Earthquake triggering of mud volcanoes and fluid seepage systems in fold-and-thrust belts and subduction zones

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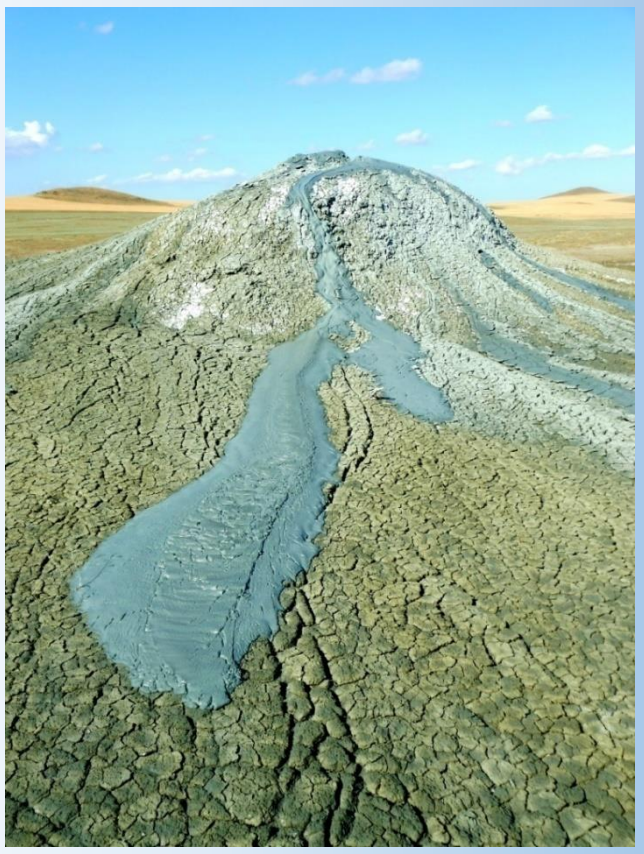
Various types of fluid expulsion features (mud volcanoes, methane vents, pockmarks, authigenic carbonate mounds and associated gas pipes, etc.) occur at fold-and-thrust belts and subduction zones. The seepage features originate from the discharge and extrusion to the topographic surface or the sea bottom of fluids, gases and solid material, which are sourced from in-depth reservoirs.



Kichik-Maraza mud volcano, Azerbaijan

Wu Shan Din mud volcano, Taiwan

Nirano mud volcano, Italy

Earthquakes can occasionally trigger the eruption or increase the activity of mud volcanoes and other seepage systems.

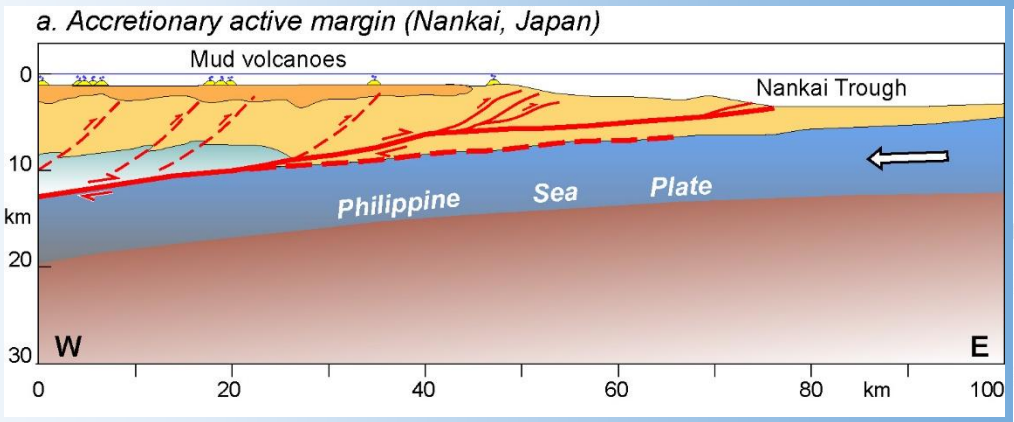
Gas explosion at Lokbatan mud volcano, Azerbaijan (photo by Phil Hardy—from BBC NEWS 29th October 2001, Clare Doyle in Baku)

