Chapter 4
Earthquakes Influenced by Water

Abstract Injecting fluids in the crust, or their extraction, changes pore pressure and poroelastic stresses. Both pressure and stress changes can promote seismicity and, hence, the seismic events are called induced earthquakes. The filling of reservoirs on Earth's surface can also induce earthquakes from some combination of surface loading and pore pressure changes. Attribution of any given earthquake to human activities, however, is not always straightforward. There remains debate about what controls the magnitude of induced earthquakes, the relative importance of pore pressure changes and poroelastic stresses, and how to best manage injection and extraction to minimize seismicity. As the scale and distribution of subsurface engineering expand globally, we should expect more and larger induced earthquakes in the future.

4.1 Introduction

Hydro-mechanical coupling (Chap. 3) connects changes in pore pressure to changes in stress. Changes in stress can also promote rock failure and motion on pre-existing faults and fractures. Changes in pore pressure can thus cause earthquakes. In the past decades our manipulation of the subsurface by injecting and extracting fluids has led to a dramatic increase in the number and magnitude of human-caused earthquakes. A particularly striking example is the rapid increase in seismicity in the tectonically stable mid-continent of the USA (Fig. 4.1) including the magnitude 5.8 Pawnee earthquake, Oklahoma in 2016. This increase is acknowledged to be the result of injecting co-produced brines that are extracted during hydrocarbon recovery (Ellsworth 2013) and the flowback of the injected fluids (EPA 2011). In this chapter we thus discuss several ways in which hydrology influences seismicity.

The expressions "induced" and "triggered" are sometimes used interchangeably. Here we use the definition that an "induced earthquake" is one caused by human activity that alters stresses in the crust. A "triggered earthquake" is one caused by natural stress changes, either static of dynamic. In practice, the distinction can be difficult to make because the mechanisms through which water influences seismicity are not always straightforward to quantify.

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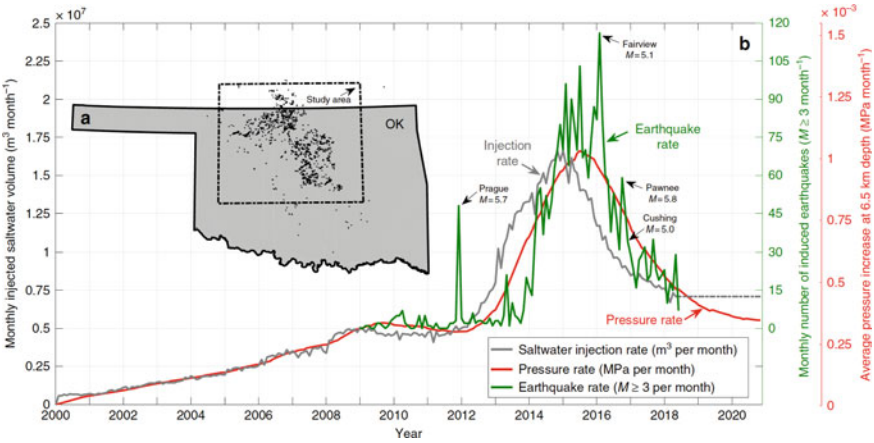

Fig. 4.1 Induced seismicity and injection in Oklahoma (OK), USA. **a** Map showing the spatial distribution of events. **b** Time series of earthquakes with magnitude greater than or equal to 3, injection rate, and modeled rate of pressure increase. From Langenbruch et al. (2018)

Davis and Frolich (1993) proposed a straightforward approach for deciding whether an earthquake was induced by fluid injection (Table 4.1). They assess the past history of seismicity, temporal and spatial relationships, as well as features of the injection. The end result is a score that expresses the confidence in ascribing earthquakes to injection. Foulger et al. (2018) created a database of induced earthquakes, summarized in a 77-page paper with 119 figures. Beyond identifying likely induced earthquakes, they note several additional challenges in constructing this database and hence summarizing observations: incomplete or ambiguous reporting, lack of operation data, multiple subsurface disturbances, limitations imposed by minimal seismic monitoring, and inaccuracies in earthquake locations.

4.2 Fluids and Rock Failure

The basis for fluids influencing friction and fault motion is summarized in Sect. 3.5. Here rock failure does not mean the failure of intact rocks but frictional motion on existing fractures or faults. Motion initiates when the shear stress τ on an existing surface exceeds the Coulomb failure criterion (Eq. 3.121)

$$\tau = c + \mu(|\sigma| - \alpha P). \tag{4.1}$$

where σ is the normal stress on this fracture or fault (extension positive), μ the friction coefficient that may be a function of slip rate and state, c the cohesion strength across the surface, P the pore pressure, and α the Biot-Willis coefficient.

Table 4.1 A set of questions to assess whether earthquakes are induced (from Davis and Frolich 1993)

Question	Earthquake clearly not induced	Earthquakes clearly induced	I Denver, Colorado	II Painesville, Ohio
Background seismicity				
1. Are these events the first known earthquakes of this character in the regions?	NO	YES	YES	NO
Temporal correlation				
2. Is there a clear correlation between injection and seismicity?	NO	YES	YES	NO
Spatial correlation				
3a Are epicenters near wells (within 5 km)?	NO	YES	YES	YES?
3b Do some earthquakes occur at or near injection depths?	NO	YES	YES	YES?
3c If not, are there known geologic structures that may channel flow to sites of earthquakes?	NO	YES	NO?	NO?
Injection practices				
4a Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	NO	YES	YES	YES
4b Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	NO	YES	YES	NO?
Total "YES" answers	0	7	6	3

This so-called Mohr-Coulomb law and the concept of effective stress do not capture the effects of viscous deformation or dilatation that depend on deformation rate and history—processes that can have a non-trivial effect on earthquake nucleation and rupture. It is nevertheless useful for illustrating how and why fluids can have a significant influence on earthquakes. Equation (4.1) shows that earthquakes can be induced by increasing the shear stress, reducing the normal stresses clamping faults shut, or increasing fluid pressure (or some combination).

The transition from stable to unstable sliding depends on the properties and slip history of the surfaces, captured with the rate-and-state friction models described in Chap. 3.5.2. These processes also depend on stressing rate. Rate-and-state models are useful for studying induced seismicity because they connect changes in stress and pressure to changes in seismicity.

4.3 Earthquakes Induced by Fluid Injection

There are both natural and engineering processes that can raise pore pressures and hence influence seismicity. Here we focus on the engineered examples because the sources of fluids are constrained in both space and time. The growth of case studies and literature on injection-induced earthquakes has paralleled the rapid increase in the number and size of induced earthquakes (Keranen and Weingarten 2018).

The first well-studied example of human-induced earthquakes caused by an increase of pore pressure occurred at the Rocky Mountain Arsenal, Colorado, USA. Here, a magnitude 5.5 earthquake likely occurred in response to fluid injection at a depth of 3.6 km (Evans 1966). Continued and controlled monitoring established a relationship between injection and seismicity: Fig. 4.2 from Healy et al. (1968) shows the history of fluid injected and occurrence of earthquakes. Here, seismicity persisted after injection ended, reflecting the continued diffusion of high pore pressures away from the injection site (Healy et al. 1968; Hsieh and Bredehoeft 1981).

Pore pressure diffusion allows stress changes to spread over time, inducing earthquakes several tens of km from wells (Keranen et al. 2014) to distances approaching 100 km (Peterie et al. 2018; Zhai et al. 2020). Strains produced by pore pressure changes can also create poroelastic stresses that further extend the spatial reach of pressure changes (Goebel and Brodsky 2018) and may promote or decrease seismicity depending on fault orientation (e.g., Segall and Lu 2015). Aseismic creep may also accompany fluid injection (e.g., Guglielmi et al. 2015; McGarr and Barbour 2018; Cappa et al. 2019) and hence stressing rate may influence seismicity through rate-and-state friction. Lab experiments have documented a dependence of fault behavior on pressurization rate, with creep favored by slow pressure changes and stick-slip episodes for high pressurization rates (Wang et al. 2019).

