EARTHQUAKES

# Human-induced shaking

In 2011, a modest earthquake in southern Spain seriously damaged the city of Lorca. Analysis of surface deformation suggests that the quake was caused by rupture of a shallow fault patch brought closer to failure by the pumping of water from a nearby aquifer.

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It does not take much to trigger an earthquake — even strong rainfall can do the job[1]. A variety of human activities can trigger earthquakes as well[2,3]. Numerous examples of seismicity triggered by the impoundment of reservoir lakes, hydrocarbon extraction, quarrying and deep well injections have been documented over the years[3]. If the stress perturbations that triggered those earthquakes were known exactly, they could help us understand the mechanisms that govern the initiation, rupture and arrest of earthquakes, and also help with seismic hazard mitigation[4]. On 11 May 2011, a $M_w$ 5.1 earthquake struck southern Spain, killing nine people and seriously damaging buildings in the nearby town of Lorca (Fig. 1). The earthquake was surprisingly destructive, given its modest magnitude. Writing in *Nature Geoscience*, González *et al.*[5] show that known human-induced stress changes related to groundwater extraction probably triggered the Lorca earthquake and caused its shallow depth.

There are a number of unsolved questions that relate to triggered earthquakes[6]. For example, the duration and magnitude of the stress perturbation required to trigger an earthquake is unknown. It is also unclear whether the magnitude of the stress perturbation also affects the size of the earthquake, or whether the rupture evolves independently of how it was initiated. Furthermore, it is not clear whether earthquakes triggered by human activities are different from natural earthquakes or are simply prematurely induced natural earthquakes that would have happened anyway at a later time once enough natural stress had built up. More generally, a better understanding of triggered quakes will not only help mitigate against human-induced tremors, but could also improve our understanding of earthquakes that are naturally triggered by crustal stresses induced by past earthquakes, tectonic deformation or movements of magma[4].

To better characterize the source of the 2011 Lorca earthquake, González *et al.*[5] used interferometric synthetic aperture radar (InSAR) to measure the ground deformation caused by the quake. In spite of relatively strong atmospheric noise in the data set, they were able to measure the small amounts of deformation produced by the earthquake and model the data to identify its source. They found that the earthquake resulted from slip on the Alhama de Murcia fault, which bounds the Alto Guadalentin Basin just south of Lorca. Their model shows that most of the seismic moment was released by about 20 cm of slip on a compact fault patch, about 2 by 3 km² in size, located at a surprisingly shallow depth of about 3 km. Another, much smaller fault patch, located at only 1 km depth, slipped just a few centimetres.