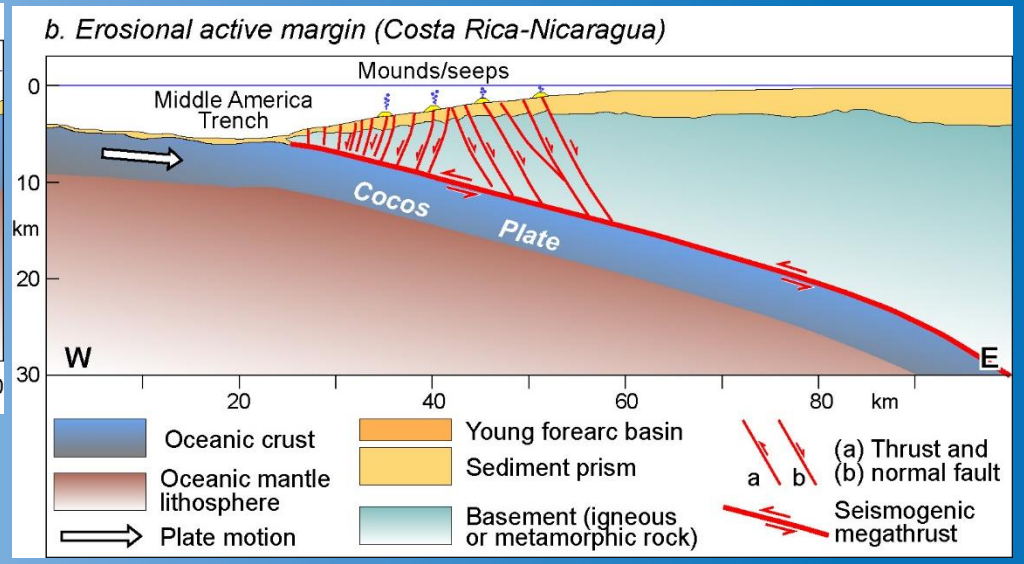
The role of static and dynamic stress changes in the triggering will vary depending on the *position* and *distance* of the seepage features with respect to the earthquake source fault.

We analyze cases when the ruptured fault is (1) structurally controlling the seepage system and (2) when the seepage system is external to the ruptured fault.

(1) Structurally controlled seepage system: Subduction zones and fold-and-thrust belts (near-field, i.e., within one ruptured fault length)
(2) Seepage systems external to the ruptured fault (intermediate to far-field, several ruptured fault lengths)

Subduction zones have the highest seismic potential on Earth, so that large subduction earthquakes can stress massively the plumbing systems of seepage features located above subduction thrusts. Earthquakes can thus potentially drive episodic mobilization of stored hydrocarbon gases, though the mechanisms remain poorly understood. Two main types of subduction margins can be identified, (i) accretionary and (ii) erosive margins.