To compute seismicity rates from pore pressure and stress changes, some authors use the rate-and-state friction models described in Sect. 3.5.2 (e.g., Dieterich 1994; Segall and Lu 2015; Zhai et al. 2019). Figure 4.3 shows computed changes in stressing rate from changes in pore pressure and poroelastic stresses, and how the changes

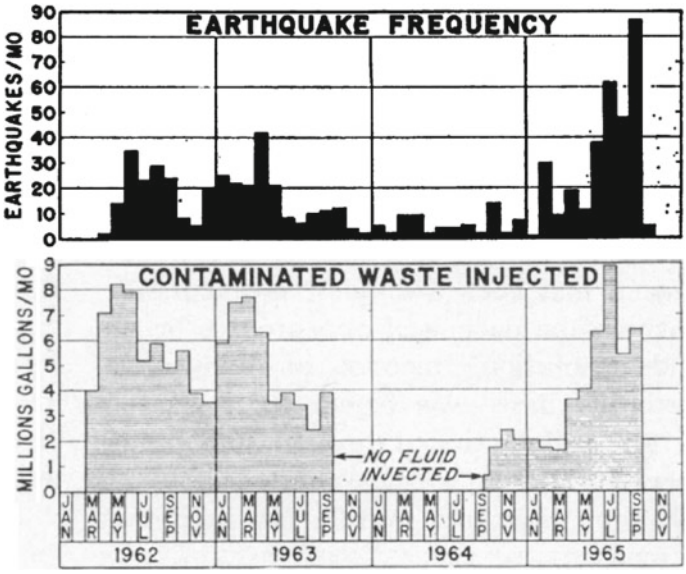

Fig. 4.2 Number of earthquakes recorded at the Rocky Mountain Arsenal waste injection site (top) and volume of fluid injected (bottom). From Healy et al. (1968)

contribute to a computed seismicity rate. These models involve parameters that are not necessarily known a priori, such as the background seismicity rate and background stress. In some cases, it may be possible to use induced seismicity to constrain some of those unknown parameters (e.g., Zhai et al. 2020). Other approaches to forecast seismicity have been introduced. For example, Langenbruch and Zoback (2016) connect the seismicity rate to the volume injected and a seismogenic index that captures the number of, and stress state on, existing faults; Langenbruch et al. (2018) allow the productivity of earthquakes to also scale with the square of the rate of pressure change. Since in both models the effects of a decrease in pressure are not captured (pressure rate squared is always positive), a different model must be introduced when pressure is no longer increasing.

To convert seismicity rate to earthquake magnitude, a Gutenberg-Richter scaling is normally used

$$\log_{10} N = a - bM \tag{4.2}$$

where N is the number of earthquakes with magnitude greater than M, and a and b are constants that may vary from region to region. In general b is close to 1. Deviation of observations from this logarithmic scaling at low magnitudes is generally assumed to reflect the incompleteness of the earthquake catalog because small events are difficult to detect. A topic of active debate and discussion is the maximum size of induced earthquakes, and whether it scales with the volume injected (McGarr 2014) or the

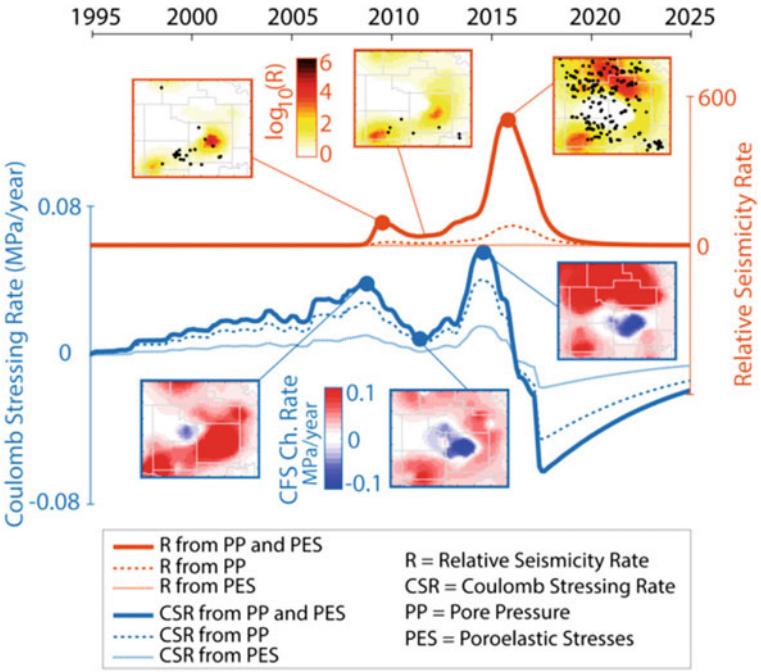

Fig. 4.3 Evolution of stressing rate and modeled seismicity rate from injection in central Oklahoma. Curves show average values within the region and the maps show the spatial distribution. Black dots in the maps are the locations of earthquakes in the time period between successive maps, or since 1995 for the first map. Simulation curves show the effects of pore pressure changes (PP), poroelastic stresses (PES), or both combined. From Zhai et al. (2019)

largest possible earthquake in a region (van der Elst et al. 2016)—that is, is size controlled by injection parameters or tectonics?

An increase in seismicity, and indeed some of the largest earthquakes, sometimes occurs following a shut in or reduction of injection (e.g., Chang et al. 2018). This can arise from the rapid change in stress before pore pressure can decrease. This effect in hydrogeology is sometimes called the Noodbergum effect: a quick and short term rise in water level in wells near a well from which water is pumped. This reverse and paradoxical response is an example of a poroelastic effect that arises because elastic stresses are transmitted much faster than pore pressure changes. The effect is named after the location in the Netherlands where it was documented and explained (Verruijt 1969). The operational implication is that tapering of injection reduction may reduce the seismicity rate (e.g., Segall and Lu 2015).

The most compelling seismic evidence for seismicity induced by fluid injection is a space and time pattern consistent with pore pressure diffusion, with the distance of induced seismicity from the well increasing with the square root of time. These patterns are sometimes seen (e.g., Tadokoro et al. 2000; Shapiro et al. 2006) at least for a subset of events (Goebel and Brodsky 2018). The migration rate of seismicity

provides constraints on fault zone or aquifer hydraulic diffusivity (hence permeability) and, when combined with the known pressure at the injection sites, the state of stress on the fault.

It is worth highlighting additional geological factors that may contribute to induced seismicity and fault reactivation: fault orientation, the hydraulic connectivity between injection formations and the seismogenic faults in basement rocks, and the state of stress on those faults (Kolawole et al. 2019). The spatial variations of induced events, their isolation to narrow fault planes, the vast range of earthquake productivity between basins, highlight the importance of subsurface heterogeneity and geological setting and history (Keranen and Weingarten 2018).

Another example of rock failure caused by high pore pressure is hydraulic fracturing. Here, pore pressure is increased to the point that tensile failure occurs. Hydraulic fracture is induced intentionally to increase the permeability of oil and gas bearing units to enhance recovery, the process colloquially called "fracking". It is the now widespread use of hydraulic fracturing to extract non-conventional hydrocarbons that has led to the massive increase in wastewater injection that in turn induces earthquakes. While the goal of hydraulic fracturing is to break rock (many small earthquakes), earthquakes with magnitude greater than 3 have been attributed to hydraulic fracturing (e.g., Atkinson et al. 2016).

Geothermal systems are another setting where injection induced earthquakes are common. Figure 4.4 shows one example of the relationship between injected volume and seismicity at the Geysers, California, the largest geothermal facility globally (Hartlin et al. 2019). Here, temperature changes may play an additional role in creating stresses through thermal contraction (e.g., Segall and Fitzgerald 1998; Majer et al. 2007). Rock failure is often induced in geothermal settings to create or enhance permeability to enable production and create an Enhanced Geothermal Systems (EGS). Rather than being called "fracking", this process is called "stimulation". In general, EGS earthquakes are small. However, in 2017 a magnitude 5.5 earthquake near Pohang, South Korea injured many people and caused extensive damage and has been attributed to injection at a geothermal facility (Grigoli et al. 2018; Kim et al. 2018).

