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Fatigue hydraulic fracturing by cyclic reservoir treatment enhances permeability and reduces induced seismicity

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SUMMARY
The occurrence of induced seismic events during hydraulic fracturing of reservoirs to enhance permeability is an unavoidable process. Due to the increased public concern with respect to the risks imposed by induced seismicity, however, the development of a soft stimulation method is needed creating higher permeability with less induced seismicity. We use a discrete element model of naturally fractured rock with pore fluid flow algorithm in order to analyse two scenarios of high-pressure fluid injection (hydraulic fracturing) at depth and associated induced seismicity. The ratio of pumped-in energy to released seismic energy is in agreement with field data. Our results suggest that cyclic reservoir treatment is a safer alternative to conventional hydraulic fracture stimulation as both, the total number of induced events as well as the occurrence of larger magnitude events are lowered. This work is motivated by results of laboratory triaxial indenter tests on granite rock samples where continuous loading leads to a wide fracture process zone while cyclic treatment with frequent starting and stopping of loading fatigues the rock, resulting in smaller damage volume and more persistent fracture growth.

Key words: Geomechanics; Fracture and flow; Seismicity and tectonics.

1 INTRODUCTION
Hydraulic stimulation of rock mass at depth is an essential component to enhance permeability in the development of hydrocarbon and geothermal reservoirs (MIT Report 2006; Majer et al. 2007). An unavoidable by-product of hydraulic stimulation, however, is the generation of induced seismic events (Suckale 2009) which became a major concern in particular for geothermal sites near densely populated areas (Deichmann & Gardini 2009). The stimulation of the geothermal site in the suburb of Basel in Switzerland for example, induced a seismic event with moment magnitude, $M_w$ 3.2 which finally stopped the project. This event was, in particular in Europe, the nucleus of an on-going discussion on induced seismicity not only for hydraulic fracturing (HF) at geothermal sites, but also for the potential risk of induced seismicity in general (Giardini 2009).

Since then, several approaches were proposed that potentially lower the occurrence probability of induced seismic events (Bommer et al. 2006; Shapiro et al. 2010; Barth et al. 2013). These approaches have in common that they are based on a recorded catalogue of induced seismicity and thus can only be applied in real-time during the stimulation. Furthermore, since the recorded seismicity is analysed with either empirical laws (Bachmann et al. 2012) or with a point source of constant or increasing pressure (Dinske & Shapiro 2013), these approaches cannot provide a priori practical recommendations to the reservoir engineer of how to perform the stimulation experiment in order to lower the released seismic energy and enhance permeability at the same time.

To overcome these problems, one can use hydro-mechanical coupled, discrete element models which not only help to understand the mechanics of fluid-induced seismicity, provide insights on the relationship between seismicity, stress field, damage pattern and propagating fluid front (Zhao & Young 2011), but also have a priori predictive power. Therefore, we propose to use the forward hydro-mechanical coupled model with discrete element-fracture network of Yoon et al. (2013). This model is able to (1) simulate injection in fractured reservoirs with arbitrary fluid injection pressure schemes, (2) propagate mode I (tensile) and mode II (shear) fractures, and (3) generate fluid-induced seismicity catalogues. This model allows testing of different stimulation scenarios with the same initial conditions in terms of rock properties and in situ stress. In particular, cyclic stimulation is tested versus the established, continuous stimulation where the injection pressure is increased in steps (e.g. Evans et al. 2005). During cyclic treatment fluid injection is stopped frequently to allow for relaxation of peak stress at the fracture tip (2-D)/front (3-D).

The motivation for testing cyclic stimulation is derived from laboratory triaxial indenter tests of granite cores (Zang et al. 1998, 2002). These tests indicate that displacement-controlled loading,
i.e. the monotonic increase of load with time (Figs 1a–c, Zang et al. 1998) generates a wider fracture process zone with more acoustic emissions count (seismic energy) as compared to cyclic loading, i.e. constant loading interrupted with multiple stopping phases of no further deformation (Figs 1e–g, crack-rate-controlled tests, Zang et al. 2002) which results in a narrow zone of tensile and shear fractures (Zang et al. 2000). In the former test, the fracture process is controlled by the short adaption times of peak stresses that prevent the locating of the optimum growth path at the fracture tip/front. In the latter test, the frequent starting and stopping of loading fatigues the rock, resulting in smaller damage volume and more persistent fracture growth (Figs 1e–g). We translate the results of these laboratory tests into two different stimulation schemes. The first (Figs 1a–c) with monotonically increase of load resembles the continuous scheme where fluid injection rate is increased in steps (Fig. 1d). The second one (Figs 1e–g) we name cyclic stimulation where fluid injection rate is also increasing, but interrupted frequently with low fluid injection rate intervals (Fig. 1h).