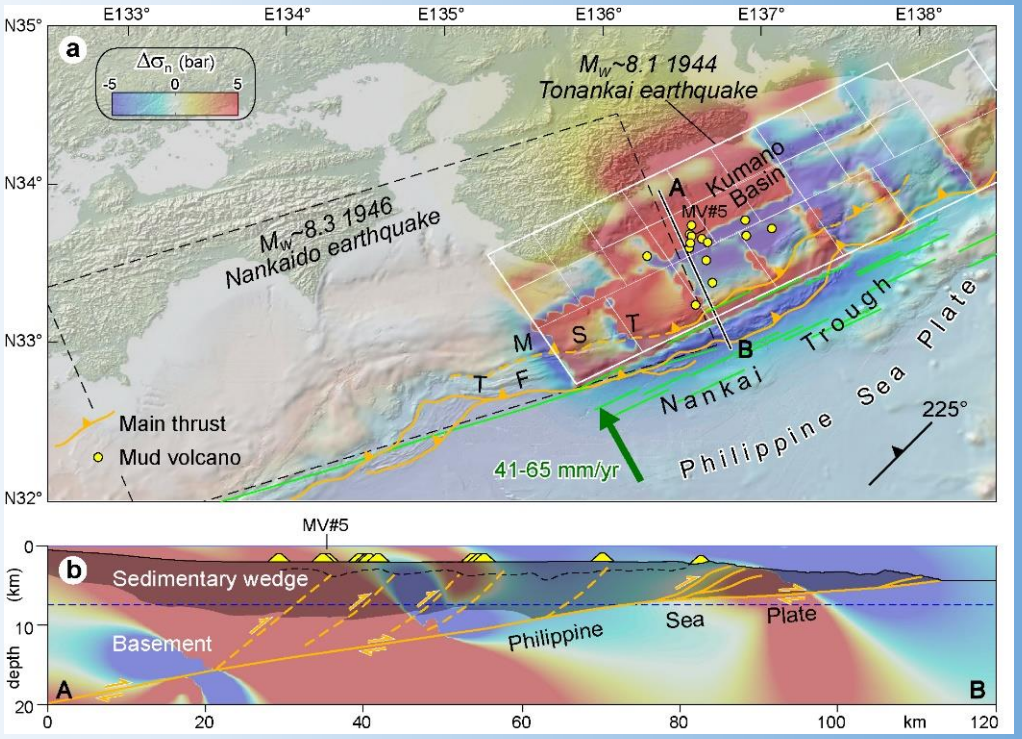


From Bonini (2019), https://doi.org/10.1038/s41598-019-47686-4

Given the nearness of fault-controlled fluid pathways of seepage systems to subduction thrusts and the potentially large magnitude of earthquakes, the role of static stress changes is likely to be influential.

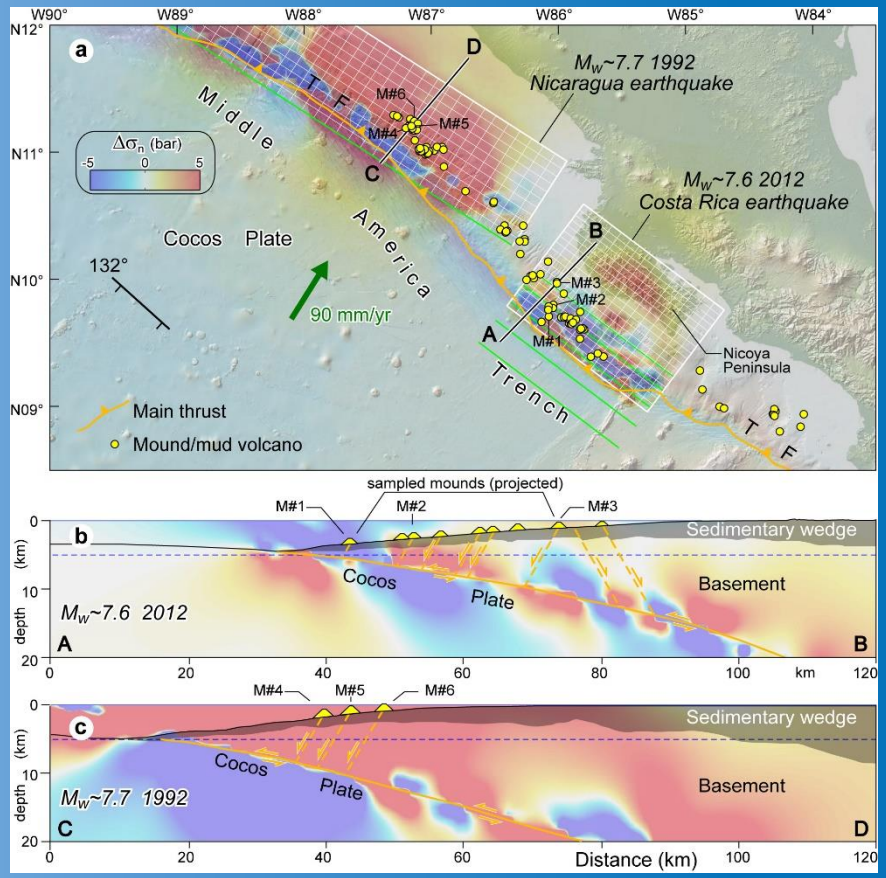
Two end-members of methane release are considered, namely those controlled by thrusts and normal faults in accretionary (e.g., Nankai Subduction Zone) and erosive (e.g., Costa Rica-Nicaragua Subduction Zone) subduction margins, respectively. We evaluate the potential role of static stress loading on fault-controlled fluid expulsion systems created by past earthquakes.

