

Understanding Induced Earthquakes

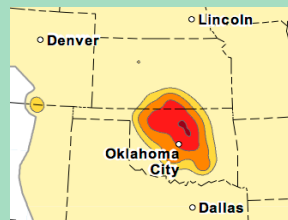
Earthquakes are now occurring in areas with little historical seismicity as a result of activities associated with resource extraction. The NISAR satellite mission will improve our ability to characterize such induced earthquakes, and increase our understanding of changing earthquake likelihoods.

The changing landscape of earthquake hazards

Over the past several decades, the number of earthquakes observed in the central and eastern United States has jumped dramatically, from an average of 21 earthquakes per year with magnitude three or larger from 1973 to 2008, up to 659 in 2014. The increase is strongest in areas that also saw a strong upward trend in the volume of wastewater injected into the subsurface.

Observations of how the ground surface rises or falls during an earthquake allow scientists to determine where the earthquake occurred, how deep and large it was, and whether there is evidence of additional motion that occurred more slowly before or after the event.

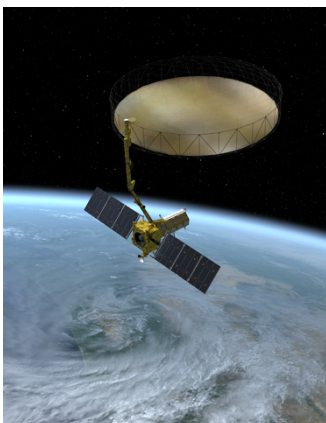
Image (clockwise): USGS, USBR (CC BY-SA 2.0), USGS, Ficelloguy/English Wikipedia (CC BY-SA 3.0)



A new era of earthquake science

Human activity sometimes causes earthquakes – particularly when large masses of material are moved from one area to another, or when fluids are extracted or injected into the subsurface. Impoundment of water on the surface behind dams, open pit and underground mining, and wastewater injection have all been linked to

changes in the frequency of regional earthquakes. Some of these changes, such as those that occur in areas of geothermal power generation, are subtle, since they occur in regions that may naturally experience frequent earthquakes. Others, such as those now occurring in the central United States, represent a significant change.



The NISAR Mission – Reliable, Consistent Observations

The NASA–ISRO Synthetic Aperture Radar (NISAR) mission, a collaboration between the National Aeronautics and Space Administration (NASA) and the Indian Space Research Organization (ISRO), will provide all-weather, day/night imaging of nearly the entire land and ice masses of the Earth repeated 4-6 times per month. NISAR's orbiting radars will image at resolutions of 5-10 meters to identify and track subtle movement of the Earth's land and its sea ice, and even provide information about what is happening below the surface. Its repeated set of high resolution images can inform resource management and be used to detect small-scale changes before they are visible to the eye. Products are expected to be available 1-2 days after observation, and within hours in response to disasters, providing actionable, timely data for many applications.

The past decade has seen a substantial increase in the number of earthquakes triggered by human activity, particularly the injection and production of subsurface fluids associated with hydrocarbon production. Oklahoma now experiences more earthquakes each year than California. Efforts to reduce our society's reliance on fossil fuels also compound the problem, with increases in earthquake frequency associated with energy production at geothermal power plants and at large dams that contribute hydrothermal power to the electricity grid.

The increased frequency of earthquakes in regions such as the central United States create new challenges, particularly since the energy and resource needs of our population are likely to continue to grow. Even forecasting the expected damage from these new types of earthquakes is not just "business as usual." Analyses of shaking reports from the central United States suggest that the distribution of damage from these earthquakes, which tend to be shallower and could have more involvement from fluids within the rock, are different from the damage expected from "traditional"

earthquakes, which often occur deep underground. Precise estimates of the location and timing of these earthquakes are needed to characterize how they interact with each other and with the perturbations to the subsurface that are driving them.