In summary, observations, theory and lab experiments show that pore pressure changes, poroelastic stresses, and stressing rate all contribute to injection induced seismicity. In geothermal systems, temperature changes also matter. A combination of geological conditions and operational parameters (injection pressure, rate and history) thus control induced seismicity.

4.4 Earthquakes Induced by Fluid Extraction

The concept of effective stress makes it straightforward to understand how injection (i.e., pressure increases) can induce earthquakes. The opposite case, fluid extraction, can also induce earthquakes, even though pore pressure reduction acts to stabilize faults. The best and most widespread documented examples are associated with

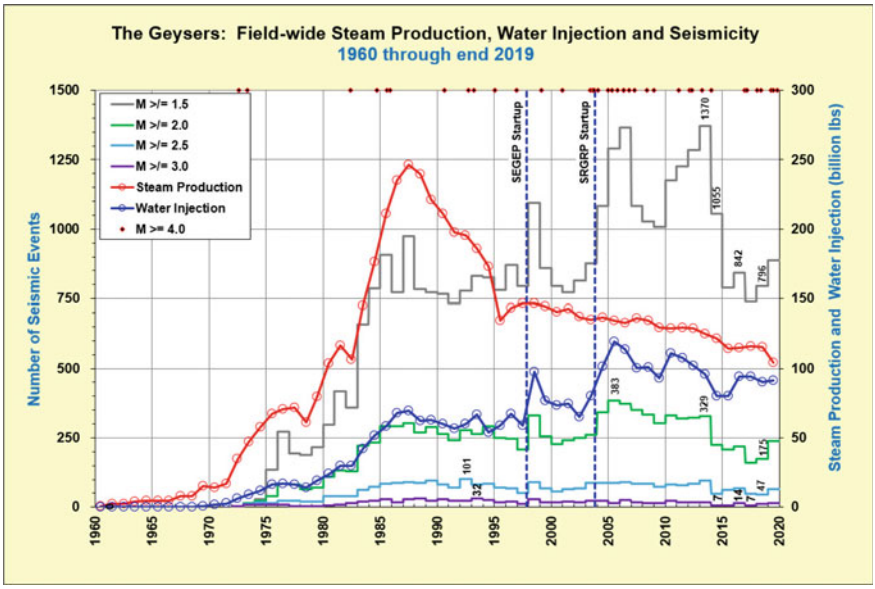

Fig. 4.4 Number of seismic events and history of steam production and water injection at the Geysers, California. The red symbols show when magnitude 4 or greater earthquakes occurred. The decrease is 2015 is partly due to instrument loss in a fire. 2016 values are projected. Figure provided by Craig Hartline

the extraction of oil and gas (e.g., Segall et al. 1994; Gomberg and Wolf 1999; Zoback and Zinke 2002). There are also a few examples of earthquakes attributed to groundwater extraction (e.g., Gonzalez et al. 2012; Wetzler et al. 2019). The much smaller number of examples connected to groundwater extraction (compared with hydrocarbon extraction), despite being volumetrically so much greater, may reflect the shallower depths from which water is extracted and that earthquakes tend to nucleate at depths of at least several kilometers.

There are a couple of processes by which extraction can cause earthquakes, illustrated schematically in Fig. 4.5. Segall (1989) shows how poroelastic deformation will increase the magnitude of deviatoric stresses away from the region from which fluid is extracted and where there are no changes in pore-fluid content. The focal mechanisms of seismic events should be diagnostic of whether they are possibly induced, with details depending on the orientation of pre-existing structures and elastic properties. A second mechanism to create seismicity is the differential rock compaction that may build up stresses (Candela et al. 2018). For each process, knowing the location, orientation, and stress state of faults can play a role in mitigating seismic hazard.

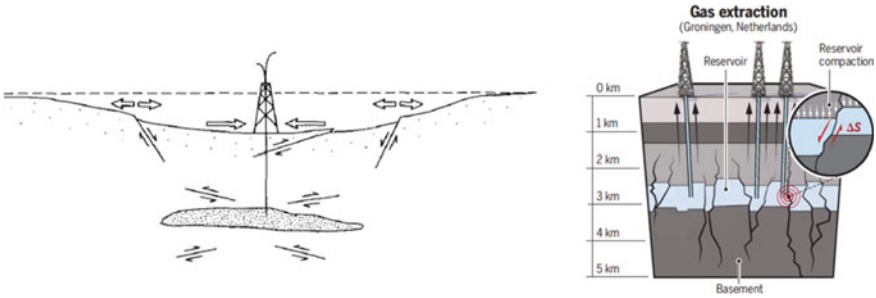

Fig. 4.5 Schematic illustration of processes that can induce earthquakes by fluid extraction. **a** Extraction from the stippled region contracts the reservoir producing stresses in the surroundings (from Segall 1989). **b** Extraction of fluids compresses reservoirs and differential stresses can increase shear stress (from Goebel et al. 2019)

4.5 Reservoir-Induced Seismicity

The filling of surface reservoirs with water also causes earthquakes. This so-called "reservoir-induced" seismicity has been documented ever since large reservoirs were constructed. The first well studied example accompanied the impoundment of the Colorado River, USA by the Hoover Dam to form Lake Mead (Carder 1945). Figure 4.6 shows that as water level rose, the number of earthquakes increased with a very large number early on. This topic is reviewed in more detail in a number of books (e.g., Gupta 1992) and review papers (e.g., Simpson 1976; Gupta 2002).

Earthquakes associated with reservoirs are not confined only to tectonically active regions, hence the reason it is usually called "induced" seismicity. Gupta (2002) in contrast notes that the stresses caused by reservoir loading are of order 0.1 MPa, much smaller than earthquake stress drops and hence that these events are better classified as "triggered". Regardless, earthquakes near reservoirs appear to be ubiquitous.

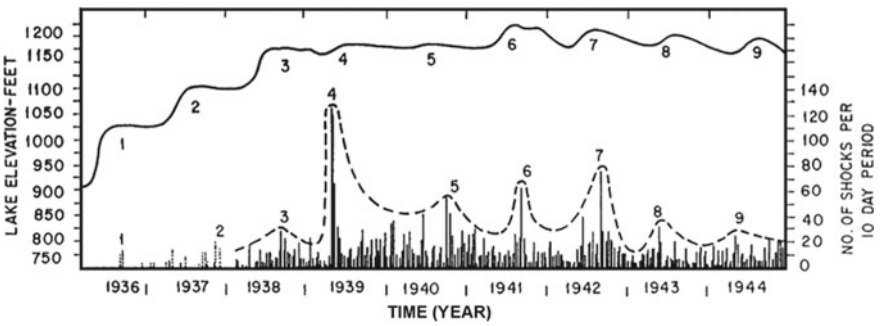

Fig. 4.6 Lake Mead water level and the local seismicity. The rises in water levels and the corresponding bursts of seismic activity are numbered. General trend of tremor-frequency variation is shown by dotted lines (after Carder 1945)

Seismicity associated with reservoirs has been documented at passive margins in the United States and South America and within stable cratons in Canada and Africa. Foulger et al. (2018) include 24 different reservoirs with associated earthquakes of magnitude >5, large enough to cause damage. The Kariba dam between Zambia and Zimbabwe induced a M 6.2 event 5 years after impounding began (Gough and Gough 1970). A M 6.3 event in 1967 in Western India was induced by water impoundment behind the Koyna dam (Gupta and Rastogi 1976). In some cases, the seismicity peaks soon after filling and decays (e.g., Figure 4.7), suggesting that preexisting tectonic stresses were relieved. In the Koyna region, seismicity has been decreasing over the 50 years since the largest earthquake (Gupta 2018).