Normal stress changes produced by the 1944 Mw8.1 Tonankai earthquake (red unclamping, blue clamping)

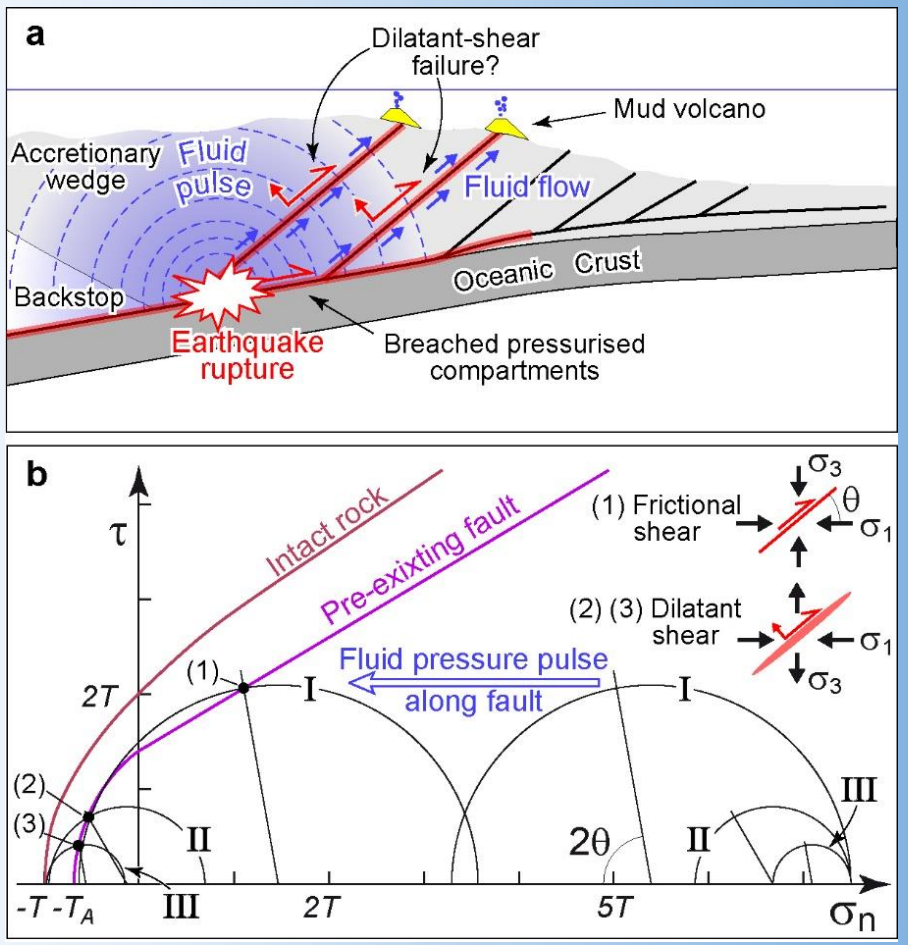


From Bonini (2019), https://doi.org/10.1038/s41598-019-47686-4

Normal stress changes produced by the Mw7.6 2012 Costa Rica and Mw7.7 1992 Nicaragua earthquakes



