Challenges of reducing the hazard of injection-induced seismicity

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Fluid-injection activities associated with the development of energy resources have contributed significantly to seismic hazard. The injection activities that are prone to inducing earthquakes include hydraulic fracturing of low-permeability oil and gas reservoirs, the disposal of co-produced wastewater by injection into deep brine aquifers, and the development of geothermal resources from natural reservoirs and by injecting water into hot low-permeability rock, termed Enhanced Geothermal Systems or EGS. Of these activities, wastewater disposal has induced the largest and most damaging earthquakes, but the other injection operations also contribute to the seismic hazard. For all three types of injection, the largest earthquakes occur when injected fluid is diverted from the target formation into a pre-existing fault zone which is then reactivated due to the increase in pore pressure and/or failure-promoting stress changes. These fault zones are most often revealed when imaged by well-located earthquake hypocenters. This raises some questions: (1) How much of an increase in pore pressure is needed for fault reactivation? (2) What controls the maximum magnitude of the largest earthquake induced along the fault zone? (3) Can the timely identification of a fault prone to reactivation be of use in reducing its seismic hazard? Case histories of various fluid injection projects provide answers to several of these questions. First, pore pressure changes of about 3 to 5 MPa appear to be sufficient to reactivate faults. Second, the maximum magnitude of an injection-induced earthquake is evidently limited according to the total volume of injected fluid, although counterexamples have been reported. Third, progress has been made regarding the timely identification of faults prone to reactivation in the contemporaneous crustal state of stress. That is, Schoenball and Ellsworth (Seismological Research Letters, 2017) identified numerous previously-unmapped buried faults in Oklahoma and Kansas based on precise locations of small-magnitude earthquakes. Avoiding injection activities near these faults may prove to be an effective way to reduce the hazard of injection-induced seismicity. Reducing

the hazard of wastewater disposal projects is particularly challenging, however, because of their lifetimes, often more than a decade, and the considerable volumes injected; the injected fluids have time to migrate substantial distances from the well, increasing the likelihood of encountering a fault that is prone to reactivation and the large volumes of injected fluid enhance the possibility of large magnitude events. Limited success in reducing the hazard of earthquakes induced by injection has come about mostly due to economic factors, such as reduced oil and gas prices, and to regulatory decisions intended to reduce the hazard of induced seismicity by imposing reduced injection rates in regions of high seismicity. These successes notwithstanding, there are many gaps in our understanding of induced seismicity that need to be filled in order to achieve a significant reduction in its hazard. The highly-destructive Pohang, South Korea M5.5 earthquake of 15 November 2017, reported to have been induced by an EGS project, is stark evidence that there are some fundamental questions that must be resolved before achieving the capability to reduce the hazard of injection-induced seismicity with true confidence.