Fluid Injection's Role in Man-Made Earthquakes Revealed

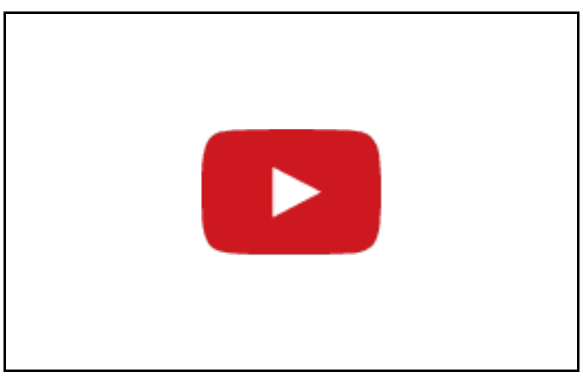
Usually small though occasionally damaging earthquakes are a side-effect of industrial processes such as geothermal energy and oil-gas production that involve injecting water underground. But scientists have been unclear about the exact role of fluid injection in triggering these man-made earthquakes.

Now, for the first time, researchers at Caltech and other institutions in the United States and France have observed how fluid injection sets off microearthquakes on a sizable, subterranean fault. The findings could lead to better seismic risk management through improved understanding of fluid flow on faults, while also illuminating the mechanics of natural earthquakes.

"At the moment, a major issue for industry is that there is no established theory to evaluate the seismic hazard associated with fluid injections," says paper coauthor Jean-Philippe Avouac, a professor of geophysics at the University of Cambridge, as well as the Earle C. Anthony Professor of Geology at Caltech, and the former director of Caltech's Tectonics Observatory (now closed), where the research began. "With experiments such as ours, we can build much-needed models that would help assess the possible location, magnitude, and likelihood of earthquakes."

The research, led by Yves Guglielmi, a professor at the European Center for Research and Education in Environmental Geosciences (CEREGE) at Aix-Marseille University in France, appears in the June 12 issue of *Science*.

Earthquakes typically occur when segments of the earth's crust slip along faults due to the built-up pressure. The best-known faults are those between the continent-sized tectonic plates that compose the earth's crust, such as California's San Andreas fault, the boundary between the Pacific and the North American plates. However, many smaller faults branch off these major faults, extending down to microscopic cracks that exist in most if not all rocks.



Injection of water into the fault zone produces initially

"One of the challenges in my field is to relate deformation of rock on the scale we can simulate in the lab with what we observe in nature, which reflects deformation to scales that are many orders of magnitude larger," says Avouac. "There is a very large gap in scale."

The new study helps to fill that gap. Avouac and his colleagues ran a fluid-injection experiment on a fault slow, creeping slip of the rocks as fluid pumps in. Faster slip sets in over 18 minutes into the experiment, generating seismic waves. The experiment reveals that fluid injection itself does not directly provoke an earthquake. Instead, the induced aseismic slip builds up stress at the edges of the creeping zone of rock, causing the seismic activity. *(Credit: Jean-Philippe Avouac and Paul Avouac)*

running more than a quarter of a mile through limestone. The fault is accessible thanks to its location adjacent to the Laboratoire Souterrain à Bas Bruit (LSBB), a former underground military facility in southeastern France now available to scientists.

The research team drilled a hole into the fault at a depth of about 925 feet. They then lowered a five-foot-long canister outfitted with sensors called the Step-Rate Injection Method for Fracture In-Situ Properties, or SIMFIP, into the hole. The SIMFIP was designed to measure pressure, water flow rate, rock movement, and other key data while suspended in the fault zone.

"The SIMFIP probe opens the way to characterizing fault properties, which are critical for seismic hazard studies and understanding the physics of earthquakes," says paper coauthor Frédéric Cappa, a professor at the Géoazur Earth and Planetary Sciences Laboratory at the University of Nice Sophia Antipolis in France. Cappa, who developed the experiments and models jointly with Guglielmi and Avouac, was a visiting professor at the Tectonics Observatory during the preparation of the study.

"The SIMFIP technology is a breakthrough," says Avouac. "We hope to see this or similar technologies used in the future to study faults in a variety of geological contexts."

After inserting the SIMFIT probe, the researchers injected 250 gallons of water into the fault zone. The SIMFIP recorded an initially slow, creeping slip of the rocks as fluid was pumped in; this type of movement on a fault is referred to as aseismic slip since no measurable microearthquakes occur. As rock on the two sides of the fault separated during this minor movement, however, the rate of water flow into the fault increased dramatically. About 18 minutes into the experiment, the slip rate increased, generating the seismic waves and dozens of measurable microearthquakes.

The experiment revealed that fluid injection itself did not directly provoke an earthquake. Instead, the aseismic slip likely built up stress at the edges of the creeping zone of rock. Eventually, the stress overcame the friction between the rock faces within the fault, triggering earthquakes.

Emily Brodsky, a seismologist at UC Santa Cruz who was not involved with the study, comments that the "close-in observations" in the research "provide the most complete picture of earthquake initiation to date. The transition from silent creeping to earthquakes is rich in this data set and surprisingly well-matched by a very simple model."

The work provides information about seismic hazards related to fluid injection by the oil and gas industry and to power facility installation by geothermal energy companies. Continued study using the SIMFIP also could aid the development of carbon-capture and storage technologies for the underground trapping of carbon dioxide emitted by power stations, preventing the greenhouse gas from entering the atmosphere. Of concern is the potential induction of earthquakes, which could, for example, cause subsurface damage to the carbon reservoirs, leading to leaks.

Finally, Avouac and colleagues suggest that a better understanding of shallow, man-made earthquakes resulting from fluid injection will inform theories of how water at great depths influences faults and their potential to generate large earthquakes.

The paper is entitled "Seismicity triggered by fluid injection-induced aseismic slip." The experimental work was funded by the Agence Nationale de la Recherche (ANR) Captage de CO_2 through the HPPP-CO_2 project and by PACA through the PETRO-PRO project. The rate-and-state fault models for this study were supported by the French Academy of Sciences, the Caltech Tectonics Observatory, and the ANR HYDROSEIS.