2 SYNTHETIC CRYSTALLINE GEOTHERMAL RESERVOIR MODEL

A 3-D schematic view of the fluid injection in naturally fractured geothermal reservoir and horizontal cross section at specific target depth is shown in Fig. 2(a). In the 2-D simulated reservoir section (2 km × 2 km in size, Fig. 2b), the intact rock matrix part is represented using enhanced parallel bond model of the software PFC2D (Itasca 2012). The discrete elements are 20–30 m in diameter and the particle ensemble has strength, stiffness and deformation characteristics calibrated against Soultz-sous-Forêts granites. The pre-existing fractures are simulated by a smooth joint contact model (Fig. 2b). The mechanical property data of the embedded discrete fractures are taken from crystalline rock at Forsmark Sweden (Hökmark et al. 2010). A hydro-mechanical coupling scheme is implemented that enables fluid flow driven bond breakages in mode I (tensile) and mode II (shear) failure, following the Mohr-Coulomb criterion. The applied in situ stresses are those at 4 km depth (\(\sigma_{H} = 75\), \(\sigma_{h} = 60\) MPa) in Soultz-sous-Forêts (Cornet et al. 2007, their eq. 1a–c). Bond breakage results in seismic energy radiation from which seismic source information is retrieved, e.g. magnitude and focal mechanisms of mode I+II failure of rock matrix (Hazzard & Young 2002, 2004; Zhao & Young 2011; Yoon et al. 2012) and mode I+II failure of pre-existing joints (Yoon et al. 2013). Along the model boundaries a ~150 m wide zone is assigned with high viscous damping properties to model energy absorption (Fig. 2b). This concept is taken to exclude side effects on bond breakages coming from reflected kinetic seismic wave energy at the model boundaries. During fluid injection in the centre of the model, the onset of tensile and shear fractures of intact rock (enhanced parallel bonds) and pre-existing joints (smooth joint contacts) are governed by Mohr-Coulomb failure criterion (e.g. Labuz & Zang 2012). More details of the model and parameters can be found in the supplementary material.

3 STIMULATION SCENARIOS AND FLUID-INDUCED SEISMICITY

In Fig. 3, we present the results of the two stimulation scenarios analysed. The left-hand side row (Figs 3a–e) shows the continuous stimulation where the flow rate is increased in three steps over 6 hr (1011 s−1 for the first 2 hr, 12.51 s−1 for the next 2 hr and 151 s−1 for the last 2 hr; Fig. 3a). The corresponding fluid pressure at the injection point is normalized to the fracture breakdown pressure (FBP) that is estimated from the classical HF theory (e.g. Zang & Stephansson 2010, their eq. 7.3), see Fig. 3(a) red line. Early seismic events occur when FBP is reached (Figs 3a and b). The 2-D nature of the model limits direct comparison with 3-D field injection tests, such as fluid injection rate and total fluid volume. Moment magnitudes (\(M_{s}\)) of induced seismic events are computed from mode I and mode II failures in the model reservoir. The related
Figure 3. Results of continuous, step-wise fluid injection (a–e), and cyclic injection (f–j). Time variation of (a, f) injection rate (1 s\(^{-1}\)), normalized fluid pressure at injection point, \(P_{\text{inj}}/F_{\text{BP}}\); (b, g) Moment magnitude (\(M_w\)) and radiated seismic energy, \(E_s\) (MJ) of the induced events; \(E_s^{\text{max}}\) is the maximum \(E_s\) of a single event; (c, h) Time variation of rate of pumped-in hydraulic energy, \(E_p\) (MJ) and cumulative radiated seismic energy, \(E_s^{\text{cum}}\) (MJ). Shaded area represents total amount of pumped-in energy, \(E_p^{\text{cum}}\) (MJ); (d, i) Fracture permeability, \(k\) (Darcy, \(10^{-12}\) m\(^2\)) computed from the average hydraulic apertures of the induced events (\(e_{avg}^2/12\)); (e, j) Spatial distribution induced seismicity. Stars are induced events with moment magnitude, \(M_w > 1.0\) which are indicated also in (b, g).