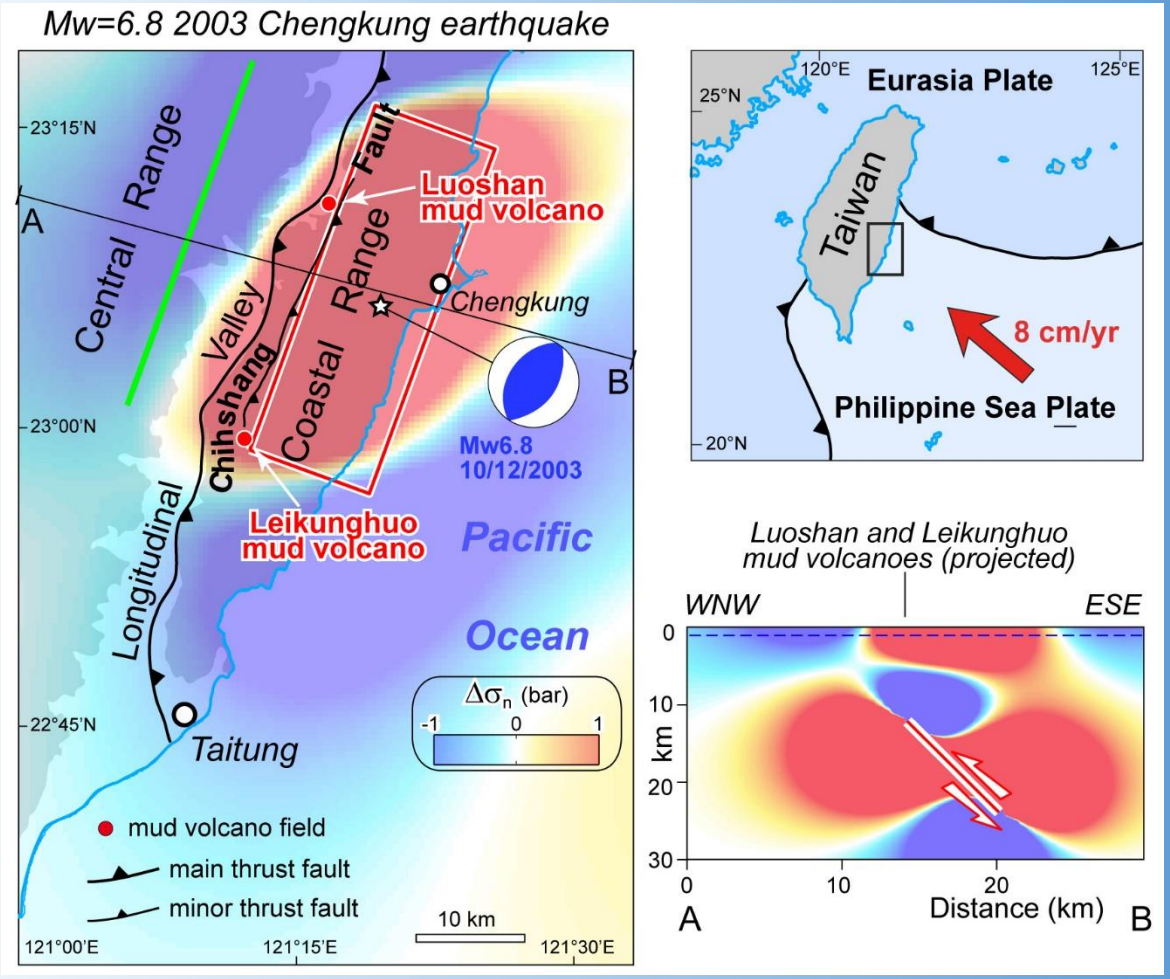
The most significant effects occur in the epicentral area where subduction earthquakes can produce normal stress changes exceeding 20-30 bar, although these are generally restricted to relatively small regions. The magnitude of coseismic normal stress changes may exceed the tensile strength of many rock anisotropies and increase crustal permeability by dilating fault-controlled conduits channeling fluids upwards.



