Elliptical mud volcano caldera as stress indicator in an active compressional setting (Nirano, Pede-Apennine margin, northern Italy)

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ABSTRACT

The relations between mud volcanism and active tectonic strain were investigated at the Nirano mud volcano field (NMVF), near the active Pede-Apennine thrust front of the Northern Apennines thrust-and-fold belt (Italy). Active fluid release occurs through numerous vents within an elliptical depression developed over the crest of a thrust-related anticline. This depression is interpreted as a caldera collapse–like structure that may have developed in response to the deflation of a shallow mud chamber triggered by eruption and sediment fluid evacuation events. Like many volcanic calderas, the NMVF caldera is elongated nearly parallel to the direction of least horizontal compressive stress S_h, and is thus deduced to reflect the regional tectonic stress axes. It is concluded that mud volcano calderas exhibit mechanical similarities to the igneous analogs, and that the methods used in this first test could be applied to other calderas imaged by seismic data and in the field.

Keywords: mud volcanism, elliptical caldera depression, active thrusting, Northern Apennines.

INTRODUCTION

Mud volcanoes are conic edifices constructed by surface extrusion of cold fluids, like mud, saline water, and gases expelled from a pressurized deep source layer up through structurally controlled conduits (e.g., Kopf, 2002). Detailed three-dimensional (3-D) seismic imaging allowed Davies and Stewart (2005) to discover the largest single (to 1.4 km thick) underwater mud volcano in the world in the South Caspian Sea, and to illustrate its close association with an asymmetric 1.2–1.6-km-wide caldera structure. Similar calderas associated with mud volcanism have been reported for other submerged regions, like the Niger Delta (Graue, 2000) and the Mediterranean Ridge (Kopf and Behrmann, 2000). Recent seismic images of South Caspian mud volcano systems have defined the internal architecture of these features as being composed of extrusive mud cones fed by discrete vertical conduits. The marked geometric similarity in the internal 3-D structure of mud volcanoes with respect to the igneous edifices has permitted some to postulate an analogy between these two systems (Davies and Stewart, 2005; Evans et al., 2006).

A possible caldera associated with mud volcanism has been identified at Nirano (Modena), in an area of active thrusting along the Pede-Apennine margin of the Northern Apennines (e.g., Benedetti et al., 2003; Fig. 1). Like examples from elsewhere, the Nirano mud volcano field occurs over the crest of a thrust anticline associated with the main Pede-Apennine thrust. The Nirano example presents an opportunity to examine onshore the relations between a mud volcano caldera structure and active thrust deformation.

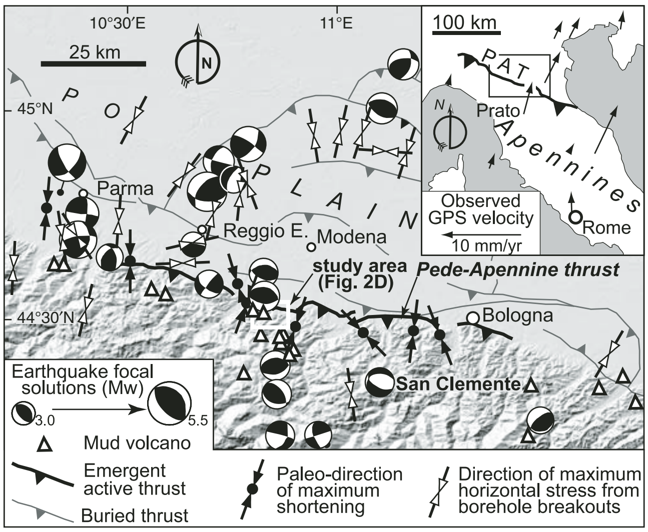

Figure 1. Structural sketch map of study area superposed above a digital shaded-relief elevation model (U.S. Geological Survey, available from: http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm). Earthquake focal mechanism solutions and shortening directions obtained from outcrop-scale structures are modified from Boccaletti et al. (2004). Directions of maximum horizontal stress from borehole breakout data are from Mariucci and Müller (2003). Global positioning system (GPS) velocities reported in the inset are from Battaglia et al. (2004). PAT—Pede-Apennine thrust.

