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Induced seismicity associated with Enhanced Geothermal Systems

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Abstract

Enhanced Geothermal Systems (EGS) have the potential to make a significant contribution to the world energy inventory. One controversial issue associated with EGS, however, is the impact of induced seismicity or microseismicity, which has been the cause of delays and threatened cancellation of at least two EGS projects worldwide. Although microseismicity has in fact had few (or no) adverse physical effects on operations or on surrounding communities, there remains public concern over the amount and magnitude of the seismicity associated with current and future EGS operations. The primary objectives of this paper are to present an up-to-date review of what is already known about the seismicity induced during the creation and operation of EGS, and of the gaps in our knowledge that, once addressed, should lead to an improved understanding of the mechanisms generating the events. Several case histories also illustrate a number of technical and public acceptance issues. We conclude that EGS-induced seismicity need not pose a threat to the development of geothermal energy resources if site selection is carried out properly, community issues are properly handled and operators understand the underlying mechanisms causing the events. Induced seismicity could indeed prove beneficial, in that it can be used to monitor the effectiveness of EGS operations and shed light on geothermal reservoir processes.

Keywords: Induced seismicity; Enhanced Geothermal Systems (EGS); The Geysers; Cooper Basin; Berlín; Soultz-sous-Forêts.

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1. Introduction

1.1. Objectives

To produce geothermal energy economically on a commercial scale, sufficient fluid and permeability must be present in the targeted subsurface hot rock masses. In many cases, there is a need to increase permeability and/or fluid content, i.e., to enhance the natural geothermal systems. One of the issues associated with Enhanced Geothermal Systems (EGS) is the effect and role of the seismicity (or microseismicity) induced during the creation, or improvement in the properties, of an underground reservoir and subsequent extraction of geothermal energy (i.e. hot fluids) (Majer et al., 2005). Microseismicity has been successfully dealt with in a variety of environments. Cypser and Davis (1998) set out the legal responsibilities of reservoir impoundment projects, as well as oil and gas, mining and geothermal operations. In this paper we review our current knowledge on the seismicity induced during the development and operation of enhanced geothermal systems, and highlight the gaps in knowledge that are an obstacle to a thorough understanding of the mechanisms generating the seismic events; we also present information that will hopefully prove useful when drafting and implementing protocols for monitoring and addressing community issues associated with induced seismicity.

1.2. History and motivation for the study

Naturally fractured hydrothermal systems are the easiest sources from which to extract heat stored in the subsurface rocks, but the total resource and its availability tend to be restricted to certain areas. Their development proceeds where conditions are ideal for cost-efficient extraction. These hydrothermal systems are sometimes difficult to locate and also run a high risk of not being commercially feasible, if their geological, physical and chemical characteristics are not favourable.

The reasons for developing EGS technology are two-fold: (1) to bring uneconomic hydrothermal systems into production by improving their underground conditions (stimulation); and (2) to engineer an underground condition that creates a hydrothermal system, whereby injected fluids can be heated by circulation through a hot fractured region at depth and then brought to the surface to deliver the captured heat for power conversion or other uses. The second approach expands the available heat resource significantly and reduces the uncertainty of exploitation costs. However, the process of enhancing permeability and the subsequent extraction of energy may often generate microseismic events.

Induced seismicity is an important reservoir management tool, especially for EGS projects, but it is also perceived as a problem in some communities near geothermal fields. Events of magnitude 2 and above near certain projects (e.g., the Soultz project in France; Baria et al., 2005) have raised residents' concern related to both damage from single events and their cumulative effects (Majer et al., 2005). Some residents believe that the induced seismicity may result in structural damage similar to that caused by larger natural earthquakes. There is also fear that the small events may be the precursors of larger ones to come, that not enough resources have been invested in finding solutions to the problems associated with larger induced events, or in providing for independent monitoring of the seismicity prior to large-scale fluid injection and production operations. During the final phases of preparing this paper (December 2006-January 2007), a number of perceptible events (of magnitude* 3.4 or less) occurred in Basel, Switzerland, in the vicinity of the Deep Heat Mining project (http://www.dhm.ch/dhm-drillingInBasel.html). No structural damage was reported but the local authorities suspended operations until investigations were completed; it is not certain whether this project will be allowed to continue (See Section 9 below). This is an example of how a more comprehensive site selection study and understanding of the nature of the seismicity would have benefited the community at large, as well as the operators liaising with the public.

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FOOTNOTE

* Unless indicated otherwise all "magnitudes" correspond to local magnitudes (i.e. Local Richter Magnitude).
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In recognition of the large potential of the geothermal resource worldwide, and in acknowledgement of the misunderstandings that might arise with regard to induced seismicity, the International Energy Agency (IEA) drafted a Geothermal Implementing Agreement (GIA), which took the form of an international collaboration (Majer et al., 2005). The mission of this collaboration, as stated in the "Environmental Impacts of Geothermal Development, Sub Task D, Seismic Risk from Fluid Injection into Enhanced Geothermal Systems Implementing Agreement (IEA/GIA)", is as follows:

> *Participants will pursue a collaborative effort to address an issue of significant concern to the acceptance of geothermal energy in general but EGS in particular. The issue is the occurrence of seismic events in conjunction with EGS reservoir development or subsequent extraction of heat from underground. These events have been large enough to be felt by populations living in the vicinity of current geothermal development sites. The objective is to investigate these events to obtain a better understanding of why they occur so that they can either be avoided or mitigated. Understanding requires considerable effort to assess and generate an appropriate source parameter model, testing of the model, and then calculating the source parameters in relation to the hydraulic injection history, stress field and the geological background. An interaction between stress modeling, rock mechanics and source parameter calculation is essential. Once the mechanism of the events is understood, the injection process, the creation of an engineered geothermal reservoir, or the extraction of heat over a prolonged period may need to be modified to reduce or eliminate the occurrence of large events.*

As an initial starting point for achieving a consensus, three international workshops were organized with participants from a variety of backgrounds, including geothermal companies and operators. They were held during the Annual Meeting of the Geothermal Resources Council, Reno, NV, USA, in October 2005, and the annual Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, held in February 2005 and February 2006

(Majer et al., 2005; Baria et al., 2006). We present the results of these workshops, along with recent updates and recommendations for future studies and fieldwork.

2. Relevant seismological concepts and history of non-geothermal-induced seismicity

Seismicity has been linked to a number of human activities, such as mining/rock removal (McGarr, 1976; Richardson and Jordan, 2002), fluid extraction in the oil and gas industry (Segall, 1989; Grasso, 1992; Segall et al., 1994), fluid injection (Raleigh et al., 1972; Seeber et al., 2004), reservoir impoundment (Simpson, 1976), and cavity collapses as a result of underground nuclear explosions (Boucher et al., 1969).

Seismicity in general occurs over many different time and spatial scales. Growth faults in the overpressurized zones of the Gulf Coast of the United States are one example of a slow earthquake, as is creep along an active fault zone (Mauk et al., 1981). The size of an earthquake (or how much energy is released from it) depends on how much slip occurs along the fault, how much stress there is on the fault before slipping, how fast it fails, and over how large an area it occurs (Brune and Thatcher, 2002). Damaging earthquakes (usually greater than magnitude 4 or 5; Bommer et al., 2001) require the surfaces to slip over relatively large distances (in the order of kilometers). In most regions where there are commercial-size geothermal resources, there is tectonic activity. These areas of high tectonic activity are more prone to seismicity than stabler areas such as the center of continents (Brune and Thatcher, 2002). (Note, however, that one of the largest earthquakes ever to occur in the U.S. was the New Madrid, Missouri, series of events in the early 1800s, near the geographic center of North America). It must also be noted that seismic activity is only a risk if (1) it is of sufficient magnitude and (2) it is close enough to a population or infrastructure.

Large or damaging earthquakes tend to take place on developed or active fault systems. In other words, large earthquakes rarely occur where no fault exists, and the small ones do not last long enough to release substantial energy. It is also difficult to create a large, new fault, because there is usually a pre-existing fault that will slip first. For example, all significant historical activity above magnitude 5.0 that has been observed in California has occurred on pre-existing faults (Bulletins of the Seismographic Stations, University of California, Berkeley).

