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Long- and short-term triggering and modulation of mud volcano eruptions by earthquakes

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ABSTRACT

Earthquakes can trigger the eruption of mud. We use eruptions in Azerbaijan, Italy, Romania, Japan, Andaman Islands, Pakistan, Taiwan, Indonesia, and California to probe the nature of stress changes that induce new eruptions and modulate ongoing eruptions. Dynamic stresses produced by earthquakes are usually inferred to be the dominant triggering mechanism; however static stress changes acting on the feeder systems of mud volcanoes may also play a role. In Azerbaijan, eruptions within 2–10 fault lengths from the epicenter are favored in the year following earthquakes where the static stress changes cause compression of the mud source and unclamp feeder dikes. In Romania, Taiwan, and some Italian sites, increased activity is also favored where the static stress changes act to unclamp feeder dikes, but responses occur within days. The eruption in the Andaman Islands, and those of the Niikappu mud volcanoes, Japan are better correlated with amplitude of dynamic stresses produced by seismic waves. Similarly, a new island that emerged off the coast of Pakistan in 2013 was likely triggered by dynamic stresses, enhanced by directivity. At the southern end of the Salton Sea, California earthquakes increase the gas flux at small mud volcanoes. Responses are best correlated with dynamic stresses. The comparison of responses in these nine settings indicates that dynamic stresses are most often correlated with triggering, although permanent stress changes as small as, and possibly smaller than, 0.1 bar may be sufficient to also influence eruptions. Unclamping stresses with magnitude similar to Earth tides (0.01 bar) persist over time and may play a role in triggering delayed responses. Unclamping stresses may be important contributors to short-term triggering only if they exceed 0.1–1 bar.

1. Introduction and aims of the work

1.1. Mud volcanoes: characteristics, processes and hazards

The mobilization of deeply buried sediments and the extrusion of mud-breccias, saline water, and gases is a process known as *mud* or *sedimentary volcanism*. This process is driven by the presence of overpressured gases in the subsurface (Brown, 1990; Kioka et al., 2015), and is often linked to hydrocarbon traps at depth (Higgins and Saunders, 1974). Methane typically comprises the dominant fraction of released gases, though occasionally other gases (e.g., CO_2 and N_2) may prevail (Kopf, 2002). Eruption creates various forms of mud volcanoes, the most distinctive of which are the steep-sided extrusive conical edifices typically topped by a crater that extrudes mud flows, and bursting bubbles at the vent generate spatter (Fig. 1a–c), features that mimic in many ways the morphology of magmatic volcanoes (Fig. 1d, e). In addition, mud volcanoes share several other processes and properties with their igneous analogs, including (i) comparable internal structure (e.g., Stewart and Davies, 2006), (ii) a similar eruptive history (e.g., Evans et al., 2008; Kopf, 2008), (iii) buoyancy is often supplied by exsolved gases (Manga et al., 2009), and (iv) eruptions triggered by earthquakes have similar sensitivities to ground deformation (Wang and Manga, 2010). This suggests that, apart from obvious differences (i.e., the role of temperature and crystallization), some similar processes govern both igneous and mud volcanoes.

The dimension of the extrusive edifices is highly variable, ranging in size from the decimeter– to meter-scale (gryphons and mud cones) to large volcanoes up to a few hundred meters high and several kilometers across (Fig. 1a–d). Mud volcanoes are quiescent for most of their lifetimes, with occasional rhythmic, sometime vigorous, seepage of water, gas, and hydrocarbons, including the expulsion of gas bubbles from muddy waters (Fig. 1c). The analysis of gas geochemistry suggests that the plumbing system of dormant mud volcanoes is continuously recharged from deep-seated reservoirs through a system of branched conduits (Mazzini et al., 2009; Tassi et al., 2012). However, mud volcanoes may experience episodic paroxysmal eruptive phases that involve the violent ejection of mud breccias and mud flows from a summit crater. The eruption rates and temperatures are significantly lower than those of magmatic volcanoes, and thus the hazard mud volcanoes

