SEISMOLOGY

Unsettled earthquake nucleation

Detailed analyses of the source characteristics of two earthquake sequences lead to seemingly contradictory interpretations: one study concludes that each earthquake triggers subsequent ones, while the other favours a slow-slip trigger.

Joan Gomberg

Knowledge of a future earthquake's attributes — when, where and how big — on time scales of seconds-to-days and spatial scales of tens-to-hundreds of kilometres, would enable more effective mitigation of its impacts. Yet, the coupled questions of how earthquakes initiate and whether their ultimate size is determined at or prior to initiation, continue to confound earthquake science[1]. Writing in *Nature Geoscience*, Ellsworth and Bulut[2] and Tape et al.[3] highlight the challenge of distinguishing the processes operating during earthquake nucleation. Both studies analysed sequences of smaller earthquakes that clustered temporally and spatially around a larger, later earthquake, but the former group concludes that earthquakes are triggered by a cascade of foreshocks, while the latter group suggests that a fault first slips slowly and then accelerates into fast rupture.

There are two end-member explanations for earthquake nucleation[1] (Fig. 1). The first is an organized, deterministic perspective that calls on other processes to trigger earthquakes, and suggests that these processes may determine the size of the largest event. Commonly invoked processes include transient slow-slip and pore-pressure changes on or surrounding ultimately triggered faults. In the former, an earthquake is the culmination of spreading or propagating transient slow slip on the surrounding fault. Slip is slow enough that only very weak seismic waves radiate while still imparting stresses sufficient to trigger seismic failure on tiny strong spots that the slipping front crosses. In the latter process, a migrating front of elevated fluid pore pressure may have similar triggering potential by locally opposing the normal stresses and unclamping stuck patches of faults.

The second explanation is more appropriately described as a stochastic process, whereby an earthquake is the response to perturbations imparted by previous earthquakes. In this model, the earthquakes themselves provide the triggering mechanism that initiates failure of the next event. The trigger may be stresses carried by seismic waves or transferred via elastic or quasi-static deformations. Encounters with physical barriers to further rupture growth determine the ultimate size of any earthquake.

Ellsworth and Bulut[2] and Tape et al.[3] conducted similar seismological analyses aimed at maximizing the resolution of the characteristics of clustered earthquakes by exploiting the similarities and differences between seismograms recorded at regional monitoring stations. Ellsworth and Bulut[2] re-examined[4] a 44-minute-long sequence of foreshocks that preceded the magnitude 7.6 Izmit earthquake in Turkey in 1999. There were 26 foreshocks with moment magnitudes between 0.9 and 2.8. Ellsworth and Bulut conclude that the sequence is best explained as a cascade of one foreshock triggering another and then finally triggering the mainshock — the researchers suggest the foreshock sequence provides no evidence of a slow-slip-driven trigger.

By estimating the hypocentres, or locations, of the four largest foreshock earthquakes and modelling the stress changes, Ellsworth and Bulut show that each foreshock reduced the stress in the surrounding rocks within a radius proportional to the foreshock magnitude. However, each foreshock elevated the stress in the rocks outside of this radius, creating a failure-promoting halo that surrounded each foreshock. In the first three foreshocks, the next earthquake occurred within this halo. The fourth foreshock and mainshock initiated where the stresses were reduced, but Ellsworth and Bulut[2] suggest that this may reflect a more heterogeneous stress pattern than modelled. Additional evidence cited in favour of a cascade of triggered earthquakes is the eastward progression of foreshock hypocentres toward the mainshock hypocentre.

Tape et al.[3] examined small earthquakes with moment magnitudes up to 3.9 that occurred on the Minto Flats fault zone in Alaska, between 2012 and 2016. They identify clustered very-low-frequency (VLF) and conventional earthquakes, which radiate

