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Probability of a given-magnitude earthquake induced by a fluid injection

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Abstract

[1] Fluid injections in geothermic and hydrocarbon reservoirs induce small earthquakes ($-3 < M < 2$). Occasionally, however, earthquakes with larger magnitudes ($M \sim 4$) occur. We investigate magnitude distributions and show that for a constant injection pressure the probability to induce an earthquake with a magnitude larger than a given value increases with injection time corresponding to a bi-logarithmical law with a proportionality coefficient close to one. We find that the process of pressure diffusion in a poroelastic medium with randomly distributed sub-critical cracks obeying a Gutenberg-Richter relation well explains our observations. The magnitude distribution is mainly inherited from the statistics of pre-existing fracture systems. The number of earthquakes greater than a given magnitude also increases with the strength of the injection source and the tectonic activity of the injection site. Our formulation provides a way to estimate expected magnitudes of induced earthquakes. It can be used to avoid significant earthquakes by correspondingly planning fluid injections.

1. Introduction

[2] Injections of fluids through a borehole into surrounding rocks are used for developments of hydrocarbon and geothermal reservoirs. They usually cause microseismic reactivation of rocks [*Pearson*, 1981; *Zoback and Harjes*, 1997; *Fehler et al.*, 1998; *Rutledge et al.*, 2004; *Shapiro et al.*, 2006a].

[3] If the pore pressure resulting from a fluid injection is larger than the minimum principal stress in low permeable rocks, a hydraulic fracture is created [*Economides and Nolte*, 2003]. In this case the properties of the induced seismicity are controlled by the parameters of the process of hydraulic fracture growth [*Rutledge et al.*, 2004; *Shapiro et al.*, 2006b].

[4] If the pore pressure resulting from an injection is smaller than the minimum principal stress, (in the absence of a major hydraulic fracture this is usually the case at distances

larger than several tenths of meters from the injection source), then in a first approximation, the behavior of seismicity triggering in space and time is controlled by a process of relaxation of stress and pore pressure perturbations initially created at the injection source. This relaxation process is governed by the pressure diffusion in fluid saturated rocks [e.g., *Shapiro et al.*, 2002]. Injecting a fluid causes the pressure in the connected pore space of rocks to increase, thereby reducing the effective normal stress. This yields to sliding along pre-existing, favorably-oriented, subcritical cracks [*Rutledge et al.*, 2004]. Sometimes events of magnitude larger than two but as a rule less than four have been observed by such injections [*Ake et al.*, 2005; *Majer et al.*, 2007].

[5] So far it has been unclear what is the probability to induce these larger events and what are the natural and man-made factors controlling their probability [*Majer et al.*, 2007].

2. Observations

[6] To analyze functional dependencies of given-magnitude probabilities we propose to consider the cumulative number of microseismic events with a magnitude larger than a given one as a function of the elapsed injection time, $N_{\geq M}(t)$. A large number of events (more than 100 or so to allow a meaningful statistics) and steady-state parameters of the injection are optimal conditions for this kind of study.

[7] We analyzed available data sets from two different locations with different spatio-temporal scales, which both reasonably well satisfy the conditions mentioned above. These are induced seismicity data collected at Ogachi (Japan) and Paradox Valley (USA) injection sites.

[8] In 1991 a water injection was performed at Ogachi geothermic site in a well drilled to a depth of 1000 m into granodiorite. More than 10000 m^3 of water were injected under quite stationary conditions, which induced a microseismic event cloud of 500 m thickness and up to 1000 m length [*Kaieda et al.*, 1993]. Figure 1 shows injection pressures, flow rates and magnitude distributions with time of the Ogachi injection experiment in 1991. The magnitudes were determined by measuring velocity amplitudes and alternatively seismogram oscillation durations [*Kaieda and Sasaki*, 1998]. Magnitude statistics were biased by the performance of the observation system and processing in the magnitude ranges $M \leq -2.5$ and $M \geq -1.5$. The $N_{\geq M}(t)$ plots in Figure 1 show high sensitivity to changes in the injection pressure. When the injection pressure is close to constant, the $N_{\geq M}(t)$ functions are nearly linear in the bilogarithmic plot. The steps between lines corresponding to different magnitudes M are regularly distributed and time-independent. A systematic decrease of these steps for small magnitudes is possibly explained by the incompleteness of observations of small magnitude events. In 1993 an injection into two open borehole sections (711–719 m and 990–1000 m) was accomplished at Ogachi injection site. The magnitude distributions exhibit a similar behaviour as for the experiment in 1991. The

magnitude range unbiased by the observation system was −2 ≤ M ≤ −1 for the injection in 1993.