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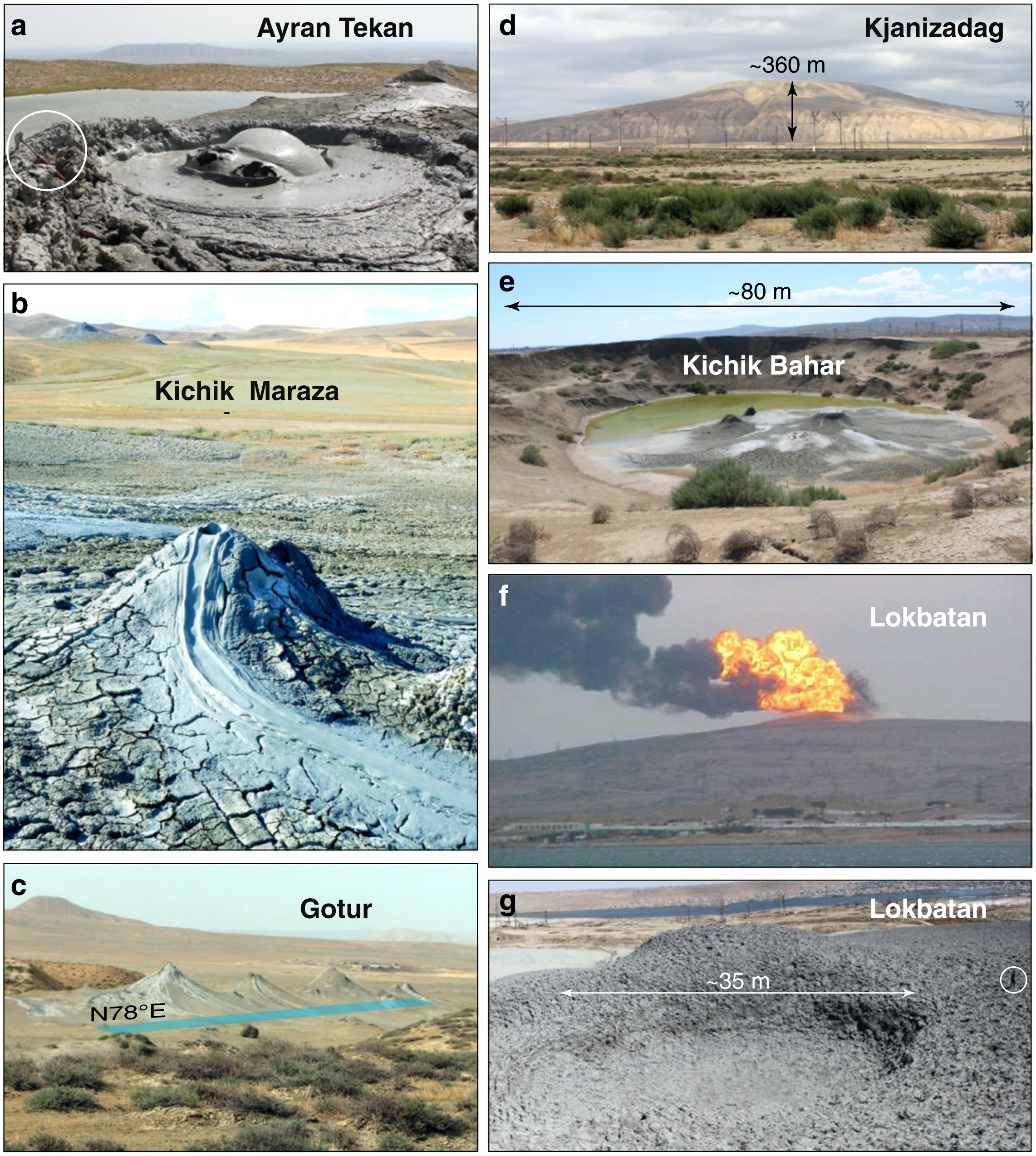

Fig. 1. Characteristics of mud volcano features from Azerbaijan. (a) Large gas bubble popping in a crater at the top of a gryphon at Ayran Tekan mud volcano; hammer (circled) for scale (N39.99389 E49.30889; photo 23 May 2010). (b) Gryphon emitting a fresh mud flow in the Kichik-Maraza mud volcano field (N40.51028 E49.03194; photo 22 June 2013). (c) Alignment of mud cones and gryphons at Gotur (extracted from Google Earth®, http://earth.google.it/download-earth.html). (d) Lateral view of the large Kjanizadag mud volcano edifice (N40.14083 E49.38222; photo 21 June 2013). (e) Small caldera topping the gentle-sided Kichik Bahar mud volcano (N39.99805 E49.45527; photo 25 May 2010). (f) Flaming eruption at the Lokbatan mud volcano on 25 October 2001; photo by Phil Hardy—from BBC NEWS 29th October 2001, Clare Doyle in Baku. According to Mukhtarov et al. (2003), this violent explosive eruption was characterized by an initial flame approximately 300 m tall and 100 m across. (g) Lateral view of the summit crater of Lokbatan (N40.30444 E49.70916; photo 27 June 2014); person (circled) for scale.

pose is primarily local (e.g., Etiope, 2015). There are however remarkable exceptions. During violent eruptions, subaerial mud volcanoes can discharge up to 500 million m^3 of flammable methane in a few hours (Kopf, 2002). Self-ignition can produce large explosive flaming eruptions leading to loss of life at some Azerbaijan mud volcanoes (Guliyev and Feyzullayev, 1997) (Fig. 1f, g).

1.2. Mud volcano eruptions and earthquakes

We can probe processes that govern the initiation of eruptions by studying the response of mud volcanoes to known external forcing such as stresses produced by earthquakes. Eruptions within hours to days of an earthquake are generally assumed to be the most convincing examples of triggered eruptions (Manga and Brodsky, 2006), as delayed triggering is more difficult to assess (Selva et al., 2004). The number of documented magmatic eruptions triggered by earthquakes is small (Linde and Sacks, 1998; Watt et al., 2009), though there is growing evidence that there may be widespread and even global increases in volcanic activity following large earthquakes (e.g., Madonia et al., 2013; Delle Donne et al., 2010; Eggert and Walter, 2009; Tsunogai et al., 2012; Kusumoto et al., 2015; Lupi et al., 2016).

The first step in understanding why earthquakes influence eruptions is to identify the responsible stress. The static stresses created by fault slip decay with distance R from the epicenter as $1/R^3$, and become