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Structural setting and earthquake triggering of mud volcanoes: examples from Azerbaijan and Italy

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The steep-sided conical mud volcanoes originate from the extrusion to the topographic surface of mud breccias, and are typically linked to in-depth hydrocarbon traps. Mud volcanoes usually occur at fold anticlines, which have the ability to trap the rising fluids within their core. Azerbaijan hosts the most numerous collection of onshore mud volcanoes, which occur along the trains of anticlines forming the frontal sector of the Greater Caucasus fold-and-thrust belt. In Italy, mud volcanoes mostly occur along thrust anticlines associated with the Pede-Apennine thrust running from Emilia to the Marche region. Specific mud volcano features (i.e. aligned vents and elongated volcanoes) may be used as potential indicators of the orientation of subsurface feeder mud dikes, which are normally subparallel to the maximum horizontal stress SH.

Earthquakes can occasionally trigger large mud volcano eruptions. In Azerbaijan, two nearly simultaneous Mw6.2 and Mw6.1 earthquakes hit offshore Baku on 25 November 2000. Eruptions markedly increased in the year following the 2000 Baku earthquakes, but the seismic events did not produce any immediate triggering of eruptions. Dynamic stresses are likely to play a fundamental role in the short-term triggering of eruptions, and thus the possible delayed, triggered response of mud volcanoes requires also the evaluation of the (permanent) static stress changes. Many of the mud volcanoes that responded to the earthquakes have feeder dikes suitably oriented for being unclamped. It is possible, therefore, that some of the delayed eruptions are favored in the year following earthquakes when the static stress changes cause compression of the mud source and unclamp overlying feeder dikes, ‘advancing the clock’ of eruptions.

In Italy, a medium-to-high magnitude earthquakes started on 24 August 2016 with the Mw 6.0 Amatrice seismic event, and the largest event was the Mw 6.5 30 October 2016 event near Norcia. After the major seismic events, 17 mud volcanoes erupted around Monteleone in the Marche region. The eruptions generally occurred a few hours to a few days after the main earthquakes, suggesting seismic triggering. The peak ground velocities and dynamic stresses during the three largest earthquakes were analyzed, and the static stress changes were also evaluated in order to assess the potential influence of normal stress changes on the feeder system of the activated mud volcanoes. There is a correlation with dynamic stresses, whereas static stress changes are negligible or negative.

The examples from Azerbaijan and Italy suggest that there is no single way in which mud eruptions respond to the stress changes produced by earthquakes. Triggering may be rapid or delayed, and mud eruptions may show different sensitivity to static and dynamic stress changes. In general, dynamic stresses are likely to exert the dominant control on the triggering. In some cases, however, static stress changes are large enough ($\geq$0.1 bar) to expect that they have been influential.