There are three ways in which filling a reservoir can induce earthquakes. First, the weight of the water can increase both elastic stresses and pore fluid pressure in response to the change in elastic stress—a poroelastic response. In this case, the orientation of faults and the background stress field will determine where and how faults get reactivated (e.g., Roeloffs 1988). Groundwater pore pressure should also rise as water seeps out of the reservoir and fluids migrate. The most distinctive signature of this second case would be a migration in space and time of the earthquakes away from the reservoir, consistent with pore pressure diffusion, i.e., the distance of the induced earthquakes from the reservoir increasing with the square root of time. This type of migration has been documented at some reservoirs (Talwani and Acree 1985; Tao et al. 2015). Third, induced seismicity may be modulated by the loading

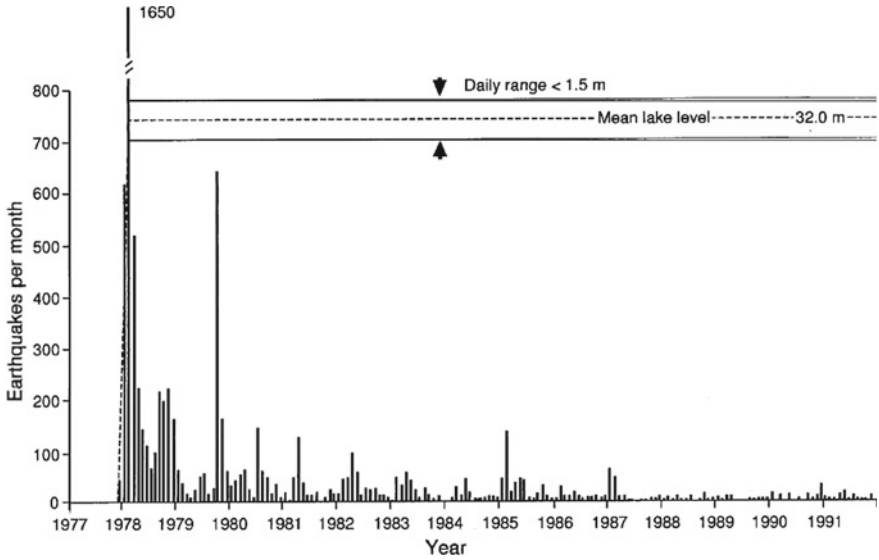

Fig. 4.7 Water level in the Monticello Reservoir, South Carolina, USA (dashed line) and the number of monthly earthquakes (histogram). Note that the peak seismicity rate reaches 1650 in one month. Seismicity returned towards background levels over a decade. From Talwani (1997)

rate, through the physics in rate-and-state friction. Annual modulation of reservoir-induced seismicity in the Koyna region appears to be influenced by loading and unloading rate as well as water level heights (Gupta 2018).

The largest proposed reservoir-induced earthquake is the May 2008 magnitude 7.9 Wenchuan earthquake (Klose 2012). Ge et al. (2009), using a two-dimensional model, suggested that it was the combination of pore pressure diffusion and surface loading that promoted slip (Fig. 4.8). This conclusion is sensitive to the assumed dip of the fault and three-dimensional effects and the proposal that the Wenchuan earthquake was induced has been contested (Deng et al. 2010; Zhou and Deng 2011; Tao et al. 2015). Tao et al. (2015) note that an expanding pattern of microseismicity likely documents the effects of pore pressure diffusion, favoring direct or indirect poroelastic triggering of seismic events that ended with the large earthquake. The case of the Wenchuan earthquake highlights the challenge in identifying induced earthquakes (Table 4.1).

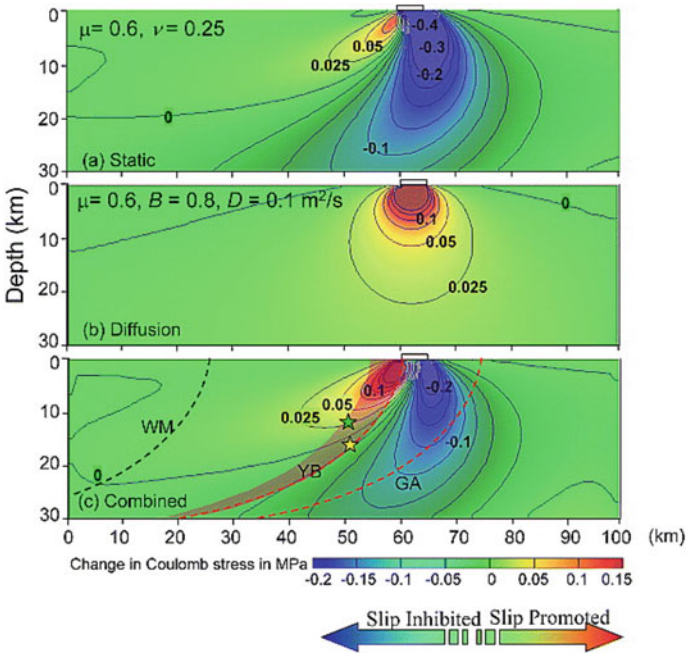

Fig. 4.8 Modeled change in Coulomb stress from reservoir filling **a**, pore pressure diffusion **b**, and the combined effects **c**. The two stars show inferred epicenter locations for the 2008 magnitude 7.9 Wenchuan earthquake. From Ge et al. (2009)

4.6 Natural Hydrological Triggering of Earthquakes

With insights gained from the engineered occurrences of hydrologically mediated earthquakes, we turn to possible examples of earthquakes triggered by natural hydrological and hydrogeological processes. Here, establishing a connection is more difficult because the magnitudes of the pressure and stress changes are usually smaller. However, their study is potentially more rewarding as they may provide unique insight into interactions between hydrogeological and tectonic processes.

Identifying seasonality in seismicity may be indicative of a hydrological influence on earthquakes. This influence could either be in the form of increased stress from the surface load of water or snow, or by changes in pore pressure that accompany groundwater recharge. The distinctive signature of the latter, as with reservoir-induced seismicity, is a time lag between the hydrological loading (groundwater recharge) and seismicity.

Seasonal variations of seismicity, while not ubiquitous, have been identified in regions with strong seasonality of recharge (e.g., Wolf et al. 1997; Bollinger et al. 2007; Johnson et al. 2017, 2020). For example, Heki (2003) identified a seasonal modulation of seismicity in Japan that he attributed to the loading of the surface by snow. Others have attributed seasonal variations of seismicity to groundwater recharge (e.g., Saar and Manga 2003; Christiansen et al. 2007; Montgomery-Brown et al. 2019). A correlation between precipitation and earthquakes (e.g., Roth et al. 1992; Jimenez and Garcia-Fernandez 2000; Hainzl et al. 2006; Kraft et al. 2006; Husen et al. 2007) supports the idea that pore pressure changes caused by recharge can influence seismicity. Over longer time scales, extended droughts and wet periods can also modulate seismicity (e.g., Hammond et al. 2019)

As with reservoir-induced earthquakes, surface loading, loading rate, and pore pressure changes can influence seismicity. In some cases, the loading appears to explain seasonal variations (e.g., Johnson et al. 2017; Craig et al. 2017; D'Agostino et al. 2018). Sometimes the seasonal variations are best correlated with stressing rate changes (Bettinelli et al. 2008) as expected from rate-and-state friction models for perpetual oscillatory loading (Heimisson and Avouac 2020). In other cases, the time lag between recharge and seismicity supports an origin from pore pressure diffusion (e.g., Saar and Manga 2003; Montgomery-Brown et al. 2019; Johnson et al. 2020). Figure 4.9 shows an example at the edge of Long Valley caldera, California. Here there are large seasonal variations in precipitation, with precipitation being dominated by snow, and recharge occurring as springtime snow melt. Downward migration of seismicity is apparent, and seismicity is ~37 times greater during spring snowmelt than the driest period (Montgomery-Brown et al. 2019). At regional scales, changes in hydrological loading, loading rate, and pore pressure changes may all contribute to seasonal variations in seismicity (Ueda and Kato 2019).