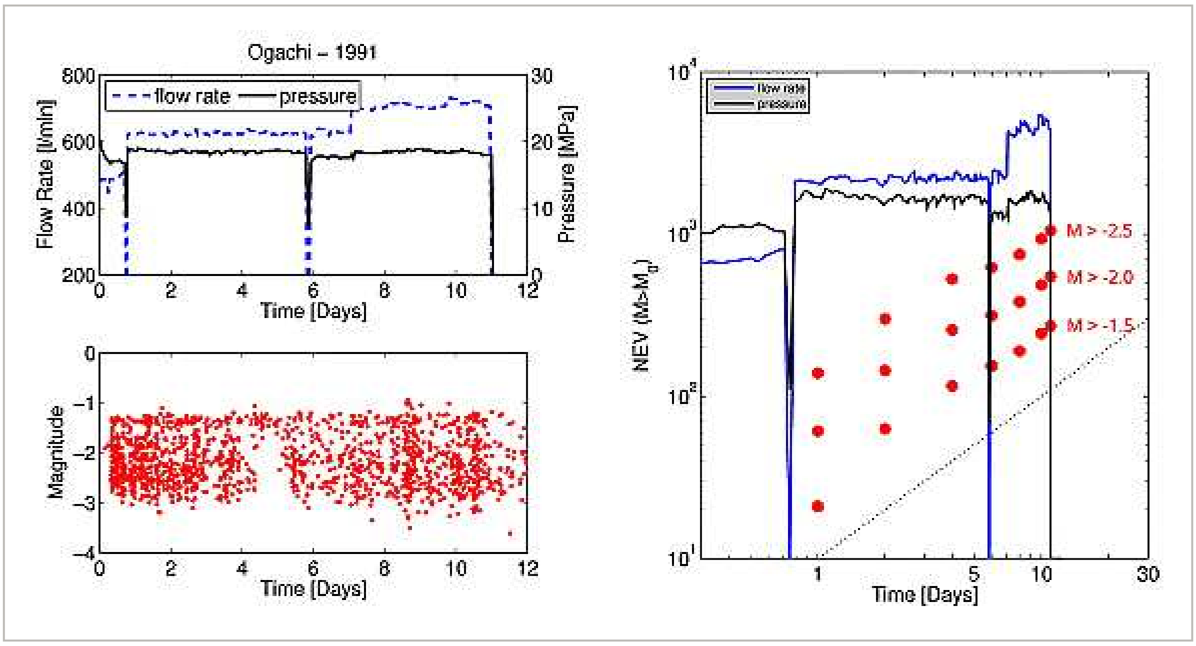

Figure 1

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Data of the Ogachi 1991 borehole injection experiment. (top left) Water injection rate and wellhead pressure as functions of injection time. (bottom left) Distribution of microearthquake magnitudes with injection time. (right) Bilogarithmic plot of cumulative number of microseismic events with magnitudes larger than indicated ones as functions of injection time. For convenience, a straight line with the slope 1 and fluid injection data in the logarithmic time scale are shown.

[9] At Paradox Valley, the injection was performed in various irregular phases between 1991 and 2004 in order to reduce salinity in the Colorado River [*Ake et al.*, 2005]. The brine was injected into the fractured Leadville Limestone formation at a depth of 4.3 km below the surface. The injection became regular in 1996. However, injection rate and injection pressure are characterized by significant variations. For example, a 20-day shut down was introduced at intervals of 6 months, starting in 2000. The microseismic event cloud extended to more than 15 km from the injection borehole. More than 2 million seismic events with magnitudes M = −3.0 or greater and about 4000 events with a magnitude larger than −0.5 were induced. The largest event had a magnitude M = 4.3. Figure 2 (left) indicates that the magnitude statistics were biased by the observation system and processing for magnitudes M ≤ 0.5.