Another noteworthy aspect of earthquake activity is that the magnitude of an event is determined by the size of the fault rupture (in addition to the forces available) and the strength of the rock. It has been shown that, in almost all cases, large earthquakes (magnitude 6 and above) start at depths of at least 5 - 10 km (Brune and Thatcher, 2002). It is only at depth that enough energy can be stored to provide the force required to move the large volumes of rock required to trigger a large earthquake.

Water injection seems to be one of the most common causes of induced seismicity. Almost half a century ago, Hubbert and Rubey (1959) suggested that an increase in pore pressure would reduce the "effective strength of rock" and thus weaken a fault. The seismicity (many events over a 10-year period, the largest having a magnitude of 5.3) associated with fluid disposal operations at the Rocky Mountain Arsenal in Colorado, USA (with injection rates of up to thirty million liters per month over a four-year period) was directly related to this phenomenon, involving a significant increase in the pore pressure at depth, which reduced the “effective strength” of the rocks in the subsurface (Brune and Thatcher, 2002).

The size, rate, and manner of seismicity are controlled by the rate and amount of fluid injected, the orientation of the stress field relative to the pore-pressure increase, the extensiveness of the local fault system, and (last but not least) the deviatoric stress field in the subsurface, i.e., how much excess stress is available to cause an earthquake (Cornet et al., 1992; Cornet and Scotti, 1992; Cornet and Julien, 1993; Cornet and Jianmin, 1995; Brune and Thatcher, 2002).

3. Description of Enhanced Geothermal Systems (EGS)

An Enhanced Geothermal System (EGS) is an engineered subsurface heat exchanger designed either to extract geothermal energy under circumstances in which conventional production is uneconomic, or to improve and potentially expand the heat extraction operations so that they become more economic. Most commonly, an EGS is needed wherever the reservoir rocks are hot but their permeability is low. In such systems, permeability may be enhanced by hydraulic fracturing, high-rate water injection, and/or chemical stimulation (Allis, 1982; Batra et al., 1984; Fehler, 1989; Beauce et al., 1991). Once permeability is increased, production can be sustained by injecting the heat-depleted geothermal water (supplemented as required from external sources) back into the reservoir and circulating it through the newly created permeability, where it is heated as it travels from the injection to the production wells. As circulation proceeds, the rocks in contact with the water will cool and crack and some minerals will dissolve, creating new permeability, expanding the reservoir further and exposing new rock surfaces from which to mine the heat stored in the subsurface rock masses.

Other EGS schemes focus on improving the chemistry of the natural reservoir fluid. Steam impurities such as non-condensable gases decrease the efficiency of the power plants, and acid constituents (principally HCl and H_2SO_4) cause corrosion in wells, pipelines, and turbines (Baria et al., 2005). Water injection is again an important EGS tool for tackling these fluid chemistry problems.

3.1. Induced seismicity within EGS applications

Each of the major EGS techniques, i.e. hydrofracturing, fluid injection, or acidization, has been used to some extent in selected geothermal fields, and in most cases there is some information on the seismicity (or lack thereof) induced by these operations. Specific examples are discussed in the Case Histories below.

Hydrofracturing, by definition and design, is a form of induced seismicity. This technique has been used extensively in the oil and gas industry to engineer permeability in tight rock formations. Hydrofracturing takes place when the fluid-injection pressure exceeds the rock fracture gradient and tensile failure occurs, creating a “driven” fracture. The failure should end when the pressure is no longer above the fracture gradient. However, shear failure has also been observed in association with hydrofracturing operations. In many instances, because of the very high frequency signals of tensile failure (seismic source at the crack tip only), microseismic monitoring can detect shear failure only (is this correct?). We do not know of any cases where hydrofracturing induced damaging earthquakes (Majer et al., 2005; Baria et al., 2006).

Injection at sub-hydrofracture pressures can also induce seismicity, as documented in a number of EGS projects (e.g. Mauk et al., 1981; Ludwin et al., 1982; Stevenson, 1985; Sherburn et al., 1990; O'Connell and Johnson, 1991). These studies of low-pressure injection-induced seismicity in geothermal fields have concluded that the events are predominantly of low magnitude. (The largest recorded event so far was a 4.6 earthquake at The Geysers field in northern California in the 1980s, when fluid production was at its peak. Since then, there have been a few magnitude 4 events, but none as large as the event in the early 1980s. Almost all other induced seismicity at other geothermal fields has been in the range of magnitude 3 or less).

3.2. Mechanisms of induced seismicity in geothermal environments

Induced seismicity has been documented in a number of operating geothermal fields and EGS projects. In the most significant of these, thousands of small events are generated annually. These are predominantly microearthquakes (MEQs) not felt by people, but also include earthquakes of magnitudes up to the 4–5 range. At other sites, the induced seismicity may be entirely of very low magnitudes, or a short-lived transient phenomenon. These MEQ events have led to little or no damage in most of the operating hydrothermal fields around the world.

There are several different mechanisms that have been hypothesized to explain the occurrence of induced seismicity in geothermal settings:

3.2.1. Pore-pressure increase

As explained above, in a process known as effective stress reduction, increased fluid pressure can decrease static friction and thereby facilitate seismic slip in the presence of a deviatoric stress field. In such cases, the seismicity is driven by the local stress field, but triggered on an existing fracture by the pore-pressure increase. In many instances, the pore pressure required to shear favourably oriented joints can be very low, and vast numbers of microseismic events occur as the pressure migrates away from the wellbore in a preferred direction associated with the direction of maximum principal stress. In a geothermal field, one obvious mechanism is fluid injection, which can increase pore pressure locally and thus may account for high seismicity around injection wells, if there are local regions of low permeability. At higher pressures, fluid injection can exceed the rock strength, actually creating new fractures in the rock (as discussed above).

3.2.2. Temperature decrease

Cool fluids interacting with hot rocks can cause contraction of fracture surfaces, in a process known as thermoelastic strain. As with effective stress, the slight opening of the fracture reduces static friction and triggers slip along a fracture that is already near failure in a regional stress field. Alternatively, cool fluid-hot rock interactions can create fractures and seismicity directly related to thermal contraction. In some cases, researchers have detected non-shear components, indicating tensile failure, contraction, or spalling mechanisms.

3.2.3. Volume change due to fluid withdrawal/injection

As fluid is produced from (or injected into) an underground resource, the reservoir rock may compact or be stressed. These volume changes cause a perturbation in local stress conditions, which are already close to the failure state (geothermal systems are typically located within faulted regions under high states of stress). This situation can lead to seismic slip within or around the reservoir. A similar phenomenon occurs where solid material is removed underground, such as in mines, leading to "rockbursts," as the surrounding rock adjusts to the newly created void space.

3.2.4. Chemical alteration of fracture surfaces

Injecting non-native fluids into the formation (or allowing "outside fluids" to flow into the reservoir in response to pressure drawdown) may cause geochemical alteration of fracture surfaces, thus changing the coefficient of friction on those surfaces. In the case of reduced friction, MEQs (smaller events) would be more likely to occur. Pennington et al. (1986) hypothesized that if seismic barriers evolve and asperities form (resulting in increased friction), events larger than MEQs may become more common.