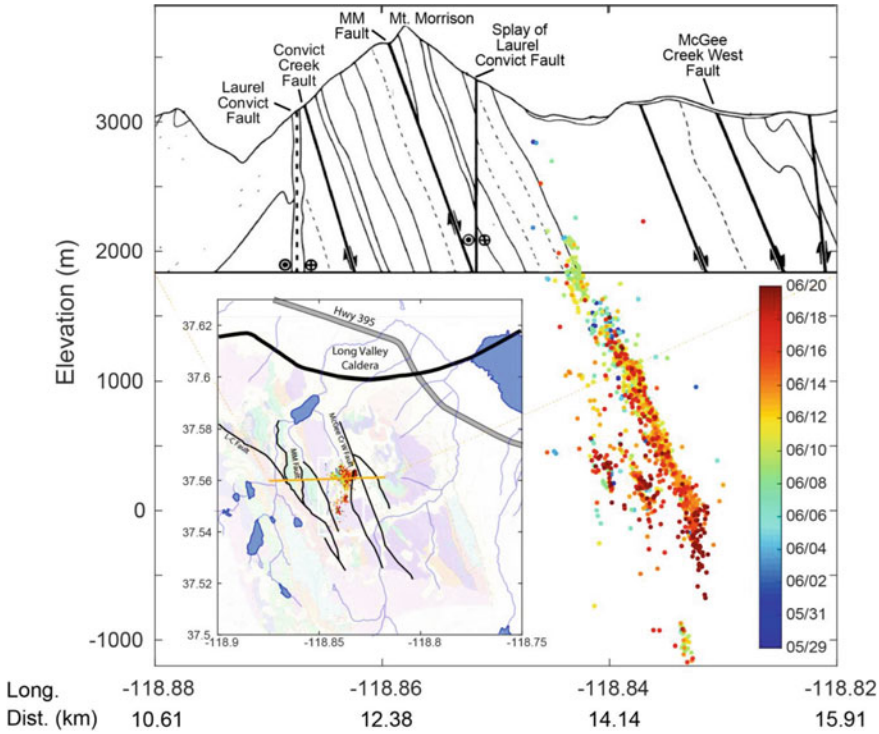

Fig. 4.9 Possible snowmelt triggered earthquakes at the edge of Long Valley caldera, California. Detected and relocated seismicity between May 28 and June 21, 2017 plotted on a geological cross-section. Color indicates date and shows downward migration over time. From Montgomery-Brown et al. (2019)

4.7 Earthquake Triggering of Earthquakes via Hydrological Processes

The stresses generated by earthquakes influence the occurrence of additional earthquakes. Many reviews have addressed such connections, including the role of (a) the coseismic static stress changes (e.g., Stein 1999; King and Deves 2015), (b) dynamic stresses associated with the passage of seismic waves (e.g., Kilb et al. 2000; Prejean and Hill 2018), and (c) the postseismic relaxation of stresses (Freed 2005). Here we focus exclusively on mechanisms and processes in which water may play a direct role.

In the near-field and intermediate-field, volumetric strains that accompany earthquakes will change pore pressure (e.g., Fig. 3.2). Stress changes resulting from postseismic pore pressure diffusion have been invoked to explain aftershocks (e.g., Nur

and Booker 1972; Bosl and Nur 2002) and similar seismic sequences (Noir et al. 1997; Antonioli et al. 2005; Miller et al. 2004).

In the far-field, fluid flow and poroelastic pressure changes caused by static stress changes are negligible. Triggering of earthquakes in the far-field is thus dominated by dynamic stresses. Examples include seismicity 1250 km away from the M 7.3 Landers earthquake in 1992 (Hill et al. 1993); 1400 km away from the M 8.1 Tokachi-oki earthquake in 2003 (Miyazawa and Mori 2005); 11,000 km away from the M 8.0 Sumatra earthquake in 2004 (West et al. 2005); triggered events after the M 9.0 Tohoku-Oki earthquake in 2011 occurred in the USA, Russia, China, Ecuador and Mexico (Gonzalez-Huizar et al. 2012); a M 8.6 east Indian Ocean earthquake triggered aftershocks globally (Pollitz et al. 2012). Distant triggering is sometimes coincident with the passage of the seismic waves, usually the surface waves that have the greatest amplitudes at these distances. Both Love and Rayleigh waves appear to trigger earthquakes (Velasco et al. 2008). Moreover, triggered events are sometimes even correlated with a particular phase of the waves. As shown in Fig. 4.10 from West et al. (2005), triggered events occur during the maximum horizontal extension associated with the waves. Remote, triggered seismicity need not only be confined to the period of shaking and can sometimes continue for days or longer (e.g., Hill et al. 1993; Li et al. 2019).

Dynamic triggering may be ubiquitous, independent of tectonic environment (Velasco et al. 2008). However, dynamic triggering is most common in regions undergoing tectonic extension, where faults transition between locked and creeping, where human perturbations are large (van der Elst et al. 2013), and in geothermal and volcanic settings (Aiken and Peng 2014).

The underlying mechanisms of dynamic triggering are not known (Brodsky and van der Elst 2014). Because dynamic strains are small in the far-field and there is no net elastic strain after the passage of the seismic waves, triggering likely requires a mechanism to translate small and periodic strains into lasting change. Larger dynamic stresses do trigger larger earthquakes (Aiken et al. 2018). One mechanism could be by accelerating creep from rate-and-state friction. If rocks are damaged and close to failure, strain oscillations can lead to nonlinear elastic behavior leading to compaction or dilation and hence change stresses (Shalev et al. 2016). Another mechanism could be changes in pore pressure or permeability (which in turn allows pore pressure to change). The mechanisms discussed in other chapters for explaining the response of streams, groundwater level, geysers and mud volcanoes to earthquakes have also been invoked to explain dynamic triggering of earthquakes: nucleation of new bubbles (Crews and Cooper 2014), advective overpressure as bubbles shaken loose by seismic waves carry high pressure to more shallow depths (Linde et al. 1994), and breaching hydrologic barriers (Brodsky et al. 2003). Changes in permeability would explain observed delays in remote triggering (Parson et al. 2017). In contrast, however, West et al. (2005) conclude that their observations (shown in Fig. 4.10) can be simply explained by failure on normal faults caused by the shear stresses generated by the

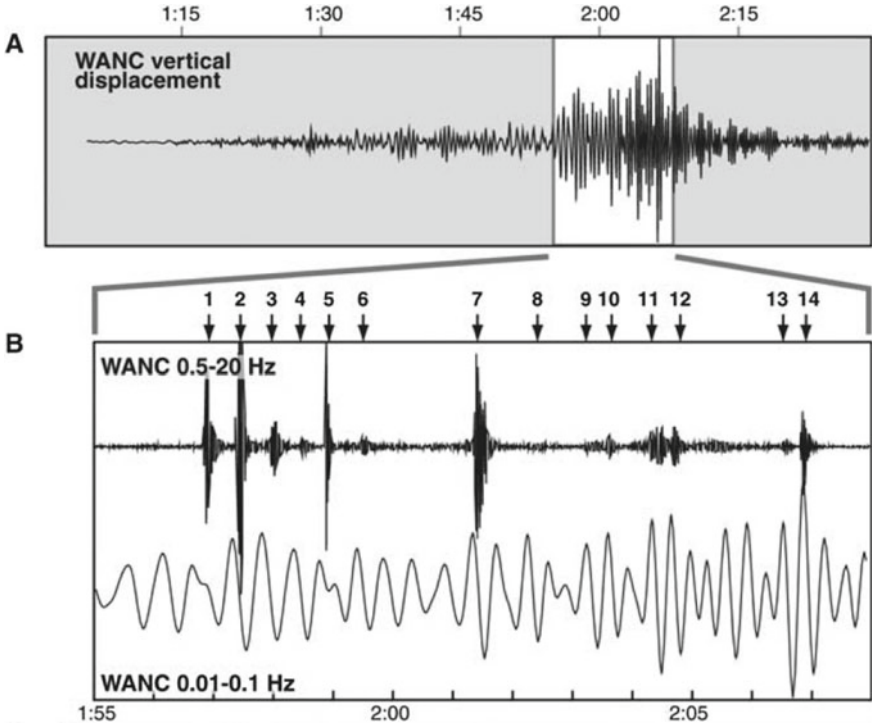

Fig. 4.10 Example of small, local earthquakes triggered in Alaska during the passage of teleseismic waves from the 26 December, 2004 Sumatra earthquake. **a** Vertical displacement with scale in hours and minutes. **b** Expanded view of surface waves filtered from 0.5 to 20 Hz and 0.01 to 0.1 Hz. The long period signals are from the Sumatra earthquake. The high frequency ground motion reveals the local triggered earthquakes. Modified from West et al. (2005)

seismic waves. Fluids only need play a role by making the pore pressure high enough that the small dynamic stresses can cause failure.

