Pore-pressure diffusion: A possible triggering mechanism for the earthquake swarms 2000 in Vogtland/NW-Bohemia, central Europe

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[1] Vogtland/NW-Bohemia (VB) at the German/Czech border region is characterized by recurring intraplate earthquake swarms, Quaternary volcanism, intersecting fault systems, and an established connection between ascending magmatic fluids and seismicity. As the triggering mechanism of seismicity in VB is still unknown, this study aims to contribute by investigating the possible role of fluids in VB, based on poromechanics. We assume that ascending fluids, of magmatic origin, trigger earthquakes by the mechanism of pore-pressure diffusion (i.e., relaxation). Two physical fields, the hydraulic diffusivity and the criticality (i.e., critical pore-pressure value leading to failure), both heterogeneously distributed in rocks, mainly control this triggering process. The results of the analysis of the year 2000 earthquake swarm data support this concept. It is further strengthened by a numerical model, with correlated diffusivity and criticality fields, which successfully simulates the general spatio-temporal seismicity pattern of the earthquake swarms 2000. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7230 Seismology: Seismicity and seismotectonics; 7260 Seismology: Theory and modeling. **Citation:** Parotidis, M., E. Rothert, and S. A. Shapiro, Pore-pressure diffusion: A possible triggering mechanism for the earthquake swarms 2000 in Vogtland/NW-Bohemia, central Europe, *Geophys. Res. Lett.*, *30*(20), 2075, doi:10.1029/2003GL018110, 2003.

1. Introduction

[2] Earthquake swarms are seismic sequences with no dominant magnitude, i.e., no mainshock. In nature they often occur in volcanic regions, e.g., at the Somma-Vesuvius volcano in Italy [*Saccorotti et al.*, 2002], but also elsewhere, e.g., in the area of the Vosges Massif in France [*Audin et al.*, 2002], and in Vogtland/NW-Bohemia (VB) covering the northwestern part of the Bohemian Massif. After *Spicak and Horalek* [2001] many earthquake swarm regions are characterized by Quaternary volcanism, indicating that ascending magmatic fluids trigger earthquakes. These authors also suggest magmatic fluids as triggering mechanism in VB by stressing the similarity between the fault plane solutions for the earthquake swarms in VB and at the KTB borehole, about 50 km from VB, where fluid injections were carried out [*Zoback and Harjes*, 1997].

[3] In this study the following hypothesis will be tested: The swarms in VB are triggered by ascending magmatic fluids, which change effective stresses by pore-pressure perturbations. These propagate according to the pore-pressure diffusion equation. The spatio-temporal pattern of the seismic activity depends mainly on the spatial distribution of two physical fields, the hydraulic diffusivity D(r) and the criticality C(r), i.e., critical pore-pressure value leading to failure for a point r (a smaller C(r) means a more critical medium). This assumption is tested by a) Analyzing the data of the earthquake swarms in VB during the year 2000, and b) Simulating the seismicity pattern with a numerical model. Both the data analysis and the model support the hypothesis formulated above.

2. Seismicity in Vogtland/NW-Bohemia (VB)

[4] Recurring earthquake swarms in VB are known since the 16th century, and magnitudes up to M_L 4.5 have been recorded [*Fischer*, 2003]. The region exhibits CO_2-rich mineral springs, some hundreds gas vents in eight moffette fields, 0.2 to 0.5 Ma old Quaternary volcanoes, a complex tectonic environment dominated by the Eger Rift, which is crossed perpendicularly by the Marianske Lazne fault zone. The whole epicentral region covers 60×50 km^2 and corresponds to a transition zone from CO_2-dominated fluids to N_2-dominated fluids at the periphery [*Weinlich et al.*, 1998].