All four mechanisms we have just described are of concern for EGS applications. The extent to which these subsurface phenomena are active within any specific situation is influenced by a number of local and regional geologic conditions that can include the following:

1. Orientation and magnitude of the deviatoric stress field in relation to existing faults.
2. Extent of faults and fractures: the magnitude of an earthquake is related to the area of fault slippage and the stress drop across the fault. Larger faults have more potential for a larger seismic event, with the dominant frequency of the event related to the length of the shearing fault (i.e., in general, the longer the fault, the lower the dominant emitted frequency, and the wider the range of frequencies over which there is strong shaking, the greater the likelihood of structural damage). Larger earthquakes on larger faults also tend to be more damaging because of longer duration and increased energy content. Larger-magnitude events (3 to 4) can also be generated by high stress drops on smaller faults, but the frequency emitted is too high to cause structural damage. Observations at the Soultz site (see Section 8) showed that events in the local magnitude range of 2-2.7 had dominant frequencies at around 90 to 100 Hz on the down-hole broad-band seismic sensors (4-1000 Hz). As a general rule, EGS projects should be careful in conducting any operation that includes direct physical contact or hydraulic communication with large seismically active faults.
3. Rock mechanical properties (e.g. compaction coefficient, shear modulus, and ductility).
4. Hydrologic factors (e.g. static pressure profile, existence of aquifers and aquacludes, and rock permeability and porosity).
5. Historical natural seismicity: in some cases, induced seismicity has occurred in places where there was little or no baseline record of natural activity. In other instances,

exploitation of underground resources in areas of high background seismicity has resulted in little or no induced seismicity. Still, any assessment of induced seismicity potential should include a study of historical earthquake activity.

It is clear from the above that large magnitude events are not a common phenomenon, since this requires that a variety of factors all come together at the right time (enough energy is stored in the subsurface to be released) and in the right place (on a fault large enough to produce a large event) for a significant earthquake to take place. It is also easy to understand why seismicity may take the form of many small events.

Several conditions must therefore be met for significant (damaging) earthquakes to occur. There must be a fault system large enough to allow significant slip, forces must be present to cause this slip along the fault (as opposed to some other direction), and these must be greater than the forces holding the fault together (the sum of the forces perpendicular to the fault, plus the strength of the material in the fault). Also, larger earthquakes, i.e. big enough to cause damage to a structure, can usually only occur at depths greater than 5 km. Even though the fault ruptures extend to the ground surface, it is only the rupture at depth that is thought to produce significant seismic radiation; indeed, some ground-motion prediction equations discount the contribution from ruptures within the uppermost 2-3 km (e.g. Campbell, 1997). The low seismogenic potential of the near-surface crust is also reflected in the finding that buried fault ruptures produce stronger shaking than surface rupturing events (Kagawa et al., 2004).

4. Geothermal case studies

The case studies presented in the following sections describe different experiences with EGS projects, and the technical and public perception issues that have been encountered. These projects are representative of a variety of conditions (see also Knoll, 1992; Talebi, 1998; and Guha, 2000).

4.1. Technical approach

The objective of fluid injection is to increase the productivity of the reservoir. Each case history will have different technical specifications and conditions. Important parameters in the design of injection programs are: 1) injection pressure, 2) injection volume, 3) injection rate, 4) temperature of the injected fluids, 5) chemistry of the injectate, 6) continuity of injection, 7) location and depth of injection, 8) in situ stress magnitudes and patterns, 9) rock fracture/permeability, and 10) historical seismicity.

4.2. Public concerns

Each site will also differ in the level and type of community concern. Some geothermal areas are very remote, so that there is little public anxiety with regard to induced seismicity. Some sites, on the other hand, are near or close to urban areas. Felt seismicity may be perceived as an isolated annoyance, but there also may be concern about the cumulative effects of repeated events and the possibility of larger earthquakes in the future.

4.3. Commonalities and lessons learned

To formulate recommendations on how to mitigate the effects of induced seismicity, we must first examine the aspects common to the different environments and any lessons learned to date. In some cases a preliminary examination of the data revealed an emerging pattern of larger events occurring on the edges of the injection areas, even after injection had ended. In other instances, there was an initial burst of seismicity as injection commenced, but then seismicity decreased or even ceased as the injection rate stabilized.

The case histories discussed in this study are The Geysers (USA), Cooper Basin (Australia), Berlín (El Salvador), Soultz-sous-Forêts (France), and, briefly, Basel (Switzerland).

4.3.1. The Geysers, USA

A large body of seismic and production/injection data has been compiled over the last 35 years, and induced seismicity at The Geysers has been tied to both steam production and water injection. Supplemental injection projects met strong community opposition, despite prior studies predicting less than significant impact. The opposition has abated somewhat because of improved communications with residents and actual experience with the increased injection.

4.3.2. Cooper Basin, Australia

Cooper Basin is an example of a new project with the potential for massive injection. Test injections have triggered seismic events with magnitude above 3.0. The project is, however, in a remote area, and there is little or no community concern.

4.3.3. Berlín, El Salvador

At Berlín the EGS project is on the margins of a producing geothermal field. The proponents have developed and implemented a procedure for managing injection-induced seismicity that involves simple criteria to determine whether injection should continue (see detailed case history below). This procedure could prove applicable to other EGS projects.

4.3.4. Soultz-sous-Forêts, France

Soultz is a well-studied example, with many types of data collected over the last 15 years in addition to the seismic data. The EGS reservoirs were created at two depths (3500 and 5000 m), with the deeper reservoir aimed at proving the concept at great depth and high temperature (200ºC). Concern about induced seismicity has curtailed activities, and no further large-scale hydraulic stimulations are planned until the issues raised by the local community have been resolved (i.e. microseismicity and possible damage to structures from an event of around local magnitude 2.9).

4.3.5. Basel Deep Heat Mining, Switzerland

This very recent project at Basel was suspended during the revision of this paper as a result of induced seismicity. It is too early to include a detailed report, but given the relevance of the project to the issues being discussed here, we have provided a brief overview.

5. The Geysers geothermal field, USA

The Geysers vapour-dominated geothermal field is located about 120 km north of San Francisco, California (**Fig. 1**). The area is in the Coastal Ranges and is influenced by the general strike-slip tectonics of Northern California. Oppenheimer (1986) described the tectonic setting as extensional, with the regional stress field predominating over locally induced stresses, mainly as a result of reservoir contraction. Note that, although there are several faults nearby, there are no mapped through-going faults (Oppenheimer, 1986).

The Geysers is a good case study for several reasons. Seismicity has been monitored for a number of years, creating one of the most comprehensive data sets available. In addition, two large injection projects over the last nine years have provided the opportunity to examine the seismicity (and changes in seismicity) resulting from large influxes of water. Finally, but of no less importance, seismic arrays have been deployed over the entire field, not just the planned injection region, to examine the field-wide response to injection.

The increased microearthquake activity at The Geysers results from a diverse set of mechanisms: that is, there is not one "triggering" mechanism, but rather a variety of processes in operation, working independently, together, or superimposed on one another to enhance or reduce seismicity. For example, as water is injected into the reservoir, there is an obvious cooling, a change in pore pressure (at least locally around the injection wells), and possibly wider-ranging stress effects. A long-held hypothesis is that volume change caused by fluid withdrawal (or injection) causes local stress redistribution. In an area already near to failure, MEQ activity could therefore be activated.

Vapour-dominated and very hot "sealed" geothermal reservoirs, by their very nature, are water-short systems. Without the injected water, the geothermal resources of these areas would be under-utilized. High-temperature, water-short systems are prime candidates for enhanced geothermal activities. The increases in injection rates and the spatial extent of injection, however, have raised local community concern regarding the social and economic impact of injection-related seismicity.

Injection operations have been carried out at The Geysers for many years, but there have been two particularly large increases in the injection rates since the mid 1980s. The first started in 1997, when a 46.4 km long pipeline began delivering treated wastewater and lake water from Lake County (to the north) at a rate of about 22 million litres/day. The second started in 2003 with the delivery of about 30 million litres/day of treated wastewater from the city of Santa Rosa to The Geysers through a 64 km pipeline.

Many studies have demonstrated that MEQs at The Geysers are associated with water injection and steam extraction (Majer and McEvilly, 1979; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Enedy et al., 1992; Stark, 1992; Foulger et al., 1997; Kirkpatrick et al., 1999; Ross et al., 1999; Smith et al., 2000; Stark, 2003; Antony Mossop, pers. comm., July 2004; Majer and Peterson, 2005). These investigations conclude that there is a definite correlation of spatial and temporal MEQ distributions with injection/production data. The events that occur are consistent with the regional stress field, but there are also studies that suggest that non-double-couple events are also occurring (e.g. Ross et al., 1996).

