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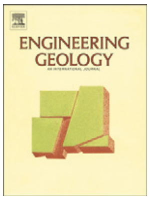

Correlations between formation properties and induced seismicity during high pressure injection into granitic rock

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ABSTRACT

We reviewed published results from six projects where hydraulic stimulation was performed in granitic rock. At each project, fractures in the formation were well-oriented to slip at the injection pressures used during stimulation. In all but one case, thousands of cubic meters of water were injected, and in every case, flow rates on the order of tens of liters per second were used. Despite these similarities, there was a large variation in the severity of induced seismicity that occurred in response to injection. At the three projects where induced seismicity was significant, observations at the wellbore showed evidence of well-developed brittle fault zones. At the three projects where induced seismicity was less significant, observations at the wellbore indicated only crack-like features and did not suggest significant fault development. These results suggest that assessments of the degree of fault development at the wellbore may be useful for predicting induced seismicity hazard. We cannot rule out that the differences were caused by variations in frictional properties that were unrelated to the degree of fault development (and it is possible that there is a relationship between these two parameters). The projects with more significant seismicity tended to be deeper, and if this is a meaningful correlation, it is unclear whether depth influenced seismic hazard through the degree of fault development, frictional properties, or some other variable. The results of this paper are not conclusive, but they suggest that there may be significant opportunity for future research on identifying geological conditions that increase induced seismicity hazard.

1. Introduction

Induced seismicity is an issue of growing importance for the exploitation of geothermal energy (Majer et al., 2007, 2011; Cladouhos et al., 2010; Evans et al., 2012), wastewater disposal (Frohlich et al., 2011; Kim, 2013; Zhang et al., 2013), CO_2 sequestration (Zoback and Gorelick, 2012), hydrocarbon production (Suckale, 2009), and other activities (McGarr et al., 2002; Hitzman, 2012). Appropriate management of induced seismicity requires estimation of induced seismic hazard.

Some methodologies for estimating induced seismic hazard are purely statistical (Bommer et al., 2006; Bachmann et al., 2011) or hybrid statistical/fluid flow models (Shapiro et al., 2007; Gischig and Wiemer, 2013). However, these methods are site-specific and must be conditioned by performing the activity for which seismic hazard needs to be assessed. Low natural seismicity does not necessarily indicate that induced seismic hazard will be low, though there is some correlation (Evans et al., 2012).

In addition to purely statistical methods, numerical simulation has been used for induced seismic hazard analysis. This may involve kinematic modeling of deformation to estimate induced stress on neighboring faults (Segall, 1989; Hunt and Morelli, 2006; Vörös and Baisch, 2009) or dynamic modeling that couples fluid flow, stresses induced by deformation, and friction evolution (Baisch et al., 2010; McClure and Horne, 2011). However, model results are dependent on assumptions and input parameters that may be challenging to estimate. For example, change in stress on a fault may be estimated, but it is unclear how this should be related quantitatively to increased hazard (due to uncertainties such as the fault stress state and frictional properties).

All approaches to induced seismicity hazard analysis, whether purely statistical, physically based, or a hybrid of both, could benefit from methodologies that relate geophysical and geological observations to hazard (e.g., Davis and Frohlich, 1993). McGarr (1976) predicted that induced seismic moment release should be proportional to the volume of fluid injected, and this has been borne out by subsequent experience (Rutledge et al., 2004; Bommer et al., 2006; Hunt and Morelli, 2006; Baisch and Vörös, 2009). However, the constant of proportionality between injection volume and moment release varies over orders of magnitude between different locations. For example, there are over 35,000 wells in the United States that have been hydraulically fractured in unconventional shale resources, and there are only a handful of

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confirmed instances of an induced event felt at the surface (page 76 of Hitzman, 2012). Induced seismicity does appear to be associated with oil and gas activities in many cases, but this is apparently due to long term fluid injection (Frohlich et al., 2011) or extraction (van Eijs et al., 2006). On the other hand, hydraulic stimulation for exploitation of geothermal resources in crystalline rock has routinely induced seismic events felt at the surface (Majer et al., 2007, 2011; Cladouhos et al., 2010; Evans et al., 2012). Even among geothermal hydraulic fracturing projects, a huge diversity in induced seismicity hazard has been observed (Table 1; Kaieda et al., 2010). More work is needed to explain how geological conditions cause these large variations in induced seismicity.

