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Pre-eruptive ground deformation of Azerbaijan mud volcanoes detected through satellite radar interferometry (DInSAR)

Benedetta Antonielli [a,b,*], Oriol Monserrat [c], Marco Bonini [d], Gaia Righini [e], Federico Sani [a], Guido Luzi [c], Akper A. Feyzullayev [f], Chingiz S. Aliyev [f]

[a] Dipartimento di Scienze della Terra, Università di Firenze, via G. La Pira n.4, 50121, Firenze, Italy
[b] Tuscan Earth Science PhD Program, Earth Science Department, University of Pisa, Via S. Maria 53, 56126 Pisa, Italy
[c] Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Av. Carl Friedrich Gauss, 7, Castelldefels, Spain
[d] CNR, Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, via G. La Pira 4, I-50121 Firenze, Italy
[e] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, via Martiri di Monte Sole, 4, 40129, Bologna, Italy
[f] Geology Institute of the Azerbaijan National Academy of Sciences, H. Javid pr., 29 A, Baku AZ1143, Azerbaijan

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ABSTRACT

Mud volcanism is a process that leads to the extrusion of subsurface mud, fragments of country rocks, saline waters and gases. This mechanism is typically linked to hydrocarbon traps, and the extrusion of this material builds up a variety of conical edifices with a similar morphology to those of magmatic volcanoes, though smaller in size. The Differential Interferometry Synthetic Aperture Radar (DInSAR) technique has been used to investigate the ground deformation related to the activity of the mud volcanoes of Azerbaijan. The analysis of a set of wrapped and unwrapped interferograms, selected according to their coherence, allowed the detection of significant superficial deformation related to the activity of four mud volcanoes. The ground displacement patterns observed during the period spanning from October 2003 to November 2005 are dominated by uplift, which reach a cumulative value of up to 20 and 10 cm at the Ayaz–Akhtarma and Khara-Zira Island mud volcanoes, respectively. However, some sectors of the mud volcano edifices are affected by subsidence, which might correspond to deflation zones that coexist with the inflation zones characterized by the dominant uplift. Important deformation events, caused by fluid pressure and volume variations, have been observed both (1) in connection with main eruptive events in the form of pre-eruptive uplift, and (2) in the form of short-lived deformation pulses that interrupt a period of quiescence. Both deformation patterns show important similarities to those identified in some magmatic systems. The pre-eruptive uplift has been observed in many magmatic volcanoes as a consequence of magma intrusion or hydrothermal fluid injection. Moreover, discrete short-duration pulses of deformation are also experienced by magmatic volcanoes and are repeated over time as multiple inflation and deflation events.

1. Introduction and aims of the work

Mud volcanism is a well-known phenomenon that drives the extrusion of fluids and solid material originated from deeply buried sediments, such as saline waters, gases (mostly methane), mud and clasts of country rock. This mechanism is typically linked to hydrocarbon traps (Higgins and Saunders, 1974) and builds up a variety of features. Conical extrusive edifices are the most typical feature and may vary in size from centimeters to a few hundred meters in height and several kilometers long. Mud volcanoes are generally smaller than magmatic volcanoes, although in some cases their size is comparable to that of the large magmatic edifices. In particular, in the Marianas subduction zone, mud volcanoes may be 2 km high and have a diameter of 25 km (Fryer et al, 1999).

Mud volcanoes are usually located in fold-and-thrust belts and accretionary prisms, and develop at convergent plate margins where the active tectonic shortening affects the sediments by increasing stresses and temperatures leading to the maturation of organic matter (Brown, 1990; Higgins and Saunders, 1974; Kopf, 2002). During most of their lifetime, mud volcanoes show a background activity of quiet to vigorous expulsion of fluids and mud breccias. However, such quiescent activity may be occasionally interrupted by paroxysmal events which violently release large mud flows and flaming eruptions caused by the self-ignition of the methane.

The eastern Greater Caucasus in Azerbaijan hosts the highest density of mud volcanoes in the world (Jakubov et al., 1971; Guliyev and Feizullayev, 1997; Figs. 1 and 3a). Some mud volcanoes may be up to 400 m tall, and 4–5 km long, with a dimension and morphological

* Corresponding author.
E-mail address: benedetta.antonielli@unifi.it (B. Antonielli).