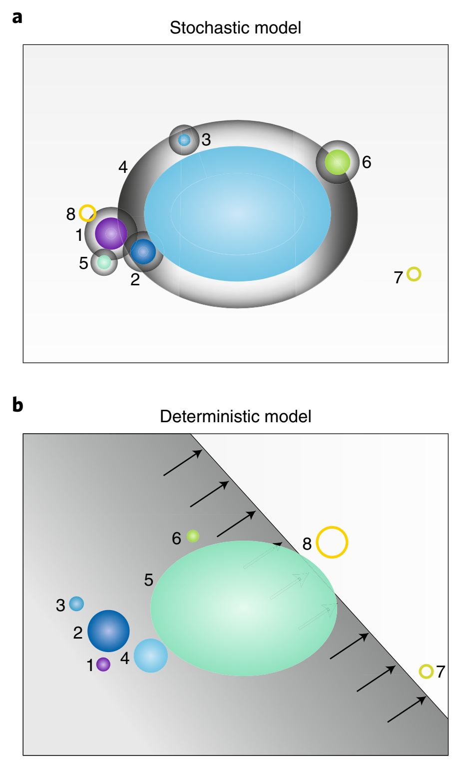

Fig. 1 | Schematic illustration of end-member earthquake triggering models. A fault surface contains strong patches (coloured open or solid ellipsoids) that ultimately fail and slip so rapidly that they radiate seismic waves. Numbers and colours indicate a possible temporal order of failures. **a**, In a stochastic model, the timing and size of any seismic failure is independent of the initiating perturbation. Grey shaded regions surrounding each failed strong patch indicate resulting stresses (decreased stress in white and increased stress in black) that perturb and trigger failure on nearby strong patches. **b**, A propagating slow-slip front (dark grey shading and arrows) triggers failure of strong patches as it passes over them. Ellsworth and Bulut[2] use seismic analyses of the 1999 Izmit earthquake in Turkey to argue for a stochastic model of earthquake nucleation, whereas Tape and colleagues[3] use similar analyses from central Alaska to support the deterministic model. Inspired by elements of figures in refs [3,8] and ref. [9], Macmillan Publishers Ltd.

higher-frequency seismic energy. Building on their observation[5] of a VLF earthquake in this region in 2012, the researchers show that some VLF earthquakes culminated in regular earthquakes nearby within tens of seconds. In addition to the precursory VLF signal, the largest earthquake was preceded by a foreshock sequence of about 10 tiny earthquakes that radiated bursts of high-frequency signals and lasted 12 hours. Tape et al. acknowledge that the VLF signals might be the envelope of clustered seismic wave arrivals from multiple small, high-frequency earthquakes[6]. However, Tape and colleagues use modelling of frictional fault failure to argue that these observations more likely represent the nucleation phases and failure events triggered by propagating pulses of slow slip. That is, they suggest that the VLF signals radiated from a weak fault that ruptured slowly, but still seismically, in response to a broader transient slow-slip event. In some instances, the VLF-generating earthquakes nucleated a larger, ordinary earthquake.

Multiple processes probably trigger earthquakes — some imply a degree of determinism, while others do not. Both studies demonstrate the power of modern seismic network data, coupled with careful and creative analyses. But they also highlight the outstanding non-uniqueness of plausible interpretations. Indeed, it is possible that the two contrary conclusions may plausibly be reversed. For example, Ellsworth and Bulut[2] cite the eastward progression of foreshocks toward the Izmit mainshock as evidence for a cascade of earthquake-driven triggering, yet this systematic progression also seems consistent with propagating slow slip (Fig. 1b) and occurred at a rate consistent with values measured elsewhere[7]. And the observations of VLF earthquakes in Alaska could result from the superposition of signals from a swarm of small earthquakes[6], triggered by some process other than slow slip.

In my view, there is probably some role for slow slip in earthquake nucleation. Most observations of seismic events accompanying transient slow slip and documented independently on seismic and geodetic networks, respectively, have come from subduction zone plate interfaces. The deterministic model of earthquake nucleation (Fig. 1b) was largely informed by such studies and this model appears consistent with a growing number of observations from crustal faults[8], similar to the fault zones of Izmit and Minto Flats. The deterministic model considers a heterogeneous distribution of small strong, stuck patches that fail as a slow-slip front passes them, manifesting as sporadic bursts of seismic signals[7]. Such a propagating front could explain the spatial progression noted in the Izmit sequence, as well as the delays between subsequent failures in both the Izmit and the Minto Flats sequences, whereas simple static or dynamic stress transfer models alone cannot.

Ellsworth and Bulut[2] argue against a role for slow slip in earthquake triggering, at least in the case of the 1999 Izmit earthquake, whereas Tape and colleagues[3] favour a role for slow slip in nucleating earthquakes in central Alaska. I contend that more definitive answers about the role of slow slip in earthquake nucleation and growth will come by including acquisition and analysis of observations not only of the triggered events, but also more direct observations of the posited triggers — the presence or absence of slow slip. ❐

Joan Gomberg
Earthquake Science Center, US Geological Survey, University of Washington, Seattle, WA, USA.
e-mail: gomberg@usgs.gov

Published online: 04 June 2018
https://doi.org/10.1038/s41561-018-0149-x

References

1. Bouchon, M., Durand, V., Marsan, D., Karabulut, H. & Schmittbuhl, J. *Nat. Geosci.* **6**, 299–302 (2013).
2. Ellsworth, W. L. & Bulut, F. *Nat. Geosci.* https://doi.org/10.1038/s41561-018-0145-1 (2018).
3. Tape, C. et al. *Nat. Geosci.* https://doi.org/10.1038/s41561-018-0144-2 (2018).
4. Bouchon, M. et al. *Science* **331**, 877–880 (2011).
5. Tape, C., West, M., Silwal, V. & Ruppert, N. *Earth Planet. Sci. Lett.* **363**, 231–241 (2013).
6. Gomberg, J., Agnew, D. C. & Schwartz, S. Y. *J. Geophys. Res.* **121**, 6722–6740 (2016).
7. Ide, S. *Proc. Jpn Acad. Ser. B Phys. Biol. Sci.* **90**, 259–277 (2014).
8. Harris, R. A. *Rev. Geophys.* **55**, 169–198.
9. Mignan, A. *Sci. Rep.* **4**, 4099 (2014).