GEOLOGICAL SETTING

The WNW-trending and SSW-dipping Pede-Apennine thrust zone separates the Apennine foothills from a more external belt consisting of blind thrusts and folds buried underneath the Po Plain deposits (Pieri and Groppi, 1981; Fig. 1). In the investigated sector, NNE-facing fresh scarps in semiconsolidated deposits mark the surfacing of a main active thrust referred to as the Pede-Apennine thrust (PAT), which is inferred to be the locus of surface rupturing (Benedetti et al., 2003; Boccaletti et al., 2004). Current thrust activity is coherent with the several compressional fault plane solutions of earthquakes (e.g., Selvaggi et al., 2001; Fig. 1).

The PAT area also corresponds to the maximum translation toward the Adriatic foreland of the Ligurian Units, which accompanied the northeastward shifting of the Apennine thrust wedge that progressively incorporated tectonic units deposited as late Oligocene–Miocene foredeep sequences (Ricci Lucchi, 1986). Satellite basins hosting the sedimentation of the Epi-Ligurian succession eventually developed over the migrating Ligurian Units. As a result, these latter units are tectonically superposed onto the Marnoso Arenacea foredeep system. Later, marine sedimentation took place in piggyback basins controlled by thrust activity at the Pede-Apennine margin and in the buried belt during Messinian and Pliocene–early Pleistocene time. Continual thrust-and-fold deformation has been affecting the post–800 ka Po Plain alluvial deposits (Boccaletti et al., 2004).

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NIRANO MUD VOLCANO FIELD

Structural Setting

The Nirano mud volcano field (NMVF) is currently formed by four main vents composed of a number of individual active cones (or gryphons) defining structural alignments trending ~N55°E (Figs. 2A–2C). Such cones are up to 3 m high, and emit mud breccias and mudflows spreading over an elliptical (~500 m long, 350 m wide, ≤60 m deep) depression with essentially planar morphology (Figs. 2A, 2C). This depression is bound by steep flanks excavated in the marine claystones (Argille Azzurre Formation), and exhibits morphological and structural characteristics similar to those of igneous calderas, most notably an abrupt and circular rim enclosing vents and lava domes erecting from a topographically depressed area (Figs. 2A, 2C, 2D).

The NMVF occurs at the crest of a fault-propagation fold anticline generated by a blind thrust (Bonini, 2007; Fig. 2E). The NMVF develops in correspondence to an inflection in the trace of the thrust-related anticline axis, which deviates from the mean WNW-ESE trend in the vicinity of a