Pore fluid depletion has also been shown to correlate with seismicity at The Geysers (Gunasekera et al., 2003). Antony Mossop (pers. comm., July 2004) makes a comprehensive correlation study based on induced seismicity and operational data from 1976 to 1998. He identified three types of induced seismicity of high significance: (1) shallow production-induced seismicity that has a long time lag (on the order of one year); (2) deep injection-induced seismicity with a short time lag (<2 months); and (3) deep production-induced seismicity with short time lag, <2 months, that appears to diminish in the late 1980s. Studying one specific case in detail, he found that shallow MEQs are well correlated to injection, rather than production, and with a relatively short time lag of about one week. For shallow MEQs, there might be a long-term effect caused by the overall steam production and local short-term responses related to injections.

Figure 1 shows the historical seismicity of Northern California over the last 100 years between magnitude 3.0 and 5.0 (there have been no events located at The Geysers greater than 5.0). As can be seen from this figure, the historical seismicity of events over 3.0 in the area has not been high during this 100-year period. The seismicity since 1965 (roughly the date of significant production at The Geysers) is given in **Fig. 2**, which reveals that the seismicity below magnitude 3.0 has been increasing significantly over the years. The steam production and seismicity trends clearly diverge after additional sources of water (other than condensed steam) were used for injection, starting in the late 1980s. The level of seismicity is shown to have very little (if any) direct relationship with production. Also, the "injection" chart is scaled such that the injection and seismicity values, at the time of the injection peak in 1998, plot more or less together. What is striking is that the injection and seismicity plots are now very similar for every year thereafter (including the recent period of increasing Santa Rosa wastewater deliveries), as well as being quite similar for all the years previous to 1998. This finding clearly indicates a remarkably strong correlation of seismicity with fluid injection, a correlation that has been rather consistent throughout the past 30 years.

These data seem to confirm that shallow and deep induced MEQs occurring after the 1980s are correlated to local injection rates, after a certain time lag (Enedy et al., 1992; Stark, 1992; Romero et al., 1995; Kirkpatrick et al., 1999; Smith et al., 2000; Stark, 2003). For example, Stark (1992) showed that plumes of MEQs are clustered around many injection wells, and the seismic activity around each of these wells correlates with its injection rate.

The location of the wells and pipelines for the two large injection projects at The Geysers, and of the various seismic arrays [the Northern California Seismic Network (NCSN) of the U.S. Geological Survey (USGS), the geothermal operator's array (Calpine Corporation; Calpine), and the Lawrence Berkeley National Laboratory (LBNL) array installed in 2001] is shown in **Fig. 3**. Each of these arrays was designed for a different sensitivity and purpose.

Figure 2 shows that seismicity increases with injection, but not at all levels. Taking the larger events only (i.e. those with magnitudes of around 3), the seismicity has remained fairly constant since 1985.

Definite patterns emerge from The Geysers data gathered by the LBNL array. **Figure 4** shows all of the events located by this array in October 2003 (one month prior to the start of injection of treated Santa Rosa waste waters); the seismicity in March 2004 (after the injection start-up in December 2003) is given in **Fig. 5**. Also shown in these figures is the location of the magnitude 4.4 event of 18 February 2004. These two periods were chosen because the seismic array was fully operational throughout. The plots clearly show an increase in overall seismicity in the injection area. As stated before, this is typical of seismicity at The Geysers, and some or all of the increase may just be normal seasonal variation as the non-Santa Rosa water injection ramps up.

Low-magnitude seismicity increased in the Southeast (SE) Geysers when supplemental injection began there (Beall et al., 1999; Kirkpatrick et al., 1999; Smith et al., 2000), and it is not surprising that it is occurring now. If past experience is any indication, the system will reach equilibrium as time goes on, and seismicity will level off and possibly decrease. It has been our experience that the initial injections will perturb the system, cause an increase in seismicity, then level off and/or decrease. The time to reach equilibrium will be a function of the size of the disturbance and the volume of the affected area.

Injection rate also seems to be an important factor. One hypothesis worth considering is that, if the rate of increase in injection is varied (giving the system a chance to equilibrate), there may be less initial seismicity. Also, as pointed out with respect to the historical seismicity at The Geysers, the yearly seismic energy release is actually decreasing (Majer and Peterson, 2005). The recent injections may reverse this trend, but it is too early in the monitoring process to draw conclusions.

There have been queries about the trend of the maximum event. The largest recorded so far at The Geysers occurred in 1982 (4.6 magnitude), but during 2006 there were three of magnitude greater than 4.0 (see **Fig. 2**). The maximum event will depend upon the size of the fault available for slippage, as well as the stress redistribution caused by fluid injection and production. To date, there have been no faults mapped in The Geysers that would generate an event of magnitude 5.0 or greater. This is not an absolute guarantee that one would not happen, but it does lower the likelihood of larger events. There are several possible approaches to this issue, one of which is to carry out fractal analysis (Henderson et al., 1999) or use probabilistic seismic analysis. However, it is not clear whether, in cases of induced seismicity, probabilistic seismic hazard analysis would be reliable (Bommer and Abrahamson, 2006).

In terms of public response, the community around The Geysers is worrying more about the number of MEQs and the largest-magnitude event. In light of this anxiety, the following consensus opinion was presented to the local seismic advisory board by David Oppenheimer (USGS), Ernest Majer (LBNL), Mitch Stark (Calpine) and William Smith (Northern California Power Agency; NCPA), which reflected their current understanding of The Geysers seismicity and should be considered a work in progress. As more data are collected, interpretations may change. *

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FOOTNOTE

*The observations that follow are not endorsed by Calpine, LBNL, NCPA or USGS. They represent the professional opinions of the authors, based on many years of studying seismicity at The Geysers, and on relevant publications.
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1. The region surrounding The Geysers is tectonically stressed, cut by numerous faults, and subject to a high level of earthquake activity. In The Geysers field, there are no mapped faults active in the last 10,000 years (as determined by geologic mapping). The Collayomi Fault, running approximately 1.6 km NE of the field limit, is mapped as an inactive fault. The nearest active fault is the Mayacamas Fault, located about 6 km SW of the field limit. On the Lake County side, the active Konocti Bay fault system is located approximately 13 km north of the field limit.
2. Pre-production baseline data sets, though incomplete, strongly indicate that little seismicity occurred in the field for at least 10 years prior to the 1960 start-up of commercial production.
3. Seismicity has become more frequent and has expanded as field development expanded. Scientists who have studied The Geysers' seismicity universally agree that most of these earthquakes have been induced by geothermal activities. It is likely that both injection and production operations have contributed to induced seismicity.
4. Earthquake frequency and magnitude distributions at The Geysers have been approximately stable since 1985. Since 1980, two or three events per decade of magnitude $\geq$4.0 have occurred, along with an average of about 18 events per year of magnitude $\geq$3.0. In the two years (2004 and 2005) after starting injection of the Santa Rosa wastewater, the number of events with magnitudes higher than 4.0 increased. The largest Geysers earthquake ever recorded had a magnitude 4.6 in 1982. Based on Greensfelder (1996)'s analysis of historical seismicity, and supported by the intensive fracturing, the absence of continuous long faults, and the lack of alignment of earthquake epicenters, it has been tentatively inferred that the largest earthquake possible at The Geysers would be of magnitude 5.0.
5. Production-induced seismicity is very evident on a field-wide scale, but is not tied to specific wells. That is because there are hundreds of producing wells, and the mechanical effects of steam production (principally reservoir pressure decline and heat extraction) are diffuse and spread out into the reservoir. Indeed, seismicity occurs in reservoir regions well beyond the location of geothermal production and fluid injection wells. Since 1987, steam production has declined substantially, but seismicity has remained stable.
6. Injection-induced seismicity is very evident on a field-wide scale, but is not tied to being primarily downward from some injection wells. At such a well, the seismic clouds generally appear shortly after injection begins, and earthquake activity within each cloud

shows good temporal correlation with injection rates. It has been demonstrated in several papers and environmental analyses (Raleigh et al., 1972; Majer and McEvilly, 1979; Allis, 1982; Ludwin et al., 1982; Oppenheimer, 1986; Fehler, 1989; Foulger et al., 1997; Kirkpatrick et al., 1999; Majer and Peterson, 2005; Bommer et al, 2006) that injection-induced seismicity is generally of low magnitude (≤3.0). On a field-wide basis, seismicity of magnitude ≥1.5 has generally followed injection trends, but this correlation has not been observed for earthquakes of magnitude ≥3.0.