It is universally accepted that hydraulic fracturing in an oil and gas settings causes the initiation and propagation of new fractures (Economides and Nolte, 2000). However, during injection, fluid could leakoff into existing faults and cause slip (and potentially seismicity). In EGS, it is typically believed that injection predominantly causes induced slip on preexisting fractures (Cladouhos et al., 2011), though some authors have argued that there is probably more new fracture propagation than is commonly believed (McClure, 2012; Jung, 2013; McClure and Horne, submitted for publication).

For significant induced seismicity to occur: (1) faults must be oriented properly with respect to the prevailing stress field so that they slip in response to imposed changes in stress and/or fluid pressure, (2) faults must have appropriate frictional properties so that slip occurs rapidly enough to generate seismicity, and (3) faults must be large enough to host significant events.

The first requirement, appropriately oriented faults, can be understood in the context of Coulomb theory (Chapter 2 of Hitzman, 2012). It has been argued that, in general, the crust is in a state of failure equilibrium (Townend and Zoback, 2000), suggesting that nearly everywhere in the subsurface, faults are present that will slip in response to an increase in fluid pressure.

The second requirement, rapid slip, can be explained in the context of results from laboratory friction experiments. Experiments have shown that the tendency for faults to slip seismically (rapidly) or aseismically (gradually) depends on the frictional properties of the minerals contacting in the fracture walls. Rock type, temperature, and other factors affect the tendency for fractures to slip seismically or aseismically (Dieterich, 2007).

There is a significant untapped opportunity to apply the results from friction experiments to help relate induced seismic hazard to lithology and depth. For example, differences in frictional properties may be the reason why hydraulic fracturing in granite has led to much greater induced seismic hazard than hydraulic fracturing in sedimentary formations. Assessments of induced seismic hazard from fluid injection in sedimentary formations (e.g. CO_2 sequestration or wastewater disposal) would benefit from efforts to identify lithologies where fault frictional properties are most favorable for seismic slip. Zhang et al. (2013) identified an apparent correlation between induced seismicity hazard and injection into basal aquifers.

The third requirement is that faults must be large enough to host significant-sized events. Seismic imaging and stratigraphic study can be used to identify major faults in layered formations. But in nonlayered formations such as crystalline basement rock, these techniques are limited because of the lack of seismic reflectors and discernible stratigraphic offsets. A very thick fault zone is required to generate a visible reflection at significant depth in crystalline rock. Faults in the basement may not extend into the overlying sediments. Even in layered sedimentary formations, hidden faults may be capable of hosting significant induced seismicity.

In this paper, we investigate whether wellbore observations could be used to estimate induced seismic hazard by assessing the degree to which large, brittle faults are present in a formation. Wells only sample the formation locally and may not intersect the most seismically important faults. However, formations that contain large faults are likely to contain abundant faults at all levels of development, and the overall degree of fault development in the formation should be observable at the wellbore. This theory is supported by the general observation that induced seismicity typically follows a Gutenberg–Richter distribution (Baisch et al., 2009, 2010; Bachmann et al., 2011), that large faults are surrounded by sizable damage zones, and that fracture size distributions are usually found to obey a power law or exponential distribution (Chapter 3 of Scholz, 2002). The mechanistic reason is that faults develop from accumulated deformation over time, starting with small, isolated cracks, which eventually link up and develop into large, continuous features (Chapter 3 of Segall and Pollard, 1983; Scholz, 2002; Mutlu and Pollard, 2008). We refer to formations that have significantly developed faults that have linked up and formed larger features as having a high "degree of fault development."