Radiated seismic energy (\(E_s\)) presented in Fig. 3(b) is calculated from moment magnitudes using the relation

\[
\log_{10}(E_s) = 4.8 + 1.5M_w
\]

from Gutenberg & Richter (1956) and Kanamori (1977). As observed in field experiments the peak seismic activity coincides with the termination of fluid injection (Dorbath et al. 2009). Sometimes, larger magnitude events occur in the post-shut-in phase (Baisch et al. 2010). In Fig. 3(c), the time variation of hydraulic pumped-in energy rate (\(\Delta E_p/\Delta t\)) and the cumulative seismic radiated energy (\(E_s^{\text{cum}}\)) is shown. At the time fluid injection terminated, the total pumped-in energy is 25 676 MJ while the seismic radiated energy generated is only 45 MJ in the model reservoir. Most of the induced seismic energy is released in the time interval after the fluid pressure at the injection point has dropped (Fig. 3c, time 6.5 to 8.5 hr). In this interval, the cumulative value of radiated seismic energy increases from 45 MJ to 150 MJ, the latter value accounts for 80 per cent of the total value (188 MJ). Computation of seismic moment magnitude, seismic energy and permeability is described in the Supporting Information.

In Fig. 3(d), the permeability evolution with time is shown computed from average hydraulic aperture of induced fracture events. After a prominent peak in permeability during the stimulation the value remains after shut-in at around 590 Darcy (\(10^{-12}\) m\(^2\)). Fig. 3(e)
shows the spatial distribution of all induced seismic events displayed in Fig. 3(b). In analogy to the result of the laboratory rock tests (Fig. 1, upper row) the induced seismicity affects a wider area and six events with $M_w > 1.0$ are detected (red stars in Figs 3b and e). In total, 785 induced events are observed; 643 of these occur after the shut-in of fluid injection.

The right-hand side column of Fig. 3 shows results of the cyclic stimulation scenario where fluid flow rate is also increasing with time, but interrupted frequently (Figs 3f–j). The flow rate is lowered to a residual value of 11 l s$^{-1}$ before each step-wise increase from 51 l s$^{-1}$ initial to 151 l s$^{-1}$ final value (Fig. 3f). Most seismic activity is related to the pre-shut-in period of the stimulation before the fluid pressure at the injection point decays exponentially (Figs 3f and g). The largest magnitude induced seismic event occurs at the end of the fourth cycle (Fig. 3g, time 11.5 hr). The time variation of energy partition for cyclic stimulation is presented in Fig. 3(h). Even though the total cumulative pumped-in energy value is higher after the cyclic injection (35 714 MJ) as compared to the continuous, step-wise injection (25 676 MJ), the cumulative seismic energy released in cyclic stimulation (Fig. 3h, 41 MJ) is only a fraction (22 per cent) of the corresponding value in continuous fluid stimulation (Fig. 3c, 188 MJ). The faster relaxation of fluid pressure after shut-in of the continuous injection (Fig. 3b), results in a denser cluster of induced events with larger crack apertures for fluid path ways.

The increase in permeability during cyclic treatment (Fig. 3i) is not as steep as for the continuous step-wise fluid injection (Fig. 3d), but at the end of the treatment the remaining value of 660 Darcy is slightly higher compared to the value of 590 Darcy after continuous injection (Fig. 3d). Fig. 3(j) shows the spatial distribution of all induced seismic events of the cyclic injection displayed in Fig. 3(g). In analogy to the result of the laboratory tests (Fig. 1, lower row) the induced seismicity affects a substantially smaller area and only one event with $M_w > 1.0$ is detected (red star in Figs 3g and j). The cyclic injection generates an Y-shape seismicity pattern with early events close to the injection point (Figs 3g and j). The branching of the fracture propagating towards North occurs parallel and conjugate to the pre-existing fracture network. Fracture growth towards South is almost parallel to the maximum compressive stress orientation. The cyclic injection generates very few post-shut-in events in particular for induced events with higher magnitudes (Fig. 3g). In total, only 244 induced events are observed in cyclic injection, from which 76 occur in the post-shut-in phase.

### 4 Hydraulic versus Seismic Radiated Energy

In Table 1, we summarize the main characteristics of the two simulated injection scenarios. While in the continuous, step-wise injection scenario 270 m$^3$ of fluid is pumped into the model reservoir, the cyclic testing involves injecting 374 m$^3$. The total pumped-in hydraulic energy ($E_p$) after the continuous injection is 25 676 MJ and 35 714 MJ after the cyclic injection. Only 244 induced events are observed during cyclic stimulation while 785 induced events are generated in the continuous injection scenario. The maximum occurrence rate of induced events drops to about half the value from continuous to cyclic injection. The cumulative seismic radiated energy ($E_{\text{r,cum}}$) in the continuous and cyclic injections is 188 and 41 MJ, respectively. This means that about 0.1 per cent of the $E_p$ has been converted into $E_r$ in the cyclic injection, while seven times more was generated in the continuous injection. Therefore, we interpret that the cyclic treatment is a softer stimulation strategy (in terms of seismic energy radiated) as compared to the continuous, step-wise increase of the flow rate used in geothermal field operation thus far.