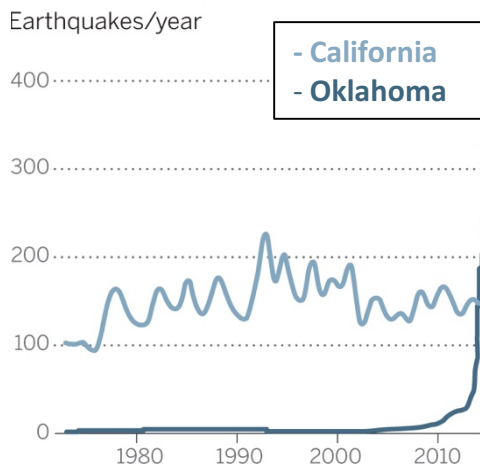
The upcoming NISAR radar mission includes a dependable, regular observation plan that will collect high resolution images over 90% of the Earth's land surfaces at weekly intervals. NISAR's focus on regular and repeated observations contrasts with that of existing satellite synthetic aperture radars, which typically focus only on areas of interest to a specific government or scientific agency. This leaves out much of the United States, because none of the other radars are U.S. missions. For instance, the central and eastern United States was not observed frequently, if at all, by most previous missions. The observations made over the lifetime of NISAR will be a giant step forward in our understanding of induced seismicity, and will inform the next generation of methods for characterizing and managing these hazards.

Increasing rates of earthquakes in the central United States.

Recent advances in the technology used in hydrocarbon production, including enhanced oil recovery and increases in the volume of wastewater injected into the subsurface, are associated with a dramatic increase in earthquakes felt in the central United States since the mid-2000's. Damaging earthquakes only appear to be related to a small fraction of wells, but there is not yet enough data to definitively determine in advance the safety of operations at a particular site.

Earthquake locations derived from seismic data (see figure at left) illuminate part of the picture – new research shows that induced earthquakes may behave in slightly different ways than "natural" events, providing a potential pathway to better understanding and management. However, seismic data is blind to the slow, longer term deformation of the ground surface associated with pumping, injection and even incipient creep on faults that will eventually rupture in a more damaging earthquake. NISAR can provide the missing link to this puzzle, complementing the available seismic data and helping to track how patterns of fluid flow beneath the surface relate to patterns of observed earthquakes.

Seismic surge in Oklahoma



Number of earthquake sequences each year that contain at least one magnitude 3 or larger earthquake, since 1973, for California (light blue) and Oklahoma (dark blue). From McGarr et al., 2015, in the journal *Science*.

Induced earthquakes imaged from space:

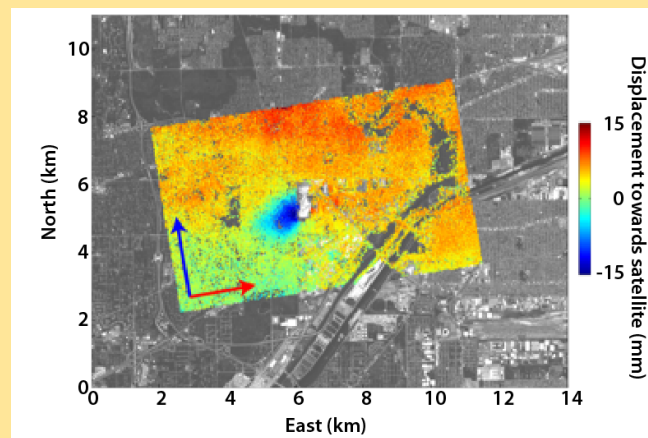
Satellite-based radar imagery, when available, can be an extraordinary tool for characterizing how the Earth's surface warps and deforms before, during, and after induced earthquakes. However, these observations cannot be made when the ground surface changes significantly between image acquisitions. Growth of crops, tilling of fields, trees shedding their leaves are all processes that degrade data quality. The examples of induced earthquakes in the central United States shown below are cases where we were fortunate to have data both before

and after the earthquake. Many other earthquakes in these regions have been impossible to study because of the complete lack of data before the event.