7. Seismicity in the vicinity of Power Plant 15 (located SW of injection well OF45A12; see **Fig. 3**), which ceased production in 1989, had also stopped by the end of 1990. However, this has not been the case in the vicinity of the CCPA plant (located NE of injection well DX19; see **Fig. 3**), where production ceased in 1996, but seismicity has continued up to the present.
8. Since 1989, the SE Geysers area has experienced a long-term increase in earthquakes of magnitude ≥1.5. Magnitude 1.5 is the minimum magnitude of uniform detection threshold since 1979. The same general trend has been observed in the part of the SE Geysers study area within 3.2 km of Anderson Springs (the general location of this town is shown in Figs. 4 and 5).
9. Injection rates in the SE Geysers doubled starting in late 1997, owing to the introduction of SE Geysers Effluent Pipeline (SEGEP) water from Lake County. This injection-rate doubling did not lead to any significant change in the continuing rate of increase for seismic events of magnitude ≥1.5 in the SE Geysers area. Events of magnitude ≥2.5 initially continued at about the pre-pipeline rate for the next 4 years, but they have increased more recently, along with events of magnitude 1.5 and greater, even though injection in the area has been reduced. Consequently, the seismicity observed in this area during the 2000-2006 period is apparently not directly related to the injection of wastewater from these pipeline operations.
10. A preliminary analysis of the amplitudes of recorded earthquakes in the Anderson Springs area suggests that, theoretically, shaking large enough to be felt by residents occurs about 1.5 times per day on the average. Measured peak accelerations are generally consistent with the observations reported by residents; i.e. in the Modified Mercalli Scale II to VI range. However, reports of higher-intensity damage, such as the fall of a large tree and a retaining wall, are clearly not consistent with seismicity as the singular cause.

6. Cooper Basin, Australia

Cooper Basin is an example of a geothermal resource under development, located in the northeast of South Australia, close to Moomba (not in the figure), in a sparsely populated region (**Fig. 6**). In 2003, Geodynamics Limited, Australia, drilled the first injection well (Habanero-1) into a granitic basement to a depth of 4421 m (754 m into granite) (Asanuma et al., 2005a; Baisch et al., 2006). The granite basement is overlain by 3.6 km of sediments. The main stimulation of this well, i.e. water injected into a hot zone to induce fracturing, took place after several tests to initiate fractures in the granite (Fracture Initiation Tests—FIT) and evaluate their hydraulic characteristics (Long-term Flow Test—LFT). The total amount of liquid injected was 20,000 m^3, with a maximum pumping rate of 48 L/s. Temperature and flow profiles taken in the open-hole section indicated an outflow zone at 4254 m depth. The main stimulation started on 30 November and ended on 9 December 2003. The casing was then perforated between 3994 and 4136 m depth and pressurized in several cycles between 12 and 22 December 2003 (Asanuma et al., 2005a; Baisch et al., 2006).

Seismic events were detected by the network from the initial stage of the FIT, when the pumping rate was around 8 L/s. The monitoring array was a local eight-station network of three-component geophones in boreholes between 70 m and 1800 m depth (see **Fig**. **5**). The recording system was a 16 bit, 5 kHz system in triggered mode (Asanuma et al., 2005a). Seismic signals were picked up by the deep detector (at 1700 m depth) and in most cases also by the near-surface stations, with clear onsets of P and S waves. Asanuma et al. (2005a) recorded 32,000 triggers, with 11,724 of them located in 3D space and time on site during the stimulations.

During the FIT, LFT, and the main injection tests, Asanuma et al. (2005a) observed several events approaching magnitudes of 3.7. The largest event occurred at 00:03 on 14 November 2003. This event was detected by the Australian national earthquake-monitoring network of Geoscience Australia (GA) and had a moment magnitude M (as defined by Hanks and Kanamori, 1979) of 3.7. Because of the unexpectedly large seismic vibration, the trace was saturated just after the P-wave onset, and most of the information on the trace after the saturation was lost. Consequently, the length of the coda was used to estimate the local magnitude and calibrated to the moment magnitude by means of two reference events. One is the previously-mentioned largest event that had a duration time of 180 seconds. The other reference event was one that had a critical amplitude for saturation with a duration time of 63 seconds. From experience with the same detectors at Japanese Hot Dry Rock (HDR) sites (Asanuma et al., 2005a), where the configuration of the seismic source and detector is similar to the one at the site in the Cooper Basin, such critically saturated events have a moment magnitude M of 1.0, although the attenuation in the Australian and Japanese sites may be different.

These results were used to calibrate the moment magnitude of all the events to the frequency distribution of the moment magnitude. Following the Gutenberg-Richter law (Richter, 1958), the accumulated histogram of event magnitudes plotted on a logarithmic scale should define a linear relationship. In this case, however, there is an apparent inflection point at around M 1.0, suggesting that the seismic origin or mechanism may be different for events with magnitude higher than M 1.0. Hence the designation of such events as “big events” (30 of such events in the FIT and LFT were analyzed). We assume that these bigger events were caused by rapid fracture extension.

Microseismic events were manually clustered in the FIT and LFT by their location and the origin time, because the extension of the seismic cloud at the Cooper Basin site was heterogeneous. An example of the location of the events before and after the big events, where an extension of the seismic cloud was clearly seen after the 3.0 event, is shown in **Fig.** 7. The size of the circle at the location of the MEQs shows the source radius of the event estimated from the moment magnitude. In this case, the seismic cloud subsequently extends beyond the magnitude 3.0 events, which occurs at the edge of the seismic cloud. In a recent study, Baisch et al. (2006) find that “the hypocenter distribution exhibits a high degree of spatio-temporal ordering, with the seismic activity systematically migrating away from the injection well with increasing time. Previously activated regions become seismically quiet, indicating relaxation processes. High-resolution relative hypocenter locations determined for clusters of "similar" events locally reduce the apparent thickness of the structure to the level of a few tens of meters, indicating that the reservoir is dominated by a single fracture zone only."

In view of the above, the physical processes responsible for the big events at the Cooper Basin site are similar to those responsible for the smaller events, namely:

> - The induced slip of the existing sub-horizontal fracture at this site can be modelled by slip on a plane containing heterogeneously distributed asperities. It has been revealed that the size of the asperity is correlated to the moment magnitude of the earthquake in the case of repeating events at a tectonic plate boundary. Assuming that scaling applies, one would expect the same to hold true on most faults. In the same manner, the magnitude of the earthquakes may be correlated to the size of the asperity, and the "aftershock" MEQs within the source radius of the big events may be correlated to the non-geometrical shape of the asperity or asperities remaining after those larger events.
>
> - It is reasonable to assume that, prior to the larger events, water could not flow easily beyond the asperity, and that the subsequent extension of the seismic cloud after those events indicates an improvement in permeability.
>
> - The fact that larger events occurred after shut-in lends support to the theory that the initial stress state of the fractures was critical/overcritical.

There was no distinct change in wellhead pressure associated with the larger events, which may indicate that reservoir capacity at this site in the Cooper Basin is very large compared to the improvement in permeability caused by a big event.

In terms of public acceptance, the site is remote, with few inhabitants in the vicinity; thus there is little cause for concern as regards the possible effects of induced seismicity.

7. Berlín, El Salvador

The Berlín case history is an example of a project with a built-in warning system for monitoring, quantifying and controlling the risk associated with induced seismicity. The system is summarized here; full details are given in Bommer et al. (2006).