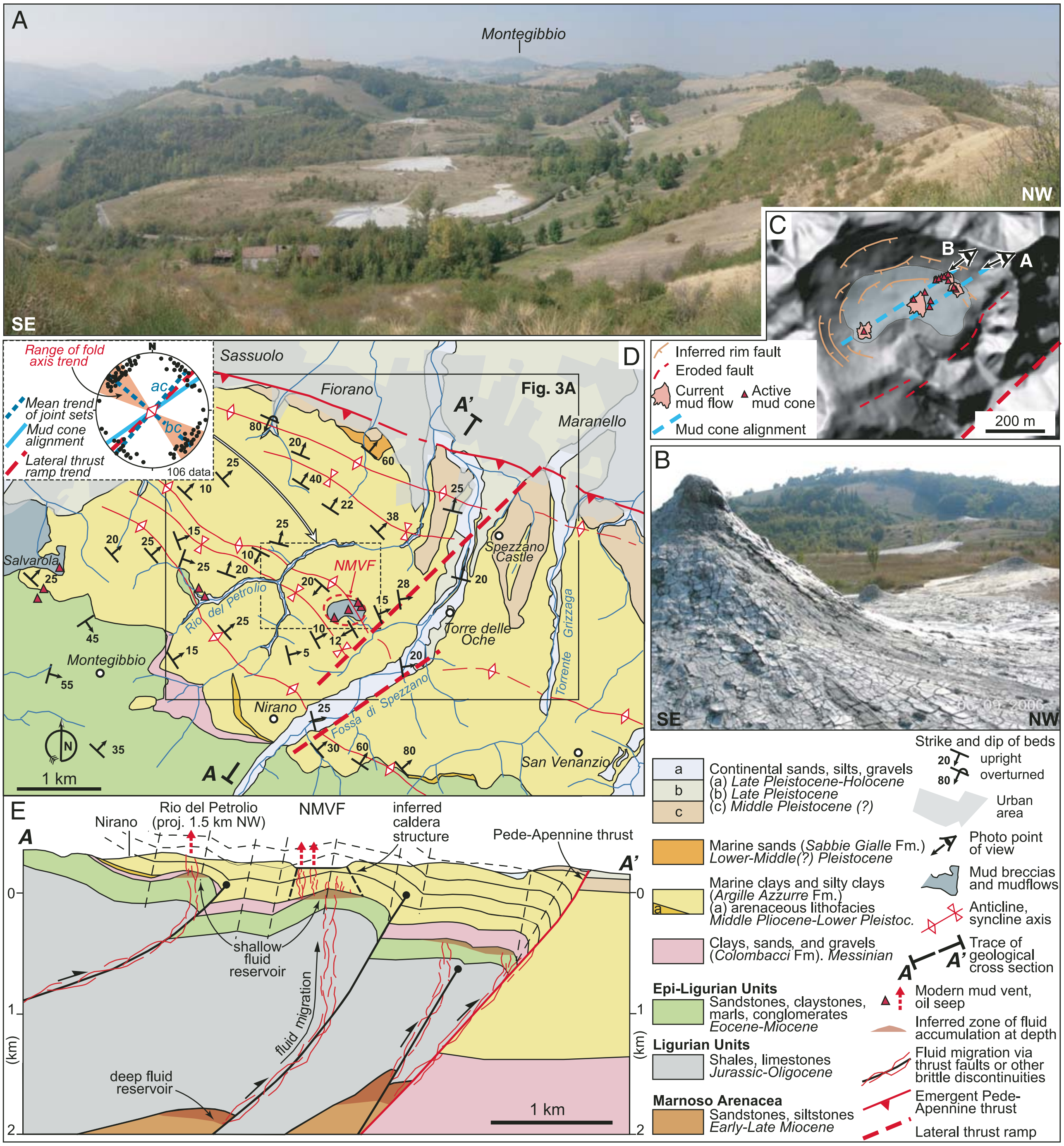

Figure 2. A: Panoramic view of the elliptical depression containing the Nirano mud volcano field (NMVF). B: Close-up of active mud cone; note alignment with other cones in background. C: Morphologic and structural characteristics of the NMVF depression superimposed onto 5-m-resolution digital terrain model (DTM) (courtesy of Regione Emilia-Romagna). D: Geological-structural map (adapted from the Geological map of the Emilia-Romagna Region, available at: http://www.regione.emilia-romagna.it/wcm/geologia). Inset shows distribution of joints in relation to the direction of fold axes, lateral thrust ramps, and mud volcano alignments (black dots indicate the pole to joint planes; Schmidt net, lower hemisphere; modified from Bonini, 2007). Dashed box indicates area of joint collection. E: Typical geological cross section. Note preferential localization of seepage over the crests of anticlines.

lateral thrust ramp (Fig. 2D). Two main families of steep, near perpendicular, fractures are oriented roughly parallel and orthogonal to the anticline axis, and are related to the classic bc and ac joint sets, respectively (Bonini, 2007; Fig. 2D, inset). It is interesting that the ac set essentially parallels both the lateral thrust ramp and the structural alignments defined by mud cones (Figs. 2B–2D), and provides structural conduits channeling fluids at the surface from the anticline core, where the fluidized mud may fill the fractures associated with the folding (i.e., outer-arc fracturing) and achieve extra pressure in connection with the presence of sealing layers, such as the Argille Azzurre claystones. Conceptually similar confined mud reservoirs are reported from the Lokbatan mud volcano in Azerbaijan (Planke et al., 2003).

Characteristics of Discharged Fluids

The fluids currently expelled at Nirano mostly consist of mud, gas bubbles (methane represents the largest part of emitted gases), and muddy water, which may also contain a small fraction of liquid hydrocarbons (Martinelli and Rabbi, 1998). Analysis of the extruded mud has revealed the presence of submillimeter angular fragments of claystones and carbonates that are indicative of the source layer and wall rocks encountered by the rising fluids. The erased fragments are referable to the Argille Azzurre Formation as well as to the underlying Eocene–Miocene Epi-Ligurian and Cretaceous Ligurian Units (see Fig. 2E). This attribution is corroborated by the analysis of well-preserved microfossils (calcareous nannoplankton) contained in the mud. Upper Cretaceous microfossil markers suggest a fluid migration through the essentially impermeable Ligurian Units (mostly consisting of shales and carbonates), which may induce fluid overpressuring in the underlying Marnoso Arenacea turbidites. The preferred geological model involves pressurized fluids moving up through discontinuities in the Ligurian Units, and accumulating at shallower reservoirs controlled by the lithological boundary between the impermeable claystones (Argille Azzurre Formation) and the underlying, more permeable, Epi-Ligurian Units and Colombacci deposits (Fig. 2E).

