Injection-induced seismicity: Placing the problem in perspective

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Induced or triggered seismicity (here taken to mean the same) is a recognised hazard in practically all engineering endeavours where stress or pore pressure in the Earth's crust are altered. This can be taken as a reflection of the realisation that has dawned in the past 20 years that the Earth's crust generally supports high shear stress levels and is often close to failure. Historically, the most damaging events, which in some cases have sometimes even caused numerousmany fatalities, are associated with the impoundment of reservoirs. However, earthquakes of sufficient size to threaten material damage to localities damage to localities have also been associated with mining activity, long-term fluid withdrawal wells, and long-term fluid injection wells. There are also several incidences where periods of heavy rainfall have triggered seismicity.

Recently, the phenomenon of injection-induced seismicity received considerable media attention when water injection into granite at 5 km depth during the development of an Engineered Geothermal System (EGS) beneath the Swiss city of Basel resulted in the generation of a M_L 3.4 earthquake. The purpose of the injection was to raise the pore pressure in the granite, thereby reducing the shear strength of fractures and fracture zones and promoting their localised shear failure. The shearing of the rough interfaces of the fractures forces them to dilate and increase their hydraulic permeability. In this way, the bulk permeability of the granite is increased so that water can be circulated through the rock and the heat extracted. The shearing movement generates earthquakes or microearthquakes, depending upon the scale of the failure, whose location can be mapped to obtain an image of the geometry of pressure diffusion within the reservoir. Such information is vital for targeting subsequent wells drilled to complete the circulation system. Shear failure activated through weakening of fractures and faults by increased pore pressure is the mechanism underlying most incidences of injection- and rainfall-induced seismicity. The pore pressure increase above ambient that is required to initiate shearing is invariably lower than required for conventional hydrofracturing operations, often substantially so, and may be less than a megapascal, reflecting the tendency for high shear stress levels in the crust.

Long-term injection of fluid generally carries a higher risk of inducing felt or damaging events than short-term injection, such as in EGS stimulation operations, since the volume of rock in which pore pressure is disturbed is expected to be larger. The largest events generally recognised as having been induced by injection fall into this category (M_L 5.5 at Rocky-Mountain Arsenal; M_L 4.3 at Paradox Valley). For similar reasons, the disturbed volume is also limited for balanced circulation of geothermal systems, where the produced fluid is re-injected into the same reservoir several hundred meters away. For example, the flow field of a duplet system operating in balanced mode in an homogeneous reservoir will approximate a dipole. In practice, the presence of permeable structures such as faults or fracture zones will complicate the flow field. Thus, even for balanced systems, pressure perturbations can migrate greater distances along such structures, which are of greatest concern from the hazard point of view. A case in point are the subset of 'hydrothermal'-type geothermal systems that exploit the natural permeability of faults by drilling wells to intersect them. In these systems, injection and production wells may be several kilometres apart, and the flow between the wells will occur primarily through the natural fault systems. There have been a few recent examples of these systems where felt but not damaging earthquakes have been induced by the operation of such systems (e.g. Unterhaching near Munich, Landau in the Rhinegraben).

Returning to the EGSs, the massive 'stimulation' injections used to create permeability in the reservoir typically last for only 1-2 weeks. Such injections have routinely been performed at EGS sites since the early 70s. Given this, it is perhaps surprising that the seismic hazard associated with these operations has only recently become an issue. In large part this is because the massive fluid injections of early projects, whilst generating abundant microseismicity, did not produce events large enough to disturb the local population. Examples include the projects at Fenton Hill in New Mexico (up to 4.2 km depth; maximum M_L 1.5), Rosemanowes in Cornwall, UK (2.2 km; max. M_L 2.0), Hijiori in Japan (1.8-2.2 km; max. M_L 2.4), Bad Urach, Germany (3.5-4.5 km; max. M_L 1.8) and Soultz (3.5 km; max. M_L 2.0). It is only recently that events approaching or exceeding ML 3.0 have occurred during or shortly after injections at Soultz (4.5-5.0 km; M_L 2.9), Cooper Basin - Australia (4.2 km; M_L 3.7) and Basel (4.7-5.0; M_L 3.4). Greater depth may be a factor in promoting larger magnitudes, but it is not the only factor, since injections at the Fenton Hill and Urach EGS sites were also deep yet no felt events were generated, and injections at 6.0 and 9.0 km in the KTB main hole yielded a max. M_L of 1.5.

The maximum magnitudes generated through EGS stimulation operations to date are comparable to or smaller than the largest events recorded for other types of induced seismicity. This fact alone, whilst very relevant, does not in itself satisfy public concern about the seismic risk posed by geothermal operations. The media coverage of the Basel event arising from its location below a major city and claims for damage amounting to CHF 8M has placed the issue firmly in the spotlight, and the small-but-felt events associated with some fault-targeted hydrothermal systems has served to highlight the concern. Whilst it is important that the hazard be recognised and steps taken to mitigate it, it is equally important to place it into perspective. Seismic risk has not halted reservoir impoundment, mining, oil or gas extraction, or liquid waste injection. As with these other economic activities, the complete elimination of risk for EGS development and operation is not possible. This fact should be accepted. Nevertheless, it is incumbent upon us to find ways of assessing the risk, and develop practices that minimise it.