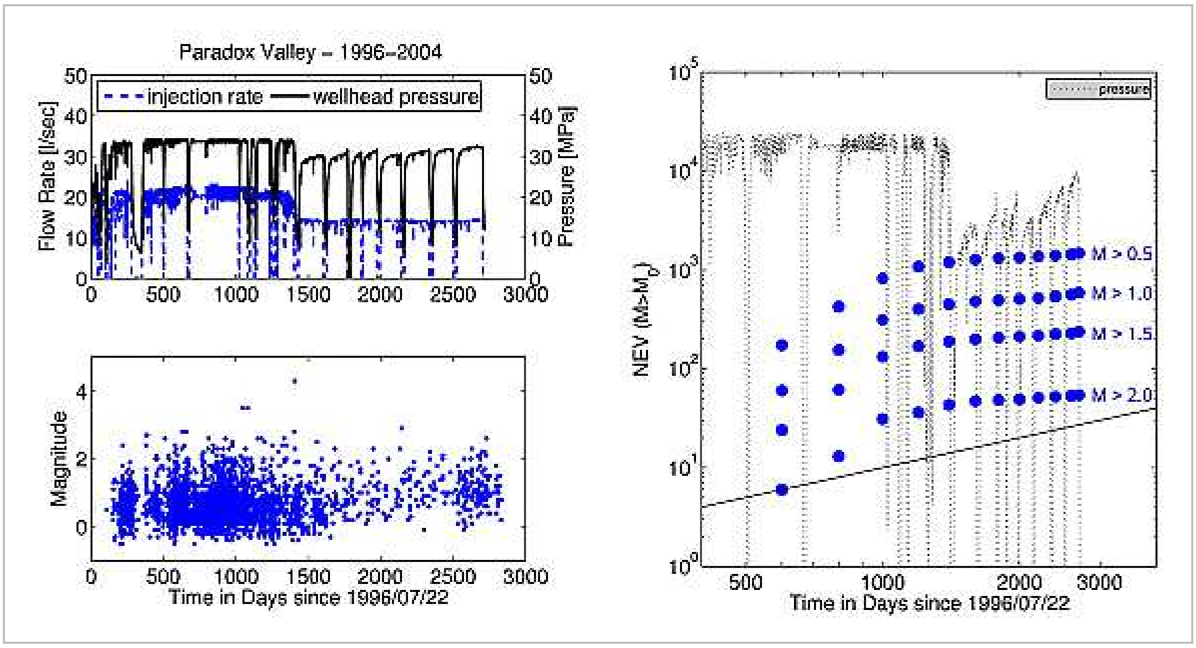

Figure 2

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The same as Figure 1, but for the Paradox Valley brine injection experiment.

[10] Though being one order of magnitude larger on the spatial scale and two orders of magnitude larger on the temporal scale, the microseismic activity in Paradox Valley shows the same features as described above for the Ogachi injections.

3. Theory

[11] In the following we propose a model based on a pore-pressure relaxation mechanism to explain the observed features of the frequency-magnitude distributions. In spite of its simplicity and schematic character this model is able to explain the observed phenomena and to identify important factors parametrizing magnitude probabilities of fluid induced seismicity.

[12] Let us consider a point pressure source in an infinite, homogeneous, permeable, porous continuum. We assume that the hydraulic diffusivity of this continuum is independent of position and time. Due to a fluid injection and the consequent process of pressure relaxation, the pore pressure p changes throughout the pore space. Furthermore, we assume that a random set of pre-existing cracks (defects) is statistically homogeneously distributed in the medium and is characterized by its volume concentration ξ. For simplicity the cracks do not mutually interact. Each crack is characterized by an individual critical value C of the pore pressure necessary in accordance with the Coulomb failure criterion for the occurrence of a slip event (i.e., an earthquake) along such a defect. This critical pressure C is randomly distributed on the set of pre-existing cracks. Statistical properties of C are supposed to be independent of the spatial locations (i.e., $C(\boldsymbol{r})$ is a statistically homogeneous random field). If at a point $\boldsymbol{r}$ of the medium (with a pre-existing crack) pore pressure $p(t, \boldsymbol{r})$

increases with time, and at time t_0 it becomes equal to $C(\mathbf{r})$, then this point is considered as a hypocenter of an earthquake occurring at time t_0. For simplicity we assume that no earthquake will be released in this point again. This is equivalent to the assumption that stress corrosion, tectonic load and deformation, and other phenomena related to rate and state dependent friction [*Dietrich*, 1994; *Segall and Rice*, 1995; *Kanamori and Brodsky*, 2004] which lead to recharging of critical cracks are much slower than the diffusion process of pore pressure relaxation (see also discussion by *Rothert and Shapiro* [2007]).