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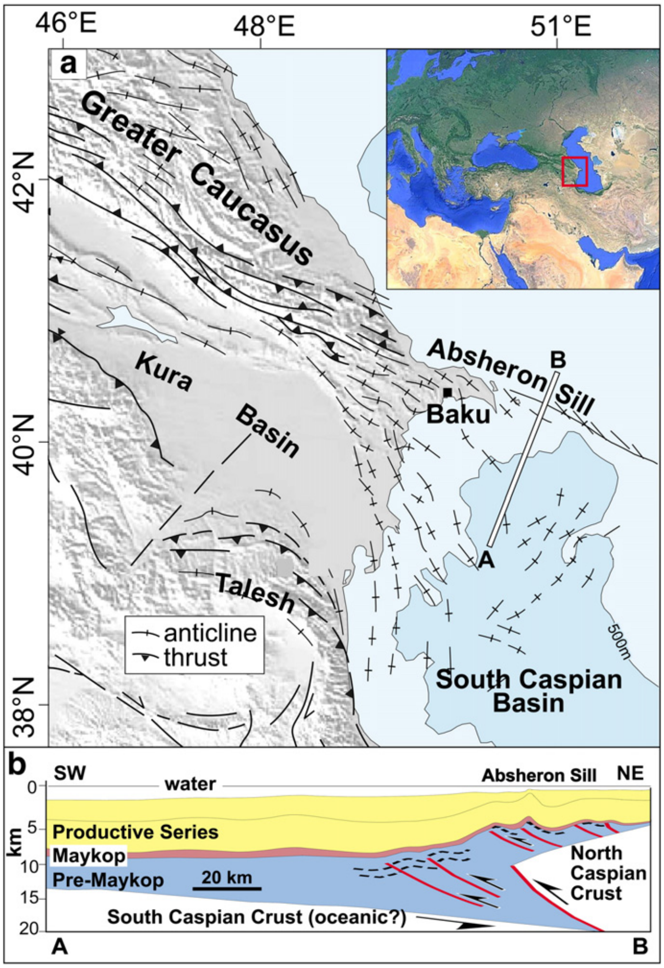

Fig. 1. (a) Simplified structural sketch map of the Greater Caucasus–eastern Caspian Basin (modified from Jackson et al., 2002). (b) Regional cross-section through the Absheron Sill and the South Caspian Basin (vertical exaggeration 2×; simplified from Stewart and Davies, 2006).

characteristics similar to those of magmatic volcanoes. There is a rather complete record of mud volcanoes eruptions since 1810 (Mellors et al., 2007). In particular, the second edition of the catalogue provides the chronology and a brief description of 387 eruptions occurred between 1810 and 2007 at 93 mud volcanoes located, both onshore and offshore, in Azerbaijan (Aliyev et al., 2009).

Satellite based Synthetic Aperture Radar Interferometry (InSAR) techniques have been commonly used to monitor and investigate the ground deformation connected to the eruptive phases of magmatic volcanoes. In the early 90s, the launch of satellites carrying SAR sensors onboard purposely built for interferometric applications, opened new opportunities for mapping and monitoring ground deformations produced by different processes at active magmatic volcanoes, particularly: (i) uplift before eruption and co-eruptive subsidence (Amelung et al., 2000; Jay et al., 2014), (ii) pulses of inflation and deflation on volcanic systems (Biggs et al., 2009, 2011; Brunori et al., 2013; Chang et al., 2007; Pagli et al., 2006; Pritchard and Simons, 2004), (iii) subsidence associated with magma phase change (Caricchi et al., 2014), (iv) linked hydrothermal and magmatic systems (Wicks et al., 1998), (v) crustal rifting episodes (Pagli et al., 2012; Sigmundsson et al., 1997; Wright et al., 2012), (vi) downslope movements on the volcano flanks (Ebmeier et al., 2010), and (vi) lava thicknesses and extrusion rate (Ebmeier et al., 2012). InSAR techniques have also been employed to explore the ground deformation associated with the LUSI mud volcano in Indonesia (Abidin et al., 2009; Aoki and Sidiq, 2014; Fukushima et al., 2009; Rudolph et al., 2013).