Identifying whether fluids play any role in causing aftershocks, seismic sequences, or far-field triggering is difficult to confirm observationally because pore pressure measurements are not available. At best, model simulations can be compared with the distribution of earthquakes in space and time, and plausibility can be assessed if the needed parameters are reasonable. New approaches for detecting small triggered earthquakes, such as machine learning, may at least help to improve the observational record (Tang et al. 2020).

4.8 Concluding Remarks and Outlook

The theory of poroelasticity (Chap. 3) provides an explanation for how changes in fluid pressure and stress can influence seismicity. Coupled with models for how stress changes influence seismicity, in principle it is possible to forecast induced seismicity. However, there are many idealizations in these physical models and unknown parameters and properties that limit forecasts and hence our ability to identify whether and how earthquakes were induced. Figure 4.11 summarizes how stress and pressure perturbations influence induced seismicity.

There remain many open questions about human induced earthquakes. Why do some areas, for example California and North Dakota, seem to have few induced earthquakes? Is it just a matter of time? In Oklahoma, for example, it has been argued that there is a critical time for aquifers to be pressurized to the point that earthquakes can be induced. Or, is the hydrogeology such that pore pressure and poroelastic stress changes are not able to reach critical values? Can we identify signatures of induced earthquakes that are different from those that would otherwise have occurred? Progress, as briefly reviewed, has been made in forecasting induced earthquakes from hydromechanical models. But, is the subsurface too heterogeneous and with too many unknowns, that a useful forecast cannot be made prior to injection? With mitigation in mind, what measurements should be acquired prior to injection?

The rapid increase in the number of induced earthquakes around the world and their increasing magnitude are trends we should expect to continue. The scale of engineering projects has increased, hence their ability to change stresses in the subsurface. Figure 4.12 from Foulger et al. (2018) shows their compilation of the magnitude of induced earthquakes and the magnitude of the disturbance, characterized by the mass of fluid involved. Some of the included events may be controversial, but regardless, there is a pattern of increasing maximum earthquake size with magnitude of disturbance. Some of these proposed induced earthquakes are large enough to cause disasters depending on location. If carbon capture and sequestration expand

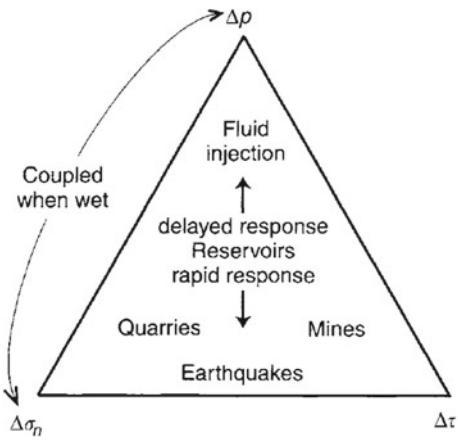

Fig. 4.11 Schematic illustration of the mechanisms that influence seismicity from perturbations in stress and the time scales over which responses will be seen. Reservoirs (in the middle) influence pore pressure, normal stress and shear stress. From McGarr et al. (2002)

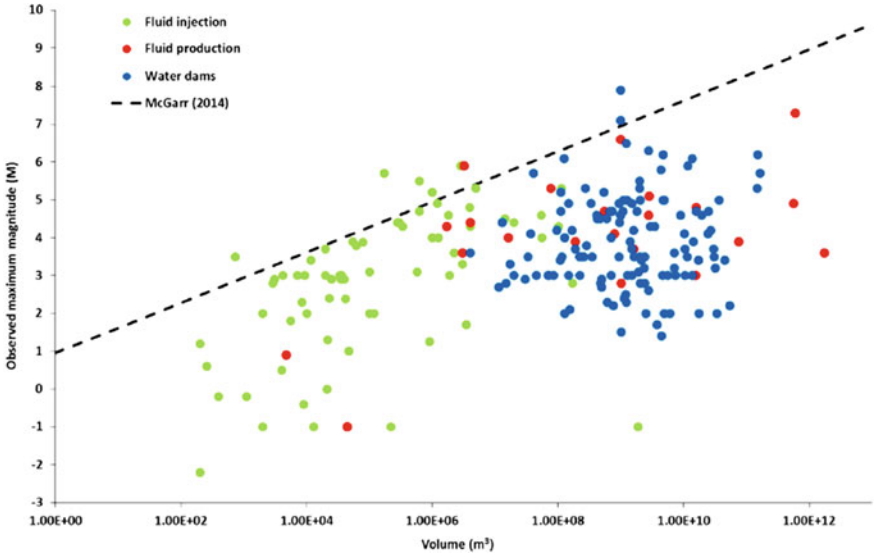

Fig. 4.12 Maximum earthquake magnitude as a function of the volume of fluid added, removed or accumulated in reservoirs. The dashed line is a proposed maximum size from McGarr (2014). From Foulger et al. (2018)

to become a climate-change solution, we can also expect new large-scale changes in subsurface stress. The public finds induced earthquakes less acceptable than natural ones, however, even if the earthquakes are a byproduct of climate change mitigation (McComas et al. 2016). The hope is that a better quantitative understanding of how earthquakes are induced can inspire management practices and inform decisions about where and how to inject and extract fluids.

References

Aiken C, Peng Z (2014) Dynamic triggering of microearthquakes in three geothermal/volcanic regions of California. J Geophys Res Solid Earth 119:6992–7009

Aiken C, Meng X, Hardebeck J (2018) Testing for the 'predictability'of dynamically triggered earthquakes in the Geysers geothermal field. Earth Planet Sci Lett 486:129–140

Atkinson GM, Eaton DW, Ghofrani H et al (2016) Hydraulic fracturing and seismicity in the western Canada sedimentary basin. Seismol Res Lett 87:631–647

Antonioli A, Piccinini D, Chiaraluce L, Cocco M (2005) Fluid flow and seismicity pattern: evidence from the 1997 Umbria-Marche (central Italy) seismic sequence. Geophys Res Lett 32:L10311. https://doi.org/10.1029/2004GL022256

Bettinelli P, Avouac JP, Flouzat M et al (2008) Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. Earth Planet Sci Lett 266(3–4):332–344

Bollinger L, Perrier F, Avouac JP et al (2007) Seasonal modulation of seismicity in the Himalaya of Nepal. Geophys Res Lett 34:L08304. https://doi.org/10.1029/2006GL029192

Bosl WJ, Nur A (2002) Aftershocks and pore fluid diffusion following the 1992 Landers earthquake. J Geophys Res Solid Earth 107(B12):2366. https://doi.org/10.1029/2001JB000155

Brodsky EE, van der Elst NJ (2014) The uses of dynamic earthquake triggering. Annu Rev Earth Planet Sci 42:317–339

Brodsky EE, Roeloffs E, Woodcock D et al (2003) A mechanism for sustained groundwater pressure changes induced by distant earthquakes. J Geophys Res Solid Earth 108(B8):2390. https://doi.org/10.1029/2002JB002321

Candela T, Wassing B, Ter Heege J et al (2018) How earthquakes are induced. Science 360(6389):598–600

Cappa F, Scuderi MM, Collettini C et al (2019) Stabilization of fault slip by fluid injection in the laboratory and in situ. Sci Adv 5:eaau4065. https://doi.org/10.1126/sciadv.aau4065

Carder DS (1945) Seismic investigations in the Boulder Dam area, 1940–1944, and the influence of reservoir loading on local earthquake activity. Bull Seismol Soc Am 35(4):175–192