[13] Under these assumptions the probability of an earthquake to occur at a given time and point (with crack) is equal to $W_{ev}(C(\mathbf{r}) \le p(t, \mathbf{r}))$, which is the probability of the critical pressure to be smaller than or equal to the pore pressure $p(t, \mathbf{r})$. If the pore pressure perturbation caused by the fluid injection is a non-decreasing function (which is the case for step-function-like injection pressures) this probability is equal to $W_{ev} = \int_0^{p(t,\mathbf{r})} f(C)dC$, where $f(C)$ is the probability density function of the critical pressure. The pore pressure $p(t, \mathbf{r})$ is a solution of an equation describing the process of pore pressure relaxation. The seismic criticality of rocks is defined by the quantity C. The larger C the more stable is a pre-existing crack. Recently, *Rothert and Shapiro* [2007] have shown that C is usually of the order of 10^2–10^6 Pa. Comparable pressure thresholds have also been found for the dynamic triggering of earthquakes in geothermal areas [*Brodsky et al.*, 2000; *Gomberg et al.*, 2001]. The probability density function $f(C)$ is approximately a uniform function $f = 1/A$, where A is a normalizing constant, $A = C_{max} - C_{min}$, with C_{max} and C_{min} the maximum and minimum possible critical pressures of pre-existing cracks, respectively. Usually C_{max} is several orders of magnitude larger than C_{min}, and thus $f(C) \approx 1/C_{max}$, resulting in $W_{ev} = p(t, \mathbf{r})/C_{max}$. Therefore the event probability is proportional to the pore pressure perturbation. Since the spatial density of events is proportional to the event probability, it is also proportional to the pore pressure perturbation. Such a distribution of micro-earthquake spatial density is indeed observed [*Shapiro et al.*, 2005].

[14] It is apparent that the magnitude probability is an increasing function of the total event number. The latter is given by the product between the crack concentration ξ and the spatial integral of the probability W, where the integral is computed by substituting a pore pressure relaxation law into the probability.

[15] The pore pressure relaxation in a porous elastic medium surrounding the injection source is described in the first approximation by the differential equation of diffusion. We approximate the borehole fluid injection by a pore pressure point source of constant strength q (this quantity has physical units of power) switched on at time $t = 0$. Then the solution of the diffusion equation is $p = \frac{q}{4\pi D r} erfc\left(\frac{r}{\sqrt{4Dt}}\right)$ [see *Carslaw and Jaeger*, 1973, chap. 10.2.2], where $erfc(x)$ is the complementary Gaussian error function and r denotes the distance from the injection point. D is the hydraulic diffusivity of the medium.

[16] Taking into account this pore pressure solution and the approximate uniformity of the probability density function of criticality $f(C)$, we obtain the total number of events, $N_{ev}(t)$,

induced by the injection until a given time t:

$$N_{ev}(t) = \frac{q\xi t}{C_{\max}} \qquad (1)$$

[17] This result shows that for a steady-state injection, the cumulative event number grows linearly with the injection time at an event rate of $q\xi/C_{\max}$. This outcome is invariant in respect of a possible hydraulic anisotropy of rocks. The quantity $F_t = C_{\max}/\xi$ is independent of injection parameters. It has units of energy and depends on the tectonic activity of an injection region. We will address this quantity F_t as a tectonic potential. In our model the tectonic potential is defined as the upper limit of the critical pressure of pre-existing cracks divided by their bulk concentration. The larger F_t, the more efforts are necessary to induce microseismicity. In reality, F_t can be a function of e.g., stress state, tectonic history, rheology, lithology, heat flow, and natural seismicity at the injection site.

[18] The quantity q is a function of the injection source. It can be approximated as $q = 4\pi p_0 DR$, where p_0 is injection pressure and R is radius of a spherical surface, where the injection pressure is applied [*Rothert and Shapiro*, 2007]. R can be seen as the radius of a sphere with the same surface as the borehole segment open for fluid injection. Then the cumulative event number is $N_{ev}(t) = 4\pi p_0 DR\xi t/C_{\max}$. This expression shows, that there is a combination of parameters, D/F_t, which controls the seismic activity. It is independent of the injection source and completely defined by rock properties. This quantity takes into account not only the tectonic activity of the injection site but also its hydraulic properties.

[19] We further assume that the frequency-magnitude relation of induced seismicity obeys the Gutenberg-Richter statistics [*Turcotte et al.*, 2007]. This is equivalent to the assumption that the statistics of pre-existing cracks has been inherited from the tectonic history of the injection site. In other words, neither the statistics of cracks depends on the injection source nor any strong non-linear interaction between cracks is required. A Gutenberg-Richter relation of fluid induced seismicity might be, e.g., a consequence of a power-law type size distribution of pre-existing cracks. The Gutenberg-Richter magnitude scale means that the probability $W_{\geq M}$ of events with a magnitude larger than M is given by $\log W_{\geq M} = a - bM$, where a and b are regional seismicity constants. The number of fluid injection induced events $N_{\geq M}(t)$ with magnitude larger than M is given by the product of the cumulative event number until injection time t and the probability of an event to have a magnitude larger than M. For the logarithm of this number we obtain:

$$\log N_{\geq M}(t) = \log[4\pi p_0 Rt D/F_t] - bM + a, \qquad (2)$$

where the above defined tectonic potential F_t has been included.