[5] Since 1985/86 the main swarm earthquake activity in VB is concentrated by 50.24N and 12.44E defining a volume of a few km^3. The last large earthquake swarms were registered during 2000 with ca. 10000 events and magnitudes up to M_L 3.3, and will be analyzed in the following. The seismic activity concentrated over the Novy Kostel area (Czech Republic) with nine swarms clustered in time, designated P1 to P9 (Figure 1, top). All swarms but P9 are clustered also in space, comprising a volume of ca. $3.0 \times 0.6 \times 2.5$ km^3 (NS $\times$ EW $\times$ depth). Approximately 4500 events were localized with an accuracy of ±100 m horizontally, and ±190 m vertically [*Fischer*, 2003].

[6] The hypothesis formulated afore, that ascending fluids trigger earthquakes in VB, is conform to the results of *Weise et al.* [2001], which after examining the gas composition and its relation to seismic activity in VB, conclude that the seismicity is very probably triggered by fluids. *Weinlich et al.* [1999] postulate a magmatic reservoir beneath the crossing of the Eger Rift and the Marianske Lazne fault zone. *Klinge et al.* [2003], *Neunhöfer and Hemman* [2003], and *Hainzl and Fischer* [2002] also consider fluids of importance for the seismic activity in VB.

3. Pore-Pressure Diffusion: The Triggering Mechanism

[7] The time-dependent interaction of fluid flow and rock deformation is described by the theory of poroelasticity,

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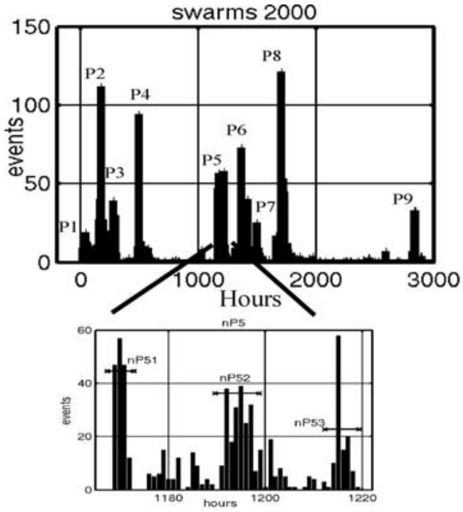

Figure 1. Top: Events versus time plot for the swarm period 2000 in VB. The first event occurred at 28 August and the last at 26 December. The hours are calculated with reference to 28 August and time 00:00. *Fischer* [2003] defined nine swarms, labeled P1 to P9. Bottom: Events versus time plot magnified for the P5 swarm, which shows that it actually comprises three swarms, labeled nP51 to nP53.

which is based on Biot's equations [*Biot*, 1962]. One governing equation of linear poroelasticity, for no fluid source, is the inhomogeneous diffusion equation for pore pressure p:

$$\frac{B}{3} \cdot \frac{\partial \sigma_{kk}}{\partial t} + \frac{\partial p}{\partial t} = \frac{k}{\mu \cdot S_\sigma} \cdot \nabla^2 p, \qquad (1)$$

with B the Skempton's coefficient, $\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$ the mean stress, k the permeability, μ the viscosity of the fluid, S_σ the unconstrained specific storage coefficient, and t the time [*Wang*, 2000]. One, out of four, special case where Equation (1) is mathematically uncoupled from the mechanical equilibrium equations, is for an irrotational displacement field in an unbounded domain, assumed here to be approximately valid for fluid injections; then Equation (1) is:

$$\frac{\partial p}{\partial t} = D \cdot \nabla^2 p, \qquad (2)$$

with D the hydraulic diffusivity. The diffusivity of the crust is generally assumed to be between 0.01 m^2/s and 10 m^2/s [*Scholz*, 2002]. In Equation (2) the medium is considered homogeneous and isotropic regarding elastic and hydraulic properties. The last equation is identical to the hydrogeologic transient flow equation [*Wang*, 2000]. The permeability is related to the diffusivity by $D = k/(\mu S)$, where S is the uniaxial specific storage coefficient.