To test whether the degree of fault development may be correlated to induced seismic hazard, we reviewed six projects where hydraulic stimulation (high rate fluid injection) was performed in granitic rock for the exploitation of geothermal energy: the projects at Cooper Basin, Australia; Soultz, France; Ogachi, Japan; Rosemanowes, United Kingdom; Basel, Switzerland; and Fjällbacka, Sweden. Projects using hydraulic fracturing to develop geothermal energy reservoirs are sometimes called "Enhanced Geothermal Systems,", or EGS. Some well-known EGS projects in granite, such as the projects at Fenton Hill, USA and Hijiori, Japan, were not included in this study because we were unable to find references that would permit an assessment of the degree of fault development. The Rosemanowes and Fjällbacka projects were performed for research purposes and targeted lower temperature reservoirs than would be typical for geothermal exploitation.

To control for the possible effect of lithology on the frictional properties of the faults, only projects in granite were included. To minimize the potential effect of fault orientation, we included only hydraulic stimulation tests where large injection pressures were used. The bottomhole fluid pressure likely reached or exceeded the minimum principal stress at every project considered, except possibly Basel, where estimates of the minimum principal stress are not available (McClure and Horne, submitted for publication). At these elevated pressures, faults with a

Table 1
Summary of experiences with induced seismicity at six EGS projects. Supporting references are given in the text below. The assessments of "volume of fluid injected" are not necessarily complete because in some projects a variety of different injection operations were carried out over many years. We have not made an extensive effort to document all of the injections performed at these projects.

	Depth range	Maximum magnitude	Temperature	Degree of fault development	Volume of fluid injected during stimulation
Basel	4.6–5.0 km	3.4	190 °C at 5.0 km	High	11,570 m^3
Cooper Basin (Habanero 1)	4.1–4.4 km	3.7	250 °C at 4.4 km	High	20,000 m^3 in 2003, 25,000 m^3 in 2005
Fjällbacka	0.5 km	−0.2	16 °C at 0.5 km	Low	400 m^3 in Fjb1 and 36 m^3 in Fjb3
Ogachi (OGC-1)	0.99–1.0 km	−1.0 except a 2.0 outlier	230 °C at 1.0 km	Low	10,140 t (approximately 9200 m^3)
Rosemanowes	1.7–2.65 km	0.16	100 °C at 2.6 km	Low	100,000 m^3 over two months in RH11 and RH12 (1982) and 5700 m^3 in RH15 (1985)
Soultz (shallow)	2.8–3.4 km	1.9	150 °C at 3.4 km	High	Two stimulations of 20,000 m^3 each
Soultz (deep)	4.5–5 km	2.9	200 °C at 5.0 km	High	Three wells stimulated at volumes between 20,000 and 35,000 m^3

wide variety of orientations are capable of slip (though not all orientations). In the "Fault orientation" section, we review literature that shows that fractures were present that were capable of slipping at the injection pressure at all six projects. A source of uncertainty is that pressure decreases with distance away from the wellbore during injection.

Fracture observations from a linear well are biased because wells are more likely to intersect faults perpendicular to their orientation than parallel to their orientation (Mauldon and Mauldon, 1997). This may particularly be an issue for vertical wells in strike-slip faulting regimes, where faults are expected to be vertical. Of the projects reviewed in this paper, Cooper Basin was in a reverse faulting regime (Baisch et al., 2006), Fjällbacka was in a reverse/strike-slip faulting regime (Wallroth et al., 1999), Soultz was in a normal/strike-slip regime (Valley and Evans, 2007), Basel, Ogachi, and Rosemanowes were in strike-slip faulting regimes (Pine and Batchelor, 1984; Häring et al., 2008), and different references specify Ogachi as either strike-slip (Kiho et al., 1999) or reverse faulting (Ito, 2003). The wells at all these projects were nearly vertical, except at Rosemanowes, where the wells were deviated around 30° (Pine and Batchelor, 1984). Despite the potential for sampling bias, the approach in this paper assumes that wellbore observations will be adequate to characterize the degree of fault development in the formation. This approach relies on the idea that there was enough natural variability in fault orientation to provide an adequate sample of the formation from a borehole, and also on the idea that a formation containing large faults (which may not be intersected by the well) will also contain numerous smaller features that provide evidence of brittle fault development.