[20] This equation clarifies which characteristics of rocks and of injection configurations define the magnitudes of induced earthquakes. The probability of inducing significant events increases with injection duration and with strength of the injection source (i.e., a product of the injection pressure and a square root of the surface of the open-hole section). Note that the event probability is proportional to the product of the hydraulic diffusivity and the concentration of critical cracks divided by a maximal possible critical pore pressure (note also, that division by the maximal critical pore pressure is equal to multiplication with the average probability density of critical pressure).

4. Discussion

[21] The magnitude distributions observed in Figures 1 and 2 are in good agreement with equation (2), which postulates a linear relation between log $N_{\geq M}$ and log t. Another interesting feature is the regularity of the increments between lines corresponding to different magnitude values in Figures 1 and 2. Equation (2) shows that this increment normalized to the magnitude increment should be equal to the b-value of the Gutenberg-Richter relation of the correspondent injection experiment. This is indeed the case for the given data sets (not shown here).

[22] Our model and its main implication, equation (2), provide also a convenient frame for comparing seismicity induced in different experiments. Figure 3 shows a summary plot of magnitude frequencies as functions of time for the injection experiments discussed here. The range of observed magnitudes is mainly controlled by the sensitivity of the seismic monitoring system. However, the influence of this factor can be taken into account by extrapolation and construction of additional dashed lines corresponding to magnitudes of interest. This kind of plot provides a basic prediction tool. For example, it is clear that injection durations at the Ogachi site are at least two orders of magnitude too short to induce seismic events of magnitude 2. Figure 3 indicates that the two Ogachi and the Paradox Valley experiments are characterized by the same order of magnitude for the parameter combination a + log(D/F_t). Given that the parameters p_0 and R are similar for both experiments, this results from the fact, that the identical system of dashed lines fits the magnitude distributions of all three data sets.

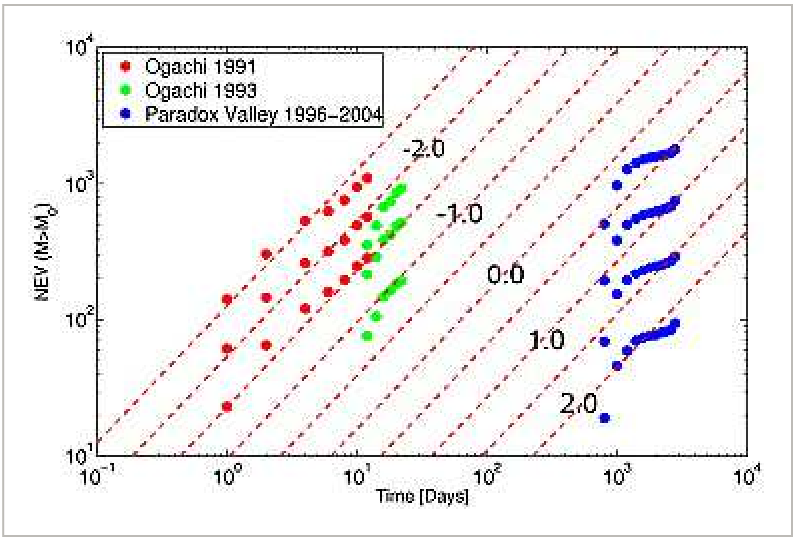

Figure 3

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Numbers of events with a magnitude larger then a given value as functions of injection durations of the Ogachi and of the Paradox Valley borehole injection experiments. The system of thin dashed lines with a slope 1 and a constant separation $b\Delta m = 0.5$ fits the data of the Ogachi 1991 experiment for the magnitude range $-2.5 \le M \le -1.5$. Additional lines are extrapolated for magnitudes $-1.0 \le M \le 2.0$.

5. Conclusions

[23] We have shown that the process of injection pressure diffusion in a poroelastic medium with randomly distributed sub-critical cracks obeying a Gutenberg-Richter statistics well explains our observations of the temporal magnitude distribution of fluid induced seismicity. The temporal distribution of microearthquake magnitudes depends on the injection pressure, the surface of the injection section, the hydraulic diffusivity, and is also inherited from the statistics of pre-existing crack/fracture systems controlling the local seismicity. In this sense magnitude distributions are indicative for the character of seismogenic criticality of rocks in the shallow crust and the triggering reason of fluid induced earthquakes (i.e., we see a clear indication of a pore pressure induced triggering of events on pre-existing critical defects with Gutenberg-Richter statistics, which possibly corresponds to the size distribution of cracks). Our parametrization can be used to optimize the design of injection experiments thereby reducing their seismic risk.

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