Using similar techniques, we have carried out research on ground deformation related to the activity of the mud volcanoes of Azerbaijan. For this purpose, the deformation of mud volcanic systems has been analyzed using the differential interferometry (DInSAR) technique applied to ENVISAT data. A few studies have been carried out using the InSAR technique to analyze the mud volcanoes of Azerbaijan. Hommels et al. (2003) investigated the dynamics of the largest mud volcanoes (Touragai, Great and Lesser Kjanizadag) and found preliminary indications of deformation in the dataset analyzed. Mellors et al. (2005) focused on the analysis of the Absheron Peninsula and the Lokbatan mud volcano, but they did not observe any large-scale movement (>10 cm line-of-sight) during the analyzed period. In the following sections we describe the concepts and tools that drive the assessment of mud volcanism and the geological framework of the area (Section 2), the key steps of the DInSAR data processing (Section 3), and the results for each case study (Section 4). Finally, the principal strengths and weaknesses are discussed together with the follow-up and recommendations for future work (Sections 5 and 6).

2. Mud volcanism

2.1. Mud volcano processes and terminology

Several theories have been proposed in the literature regarding the mechanisms that might control the development of mud volcanism. In particular, this process has often been related to subsurface intrusive mud or shale diapirism (Fig. 2a; Brown, 1990; Morley and Guerin, 1996; Kopf, 2002). Mud diapirs are subsurface fluid-rich overpressured muddy masses that are driven upward in response to their buoyancy resulting from the bulk density contrast with respect to the denser surrounding overburden (Brown, 1990). The overpressure is produced by the organogenic activity and the subsequent gas production at depth (e.g., Higgins and Saunders, 1974). The expansion and degassing of the methane dissolved in the mud may further increase both the overpressure and buoyancy of the rising diapir (Brown, 1990). Other models suggest that mud volcanism is sourced from mud–water–gas mixes rising up through intricate systems of conduits and pipes and networks of anastomosing fault-controlled planar pathways exploiting deeper fluid-rich source layers (Cooper, 2001; Davies et al., 2007; Dimitrov, 2002; Fowler et al., 2000; Mazzini et al., 2009; Morley, 2003; Planke et al., 2003; Roberts et al., 2010). Fluid reservoirs may occur at various depths and are likely to contain zones with dense networks of mud-filled fractures.

Mud volcanoes are thus closely associated with petroleum systems, and the development of overpressures in source rocks is a necessary condition to trigger mud volcanism (Dimitrov, 2002). For this reason, mud volcanoes are often located at anticlines where sealing layers in the fold core may efficiently trap the rising hydrocarbon fluids and readily built-up overpressures (Bonini, 2012). Tectonic stress provides an important source of overpressure, as indicated by the widespread occurrence of mud volcanoes in many active compressional belts worldwide (e.g., Kopf, 2002). The state of stress is also inferred to control distribution, geometry and shape of mud volcano features (Bonini, 2012).

'Mud volcano' is a generic term that indicates the various morphologic features associated with the extrusion of subsurface material. As soon as it reaches the topographic surface, the extruded mud gives rise to the typical conical edifices. Conventional nomenclature subdivides the small sub-conical extrusive edifices in gryphons (≤3 m high, Fig. 2b) and mud cones (>3 m high, Fig. 2c), while the term mud volcano should be restricted to the edifices reaching some tens of meters in height (say ≥50 m) or a few kilometers across (Fig. 2d). The largest mud volcanoes are the gigantic submarine serpentinite mud volcanoes (conical seamounts) of the Marianas forearc, which may reach 25 km in diameter and exceed 2 km in height. Mud volcanoes and magmatic volcanoes display very similar morphologic features and, for this reason, many terms used for mud volcanism are borrowed from the terminology of magmatic features. For instance 'crater' is used to indicate the sub-