The six projects could be placed in two categories. At three of the projects, cataclasite and evidence of well-developed faults were observed at the wellbore, and induced seismicity was significant. At the other three projects, cataclasite and well-developed faults were not observed at the wellbore, and induced seismicity was much less significant. These results seem to indicate that the degree of fault development is a good indicator for induced seismic hazard, as long as the faults are well-oriented for slip in the ambient stress field and have frictional properties favorable for seismicity.

The results cannot be considered conclusive, especially because only six projects were included in the study. It cannot be ruled out that variation in frictional properties and/or depth accounted for the variation in seismicity, nor can their effects be fully disentangled because they may be interrelated. Even though the results are not conclusive, the results of this study suggest that formation frictional properties and degree of fault development could be useful in seismic hazard assessment and that these concepts merit further study.

2. Methodology

Six EGS projects in granitic rock were reviewed. Many projects involved multiple wells and stimulations. Other than at Fjällbacka, thousands or tens of thousands of cubic meters of fresh water were injected into the wells during stimulation. At Fjällbacka, injection volume was on the order of hundreds of cubic meters. In all cases, injection was performed into uncased sections of the wellbore at rates in excess of ten liters per second. Maximum magnitudes at each project are quoted directly from literature sources.

The degree of fault development was assessed from the thickness of observed faults and/or the presence of cataclasite and ultracataclasite. In projects with a "high" degree of fault development, fault zone features with thicknesses of meters were observed, or alternatively, drilling cuttings or core showed the presence of cataclasite and ultracataclasite, consistent with the classical concept of a fault with a damage zone (Faulkner et al., 2010). In projects with a "low" degree of fault development, only crack-like features were observed with thickness no greater than a few millimeters. These categorizations are coarse, but this was intentional due to the lack of precision inherent to assembling results from many different sources.

Maximum magnitudes are reported for the period during stimulation or shortly after. At Rosemanowes and Fjällbacka, larger events occurred during long-term unbalanced circulation (more fluid injected that produced) between injector/producer pairs. Long-term unbalanced circulation is a different process from stimulation, involving the net injection of a greater volume of fluid over a larger period of time and contained in a larger spatial region. Therefore, the induced seismic hazard would reasonably be expected to be greater in these cases, and so for consistency, induced events during long-term unbalanced circulation were not included in the assessments of maximum magnitude that are reported in Table 1.

3. Results

Table 1 summarizes the results. In the following sections, the specific details of each project are reviewed.

3.1. Basel

One well was stimulated in an openhole section from 4629 m to 5000 m with 11,570 m^3 of water. The temperature at the bottom of the hole was around 190 °C. When the well was being drilled, drill cuttings were recovered containing ultracataclasite and cataclasite from five discrete zones (Kaeser et al., 2007; Häring et al., 2008). The fault thickness could not be directly observed with image logs due to enlarged borehole diameter (Häring et al., 2008), but the presence of cataclasite indicates that well-developed faults were present. Mazurek (1998) described wells that were continuously cored through the crystalline basement of northern Switzerland within distances of 20–100 km from the Basel site. In these wells, thick well-developed faults were abundant. We classified the degree of fault development as high. The maximum magnitude was 3.4 (Evans et al., 2012).

3.2. Cooper Basin

The well Habanero 1 was completed openhole in granite from 4135 m to 4421 m and stimulated twice, in 2003 and 2005. In 2003, over 20,000 m^3 was injected (Baisch et al., 2006), and in 2005, around 25,000 m^3 was injected (Baisch et al., 2009). The temperature at the bottom of the hole was around 250 °C (Baisch et al., 2006, 2009). In wellbore imaging logs, a major fault zone was identified with a core with thickness of a few meters, surrounded by subsidiary fracturing within ten meters of the core [*Doone Wyborn, personal communication*]. Flow from the wellbore localized at this major fault. A broad, horizontal region of microseismicity spread from the well at the same depth as the fault (the minimum principal stress is vertical), and a well drilled subsequently several hundred meters away intersected a large fault at the same depth as the microseismic cloud (Baisch et al., 2006). We classified the degree of fault development as high. Maximum magnitude was 3.7 (Asanuma et al., 2005).