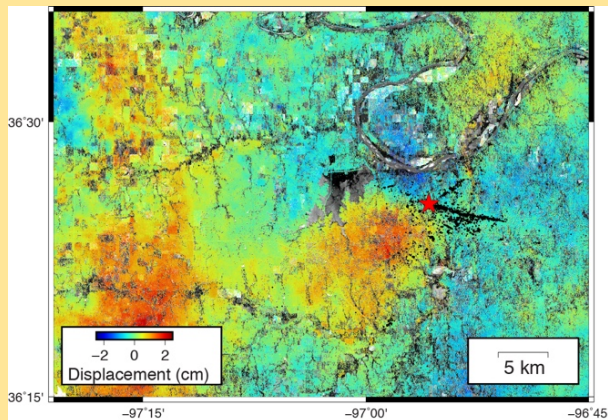
This situation can change in the future: NISAR data would be acquired regularly over the entire United States, allowing imaging of areas like Oklahoma, Texas and Kansas that have both active agriculture and hydrocarbon/water resource development.

Examples:

Right: Even tiny earthquakes can be imaged when enough data is available. This image uses data from the European Space Agency's TerraSAR-X platform to constrain subsidence of the ground during a 2013 magnitude 3.2 earthquake within the Chicago metropolitan area, triggered by a blast at a limestone quarry. Color indicates displacement of the ground surface towards or away from the satellite, which was traveling to the northwest in the direction of the blue arrow and aimed down towards the Earth in the direction of the red arrow. The observed displacement shown here tightly constrains the depth of this earthquake to 700 meters, much shallower than the zone where "natural" earthquakes occur.



Left: NISAR data will permit systematic mapping and monitoring of earthquakes, even in agriculturally active areas.



In this example, using data from the European Space Agency's Sentinel-1a and -1b platforms, we can see several centimeters of displacement over a 10 km x 10 km region associated with the 2016 magnitude 5.8 Pawnee, Oklahoma, earthquake. The main earthquake location (red star) and aftershocks (black dots) outline a complicated pattern that provides insight into the patterns of weakness in the subsurface. Also in this image (red band on left) is the signature of a large storm that was present during one of the image acquisitions. When many images are available, such as would be provided by NISAR, such atmospheric effects can be averaged out more effectively to determine the true ground movement.

For more information:

General introduction:

<https://earthquake.usgs.gov/research/induced/>
<http://nisar.jpl.nasa.gov/>

Community reports

Petersen, M.D. et al. (2016), 2016 One-year seismic hazard forecast for the Central and Eastern United States from induced and natural earthquakes, *U.S. Geological Survey Open-File Report 2016-1035*, 52 p., doi:10.3133/ofr20161035.

McGarr, A. et al. (2015), Coping with earthquakes induced by fluid injection, *Science*, 347; doi: 10.1126/science.aaa0494.

National Research Council (2013), Committee on Induced Seismicity Potential in Energy Technologies. *Induced seismicity potential in energy technologies*. National Academies Press, 2013.

National Earthquake Resilience: Research, Implementation, and Outreach (2011), National Academies Press, Washington, D.C.

Relevant scientific papers.

Jha, B., et al. (2015), Reservoir characterization in an underground gas storage field using joint inversion of flow and geodetic data, *Int. J. Numer. Anal. Meth. Geomech*, 39, 1619 – 1638.

Yang, Qi., et al. (2015), InSAR monitoring of ground deformation due to CO2 injection at an enhanced oil recovery site, West Texas, *International Journal of Greenhouse Gas Control* 41; doi: 10.1016/j.ijggc.2015.06.016.

Hough, S. E. (2015), Shaking intensity from injection-induced versus tectonic earthquakes in the central-eastern United States, *The Leading Edge* 34; doi: 10.1190/tle34060690.1.

Keranen, K. M. et al. (2014), Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science*, 345; doi: 10.1126/science.1255802.

Barnhart, W. et al. (2014), Seismological and geodetic constraints on the 2011 Mw5.3 Trinidad, Colorado earthquake and induced deformation in the Raton Basin, *J. Geophys. Res.*, 119; doi:10.1002/2014JB011227.

Ellsworth, W.L. (2013), Injection-induced earthquakes, *Science*, 341; doi:10.1126/science.1225942.

González, P. J. et al. (2012), The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading, *Nature Geoscience*, 5; doi:10.1038/ngeo1610.

Ketelaar, V. B. H. (2009), Subsidence due to hydrocarbon production in the Netherlands, In: *Satellite Radar Interferometry: Subsidence Monitoring Techniques*, Springer, London, doi:10.1007/978-1-4020-9428-6_2