The permeability enhancement for both injection scenarios is documented in comparable average residual values at the end of the model runs. Due to the nature of cyclic treatment, peak and residual values are reached at a later stage as compared to the continuous injection case. Based on our result from laboratory testing on granite and interpretation (Fig. 1), the underlying process operating in situ can be compared with the concept of fatigue fracturing in material sciences. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. During cyclic loading, the nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material. Thus, the cyclic treatment (Figs 3f–j) seems to generate a kind of larger scale fatigue hydraulic fracturing (FHF) process which leads to permeability increase as observed in conventional HF with the advantage to convert less pumped-in energy into unwanted induced seismic radiated energy. This interpretation describes the short-term (hours, days) effect of cyclic hydraulic treatment on larger scale rock fractures (length ~100 to 500 m) as opposed to long-term (weeks, years), chemical processes operating at fracture tips (grain scale), so-called subcritical crack growth (e.g. Nara et al. 2013). However, we note that this observation can be overprinted by silent hydro-shears and aseismic deformation operating in naturally fractures of stimulated reservoirs.

In Fig. 4, induced seismic radiated energy ($E_r$) versus pumped-in hydraulic energy ($E_p$) from the simulations obtained in this numerical study is compared with field data. We use data from European geothermal sites in Bad Urach, Basel and Soultz-sous-Forêts (Fig. 4, red squares with numbers) and data from Canadian shale gas fracturing (Fig. 4, blue circles). Squares denote that the $E_r$ is calculated using only the largest induced event ($M_{\text{w,max}}$), whereas circles indicate cumulative values for $E_r$ of all induced events during stimulation. We convert the local magnitude $M_l$ to the moment magnitude $M_w$ using the empirical relation

$$M_w = 0.0376 M_l^2 + 0.646 M_l + 0.53 \quad (2)$$

of Grünthal et al. (2009). Fig. 4 shows that both, fatigue cyclic and continuous step-wise injection generate a degree of efficiency ($E_r/E_p$ in per cent) that is in agreement with field observations (about
Figure 4. Relation between total pumped-in energy ($E_p$) and total radiated seismic energy ($E_s$). Red squares with numbers indicate calculations for European geothermal fields that are based on the largest event only. Blue circles indicate calculations from shale gas reservoirs that are based on all induced events (Boroumand & Dave 2012). For comparison the results of the two stimulation models are shown for both calculation procedures of the released seismic energy (S and C for step-wise continuous and cyclic, respectively). Dashed lines are degree of seismic efficiency, i.e. the ratio of seismic to pumped-in energy in percentage values. Data points (1–10) are computed from field data listed in Baisch & Vörös (2009).

0.01 per cent in shale gas fracturing, and up to about 1 per cent in geothermal.

5 CONCLUSIONS

We use a hydro-mechanical model to investigate different injection scenarios in order to test which stimulation is efficient in terms of permeability enhancement, but lowers the radiated seismic energy. Our 2-D model is capable of generating induced seismic event catalogues from tensile and shear fractures of different stimulation scenarios. The model results reproduce key observations in geothermal fields. The extension of the seismic cloud is in the orientation of maximum horizontal stress, the peak seismicity is associated with abrupt changes of injection rate and larger magnitude events occur in the post-shut-in phase. The ratio of pumped-in energy versus seismic energy radiated is in the order of field data.

Based on our findings of the damage pattern in laboratory tested granite, we propose a kind of larger scale (∼100 m) FHF process operating in situ during cyclic treatment of rock mass. The cyclic injection scheme has a degree of efficiency of radiated seismic energy with respect to the pumped-in energy of about 0.1 per cent while in conventional, continuous flow rate injection this ratio is seven times larger. The idea seems promising to be applied in the field not only for geothermal, but also for other energy technologies [CO$_2$ sequestration, oil and (shale) gas] where minimization of induced seismicity is needed.

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REFERENCES


**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

- Supplementary material for Fig. 2.
- Supplementary material for Fig. 3 (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggt301/-/DC1).

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