3.3. Fjällbacka

Two wells were stimulated from openhole sections around 500 m depth. Fjb1 was stimulated with 400 m^3 of water (Wallroth et al., 1999), and Fjb3 was stimulated with 36 m^3 (Evans et al., 2012). Temperature at 0.5 km was 16 °C (Wallroth et al., 1999). One of the wells was continuously cored, and Eliasson et al. (1990) performed a detailed analysis of the mineralogy of infilling of the fractures found in the wellbore core. Hydrothermally altered fracture zones were found, but there was no report of cataclasite. We classified the degree of fault development as low. The maximum observed magnitude during or after stimulation was -0.2. During unbalanced circulation between the wells, when more fluid was injected than produced, there was an event that was felt only at the project site, but no estimate of magnitude is available (Evans et al., 2012).

3.4. Ogachi

OGC-1 was drilled and stimulated from an openhole section from 990 to 1000 m with 10,140 t (approximately 9200 m^3) (Kaieda et al., 2010). Hundreds of meters of OGC-1 and an adjacent well, OGC-2, were continuously cored. Temperature was around 230 °C at 1 km (Kitano et al., 2000). Faults with gouge less than two millimeters were abundant, but faults were not observed with thickness greater than 5 mm (Ito, 2003). Hydrothermal breccias were observed, but Ito (2003) specifically noted that these features were associated with fluidization, not shear deformation, because they contained neither cataclasites nor slickensides. A major flowing zone in the well OGC-2 was found to occur along an andesite dike, not a brittle fault structure. We classified the degree of fault development as low.

Suzuki and Kaieda (2000) discussed the results of a seismic reflection survey and a magneto-telluric survey that were performed at the Ogachi project. Their interpretation was that there is a large fault roughly 500 m from the Ogachi wells. For several reasons, we did not include this feature in our assessment of the degree of fault development. First, the fault was not observed directly and was inferred based on assumptions made in interpretation and processing. The interpretation was especially challenging because the formation is crystalline and not layered. Second, even if a structural offset exists, the seismic interpretation did not give any detail about its inner structure — whether it is a brittle fault structure, a ductile shear zone, or some other feature. Because the inferred fault is unconfirmed by direct measurements and no information is available about its inner structure, we feel this report is not enough to change our assessment, particularly because such a detailed core analysis is available from Ito (2003).

The largest event was magnitude 2.0, but the next largest event was − 1.0 (Kaieda et al., 2010). This seismic behavior was unusual compared to other projects, where Gutenberg–Richter distributions of magnitude versus frequency were observed (Baisch et al., 2009, 2010; Bachmann et al., 2011). Other than the outlier event, the magnitude–frequency distribution at Ogachi fell along a Gutenberg–Richter distribution with a b value of 1.1 [*Hideshi Kaieda*, *personal communication*].

3.5. Rosemanowes

Three wells were stimulated in openhole sections at different depths between 1.7 and 2.65 km. Temperature at 2.6 km was around 100 °C (Richards et al., 1994). An analysis of wellbore imaging logs at the Rosemanowes wells discusses only thin fractures, not thicker fault features (Pearson et al., 1989). Fracture mapping from surface and mineshafts for the project discuss only jointing, not thicker fault features (Whittle, 1989; Randall et al., 1990). Heath (1985) studied wells that were continuously cored to 700 m depth at a separate site around 10 km from the Rosemanowes project and reported faults with displacements of no more than a few millimeters. We classified the degree of fault development as low. The maximum magnitude observed during or immediately after stimulation was 0.16, but magnitude 1.7 and magnitude 2.0 events were reported during long term, unbalanced circulation between an injector and producer (when more fluid was being injected than produced) (Evans et al., 2012). In 1982, 100,000 m^3 of water was injected into RH11 and RH12 over two months. In 1985, 5700 m^3 of water was injected into RH15 (Evans et al., 2012).

