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Meteorological triggering of earthquake swarms at Mt. Hochstaufen, SE-Germany

T. Kraft *, J. Wassermann, E. Schmedes, H. Igel

Ludwig-Maximilians-University, Department of Earth and Environmental Sciences, Geophysics Section, Theresienstr. 41, 80333 Munich, Germany

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Abstract

A growing body of evidence suggests that fluids are intimately linked to a variety of faulting processes. Yet, the particular mechanisms through which fluids and associated parameters influence the stress regime and thus the seismicity of a particular area are not well understood.

We carry out a study of the spatio-temporal behavior of earthquakes, fluid-related parameters (groundwater levels) and meteorological observables (precipitation) in the swarm earthquake area of Bad Reichenhall, southeastern Germany. The small volume in which the earthquakes take place, almost yearly occurring earthquake swarms and a permanent, seismo-meteorological monitoring network, provide nearly controlled experimental conditions to study the physics of earthquake swarms and to infer characteristic properties of the seismogenic crust.

In this paper we (1) describe this fairly unique study area in terms of geology, seismicity and atmospheric conditions; (2) present two cases of earthquake swarms that seem to follow above-average rainfall events; and (3) examine the observed migration of hypocenters with a simple pore pressure diffusion model.

We find significant correlation of seismicity with rainfall and groundwater level increase, and estimate an average hydraulic diffusivity of $D=0.75\pm0.35$ m^2/s for Mt. Hochstaufen in 2002.

Keywords: Seismology; Induced earthquakes; Swarms; Poroelasticity; Hydraulic diffusivity; Northern Limestone Alps

1. Introduction

By observing hydrothermal precipitants in mineral veins, mining geologist had for centuries achieved a quantitative appreciation of the role of fluid pressure in counteracting normal stress during faulting. The seminal paper by Hubbert and Rubey (1959) stands out as the foundation work in structural geology applying the concept of effective stress (Terzaghi, 1923) in a quantitative manner to faulting in fluid-saturated rock. They identified the development of fluid pressures to near-lithostatic levels as an important mechanism for lowering the strength of overthrust faults.

In recent years, hydromechanical coupling has been proposed as a possible explanation for several geological phenomena (e.g., Neuzil, 2003), including the anomalous weakness of many major faults, fault creep, slow earthquakes, or afterslip (e.g., Sleep and Blanpied, 1992; Byerlee, 1993); silent slip events

* Corresponding author. Tel.: +49 89 2180 4226; fax: +49 89 2180 4205.
E-mail addresses: Kraft@LMU.de (T. Kraft), Heiner.Igel@LMU.de (H. Igel).
URL: http://www.geophysik.uni-muenchen.de/~toni (T. Kraft).

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observed by GPS surveys (e.g., Kodaira et al., 2004); seismicity patterns of aftershocks (e.g., Nur and Booker, 1972; Miller et al., 2004) and remote triggering of earthquakes by transient dynamic stress fields (e.g., Prejean et al., 2004).

Direct evidence of the effects of fluid pressure on fault stability has come from earthquakes induced in intraplate regions (e.g., reservoir induced seismicity (e.g., Howells, 1974; Ferreira et al., 1995; Talwani, 2000), fluid-injections in wells (e.g., Baisch et al., 2002; Rothert and Shapiro, 2003) and increase in hydraulic head or stream discharge connected with microseismicity (e.g., Roeloffs et al., 2003; Manga et al., 2003)).

Another phenomenon that is thought to be linked to hydromechanical coupling is the occurrence of earthquake swarms. These are sequences of earthquakes that often start and end gradually and in which no single earthquake dominates the size (Scholz, 1994). Earthquake swarms are a globally observed phenomenon and are commonly associated with volcanic regions (Sykes, 1970). The temporal evolution of swarm activity can not be described by any simple law, as e.g. the Omori law for aftershock sequences. Furthermore, the frequency-size distributions of earthquake swarms are normally characterized by unusually large b-values (Sykes, 1970).