[8] *Shapiro et al.* [1997, 2000, 2002, 2003] developed a method, based on the uncoupled diffusion equation, initially for describing pore-pressure perturbations caused by fluid injections into a borehole. They solved Equation (2) for a point source in a homogeneous isotropic saturated poroelastic medium, and estimated the distance r of the propagating pore-pressure front from the source, i.e., the injection point, with

$$r = \sqrt{4 \cdot \pi \cdot D \cdot t}. \qquad (3)$$

This equation describes a parabola in an r-t plot. Such a parabola will be used in this study as a signature for detecting earthquake swarms triggered by pore-pressure diffusion.

[9] Pore-pressure diffusion as triggering mechanism has been proposed for different case studies; e.g., for reservoir (large artificial lakes) induced seismicity [*Howells*, 1974], for water table changes in large basins connected with microseismicity in central Virginia [*Costain and Bollinger*, 1991], and for volcanic seismicity in Italy [*Saccorotti et al.*, 2002].

4. Data Analysis

[10] The aim of this analysis is to identify earthquake sequences of the swarm period 2000 in VB with diffusive characteristics, i.e., that can be approximated with a parabolic envelope after Equation (3), which is a signature for pore-pressure diffusion [*Shapiro et al.*, 1997]. *Fischer* [2003] defined nine swarms by estimating a waiting time (i.e., time between consecutive events with magnitudes above a defined value) for the events (Figure 1, top). First, we assume a single pore-pressure source for all swarms, located in the hypocenter of the first event. Figure 2 shows the corresponding r-t plot. Although for D = 0.27 m^2/s an envelope could be defined, for which nearly all events lie underneath (see *Shapiro et al.* [1997], and *Shapiro et al.* [2002] for criteria of determining the best fitting parabolic envelope), large parts under the parabola are without events; the events of the later swarms, between $3 \cdot 10^6$ s and $7 \cdot 10^6$ s, are clustered away of the envelope, and the events of the first swarms are partly above the parabola, thus rising two questions: 1) Could only one source trigger such a complex seismicity pattern, and 2) If yes, what is the meaning of the estimated D. The first question is affirmatively answered by the model presented later. The response to the second question is that generally the parabolic envelope delivers

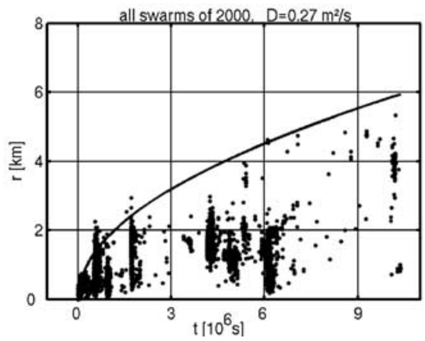

Figure 2. Swarm period 2000: r-t plot, with parabolic envelope for D = 0.27 m^2/s, for the case of a single pore-pressure source for all swarms. The spatio-temporal seismicity pattern shows vertically clustered events interrupted by time intervals of seismic quiescence.

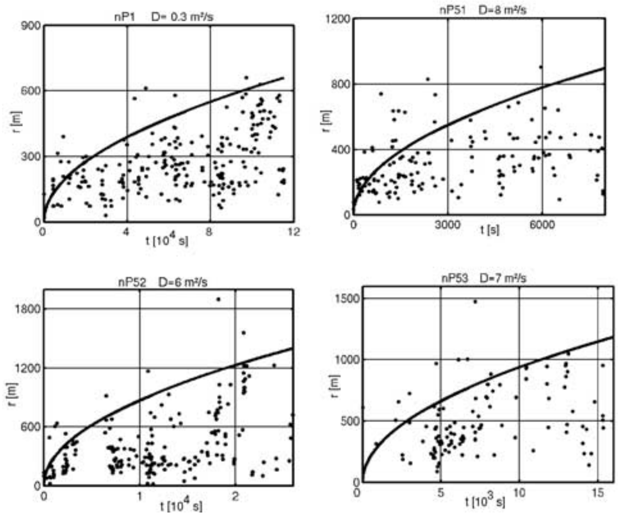

Figure 3. r-t plots with estimated hydraulic diffusivities D and corresponding parabolic envelopes for the swarms nP1, nP51 to nP53, by assuming one pore-pressure source for each swarm.

an effective upscaled value for the seismically active region [*Shapiro*, 2000], presuming the single source assumption is valid; the results of the following numerical model support this idea, too.