3.6. Soultz (shallow)

One well was stimulated from an openhole section in granite from 2.8 to 3.4 km depth. Two stimulations were performed with 20,000 m^3 each (Evans et al., 2005). Temperature at 3.4 km was around 150 °C (Genter et al., 2010). GPK1 was extensively logged with wellbore imaging logs, and an adjacent well, EPS1, was continuously cored to 2230 m. Thick fault zones (up to 27.5 m thick) with the pattern of cataclasite and breccia in a core surrounded by intensely fractured and hydrothermally altered surrounding zones were observed in the core (Genter et al., 2000). We classified the degree of fault development as high. Maximum magnitude was 1.9 (Evans et al., 2012).

3.7. Soultz (deep)

Three wells were stimulated in openhole sections in granite from roughly 4.5 to 5 km. Temperature at 5 km was around 200 °C (Genter et al., 2010). Consistent with the shallower Soultz reservoir, the degree of fault development was high (Dezayes et al., 2010). Maximum magnitude was 2.9. The wells were each stimulated with volumes from 20,000 m^3 to 37,000 m^3 (Evans et al., 2012).

4. Discussion

4.1. Seismicity

Seismicity was significantly greater at the three projects where evidence of well-developed faults was found, Cooper Basin, Soultz, and Basel, than at the three where it was not, Rosemanowes, Fjällbacka, and Ogachi.

At the less seismically active projects, there were a handful of outlier events. At Ogachi, there was a report of a single magnitude 2.0 even though the next largest event was reported to be magnitude − 1.0. At Rosemanowes and Fjällbacka, the maximum magnitudes during stimulation were very low, 0.16 and − 0.2. But there were a few reports of larger events (magnitude 1.7 and 2.0 events at Rosemanowes and an event felt at the project site at Fjällbacka) during long term unbalanced circulation. Despite these outlier events, the overall intensity of seismicity at these projects was much less than at the more active projects. These outlier events do not fall along a typical Gutenberg–Richter distribution of magnitudes, as was observed at Cooper Basin (Baisch et al., 2009), Soultz (Baisch et al., 2010), and Basel (Bachmann et al., 2011).

4.2. Degree of fault development

The correlation between the degree of fault development and seismicity could be explained in terms of slip surface continuity or by considering the overall formation deformation that occurs in response to a unit of fluid injected.

Earthquake ruptures have been observed to terminate when they reach fault stepovers (Wesnousky, 2006). Because it is difficult for ruptures to propagate from one fracture to another, large slip events should be prevented from occurring in formations with low fault development, where large, continuous fractures are less likely to be present.

However, the difference in seismicity between the projects cannot be explained only from slip surface continuity. The overall amount of seismic moment release was orders of magnitude greater for the projects with a high degree of fault development. The projects with much lower maximum magnitudes would have required a huge number of small events (with an unusually high b value) to have matched the seismic moment release from the projects with large maximum magnitudes and typical magnitude–frequency distributions. This was not observed.

Formations with a higher degree of fault development may be expected to experience more overall shear deformation in response to injection. Preexisting flaws deform much more easily than intact rock, which is why stiffness and rock strength decrease with increasing length scale (Heuze et al., 1990). As a simple example, injecting fluid into a fault cut in a granite block loaded with shear stress could lead to significant shear deformation. Injecting fluid into an intact granite block loaded under the same conditions would lead to much less shear deformation (unless the intact rock failed in compression or tension). Analogously, highly faulted formations should experience more shear deformation in response to injection than formation that are sparsely fractured. All other factors held equal, the amount of shear deformation caused by injection should be greater for formations with greater fault development. The scaling of this relationship deserves further study. It is possible that for formations with sufficiently developed faults, further fault development does not increase the amount of deformation that will occur in response to injection. van Eijs et al. (2006) performed a statistical investigation across geologically similar formations in the Netherlands and found a correlation between induced seismicity hazard and "fault density" in the formation as estimated from interpretations of seismic reflection surveys.

4.3. Fault orientation

A Coulomb analysis can be used to demonstrate that fault orientation in the ambient stress state strongly affects the tendency for a fault to slip in response to injection (Chapter 2 of Hitzman, 2012). In the EGS projects reviewed in this paper, injection pressure reached the minimum principal stress in almost every case (see review in McClure and Horne (submitted for publication)). With such high fluid pressure, critical stress analysis may be less useful for assessing hazard because many or most fractures in the formation are likely to be able to slip. Of course, there will always be a fluid pressure gradient away from the well during injection, so fluid pressure elevation during injection will decrease as a function of distance.