Fluid pressure pulses released during subduction earthquakes can greatly contribute to the rupture of fluid pathways that have been brought closer to failure from co-seismic static stress changes.

From Bonini (2019), https://doi.org/10.1038/s41598-019-47686-4

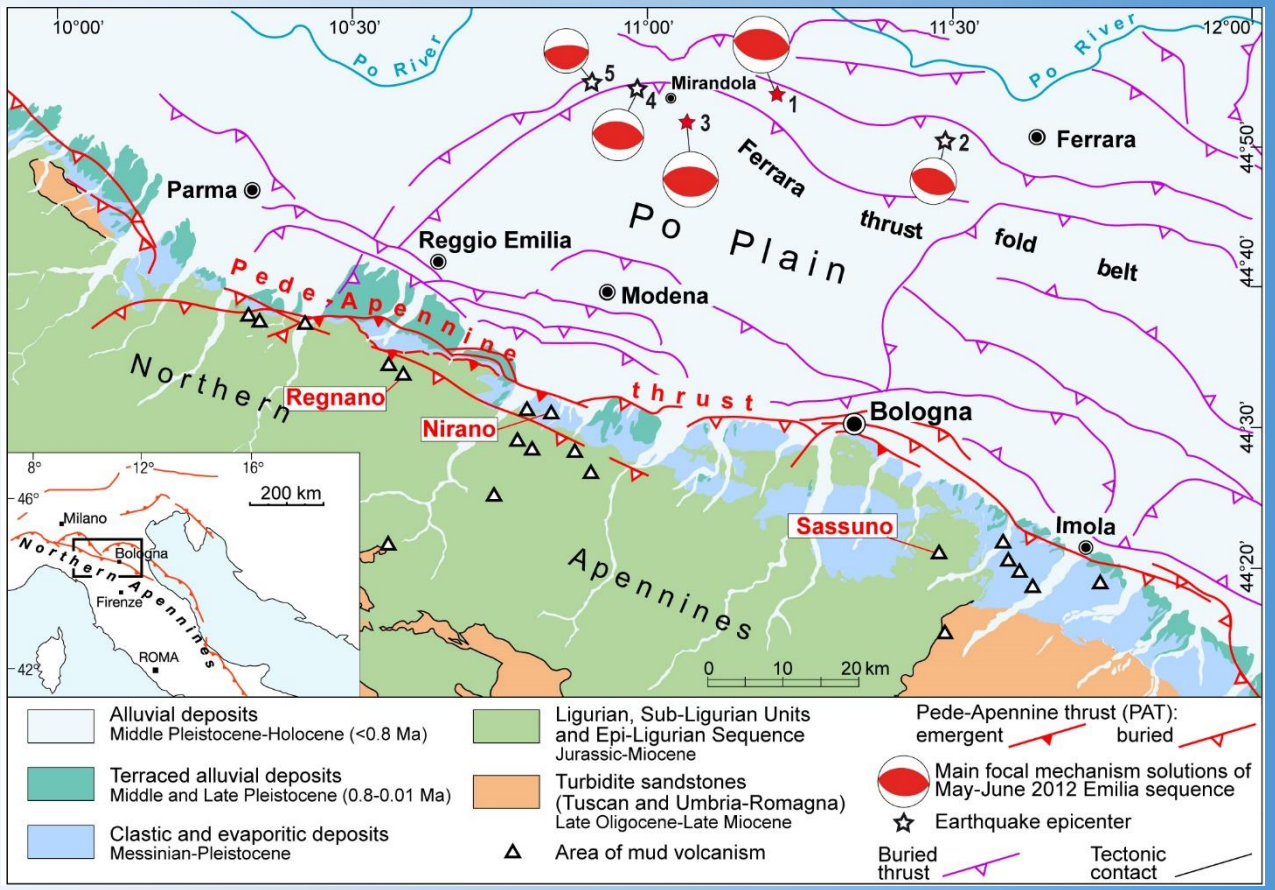
Also in fold-and-thrust belts fluid expulsion systems features can be often associated with seismogenic thrust faults. For instance, rupture of the Chihshang Fault (Taiwan) in 2003, during the Mw6.8 Chengkung earthquake, unclamped by 3 bar the feeder system of the nearby Luoshan and Leikunghuo mud volcanoes, which erupted shortly after the earthquake.