[11] In the following we investigate which earthquake swarms have diffusive characteristics. Thus, it is assumed that each swarm was triggered by its own injection point. These injection points are considered as secondary sources resulting from the single source, which initiated the whole triggering process. In order to detect such earthquake swarms the following criteria were defined:

[12] •Temporal: All events of a swarm must be within a defined time window. The first event of the defined swarm provides the starting time of the assumed injection, i.e., a secondary source of the pore-pressure perturbation.

[13] •Spatial: All events must lie within a defined volume. The assumed secondary point source is located at the centroid of the first 10 events.

[14] Applying the above spatio-temporal criteria to the year 2000 data of VB, twelve swarms were identified. These, designated nP1 to nP8 (including further subswarms, designated with a second digit), are of shorter duration but with stronger clustering, than the ones defined by *Fischer* [2003]. Figure 1, bottom, shows e.g., swarm P5, which, after applying the above criteria, resulted in three earthquake swarms, labeled nP51 to nP53. Further we seek a parabolic envelope for each swarm (Figure 3). This was achieved for all but four swarms, namely nP4, nP6, nP71, and nP72 (see Figure 4, left); the last three comprise too few events (from 50 to 100), for defining an envelope. For swarm nP4, which although comprises a sufficient number of events, a gap of data in the seismic catalogue exists (*Fischer*, pers. comm.).

[15] Figure 4 shows the temporal migration of the seismic activity for all swarms with the estimated hydraulic diffusivities. The different values of D for each swarm indicate the existence of diffusivity patches. Also, these values correspond inversely to the waiting times estimated by *Fischer* [2003]; that was expected, as a higher value of diffusivity means larger pore-pressure propagation velocities, i.e., shorter waiting times.

[16] Summarizing, the main results of the data analysis of the swarms 2000 in VB are: 1) We see diffusive characteristics for the earthquake swarms. 2) Diffusivity patches exist with values between 0.3 m^2/s and 10 m^2/s. 3) The assumption of a single pore-pressure source results in an r-t plot with a strong vertical spatio-temporal clustering of the events, and an estimation of an effective diffusivity D (Figure 2). 4) The complex seismic activity evolution (Figure 4) can be simplified described as a counterclockwise migration of activity (see also *Fischer* [2003]). Results 3 and 4 define the general seismicity pattern for the swarms 2000 in VB, that will be used in the following.

5. Numerical Model

[17] *Rothert and Shapiro* [2003] proposed a methodology to model induced seismicity for various diffusivity/criticality fields. The goal of the here presented numerical model is to simulate the general seismicity pattern of the swarms 2000 in VB, as defined above. According to the basic idea that ascending magmatic fluids trigger earthquakes, a 2D poroelastic model is defined by assuming a single pore-pressure source, i.e., injection point. The source, of $1 \cdot 10^6$ Pa, is placed at the bottom of four diffusivity patches, with diffusivities of 0.3 m^2/s, 3 m^2/s, 6 m^2/s, and 10 m^2/s, over a background with D = 0.01 m^2/s. The pore-pressure diffusion equation is solved with the Finite Element Method (FEM). High-criticality patches (with an evenly distributed $C(r) < 1 \cdot 10^5$ Pa), coinciding with the diffusivity patches, are defined over an evenly-distributed low-criticality background, with $C(r) < 1.1 \cdot 10^6$ Pa. Events are triggered in the cells where pore pressure exceeds criticality (Figure 5). The r-t plot in Figure 5 is the analogue of the data analysis result in Figure 2. The comparison of these figures shows

Swarm	D [m²/s]
nP1	0.3
nP2	2.0
nP3	3.0
nP4	-
nP51	8.0
nP52	6.0
nP53	7.0
nP6	-
nP71	-
nP72	-
nP81	10.0
nP82	9.0