Analyses performed at Soultz (Evans, 2005; Meller et al., 2012), Fjällbacka (Jupe et al., 1992), Rosemanowes (Pine and Batchelor, 1984), Ogachi (Kiho et al., 1999; Moriya et al., 2000), and Basel (Häring et al., 2008; Delacou et al., 2009) indicate that abundant fractures were present at these projects that were oriented appropriately to slip at the injection pressure. We do not have access to statistics on fracture orientation from the wellbore imaging logs at Cooper Basin, but it is certain that natural fractures slipped in response to injection at this site because there were large magnitude events and the microseismic cloud was oriented subhorizontally in a reverse faulting stress regime (Baisch et al., 2006).

In different applications, where downhole fluid pressure may be more modestly elevated, fracture orientation and stress analysis may be more useful for estimating induced seismic hazard.

4.4. Depth and temperature

In our dataset, there was a correlation between depth and induced magnitude. This was most apparent at the Soultz project, where the maximum magnitude during the stimulation of the reservoir at 3 km was lower than in the reservoir at 5 km.

One explanation could be that because stress scales linearly with depth, stress drop also scales with depth. In fact, there is some evidence that stress drop scales with depth for shallower earthquakes. Shearer et al. (2006) reviewed earthquakes in Southern California and found that the median stress drop increased from around 0.6 MPa near the surface to around 2.2 MPa at 8 km. However, the total seismic moment release and maximum magnitude at the sites reviewed in this paper varied by orders of magnitude, more than be explained solely from stress drop.

Depth might relate to seismicity in other ways. A rate and state analysis suggests that the critical patch size for unstable slip decreases for greater normal stress (Dieterich, 2007). This suggests that aseismic slip is more likely under the lower stress conditions at shallower depth, all other factors held equal.

Temperature may play a role. Blanpied et al. (1995) performed laboratory experiments on wet fractures in granite which showed that stable slip should occur above 350 °C (higher temperature than any project reviewed in this project). There were mixed results in the temperature range of 250 °C–350 °C, mostly stable slip at room temperature, and consistently unstable slip between 100 °C and 250 °C. The Fjällbacka project was within the lower temperature range where stable slip appeared to be favored (somewhere below 100 °C), and the Rosemanowes project was in the neighborhood of the (not clearly delineated) lower transition temperature between stable and unstable sliding. The Basel and Soultz projects were within the temperature range consistent with unstable slip. The Cooper Basin and Ogachi projects were approaching the upper temperature range where there were mixed results indicating the possibility of stable slip. Application of these laboratory experiments should be considered highly imprecise because variations in granite mineralogy, fault gouge, hydrothermal alteration, and other factors could lead to considerable differences between the experiments and in-situ conditions.

A final possibility is that deeper formations are more likely to contain well-developed faults because they are under greater stress (though their depth is unlikely to have been constant over geological time), and perhaps deformation at greater stress is more likely to contribute to rock failure and fault zone development. To fully disentangle this issue, more data points would be needed, either shallow projects with well-developed faults or deep projects in formations without well-developed faults.

4.5. Seismic and aseismic slip

Because all projects reviewed were in granitic rock, we hoped to control for variations in the frictional properties of the fractures in the formations. However, we cannot independently verify that the frictional properties of the fractures in these formations were the same. The frictional properties of the faults could be related to the variation in composition of the different granites, different hydrothermal alterations and fracture infilling mineralogies, or different temperatures and depths. It is also possible that well-developed cataclasite fault cores in granite have frictional properties that are especially favorable for seismic slip. These issues could only be addressed with careful studies specifically directed at addressing the frictional properties of fractures in the individual formations. Variance of frictional properties of the formation has received little attention in the induced seismicity literature, though Zoback et al. (2012) discussed this possibility with respect to variations in microseismicity during hydraulic fracturing of shale.