Several mechanisms have been proposed for earthquake swarm generation. Mogi (1963) suggested that in highly fractured regions stress concentrations around fractures promote failure already under small stresses without the occurrence of large rupture surfaces. Other models are based on the Mohr–Coulomb failure theory in its effective stress formulation. Hill (1977) proposed a model for volcanic regions, which assumes a system of magma-filled dikes interconnected by stress-field-oriented fractures that rupture under certain pore pressure conditions in the dike. Yamashita (1999) suggested that swarm-like sequences could be created by fluid flow from localized high pressure compartments controlled by permeability increase due to fracturing.

In this study we investigate the spatio-temporal behavior of earthquakes, groundwater levels, precipitation and their correlations in the swarmquake area of Bad Reichenhall, in southeastern Germany. The aim of this

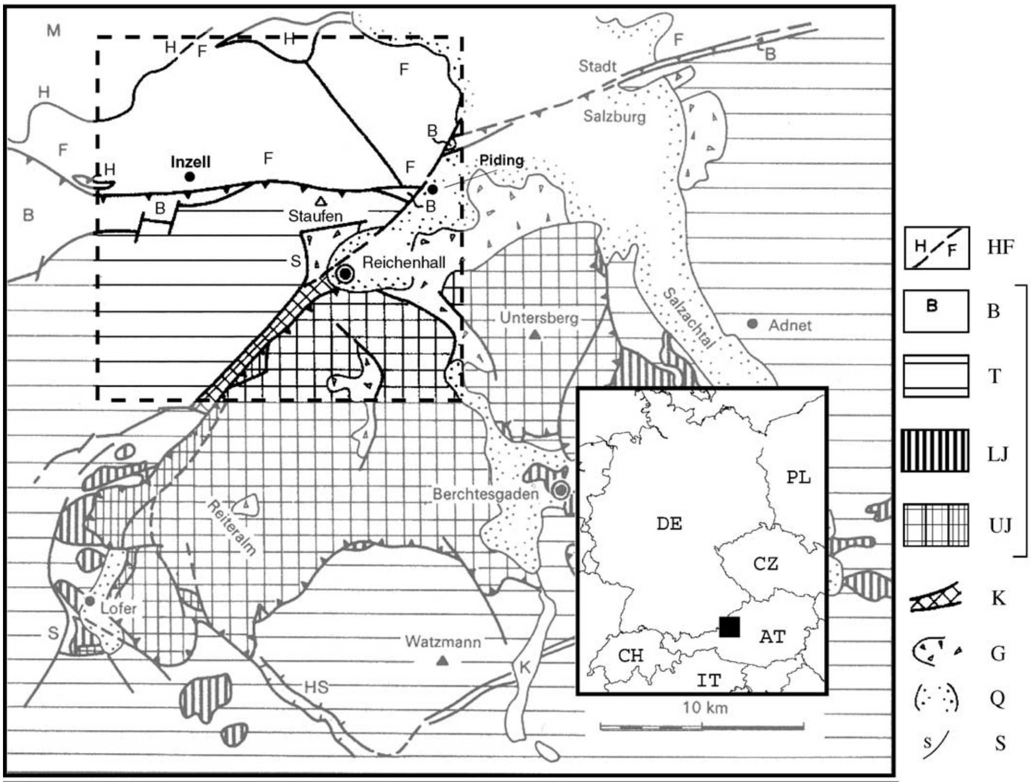

Fig. 1. Tectonic map of the region around the study area (modified from Bögel and Schmidt, 1976). The classical subdivision of the Northern Limestone Alps (**NCA**) in four nappe units is indicated. The study area is marked by a dashed square. The insert map gives the geographical location of the tectonic map. **HF** Helvetic Unit and Flysch Zone; **B** Bavaric, **T** Tirolic, **UJ** Upper and **LJ** Lower Juvavic Units; **K** Kugelbach Zone; **S** Saalach Western Fault; **G** Gossau conglomerates; **Q** Quaternary sediments.