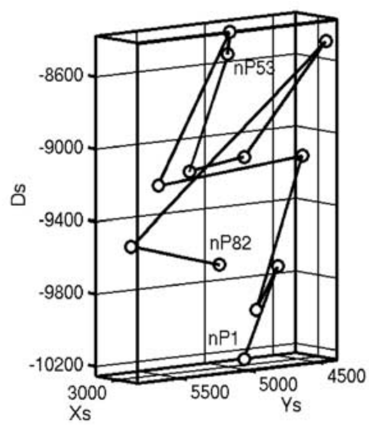

Figure 4. 3D plot with centroids (denoted with a circle) of the twelve swarms of 2000 in VB. Centroids are connected according to occurrence time. The first swarm to occur was nP1 and the last nP82. X_s, Y_s, and D_s denote the E-W, N-S, and depth coordinate components. The list (left) gives the estimated hydraulic diffusivities D for each swarm. For the swarms without a value for D no estimation was possible either because of few events (nP6 to nP72) or because of a data gap in the seismic catalogue (nP4).

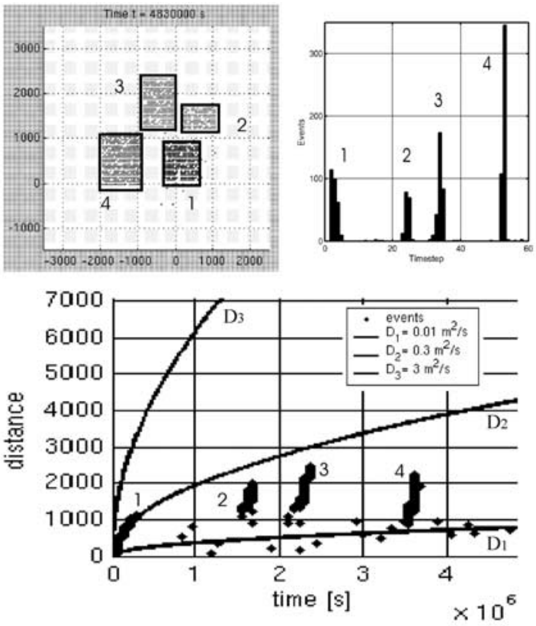

Figure 5. Results of the numerical modeling. Top left: 1238 triggered events (points), which clearly mirror the criticality patches. The numbers 1 to 4 denote identity of each patch. The injection point is placed at the origin of the coordinate system. Top right: Event versus timestep plot, where 1 timestep equals $7 \cdot 10^4$ s. Bottom: r-t plot with parabolic envelopes and corresponding diffusivities. The numbers next to the clusters denote the identity of each patch. The characteristics of the seismicity pattern are: a. The time delay of the triggering between the diffusivity patches (controlled by the diffusivity contrast of the patches to the background), and b. The vertical clustering of the events (controlled by the high-criticality patches).

that: 1) The model with a single pore-pressure source successfully simulates the general spatio-temporal seismicity pattern in VB. 2) For that, correlated criticality and diffusivity fields are required. 3) The estimated diffusivity D from the r-t plot gives an upscaled effective value representative for the seismically active region.

6. Summary

[18] Vogtland/NW-Bohemia (VB) is a region characterized by natural recurring intraplate earthquake swarms. We hypothesize that ascending magmatic fluids trigger the earthquakes by causing pore-pressure perturbations, which propagate according to the diffusion equation. These perturbations change the effective stresses causing seismic activity. The triggering of earthquake swarms is mainly controlled by two physical fields, the diffusivity and the criticality of the rock. The results of the data analysis and modeling of the year 2000 swarms in VB support such a concept. The analyzed swarms show diffusive characteristics and render possible estimates of diffusivity. A 2D numerical model was proposed, that successfully simulates the simplified seismicity pattern. For that, the definition of correlated diffusivity and high-criticality patches is required. These patches correspond to highly fractured and close to failure compartments of the fault zone region in VB, which allow fluid flow. In spite of the encouraging results, more investigations are necessary in order to account for the whole multitude of complex phenomena related to the earthquake swarms in VB.

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