In 2003, hydraulic stimulations were carried out at the Berlín geothermal field **(Fig. 8),** as part of a feasibility study for hot fractured rock (HFR) power generation. The HFR project at Berlín presented an unusual problem, in terms of induced ground shaking. El Salvador is in a region of very high seismic activity, affected by two principal sources of earthquakes: the subduction of the Cocos Plate beneath the Caribbean Plate in the Middle America Trench, producing Benioff–Wadati zones, and shallow crustal events coincident with the chain of Quaternary volcanoes (e.g. Dewey et al., 2004).

Large-magnitude earthquakes in the subduction zone tend to cause moderately intense shaking across large parts of southern El Salvador, an example of such an event being the 13 January 2001 earthquake of moment magnitude (M) 7.7. Greater risk is represented by the smaller-magnitude shallow, crustal earthquakes that occur along the Salvadoran volcanic chain, close to population centers. The Berlín field is not in the vicinity of the larger destructive earthquakes that have affected other locations along that chain, although the area experienced shaking during the 1951 Jucuapa-Chinameca earthquakes to the east (Ambraseys et al., 2001) and the M 6.6 earthquake of 13 February 2001 to the west (Bommer et al., 2002).

The geothermal field, located on the flanks of the Cerro Tecapa volcano (last eruption thought to have been in 1878), was developed in the 1990s. The Comisión Hidroeléctrica del Río Lempa (CEL), the state electricity company, began electricity production at Berlín in 1992. At the moment, 54 MWe are being generated from eight production wells; water separated from the steam is being disposed of at a temperature of 183°C using 10 injection wells. The depths range from about 700 m for some of the shallow injection wells down to approximately 2500 m for the deeper production and injection wells.

The field development activities at Berlín included a surface seismic monitoring array, the Berlín Surface Seismic Network (BSSN) (see **Fig. 9**), which was brought into use in 1996 to monitor events in and around the field. Since long-term seismic monitoring began after the start of commercial-scale fluid extraction and injection, it is difficult to say with any confidence whether the observed seismic activity is triggered by the ongoing field exploitation activities, or is rather a manifestation of the hydrothermal activity around the volcano. There is the suggestion within the BSSN catalogue that seismicity rates can be correlated with production and injection rates (Rivas et al., 2005). That is, fluid production increased at Berlín shortly before the large earthquakes of 13 January and 13 February 2001, and these events led to a step change in the observed local seismicity rate. The second possibility, that local seismicity is a manifestation of the field's natural hydrothermal state, supports the theory that, in a fracture-dominated geothermal field, it is only the still seismically active faults or fractures that will remain permeable, by virtue of their continued movement (rather than becoming sealed by mineralization). In this way, one could argue that microseismic monitoring is a valid geothermal exploration tool.

Fracture stimulation was expected to generate only small-magnitude earthquakes, if any, and the project took place in a region that had been strongly shaken by major earthquakes less than 3 years earlier. However, the need to ensure that the HFR geothermal project would be environmentally friendly in all aspects, and the highly vulnerable nature of many of the local buildings, made it necessary to consider any perceptible ground motions that might be generated locally by the rock fracturing process. A key requisite was that the induced seismicity associated with the reservoir stimulation at depths of 1–2 km should not produce levels of surface ground shaking that would present a threat or serious disturbance to those living in and around the geothermal field.

The specific context and conditions of the Berlín HFR project required the development of a calibrated control system, dubbed "traffic light," in order to enable real-time monitoring and management of the induced seismic vibrations. An important factor in this case is the high natural seismicity of the region, and the fact that it is perfectly feasible for an earthquake to occur during or after the injection operations without there being any direct connection to these activities. A most delicate situation would arise were damage to occur as a result of such a natural earthquake, because it would be difficult to establish the degree to which the damage was exacerbated by structural weakening of the houses in the area resulting from ground shaking induced by the injection process up to that time. Similarly, if a natural earthquake does cause damage, the vulnerability assessment information used for the baseline seismic risk assessment and the upper thresholds on the traffic lights may both need to be revised. Cypser and Davis (1998), in their discussion of liability under U.S. law for the effects of induced seismicity, state the following: "Seismicity induced by one source might accelerate failure of support originating from another source, leaving both of the parties at fault proportionally liable to the injured parties."

The first step was to estimate the likely dominant frequency of any ground motions that might occur as a result of the HFR project. Accelerograph recordings of small-magnitude earthquakes were used for this purpose, particularly those recorded in the 1985 swarms in Berlín and nearby Santiago de María; information on these swarms can be found on the Internet (http://www.snet.gob.sv/Geologia/Sismologia/1enjamb.htm). The response spectra from these recordings consistently showed a pronounced peak at a period close to 0.1 sec; hence, 10 Hz was adopted as the central frequency and used to infer thresholds. This may appear to be a rather high frequency for buildings, but it is appropriate to the heavy, low-rise dwellings common in the area.

The final stage in designing the monitoring system was to infer a series of Peak Ground Velocity (PGV) thresholds based on those indicated in **Fig. 10** for lower levels of shaking (controlled by human response) and on vulnerability curves defined for the local buildings for the higher levels (controlled by structural damage). In both cases, the inferred levels were checked against the implied intensity levels for each PGV threshold and the consequent human or structural responses, using the data and relationship of Wald et al. (1999). There was inevitably a significant degree of "expert judgment" involved in making these inferences, and, in the face of uncertainty, conservative decisions were made; this was particularly the case since, as explained below, the traffic light operated on the basis of median predicted PGV values and did not account for the aleatory variability in the ground-motion predictions.

The seismic monitoring system (supplied by ISS International) deployed around injection well TR8A **(Fig. 9)** allowed real-time monitoring and processing of the recorded seismicity, so that the traffic light program **(Fig. 11)** could be executed automatically at specified time intervals, reading the event catalogue for a specified number of days up to the time of execution. For each event, a PGV-equivalent magnitude, M_{equiv}, was calculated using a predictive equation for PGVs based on recordings from seismic swarms in El Salvador. The median values of the equation, which relates PGV to magnitude and hypocentral distance, were used to estimate the magnitude, M_{equiv}, required for an event located at a depth of 2 km to produce the observed epicentral PGV of a given event. A Gutenberg–Richter type plot of $\log_{10}[N(M_{\mathrm{equiv}})]$ against M_{equiv} was then constructed for the data and plotted in a window on the monitoring system's computer. The thresholds of PGV were expressed in terms of M_{equiv}, so that they could then be displayed on this pseudo-Gutenberg-Richter plot to allow a rapid assessment of the environmental compliance of the ongoing fluid injection operation using high-capacity, high-pressure pumps. The boundaries on the traffic light were then interpreted as follows, in terms of guiding decisions regarding these operations:

- *Red*. The lower magnitude bound of the red zone is the level of ground shaking at which damage to buildings in the area is expected to set in. Injection is suspended immediately.
- *Amber*. The amber zone is defined by ground motion levels at which people would be aware of the seismic activity associated with the hydraulic stimulation, but damage would be unlikely. Pumping proceeds with caution, possibly at reduced flow rates, and observations are intensified.
- *Green*. The green zone is characterized by levels of ground motion that are either below the threshold of general detectability or, at higher ground-motion levels, at occurrence rates lower than the already-established background activity level in the area. Injection operations proceed as planned.

The sloping part of the boundary between the green and amber zones (**Fig. 11**) reflects the recurrence data over a 30-day period for the background seismicity prior to the initiation of the HFR project. The rationale behind this boundary was that if the induced activity did not exceed the natural levels of microseismicity, there would be no problem with continuing the hydraulic stimulations.

Preliminary analysis of the seismicity and injection rates at the Berlín field showed an approximate doubling of the seismic event rate during periods of fluid injection. However, the correlation observed was much less convincing than at Soultz (see Section 8). This finding was in part reflected in the conservative decision to consider a large area of interest for the traffic light calculations, because of possible general ambiguity regarding the cause of seismic events in the geothermal field. Closer inspection of the seismicity revealed two distinct zones of activity, one in the general area of the producing geothermal field and another (which only became notably active during injection) directly around well TR8A. Plotting the cumulative seismic moment release of this cluster of events around that injection well, against the cumulative pumped volume for the three periods of injections between July 2003 and January 2004, showed a remarkable correlation (**Fig. 12**), leaving little doubt that this seismic activity was induced directly by the fluid injection aimed at rock fracture stimulation.