NIRANO CALDERA DEPRESSION

Inferences on Origin, and Fluid Reservoir Depth

Classical igneous calderas form primarily as a result of overburden collapse due to withdrawal of magmatic support following explosive eruptions of magma stored at depth. The NMVF depression may be interpreted as a similar collapse feature forming as a consequence of the evacuation of thousands of cubic meters of material from a shallow mud chamber. The recent and historical activity at the NMVF is characterized by a relatively quiescent fluid emission interrupted by paroxysmal events (e.g., Martinelli and Ferrari, 1991). Noteworthy is the occurrence of a giant mud volcano eruption in the area, associated with the contemporaneous destructive earthquake of 91 B.C. that struck the Pede-Apennine margin around Modena (Guidoboni, 1989). As reported by the Roman writer Plinius, sky-scraping flames and smoke were seen from a distance of ~10 km, in all likelihood a phenomenon attributable to a typical mud volcano eruption, during which the violent ejection of overpressured mud was accompanied by methane combustion. Similar correlations between large earthquakes and methane mud volcano eruptions have been documented for other mud volcanoes worldwide (Mellors et al., 2007).

The 91 B.C. mud volcano eruption can be confidently positioned in a sector of the Pede-Apennine foothills including the NMVF (Guidoboni, 1989; Martinelli and Rabbi, 1998). The consideration that the NMVF depression is apparently the only large-size collapse structure associated with mud volcanoes in the area may allow us to speculate about a link between mud volcano caldera collapse and the 91 B.C. earthquake. The lack of evidence with which to date the NMVF caldera makes this link intriguing, although at the moment, it is an unconstrained hypothesis.

In the Northern Apennines, a modern example of subcircular depressions forming as a consequence of eruption of gas (associated with salt water and mud) is provided by the San Clemente mud volcano (Bologna), located 55 km southeast of the NMVF (Capozzi et al., 1994; Fig. 1). Similar circular and/or elliptical depressions intruded by mud diapirs are also reported from submarine accretionary wedges (e.g., Barbados; Henry et al., 1990). Such collapsed areas may thus be considered to be conceptually equivalent to explosive volcanic calderas.

Applying the procedure developed by Kusumoto and Takemura (2005) for igneous calderas to the NMVF, the (initial) depth d of the deflated mud chamber may be estimated to vary between ~210 m and 300 m ($d \approx 0.5a/\tan 39.4°$, where a is the caldera diameter). This depth interval accords well with the hypothesis that the shallow fluid reservoir was located below the base of the Argille Azzurre claystones (Fig. 2E).

Relations with the Active Stress Field

It has been well established that caldera elongation is a reliable indicator of far-field stress orientation. Such a geometry may result from distortion of structures in response to a regional tectonic stress (Self et al., 1986; Holohan et al., 2005), or related to the shape of the underlying fluid chamber growing in the direction of the minimum horizontal stress (Bosworth et al., 2003). Elliptical igneous calderas are normally elongated parallel to the direction of the least horizontal compressive stress S_h, implying that, in compressional settings, the shorter caldera axis is aligned with the regional maximum shortening direction (Holohan et al., 2005, and references therein).

This analysis has also been applied to the elliptical NMVF depression by using a high-resolution digital terrain model image that shows its morphologic characteristics in great detail (Fig. 3). The results sug-