Christiansen LB, Hurwitz S, Ingebritsen SE (2007) Annual modulation of seismicity along the San Andreas Fault near Parkfield, CA. Geophys Res Lett 34(4):L04306. https://doi.org/10.1029/2006GL028634

Chang KW, Yoon H, Martinez MJ (2018) Seismicity rate surge on faults after shut-in: poroelastic response to fluid injection. Bull Seismol Soc Am 108(4):1889–1904

Craig TJ, Chanard K, Calais E (2017) Hydrologically-driven crustal stresses and seismicity in the new madrid seismic zone. Nat Commun 8(1):1–11

Crews JB, Cooper CA (2014) Experimental evidence for seismically initiated gas bubble nucleation and growth in groundwater as a mechanism for coseismic borehole water level rise and remotely triggered seismicity. J Geophys Res Solid Earth 119(9):7079–7091

D'Agostino N, Silverii F, Amoroso O et al (2018) Crustal deformation and seismicity modulated by groundwater recharge of karst aquifers. Geophys Res Lett 45(22):12–253

Davis SD, Frohlich C (1993) Did (or will) fluid injection cause earthquakes?—criteria for a rational assessment. Seismol Res Lett 64(3–4):207–224

Deng K, Zhou S, Wang R et al (2010) Evidence that the 2008 M w 7.9 Wenchuan earthquake could not have been induced by the Zipingpu Reservoir. Bull Seismol Soc Am 100(5B):2805–2814

Dieterich JH (1994) A constitutive law for rate of earthquake production and its application to earthquake clustering. J Geophys Res 99:2601–2618. https://doi.org/10.1029/93JB02581

Ellsworth WL (2013) Injection-induced earthquakes. Science 341(6142):1225942

EPA (2011) Proceedings of the technical workshops for the hydraulic fracturing study: water resources management, EPA 600/R-11/048

Evans DM (1966) The Denver area earthquakes and the Rocky Mountain Arsenal disposal well. Mt Geol 3:23–26

Foulger GR, Wilson MP, Gluyas JG et al (2018) Global review of human-induced earthquakes. Earth Sci Rev 178:438–514

Freed AM (2005) Earthquake triggering by static, dynamic, and postseismic stress transfer. Ann Rev Earth Planet Sci 33:335–367

Ge S, Liu M, Lu N et al (2009) Did the Zipingpu reservoir trigger the 2008 Wenchuan earthquake? Geophys Res Lett 36:L20315. https://doi.org/10.1029/2009GL040349

Goebel TH, Brodsky EE (2018) The spatial footprint of injection wells in a global compilation of induced earthquake sequences. Science 361(6405):899–904

Goebel TH, Rosson Z, Brodsky EE et al (2019) Aftershock deficiency of induced earthquake sequences during rapid mitigation efforts in Oklahoma. Earth Planet Sci Lett 522:135–143

Gomberg J, Wolf L (1999) Possible cause for an improbable earthquake: the 1997 Mw 4.9 southern Alabama earthquake and hydrocarbon recovery. Geology 27:367–37

González PJ, Tiampo KF, Palano M et al (2012) The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading. Nat Geosci 5(11):821–825

Gonzalez-Huizar H, Velasco AA, Peng Z, Castro RR (2012) Remote triggered seismicity caused by the 2011, M9. 0 Tohoku-Oki, Japan earthquake. Geophys Res Lett 39(10):L10302. https://doi.org/10.1029/2012gl051015

Gough DI, Gough WI (1970) Load-induced earthquakes at Lake Kariba—II. Geophys J Int 21(1):79–101
Grigoli F, Cesca S, Rinaldi AP et al (2018) The November 2017 Mw 5.5 Pohang earthquake: a possible case of induced seismicity in South Korea. Science 360:1003–1006
Guglielmi Y, Cappa F, Avouac JP et al (2015) Seismicity triggered by fluid injection–induced aseismic slip. Science 348(6240):1224–1226
Gupta HK (1992) Reservoir induced earthquakes. Elsevier
Gupta HK (2018) Reservoir triggered seismicity (RTS) at Koyna, India, over the Past 50 Yrs. Bull Seismol Soc Am 108(5B):2907–2918
Gupta HK (2002) A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India. Earth Sci Rev 58(3–4):279–310
Gupta HK, Rastogi BK (1976) Dams and earthquakes. Elsevier, Amsterdam, p 229
Hainzl S, Kraft T, Wassermann J et al (2006) Evidence for rainfall-triggered earthquake activity. Geophys Res Lett 33(19):L19303. https://doi.org/10.1029/2006gl027642
Hammond WC, Kreemer C, Zaliapin I, Blewitt G (2019) Drought-triggered magmatic inflation, crustal strain, and seismicity near the long Valley Caldera, Central Walker Lane. J Geophys Res Solid Earth 124(6):6072–6091
Hartline C, Walters M, Wright M, Rawal C, Garcia J, Farison J (2019) The Northwest Geysers enhanced geothermal system demonstration project, the Geysers, California (No. DE-FC36-08G018201). Geysers Power Company, LLC
Healy JH, Rubey WW, Griggs DT et al (1968) The Denver earthquakes. Science 161(3848):1301–1310
Heki K (2003) Snow load and seasonal variation of earthquake occurrence in Japan. Earth Planet Sci Lett 207(1–4):159–164
Heimisson ER, Avouac J (2020) Analytical prediction of seismicity rate due to tides and other oscillating stress. EarthArXiv. https://doi.org/10.31223/osf.io.duvq2
Hill DP, Reasenberg PA, Michael A et al (1993) Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. Science 260(5114):1617–1623
Husen S, Bachmann C, Giardini D (2007) Locally triggered seismicity in the central Swiss Alps following the large rainfall event of August 2005. Geophys J Int 171(3):1126–1134
Hsieh PA, Bredehoeft JD (1981) A reservoir analysis of the Denver earthquakes: a case of induced seismicity. J Geophys Res Solid Earth 86(B2):903–920
Jiménez MJ, García-Fernández M (2000) Occurrence of shallow earthquakes following periods of intense rainfall in Tenerife, Canary Islands. J Volcanol Geoth Res 103(1–4):463–468
Johnson CW, Fu Y, Bürgmann R (2017) Seasonal water storage, stress modulation, and California seismicity. Science 356(6343):1161–1164
Johnson CW, Fu Y, Bürgmann R (2020) Hydrospheric modulation of stress and seismicity on shallow faults in southern Alaska. Earth Planet Sci Lett 530:115904. https://doi.org/10.1016/j.epsl.2019.1115904
Keranen KM, Weingarten M, Abers GA et al (2014) Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. Science 345(6195):448–451
Keranen KM, Weingarten M (2018) Induced seismicity. Ann Rev Earth Planet Sci 46:149–174
Kilb D, Gomberg J, Bodin P (2000) Triggering of earthquake aftershocks by dynamic stresses. Nature 408(6812):570–574
Kim KH, Ree JH, Kim Y et al. (2018) Assessing whether the 2017 Mw 5.4 Pohang earthquake in South Korea was an induced event. Science 360(6392):1007–1009
King GCP, Devès MH (2015) Fault interaction, earthquake stress changes, and the evolution of seismicity. In: Treatise of Geophysics, 2nd ed. Elsevier
Klose CD (2012) Evidence for anthropogenic surface loading as trigger mechanism of the 2008 Wenchuan earthquake. Environ Earth Sci 66(5):1439–1447
Kolawole F, Johnston CS, Morgan CB et al (2019) The susceptibility of Oklahoma's basement to seismic reactivation. Nat Geosci 12(10):839–844