The strongest recorded ground motion was produced by a magnitude 4.4 event on 16 September 2003, occurring about 3 km to the south of injection well TR8A, two weeks after shut-in of the second period of injection. This large event had a preferred fault-plane solution corresponding to a nearly east–west, right-lateral, strike-slip rupture. An important question that arises is whether this event, located on the opposite side of the producing geothermal field from TR8A, could nevertheless have been triggered by the pumping operations in that well. Given the location, timing, and low level of induced seismicity observed around TR8A, this seems unlikely, but also of relevance in this respect is the observation that in some other reported cases of injection-induced seismicity, the largest triggered events have been observed after the shut-in of injection operations (Raleigh et al., 1972).

During the reservoir stimulation activities, generally a much lower level of induced seismicity was encountered than had been anticipated, such that the boundaries of the traffic light system were not tested. The major shortcoming of this type of approach is that it does not address the issue of seismicity that occurs after the end of the injection period.

The results of the Berlín study show that the seismic hazard presented by ground shaking, caused by small-magnitude earthquakes induced by anthropogenic activities, presents a very different problem from the usual considerations of seismic danger in the engineering design of new structures. On the one hand, the levels of ground shaking that may be generated, particularly in an environment such as rural El Salvador (where the buildings are very vulnerable), are below the levels that would normally be considered of relevance to engineering design. Indeed, in probabilistic seismic hazard analysis (PSHA) for engineering purposes, it is common practice to specify a lower bound of magnitude 5, on the basis that smaller events are not likely to be of engineering significance (e.g. Bommer et al., 2001). On the other hand, unlike the risks associated with natural seismicity, we have the possibility of actually controlling, to some degree, the induced hazard by reducing or terminating the activity that is generating the small events.

8. Soultz-sous-Forêts, France

Research at the European Hot Dry Rock (HDR) site at Soultz-sous-Forêts (hereafter referred to simply as Soultz) started in 1987, following encouragement by the European Commission to pool France's limited available funds to form a coordinated multinational team. The main task was to develop the technology needed to access the vast HDR energy resource at the site, which is about 50 km north of Strasbourg, Alsace, France (**Fig. 13**). Various authors (e.g. Baria et al., 1993, 1995, 2000, 2004, 2005; Garnish et al., 1994; Baumgärtner et al., 1995, 1998; Gérard et al., 2006) have provided summaries of the various stages of development of this technology at Soultz since 1987. It should be noted that the site is located in a zone of minor natural earthquake hazard, as defined by the seismic risk authority in France (**Fig. 14**).

The European HDR test site lies on the northern flank of the Rhine Graben, which forms part of the Western European rift system (Villemin, 1986). The rift extends approximately N-S for 300 km from Mainz (central Germany) to Basel (Switzerland). The Soultz granite that intrudes the Devonian–Early Carboniferous rocks is part of the same structural block that forms the crystalline basement in the Northern Vosges.

The geology of the Soultz site and its tectonic setting have been described by Cautru (1987). The pre-Oligocene rocks that form the graben were down-thrown by a few hundred metres during the formation of this depressed crustal unit, which is about 320 million years old. The Soultz granitic horst (above which the site is located) has subsided less than the graben. At the site the granitic basement is overlain by a roughly 1400-m thick sedimentary column.

The geothermal research program at Soultz started with the drilling of well GPK-1 down to 2002 m depth in 1987, with the assumption that bottom-hole temperature would be around 175°C, but the actual temperature was around 140°C. The basic properties of the rock mass were acquired from hydro-fracture stress measurements and small-scale hydraulic injection tests. In

1990, an attempt was made to carry out continuous coring in well EPS1 to a depth of 3200 m to attain 175°C, but drilling had to be abandoned at 2227 m because the well had deviated in excess of 20°. In 1992-93, GPK-1 was deepened to 3590 m (Baria et al., 1993; Baumgärtner et al., 1995) and has a 6 1/4-inch diameter open-hole about 780 m in length. The bottom-hole temperature was found to be 160°C instead of the anticipated 175°C.

About three years later (in 1995), GPK-2 was drilled to 3890 m, approximately 450 m south of GPK-1, and was subsequently deepened to 5084 m in 1999 to attain a temperature of 202°C. Another well, GPK3, is a 5000 m deviated well drilled in 2002-03, whose bottom is located about 600 m south of that of GPK2 (**Fig. 15**); the casing shoe was set at 4556 m depth. GPK4, the second deviated production well, was drilled in 2004 to a depth of 5260 m (true vertical depth: 4982 m), with its bottom-hole about 1200 m from the wellhead (Baumgärtner et al., 2005).

The temperature gradient in the Soultz area has been determined based on numerous borehole measurements. It starts at about 10.5°C/100 m in the upper 900 m, decreasing to 1.5°C/100 m down to 2350 m, then increasing to 3°C/100 m from around 3500 m to the maximum depth measured (5000 m), where the mean temperature is about 200°C.

Well GPK1 was hydraulically stimulated in 1993, and GPK2 in 1995 and 1996, increasing the injectivity of the reservoir at 3200 m depth to ~0.4 L/(s-bar), the best achieved for an HDR/EGS project at that time (Baria et al., 1999a). Following the deepening of well GPK2 from 3890 to 5084 m in 1999, stimulation was carried out in 2000 and the injectivity of GPK-2 improved from 0.02–0.03 to ~0.4–0.6 L/(s-bar). Following the stimulation of GPK2, injection well GPK3 was targetted on the basis of information gathered using various methods (including microseismic, hydraulic, stress, and jointing characteristics). Similarly, GPK4 (second production well) was also targetted on a similar basis to that used for GPK3 (Baria et al., 2005; Baumgärtner et al., 2005).

The first successful forced circulation test, of four months duration, was carried out in 1997 between GPK-1 and GPK-2. This test demonstrated that the HDR/EGS concept works with a bottomhole separation of 450 m (Baria et al., 1995; Baumgärtner et al., 1998). It was possible to circulate continuously about 25 kg/s of brine, at more than 140°C, without any water losses and using 250 kWe pumping power only, compared to a thermal output of up to 10 MW. Tracer tests indicated a breakthrough volume of some 6500 m^3; that is, 20 times higher than that achieved in Rosemanowes (UK) and about 70 times higher than in the Hijiori (Japan) project (Baria et al., 1999a,b).

Information on the joint network at the Soultz site has been obtained from continuous cores in EPS1 and borehole imaging logs in GPK1 (Genter and Traineau, 1992a,b). The observations suggest that there are two principal joint sets striking N10E and N170E and dipping 65°W and 70°E, respectively. The granite is pervasively fractured, with a mean joint spacing of about 3.2 joints/m, but with considerable variations in fracture density.

The local stress regime was obtained using the hydrofracture stress measurement method (Rummel, 2004). The stress magnitude at Soultz as a function of depth (for 1458–3506 m depth) can be summarized as:

$$S_h = 15.8 + 0.0149 \cdot (z - 1458)$$

$$S_H = 23.7 + 0.0336 \cdot (z - 1458)$$

$$S_V = 33.8 + 0.0255 \cdot (z - 1377)$$

where S_h (minimum horizontal stress), S_H (maximum horizontal stress) and S_V (overburden) are given in MPa, and z (depth) in metres.

A recent interpretation of the data suggests that the overburden stress may still be the maximum stress up to 5000 m depth, being very close to S_H (François Cornet, pers. comm., Feb. 2005).

A microseismic network has been installed at the site **(Fig. 15)** to detect microseismic events during fluid injection and locate their origins. The equipment consists of three 4-axis downhole accelerometers and two 3-axis downhole geophones, linked to a fast seismic data acquisition and processing system. The instruments were deployed at the bottom of wells 4550, 4601, EPS1, OPS4, and GPK1, between 1400 and 3600 m depth, where the temperatures are about 120° and 160°C, respectively. In addition, a surface network of about 35 seismic stations was installed by the Ecole et Observatoire des Sciences de la Terre (EOST) in order to characterize larger events.