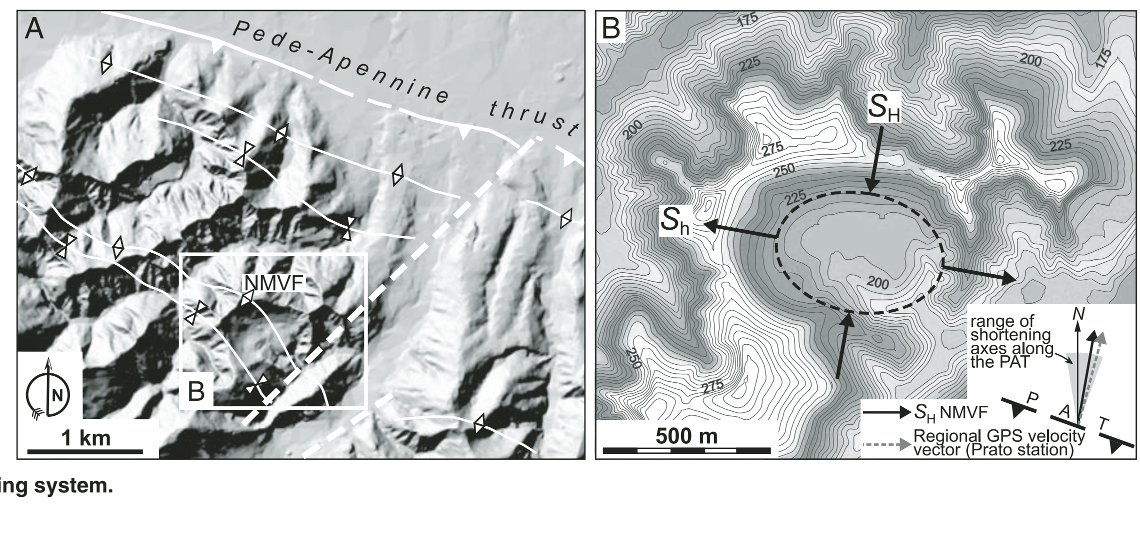

Figure 3. A: Digital terrain model (DTM, 5 m resolution) of region around Nirano mud volcano field (NMVF) depression (courtesy of Regione Emilia-Romagna); location in Figure 2D. B: Close-up of elliptical depression showing relations between caldera geometry and regional stress field. Note the essential parallelism between shorter ellipse axis S_H and direction of the maximum horizontal compressive stress axes along the Pede-Apennine thrust (PAT), shown in inset. Contour lines are 5 m. GPS—global positioning system.

gest that, like igneous calderas, the Nirano caldera is reflecting the active tectonic stress field. The caldera maximum axis (S_h) nearly parallels the active Pede-Apennine thrust, and the ~N10°E trending short ellipse axis (S_H) essentially parallels the mean N-NNE–trending direction of regional compression (Fig. 3B). The latter is constrained by various data sets (see Fig. 1), specifically (1) the P-axis of earthquake focal mechanism solutions, (2) the local paleodirections of shortening detected from outcrop-scale structures in Pleistocene sediments, and (3) the direction of the maximum horizontal stress S_H derived from borehole breakouts, and is strikingly comparable with the global positioning system (GPS) velocity vector measured at the Prato station, which is located over the Northern Apennine chain (Battaglia et al., 2004; Figs. 1 and 3B).

These findings may also have significance for the form of the past (and present) mud reservoir. As suggested by Bosworth et al. (2003), the caldera elongation may reflect a similar shape of the underlying magma chamber, and the caldera long axis could correspond to the time-averaged shallow S_h. In this scenario, a puzzling factor may concern the N55°E-trending active gryphon alignment that, instead of being perpendicular to the long caldera axis, is ~45° oblique (Figs. 2C and 3B). This setting could indicate that the present fluid venting is controlled by shallow ac fractures connected to the rotation of the anticline axis toward the interpreted lateral thrust ramp (note the parallelism between the ac joint set and the lateral ramp; Fig. 2D, inset).

In addition, the dimensions of the NMVF depression are approximately one order of magnitude smaller than those of igneous calderas. For example, the Katmai caldera, situated in an area of orthogonal compression (Aleutian Arc, Alaska), has a 4-km-long maximum axis and a 2.5-km-long minimum axis (e.g., Holohan et al., 2005). However, both NMVF and Katmai calderas show similar aspect ratios (longer axis/shorter axis); the NMVF ratio is 1.43 and the Katmai caldera ratio is 1.60. In my view, the above analogies may provide lines of evidence suggesting the mechanical similarity between mud volcano–related calderas and their igneous analogs. In both systems, the dynamics of caldera collapse are essentially controlled by the presence of pressurized melts and/or fluids into confined reservoirs.

CONCLUSIONS

The terrestrial NMVF provides a strategic example of interconnection between mud volcanism and the development of elongated caldera collapse–like structures, and their use as stress indicators in active compressional tectonic settings. The NMVF oval depression is elongate perpendicular to the regional main compressive stress. The paroxysmal fluid discharge of 91 B.C. could be connected to a triggering earthquake possibly associated with a long-term fault failure event. As a corollary, the above considerations may also involve some relevance for the potential hazard associated with the active mud volcanoes, which occur nearby, or even within, inhabited areas of the Pede-Apennine margin.

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