The Luoshan and Leikunghuo mud volcanoes are located on the hangingwall of the Chihshang thrust fault.

Adapted from Bonini et al. (2016), http://dx.doi.org/10.1016/j.tecto.2016.01.037

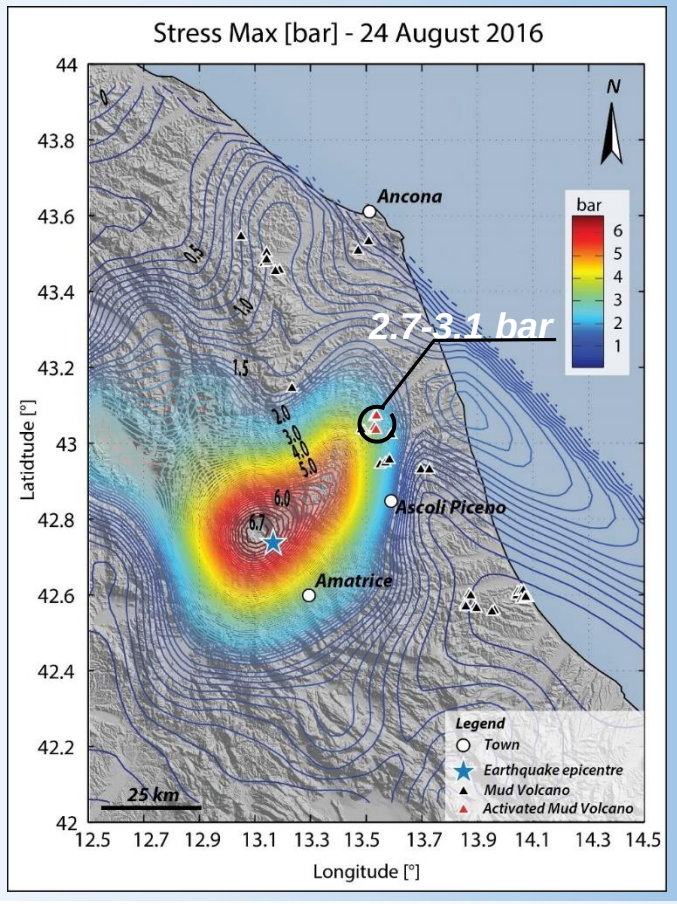
A similar setting characterizes the seismogenic Pede-Apennine thrust system in northern Italy, which is also structurally controlling a number of mud volcanoes located on its hangingwall.

