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Large earthquakes during hydraulic stimulations at the geothermal site of Soultz-sous-Forêts

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Abstract

Several deep wells were drilled in the Rhine Graben (Soultz-sous-Forêts, France) to evaluate the geothermal Hot Dry Rock potential of a deep fractured granite reservoir. Three main boreholes, which reached about 5 km depth, intersected a crystalline basement overlain by 1.4 km of Cenozoic and Mesozoic sediments. Stimulations of these three wells were carried out in 2000 for GPK2, 2003 for GPK3 and 2004, and 2005 for GPK4. During these stimulations and other hydraulic activities a seismological surface network was installed in order to monitor the seismicity induced by the massive fluid injection.

Here we analyse the seismicity of magnitude larger than or equal to 1.4, which is the lowest magnitude felt by the population. Based on a spectral analysis of the displacement recorded by a Güralp velocimeter at a depth of 200 m, we know that the source dimensions range from tens to hundreds of metres. We analyse several parts of the reservoir where obvious correlation between the fluid path and tectonic features has been pointed out. Based on seismological arguments such as location and focal mechanisms, we show that this activity is linked with tectonic features, or at least with large fractures that control the behaviour of the geothermal reservoir. To constrain the hypothesis, we study 391 events and focal mechanisms to argue in favour of the existence and stability of tectonic features that can be compared to geological data. We show that the largest events recorded on the site occurred after the shut-in. Their spatial distribution appears not to be random within the reservoir, and the focal mechanisms of these events also confirm the non-randomness of their distribution. Given their source dimensions, the largest events can only occur on large structures, such as tectonic ones. Therefore, the behaviour of the reservoir is controlled by these main fractured zones, which either lead the fluid or hinder its path.

Keywords: Microseismicity; Induced seismicity; Reservoir; Hydraulic stimulation; Late large induced microearthquake; Focal mechanism; Source parameter

1. Introduction

Since 1987, a European geothermal project has been developed at Soultz-sous-Forêts (Alsace, France) in the western part of the Upper Rhine Graben [1]. This area is characterized by an extensional tectonic regime and shows a high temperature gradient anomaly [2]. The crystalline basement is covered by about 1400 m of Cenozoic and Mesozoic sediments. Analysis of cores recovered during drilling and of borehole geophysical logs has shown that the granitic massif is highly fractured [3]. The main orientation of the fracture system is NNW–SSE. Petrographical studies have concluded that the majority of the fractures are hydrothermalized and exhibit a slight, natural permeability [4].

The aim of the geothermal project is to extract the heat stored in the deep and hot granitic rocks through the forced circulation of water between injection and production boreholes: the cold water is injected into the rock mass through the open-hole section of the injection well, exchanges heat with the rocks while circulating in the fracture network, and is then pumped up to the surface via production wells. For this purpose, four deep wells have been drilled since 1987: GPK1, drilled to about 3600 m

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depth; GPK2 initially drilled to 3800 m depth, then deepened to 5000 m depth; finally GPK3 and GPK4 also reaching 5000 m depth. At this depth, the temperature is around 200 °C. The boreholes GPK2–4 are expected to form a future geothermal triplet (one injection well and two production wells). They are now used for the study and development of the deep geothermal reservoir. They are aligned in a N170° direction, and the distance between the bottom of two adjacent wells is about 600–650 m.

Although the fracture system is naturally permeable, the permeability values and the connectivity between the wells and the fracture network on one side, and local permeable cells within fractures on the other side, are too low to reach an optimized exploitation of the geothermal resource. One of the major goals of the geothermal project is to enhance the hydraulic properties of the reservoir. This is usually achieved through massive hydraulic stimulation tests: water is injected at high flow rates into the granite in order to increase the pressure in the deep reservoir. Hubbert and Rubey [5] first showed that an increase of the pore fluid pressure tends to decrease the effective normal stress on fractures and, as a result, triggers earthquakes. Thus large-scale injections are likely to induce shearing on pre-existing joints that are favourably oriented within the prevailing stress field. Two important effects are expected: permeability and connectivity enhancement, and generation of an intense microseismic activity.