Several authors have argued that aseismic deformation must have taken place at the shallow Soultz reservoir (Cornet et al., 1997; Evans, 1998). Caliper logs indicated that faults had experienced greater shear offsets greater than could be explained from the total seismic moment release. It seems plausible that the greater maximum magnitude observed in the deeper Soultz reservoirs could be related to the frictional properties of the faults at different depths. This would suggest that even among formations with well-developed faults, variations of frictional properties will strongly affect induced seismicity hazard.

4.6. Spatial continuity

If our hypotheses are correct that the degree of fault development can be considered a formation property, it can be estimated from wellbore observations, and it can be related to seismic hazard, it would be useful to understand the spatial continuity of "degree of fault development." During hydraulic fracturing, the region of fluid pressure increase is relatively localized around the wellbore. But for long term injection (e.g., wastewater disposal, CO_2 sequestration, or unbalanced circulation in an EGS injector/producer pair) the region of pressure perturbation could spread significant distances from the wellbore. In these cases, assessments of the degree of fault development from observations made at the wellbore may be less reliable.

Analyses have shown induced seismicity at individual sites following predictable statistical behavior, such as the linear relationship between injection volume and moment release (Rutledge et al., 2004; Bommer et al., 2006; Shapiro et al., 2007; Bachmann et al., 2011). But since these statistical relationships are highly variable between sites, determining the region where statistical stationarity can be assumed becomes an important issue. If a region of stress and/or pressure perturbation is growing over time, it will become increasingly likely that the pressure perturbation will reach regions of the subsurface that behave statistically differently. These transitions may not necessarily be easy to predict. Variations in lithology could potentially cause breaks in stationarity, as could faults that have formed along preexisting interfaces between lithologies. Outlier events were observed at Rosemanowes and Ogachi, and one possible explanation for these events is that the fluid pressure perturbation reached more distant faults that had statistically different behavior than the faults sampled near the wellbore.

As discussed in Section 3.4, a detailed core analysis at Ogachi indicated a low degree of fault development (Ito, 2003), but a seismic reflection survey was interpreted to indicate that a large fault exists 500 m from the wells. One interpretation could be that the inferred fault caused the outlier event at Ogachi and that it behaves statistically differently than the formation immediately surrounding the wells.

4.7. Injection volume

There was no apparent correlation between injection volume and maximum induced magnitude. At a particular site, increasing injection volume would be expected to increase overall seismic moment release and maximum magnitude. However, when comparing between projects, no correlation is apparent, evidently because site-specific factors overwhelmed the effect due to injection volume.

5. Conclusions

In this paper, we reviewed six projects where hydraulic stimulation was performed in granitic rock. Even though similar injection volumes were used (except Fjällbacka, where a lower volume was used) and the formations contained fractures well-oriented to slip at the injection pressure, there was striking variability in the magnitude of induced earthquakes. With the limited data, it is impossible to draw firm conclusions. However, there was a correlation between the degree of fault development observed at the well and the induced seismic deformation. We cannot rule out that variations in the frictional properties of the faults in the formations caused the observed variability (or that frictional properties are related to the degree of fault development). Comparison with laboratory experiments suggests that temperature may play a role, though the effect on the projects discussed in this paper is unclear. The three projects with the greatest seismicity and degree of fault zone development were also the deepest projects. From the six projects in this comparison, the relationships between depth, degree of fault development, temperature, and induced seismicity cannot be disentangled.

To our knowledge, prediction of induced seismic hazard by characterizing the degree of fault development based on wellbore observations has not previously been proposed in the literature. At many projects, measurements are not taken that would make such characterizations possible. Wellbore imaging logs, mud logs, and (if practical) wellbore core can be used to characterize the degree of fault development observed at the wellbore. Imaging logs can identify large features, and core and mud logs can be used to identify the presence of cataclasite. The results of this study suggest that this approach deserves further consideration, and operators should attempt to characterize the degree of fault development whenever feasible. Characterizing the degree of fault zone development may have other uses, such as helping understand flow and fracture network connectivity in a reservoir. The variability in seismicity between the sites reviewed in this paper may also be related to frictional behavior, another concept that has rarely been discussed in the induced seismicity literature but which has significant promise to improve induced seismicity hazard assessments.

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