The hazard associated with long-term injection wells has long been recognised, at least in the USA, and the Environmental Protection Agency may require monitoring of any possible induced seismicity associated with injection operations. In Italy in the 1970's, plans to begin reinjection of geothermal fluids in regions of moderate natural seismicity were accompanied by a program to assess the impact of operations on seismicity. Reinjection of water and CO2 from oil and gas production is widespread, although the quantification of just how widespread, and whether the seismic response is monitored is difficult to assess since much of the data is not in the public domain. Mandatory monitoring of geothermal sites, whether they be EGS or hydrothermal, is certainly recommended (EGS sites invariably are equipped with monitoring networks since the information they provide is of engineering utility). However, what is really needed by the stakeholders (including local populations) in all operations that involve the injection of fluids is the development of means to estimate the seismic risk. It is sensible to distinguish between risk estimation prior to drilling, and risk assessment after drilling when there is the possibility to directly study the seismic response to injection.

Risk estimation prior to drilling is important because boreholes are very expensive to drill, and it is much easier to find investors if it can be shown asthat it is unlikely thatfor the project will to be stopped because of induced seismicity. It seems unlikely that pre-drilling injection-relating seismic risk can be estimated by constructing physical models of the underground because it is so difficult to parametrise them from surface-based geophysical exploration alone. For example, even if the location of major structures such as faults can be determined with reasonable confidence, the key variables that govern whether large earthquakes will be triggered by injection - the variation of strength and stress on proximate faults - cannot be deduced from surface measurements, nor from point-measurements of stress conducted in a borehole. A more promising approach to pre-drilling seismic hazard assessment is to examine incidences of induced seismicity and attempt to extract semi-quantitative guidelines for assessing the dependence of hazard on such variables as the distance to faults, seismically active and inactive, and the depth of the reservoir. One recent study for Europe suggests that the level of natural seismicity might present a useful index for evaluating injection-induced seismic hazard of a site.

Once an exploration well has been drilled, it is possible to perform trial injections and analyse, perhaps in real-time, the attributes of the microseismicity that is produced, such as moment-frequency relations. This greatly enriches the information that is available for seismic hazard assessment and may be a very fruitful approach that does not depend upon upon parameters of physical models that are difficult to parametrisequantify in advance.

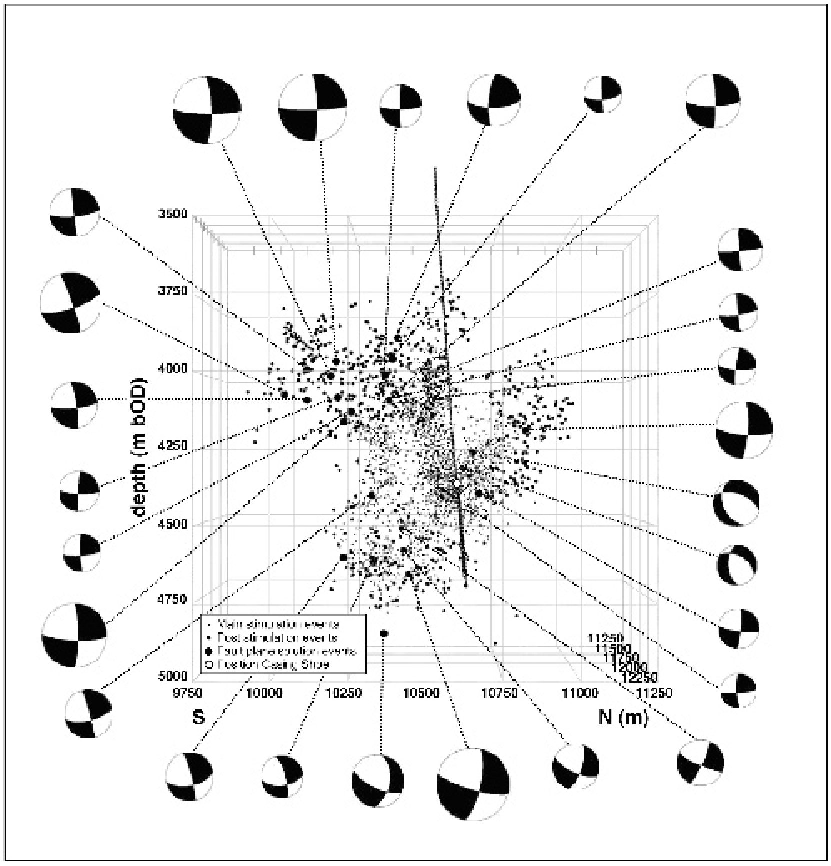

Figure 1: Seismic cloud generated during the stimulation injection into the Basel reservoir in 20068. The seismicity is a rich source of information that not only indicates the direction of preferred fluid flow within the rock mass that is needed for targeting subsequent wells, but also contains information about the failure processes underpinning the permeability enhancement. (Adapted from Häring, M.O., Schanz, U., Ladner, F. and Dyer, B.C., 2008. Characterisation of the Basel-1 Enhanced Geothermal System. Geothermics, 37: 469-495. Focal mechanisms from Deichmann, N. and Ernst, J., 2009. Earthquake focal mechanism solutions of the induced seismicity in 2006 and 2007 below Basel (Switzerland). Swiss J. Geosci., 102, 457-466.)