toward the surface when reached by a seismically-driven pore-fluid pulse. So far, I cannot find in the literature any systematic analyses of the chemical composition of the surface water filling the mud pools, particularly at the time of the major mud extrusion (May 2003). On the other hand, it should be noted that meteoric water can also affect the history of genuine mud volcano systems, which have often experienced increased activity after the rainy season (Biasutti, 1907).

2.2.3. Breccia in the discharged material

According to Kopf (2002), a mud breccia is a "type of sediment that is characterized by a clay mineral-rich matrix in which various amounts of (firmer) rock fragments and clasts (usually of the overburden rock through which the mud ascended) are embedded". It is true that I have not performed micropalentological or mineralogical analyses of the extruded mud, but the claim that there are no "solid fragments or breccia" is not correct. Sub-millimetric clasts of limestones can be recognised in the extruded mud. These may derive from the Ligurian Units, or from the deeper carbonates and marls of the Tuscan Unit (see the rock column of PSS 1 well in Fig. 4 of Bonini, 2009). Without data, my assumption that the mud is derived from Eocene shale units may be speculative, but a conservative estimate allows a postulated fluid migration at least up through the Ligurian Units, which are uppermost in the nappe pile in this area.

2.2.4. Diapirs or diatremes?

Kopf (2002) refers to diapirs as "clay- and fluid-rich intrusions", and a mud diapir as an "intrusive body of shale or clay that does not reach the surface", and to a diatreme as a "type of mud extrusive feature that evolved from a violent eruption of overpressured mud, cross-cutting the overlying strata like a dyke". No geophysics relevant to the identification of these features beneath the PSS venting areas is available, and the (current or past) presence of these features cannot be ruled out. In this respect, it may be also worth noting that the impressive eruption of the East Java mud volcano was apparently triggered by the perforation of a deep well (Davies et al., 2008). Although in the literature this eruptive centre is generally referred to as a mud volcano, the presence of diapirs/diatremes pre-dating the onset of the eruption on May 2006 is not documented in this example.

2.2.5. Link between seismic events and the generation of low viscosity mud

Etiope and Martinelli (this issue) disagree with the existence of such a link by stating that the gas manifestation is continuously active, with enhanced fluid expulsions that are also independent of earthquakes. This statement seemingly contrasts with the conclusions of Heinicke et al. (2006), who related the post-seismic anomalous fluid expulsion and surface mud extrusion to a fluid pressure pulse propagating from the earthquake damage zone. As a corollary, if the mud was not generated during such a fluid pressure pulse, then one may assume that it was mobilised from fluid reservoirs that could be similar to those of "real" mud volcanoes.

2.2.6. Compressional stress

Etiope and Martinelli (this issue) apparently relate mud volcanism to a "compressional stress, which can be related to any surface gas manifestation". It is true that mud volcanism dominates in compressive tectonic scenarios, but it has been also described in other structural settings such as those characterized by extension and high sediment supply (e.g. continental slope of the Gulf of Mexico, Neurauter and Roberts, 1994; Black Sea, Ivanov et al., 1996). Therefore, tectonic compression is not a prerequisite for mud volcanism.

2.2.7. The presence of natural gas related to catagenetic hydrocarbon production

The stringent application of this process-oriented concept to mud volcanism may involve some ambiguities, and means that some other features described in the literature as mud volcanoes shouldn't be referred to as such anymore. For instance, the "major gas" driving the Paternó mud volcano (Sicily) is CO_2 (85–99%) massively supplied by the activity of the nearby Mount Etna volcano (Silvestri, 1866; Chiodini et al., 1996), and thus unrelated to the production of hydrocarbons. Etiope and Martinelli (this issue) conclude that "The term mud volcano cannot be used for any gas manifestation resembling a mud pool or where extrusive mud gives rise to small conic edifices. Many CO_2-vents, related to geothermal or even hydrothermal environments, may show such characteristics (for example the Yellowstone gas manifestations)". In spite of this, both the Paternó and the Yellowstone are normally referred to as mud volcanoes. A mud cone at Yellowstone has been even featured as mud volcano on the cover of the volume "Subsurface Sediment Mobilization" (Van Rensbergen et al., 2003). Finally, it is worth mentioning that the term mud volcano has been used to describe extrusive features, similar to terrestrial mud volcanoes, located on the surface of other planets, such as Venus (Hamilton, 2005) and Mars (Kite et al., 2007; Skinner and Mazzini, in press). In such settings the identification of hydrocarbon fields is obviously tenuous, and the rigorous application of the "total petroleum system" concept would preclude the use of "mud volcano" for all of these extraterrestrial features.

3. Conclusion

The above discussion highlights that the term "mud volcano" has been used to represent a variety of extrusive features present in different tectonic and geological scenarios, and possibly even resulting from different processes, including man-made causes (the East Java mud volcano) and in extraterrestrial settings. It seems that many different types of mud volcanoes may exist, or at least these have been referred to in the literature as such. In my opinion, therefore, the definition required by Etiope and Martinelli (this issue) is too restrictive and cannot account for all of these complex and disparate aspects associated with mud volcanism.

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