Kraft T, Wassermann J, Schmedes E et al (2006) Meteorological triggering of earthquake swarms at Mt. Hochstaufen, SE-Germany. Tectonophysics 424(3–4):245–258
Langenbruch C, Zoback MD (2016) How will induced seismicity in Oklahoma respond to decreased saltwater injection rates? Sci Adv 2(11):e1601542
Langenbruch C, Weingarten M, Zoback MD (2018) Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas. Nat Commun 9(1):1–10
Li T, Gu YJ, Wang Z et al (2019) Spatiotemporal variations in crustal seismic anisotropy surrounding induced earthquakes near Fox Creek, Alberta. Geophys Res Lett 46(10):5180–5189
Linde AT, Sacks IS, Johnston MJ, Hill DP, Bilham RG (1994) Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity. Nature 371(6496):408–410
Majer EL, Baria R, Stark M et al (2007) Induced seismicity associated with enhanced geothermal systems. Geothermics 36(3):185–222
McComas KA, Lu H, Keranen KM et al (2016) Public perceptions and acceptance of induced earthquakes related to energy development. Energ Pol 99:27–32
McGarr A, Simpson D, Seeber L (2002) Case histories of induced and triggered seismicity. Int Handb Earthquake Eng Seismol 81(A):647–664
McGarr A (2014) Maximum magnitude earthquakes induced by fluid injection. J Geophys Res Solid Earth 119(2):1008–1019
McGarr A, Barbour AJ (2018) Injection-induced moment release can also be aseismic. Geophys Res Lett 45(11):5344–5351
Miller SA, Collettini C, Chiaraluce L et al (2004) Aftershocks driven by a high-pressure CO_2 source at depth. Nature 427(6976):724–727
Miyazawa M, Mori J (2005) Detection of triggered deep low-frequency events from the 2003 Tokachi-oki earthquake. Geophys Res Lett 32(10):L10307. https://doi.org/10.1029/2005gl022539
Montgomery-Brown EK, Shelly DR, Hsieh PA (2019) Snowmelt-triggered earthquake swarms at the margin of Long Valley Caldera, California. Geophys Res Lett 46(7):3698–3705
Noir J, Jacques E, Bekri S et al (1997) Fluid flow triggered migration of events in the 1989 Dobi earthquake sequence of Central Afar. Geophys Res Lett 24(18):2335–2338
Nur A, Booker JR (1972) Aftershocks caused by pore fluid flow? Science 175(4024):885–887
Parsons T, Malagnini L, Akinci A (2017) Nucleation speed limit on remote fluid-induced earthquakes. Sci Adv 3(8):e1700660
Peterie SL, Miller RD, Intfen JW et al (2018) Earthquakes in Kansas induced by extremely far-field pressure diffusion. Geophys Res Lett 45(3):1395–1401
Pollitz FF, Stein RS, Sevilgen V (2012) The 11 April 2012 east Indian Ocean earthquake triggered large aftershocks worldwide. Nature 490(7419):250–253
Prejean SG, Hill DP (2018) The influence of tectonic environment on dynamic earthquake triggering: a review and case study on Alaskan volcanoes. Tectonophysics 745:293–304
Roeloffs EA (1988) Fault stability changes induced beneath a reservoir with cyclic variations in water level. J Geophys Res Solid Earth 93(B3):2107–2124
Roth P, Pavoni N, Deichmann N (1992) Seismotectonics of the eastern Swiss Alps and evidence for precipitation-induced variations of seismic activity. Tectonophysics 207(1–2):183–197
Saar MO, Manga M (2003) Seismicity induced by seasonal groundwater recharge at Mt. Hood, Oregon. Earth Planet Sci Lett 214(3-4):605–618
Segall P (1989) Earthquakes triggered by fluid extraction. Geology 17(10):942–946
Segall P, Fitzgerald SD (1998) A note on induced stress changes in hydrocarbon and geothermal reservoirs. Tectonophysics 289(1–3):117–128
Segall P, Lu S (2015) Injection-induced seismicity: poroelastic and earthquake nucleation effects. J Geophys Res Solid Earth 120(7):5082–5103
Segall P, Grasso JR, Mossop A (1994) Poroelastic stressing and induced seismicity near the Lacq gas field, southwestern France. J Geophys Res Solid Earth 99(B8):15423–15438
Shalev E, Kurzon I, Doan ML et al (2016) Sustained water-level changes caused by damage and compaction induced by teleseismic earthquakes. J Geophys Res Solid Earth 121(7):4943–4954

Shapiro SA, Kummerow J, Dinske C et al (2006) Fluid induced seismicity guided by a continental fault: injection experiment of 2004/2005 at the German Deep Drilling Site (KTB). Geophys Res Lett 33(1):L01309. https://doi.org/10.1029/2005gl024659

Simpson DW (1976) Seismicity changes associated with reservoir loading. Eng Geol 10(2–4):123–150

Stein RS (1999) The role of stress transfer in earthquake occurrence. Nature 402(6762):605–609

Tadokoro K, Ando M, Nishigami KY (2000) Induced earthquakes accompanying the water injection experiment at the Nojima fault zone, Japan: seismicity and its migration. J Geophys Res Solid Earth 105(B3):6089–6104

Talwani P (1997) On the nature of reservoir-induced seismicity. Pure Appl Geophys 150(3–4):473–492

Talwani P, Acree S (1985) Pore pressure diffusion and the mechanism of reservoir-induced seismicity. In: Earthquake prediction. Birkhäuser, Basel, pp 947–965

Tang V, Seetharaman P, Chao K et al (2020) Automating the detection of dynamically triggered earthquakes via a deep metric learning algorithm. Seismol Res Lett. https://doi.org/10.1785/0220190165

Tao W, Masterlark T, Shen ZK (2015) Impoundment of the Zipingpu reservoir and triggering of the 2008 Mw 7.9 Wenchuan earthquake, China. J Geophys Res Solid Earth 120(10):7033–7047

Ueda T, Kato A (2019) Seasonal variations in Crustal Seismicity in San-in District, Southwest Japan. Geophys Res Lett 46(6):3172–3179

Van der Elst NJ, Savage HM, Keranen KM et al (2013) Enhanced remote earthquake triggering at fluid-injection sites in the midwestern United States. Science 341(6142):164–167

Van der Elst NJ, Page MT, Weiser DA (2016) Induced earthquake magnitudes are as large as (statistically) expected. J Geophys Res Solid Earth 121(6):4575–4590

Velasco AA, Hernandez S, Parsons T et al (2008) Global ubiquity of dynamic earthquake triggering. Nat Geosci 1(6):375–379

Verruijt A (1969) An interface problem with a source and a sink in the heavy fluid. J Hydrol 8(2):197–206

Wang L, Kwiatek G, Rybacki E (2019) Laboratory study on fluid-induced fault slip behavior: the role of fluid pressurization rate. Geophys Res Lett 47:e2019GL086627. https://doi.org/10.1029/2019gl086627

West M, Sánchez JJ, McNutt SR (2005) Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake. Science 308(5725):1144–1146

Wetzler N, Shalev E, Göbel T et al (2019) Earthquake swarms triggered by groundwater extraction near the Dead Sea Fault. Geophys Res Lett 46(14):8056–8063

Wolf LW, Rowe CA, Horner RB (1997) Periodic seismicity near Mt. Ogden on the Alaska-British Columbia border: a case for hydrologically triggered earthquakes? Bull Seismol Soc Am 87(6):1473–1483

Zhai G, Shirzaei M, Manga M et al (2019) Pore-pressure diffusion, enhanced by poroelastic stresses, controls induced seismicity in Oklahoma. Proc Natl Acad Sci 116(33):16228–16233

Zhai G, Shirzaei M, Manga M (2020) Elevated seismic hazard in Kansas due to high volume injections in Oklahoma. Geophys Res Lett 47:e2019GL085705. https://doi.org/10.1029/2019gl085705

Zhou S, Deng K (2011) Reply to "Comment on 'Evidence that the 2008 Mw 7.9 Wenchuan earthquake could not have been induced by the Zipingpu reservoir' by Kai Deng, Shiyong Zhou, Rui Wang, Russell Robinson, Cuiping Zhao, and Wanzheng Cheng" by Shemin Ge. Bull Seismol Soc Am 101(6):3119–3120

Zoback MD, Zinke J C (2002) Production-induced normal faulting in the Valhall and Ekofisk oil fields. In: The mechanism of induced seismicity. Birkhäuser, Basel, pp 403–420