2. Stimulations

Several stimulation tests were performed at Soultz-sous-Forêts in order to develop the reservoir at 3600–3800 m depth [6,7], but in this paper we will only focus on the last four stimulations of the deep reservoir at 5 km depth. Hydraulic parameters (flow rates and pressures) of the injections are shown in Fig. 1. In 2000, GPK2 was stimulated at flow rates up to 50 Ls^{-1} for a total injected volume of 25 000 m^3. GPK3 was stimulated in 2003 at similar flow rates but with short peaks at 60 and 90 Ls^{-1}. The total injected volume reached 37 000 m^3. Finally GPK4 was stimulated twice, in 2004 and 2005. In 2004 more than 9000 m^3 of water was injected at 30 Ls^{-1} with peaks up to 45 Ls^{-1}; in 2005, 12 500 m^3 was injected at maximum flow rate of 45 Ls^{-1}.

3. Seismicity

For each stimulation test, the induced microseismic activity was monitored by a surface seismological network, installed by the "Ecole et Observatoire des Sciences de la Terre" from the Strasbourg University (Fig. 2). In 2000, 18 temporary seismological stations, composed of one component (1-C) and three components (3-C) sensors were set up. Since 2003, a permanent network of nine stations has been deployed around Soultz-sous-Forêts to continuously

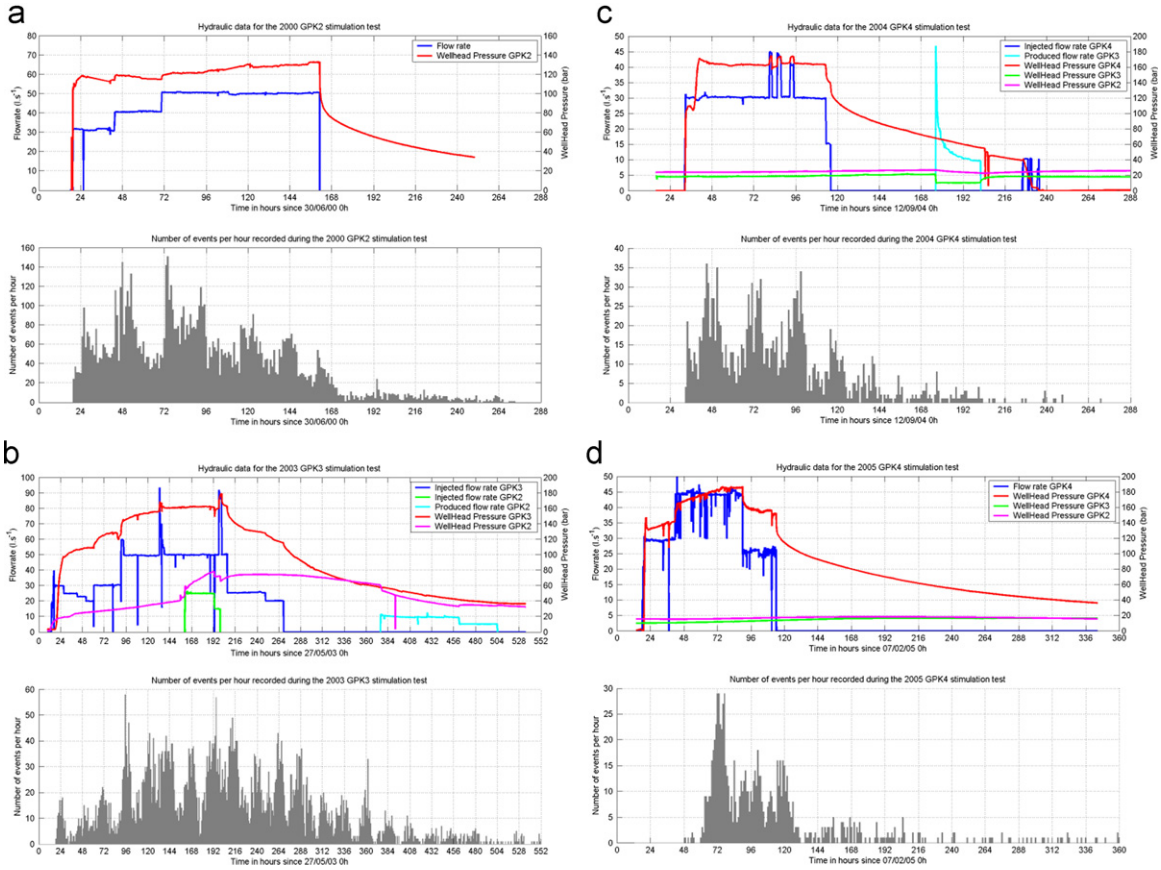

Fig. 1. Number of seismic events in front of the injection strategy for: (a) 2000, (b) 2003, (c) 2004 and (d) 2005.