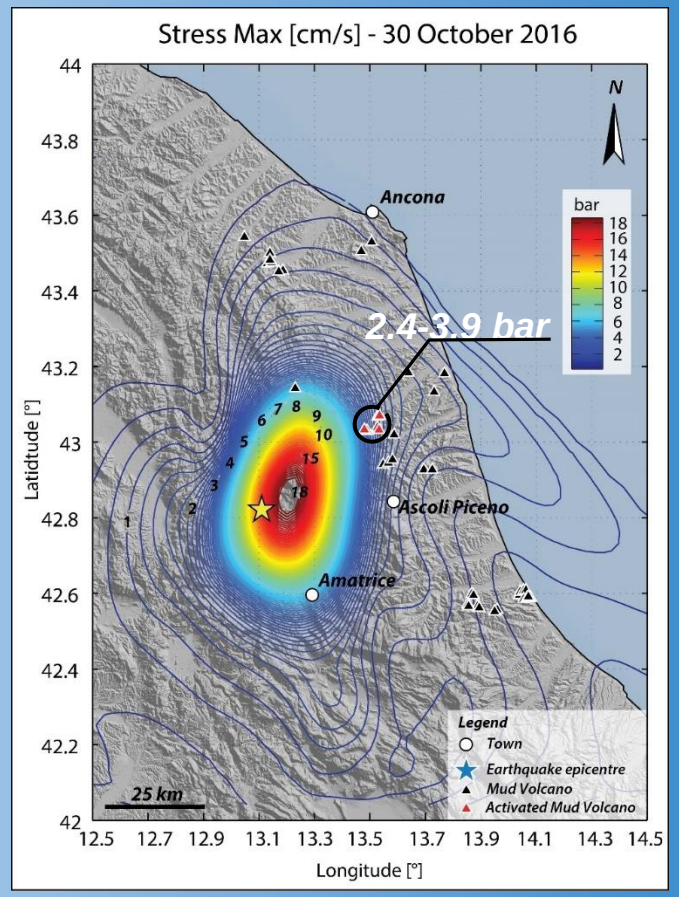


Modified from Manga and Bonini (2012), www.nat-hazards-earth-syst-sci.net/12/3377/2012/

INTERMEDIATE TO FAR FIELD TRIGGERING

Seepage features can be often triggered off by dynamic stress changes created by earthquake faults located in the intermediate- to far-field. The role of dynamic stresses is clearly exemplified by the Central Italy seismic sequence of 2016 that was generated by normal faults in the axial zone of the Apennines. After the major seismic events (i.e., the Mw6.0 Amatrice earthquake of 24 August 2016 and the Mw 6.5 Norcia earthquake of 30 October 2016), 17 mud volcanoes erupted few hours to few days after the main earthquakes at a distance of approximately 40-50 km.





Peak dynamic stresses are calculated through PGV. Only mud volcanoes experiencing maximum peak dynamic stress > 2 bar erupted (red triangles)

There is a clear correlation of eruptions with dynamic stresses, whereas static stress changes are negligible or negative.

Modified from Maestrelli et al. (2017), https://doi.org/10.1002/2017JB014777/

INTERMEDIATE TO FAR FIELD TRIGGERING

Dynamic stresses can produce co-seismic pressurization of reservoirs of fluid seepage systems in various ways (i.e., liquefaction, incoming low frequency seismic waves, amplification and focusing of seismic energy at parabolic seismic reflectors, etc.; Manga et al., 2009; Lupi et al., 2013).

In the near field, static and dynamic stress changes share similar magnitudes and can both contribute to the triggering of fluid expulsion features. However, dynamic stress changes decay with distance much slower than static stresses, and thus they have the ability to trigger seepage features up to the far field, where static stresses are instead irrelevant.

Response of seepage systems in the Northern Apennines to some historical and recent earthquakes was assessed through available Ground Motion Prediction Equations (M. Bonini, submitted). The results suggest that some expulsion features (mud volcanoes, methane vents, springs, etc.) responded to peak dynamic stress with an amplitude of just 0.3-0.4 bar, which are of the order of those that are inferred to influence magmatic systems (e.g., Avouris et al., 2017; Lupi et al., 2017).

CONCLUDING REMARKS

- The results collectively suggest that seepage features may respond in different ways to dynamic and static stresses depending on earthquake magnitude and epicentral distance, and that they may show different sensitivity to stress changes.

- When the fluid expulsion system is located in the far field of an earthquake fault, static stresses are irrelevant and triggering is related to dynamic stress changes only.

- When the fluid expulsion system is located in the near field of an earthquake and the earthquake is sufficiently large, the role of static stress changes may be influential. In this case, static and dynamic stress changes share similar magnitudes, and eruption triggering will probably result from a combination of them.

- Normal stress changes may contribute to the triggering of eruptions if they are sufficiently large and unclamp subsurface feeder pathways. The influence of static stress changes can be particularly relevant for subduction zones, and for the thrust faults that control the plumbing systems of mud volcanoes or other seepage features.

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