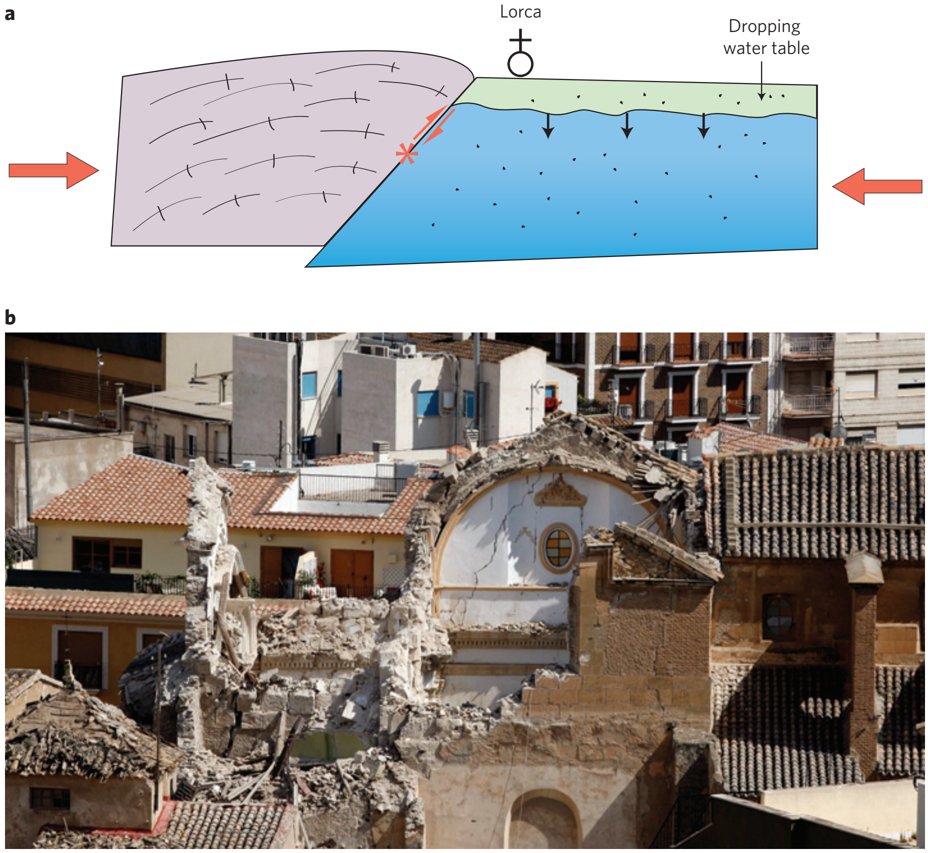


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**Figure 1 |** The May 2011 $M_w$ 5.1 Lorca earthquake. **a**, González *et al.*[5] suggest that water extraction from an aquifer could have triggered and influenced the pattern of rupture propagation of the Lorca earthquake. The earthquake ruptured a fault near the city of Lorca that runs north of the Guadalentin Basin. This fault was in horizontal compression owing to regional tectonics (red arrows). Water extraction caused a drop in the water table and unloaded an area of crust close to the fault. The unloading caused elastic rebound of the crust that induced an additional horizontal compression on the fault (because the fault lies at the edge of the unloaded area), bringing it closer to failure. The star indicates the hypocentre where the rupture initiated. **b**, The earthquake caused extensive damage to buildings, including the Church of Santiago in the city of Lorca.

The shallow depth of the rupture explains the extraordinary level of destruction for such a modest earthquake; it is very unusual for a $M_w$ 5.1 earthquake to occur at such a shallow depth. Most earthquakes, both in this area and globally, occur at greater depths.

In an attempt to investigate the factors that may have influenced this shallow earthquake, Gonzáles *et al.* noticed that the water table in the Alto Guadalentin Basin had dropped by as much as 250 m since 1960 as a result of groundwater extraction. They calculated the elastic response of the crust to removal of this amount of groundwater and show that this unloading has caused a stress perturbation on the order of a few tens of kilopascals on the shallow Alhama de Murcia fault patch, where the Lorca earthquake initiated. They also note that the ruptured patches of the fault were all located in the area where the fault was brought closer to failure by the stress increase. From this correlation, González *et al.*[5] infer that human-induced stress did not only help to trigger the quake, but also controlled the final extent of the rupture and thus the earthquake's magnitude.

The correlation between the pattern of stress change caused by groundwater extraction and the extent of fault rupture could be entirely fortuitous. However, the findings resonate with recent observations of seismicity induced by deep well injections, where the spatial extent of a newly stressed volume of crust was found to control the spatial distribution of triggered earthquakes as well as their magnitudes[7].

In the case of the Lorca earthquake, however, the stresses induced by groundwater extraction and the stresses released during the earthquake are not balanced. Indeed, a back-of-the-envelope calculation shows a coseismic stress drop of about 0.5 to 2 MPa, indicating that the elastic stresses relieved during the earthquake were orders of magnitude larger than the crustal stresses induced by removal of the groundwater load. The stress released by the earthquake therefore cannot have been caused entirely by water extraction. Instead, it must have built up over several centuries, the Alhama de Murcia fault being part of a slowly deforming zone of regional shear. Notwithstanding, water extraction may have affected how this stress was released. Ordinarily, a number of viscous aseismic deformation processes can help relax these naturally accumulating stresses[8] and help to limit the possibility of an earthquake nucleating and growing in the shallow crust. However, in the case of the Lorca earthquake, owing to the human-induced perturbation of crustal stress, stresses built up at a much faster rate than they would have done naturally. If the aseismic deformation processes could not keep up with these rates, it could explain the unusually large earthquake rupture in this shallow depth range. Such concepts might now be tested on the basis of numerical simulations calibrated from seismological and geodetic observations[9,10].

González *et al.*[5] suggest that the location and magnitude of the Lorca earthquake was influenced by anthropogenic groundwater extraction. The consequences are far reaching: if ever the effect of human-induced stress perturbations on seismicity is fully understood, and provided it is proven to be a deterministic process, we might dream of one day being able to tame natural faults with geo-engineering. For now, we should remain cautious of human-induced stress perturbations, in particular those related to carbon dioxide sequestration projects that might affect very large volumes of crust[11]. We know how to start earthquakes, but we are still far from being able to keep them under control. ❑

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