An industrial consortium decided that a temperature of ~200°C would be more appropriate for producing electrical power, so the decision was taken to drill deeper. GPK-2 was thus deepened to 5084 m, where it encountered a temperature of 202°C.

In 2000, the open-hole section of GPK-2 (4431–5084 m depth) was stimulated. Approximately 23,000 m^3 of water were injected in steps of 30, 40, and 50 L/s for 7 days. Seven days later, on 16 July 2002, a microseismic event of moment magnitude 2.4 occurred, during a small volume injection test (**Figs. 16 and 17**). The local inhabitants heard and felt it, and were concerned by the incident. A public meeting was held with the support of local mayors, during which the public was assured that further such events would be prevented wherever possible.

Following the triggering of the 2.4 M microseismic event, a committee of French experts was set up to investigate the incident and find ways to avoid inducing events of similar, or greater, magnitude in the future. One of the various findings of this committee was that the larger events were generated by a sharp increase or decrease in pressure. This was written into the procedures required for the stimulation of GPK3 and subsequent stimulations of deep wells at Soultz, although no evidence was given to substantiate the recommendations.

Abiding by these new procedures, the subsequent stimulation of GPK3 took longer and used significantly more fluid. That is, about 40,000 m^3 of water were injected into the reservoir at a rate of 20–80 L/s over about 11 days. During this injection, more than 400 events above magnitude 1.0 were generated; about 30 were above 2.0. The largest, a magnitude 2.9 MEQ (**Figs. 18 and 19**), occurred about 2 days after shut-in (i.e. on 10 June 2003 at 22:54 GMT time).

These later events caused even greater unrest among the local population. Various public meetings were held to explain the situation, but this left the project with a credibility problem that has been difficult to overcome. Fortunately, no structural damage was caused by these MEQs, but a number of residents did put in claims to insurance companies, which were turned down after close examination. Seismic data from the downhole sensors indicated that the predominant frequency was around 90 Hz, which is unlikely to cause any structural damage. The reservoir was put into production at lower fluid pressures to reduce the likelihood of generating further large microseismic events. Not surprisingly, the incident has made project management extremely sensitive to the generation of larger events. Attempts at stimulating GPK4, the third deep well (or the second production well), have been unsuccessful so far, because of the curtailed activity and the problems involved in finding alternative means of improving the hydraulic interconnection between GPK3 and GPK4 (Baria et al., 2006).

The upshot is that, after finally breaking new ground in HDR technology (Baria et al., 1999b), the Soultz project is beginning to falter, largely because of the public outcry over the triggered seismicity and the inability of existing management to break the impasse.

9. Basel Deep Heat Mining project, Switzerland

The Basel Deep Heat Mining project (http://www.dhm.ch/dhm-drillingInBasel.html) is a very pertinent case in point, as induced seismicity here has led to the suspension (and possible termination) of the project; this has clearly important implications for the future development of EGS technology. The project has two distinct features, one of which is its location in the middle of the city of Basel; secondly, Basel itself is located in a high-stress region associated with the largest and most destructive earthquake in the history of Switzerland; in 1356 the city was in fact largely destroyed by an earthquake of magnitude 6.5 or greater. One could also argue that Switzerland has one of the most risk-adverse populations in Europe, if not in the world. With this background, it is surprising that a thorough seismic risk investigation/analysis was not done before going ahead with the project.

The choice of site for the project, within the city, is related to the physics and economics of the heat mining energy extraction process. Energy conversion economics at 200°C are marginal if it involves drilling 5-km deep wells into hard rock, as was the case in Basel. To make it economic, the rejected heat from the conversion process has to be used too, and the most effective way of doing so is in district heating. A district heating grid requires a high population density since relatively low-grade heat (<200°C) cannot be transported long distances economically. The optimum site for this type of HFR geothermal project is in or very close to a city like Basel. A further incentive for siting the well close to the consumer is that the temperature of the produced fluids decreases with time.

In areas where the population is sparse and, in some cases, economically dependent on the geothermal extraction activities, we can expect a much higher tolerance of seismic risk. It is our opinion that until the citizens of Basel appreciate the benefits in terms of cheaper power and district heating, they are unlikely to be easily convinced that the worst that can happen is perceptible ground shaking.

The Basel Deep Heat Mining project adopted the general framework of the ”traffic light” system used at Berlín (see Section 7), but, in light of the sensitivities at Basel, used very low thresholds for ground motion; for example, in Berlín ”red” (i.e. suspension of fluid injection) was defined by a PGV threshold of 60 mm/s, whereas at Basel this threshold was specified as 5 mm/s (or a magnitude of 2.9). It is worth noting that in Berlín the threshold for appreciable damage was defined as 120 mm/s, but this reflects the highly vulnerable building stock in rural El Salvador; for engineered structures, damaging motions will generally need to have PGV values in excess of 200 mm/s (Martínez-Pereira and Bommer, 1998). We might add that at Basel (?) the public was provided with little in the way of information and advice with regard to the seismic aspects of such a project in such a difficult environment, although a version of the IEA/GIA protocol was drafted and submitted for consideration to the IEA; the public was also informed of the local population’s reaction to smaller induced seismic events at Soultz. Blind faith in a technical procedure is not a valid substitute for proper site investigation and a due process of informing local residents. Both are essential and should have been implented vigorously.

The project at Basel began with a pre-simulation test, designed to determine the formation strength at the borehole. The main stimulation started on 2 December 2006, when a total of 11,566 m^3 of water was injected. The maximum wellhead pressure reached 296 bars and injection rates were ramped up to a maximum of 62.5 L/s. At 16:48 Universal Time Coordinated (UTC) on 8 December, a magnitude 3.4 earthquake occurred in very close proximity to the injection well; the event was widely felt throughout Basel and led to a bleed-off of the well. The maximum recorded PGV value in the vicinity of the well was 9.3 mm/s, placing the motions in the "red" zone of the traffic light system as implemented, and leading to suspension of the pumping; the 5 mm/s threshold was also exceeded at three other monitoring stations. The largest recorded peak ground acceleration (PGA), at the station near the well, was 0.05 g (Nicolas Deichmann, pers. comm., December 2006); PGA values in excess of 0.2 g are generally viewed as a necessary, but not sufficient, condition for damaging motions (Martínez-Pereira and Bommer, 1998).

10. Gaps in knowledge

As stated in the Introduction, following the three international technical workshops on induced EGS seismicity held under the auspices of the IEA/GIA, it has been shown that existing scientific research, case histories, and industrial standards provide a solid basis for characterizing induced seismicity and planning its monitoring. The focus for additional study should therefore be on the beneficial use of induced seismicity as a tool for creating, sustaining, and characterizing the enhanced subsurface heat exchangers, whose performance is crucial to the success of future EGS projects. The following is a list of the primary scientific issues that were discussed at these workshops. They are listed in no particular order of priority, and are not meant to exclude others; they are merely the issues most discussed at the meetings:

1. Do the larger induced seismic events triggered during EGS operations exhibit patterns or characteristics that differ with respect to those of the natural seismicity in the area? It was pointed out that at Soultz, The Geysers, and other sites, the largest events tend to occur on the fringes, even outside the “main cloud” of events and often well after injection ceases. Why is this and what is the relation of this finding to the smaller events and to the stimulated reservoir? Moreover, large, apparently triggered events are often observed after shut-in of EGS injection operations, making such events still more difficult to control. The fact that such events are often the largest seen in a particular seismic catalogue means that it is essential to develop a solid understanding of the processes underlying the occurrence of post-shut-in seismicity. The development and use of suitable coupled reservoir fluid flow/geomechanical simulation codes will be a great help in this respect, and advances are being made in this area (see, for example, Hazzard et al., 2002; Kohl and Mégel, 2005; and Ghassemi et al., 2007). Building detailed subsurface models, and then running numerical simulations of the progress of the injected front through these models, with simultaneous calculation of the corresponding triggered seismicity, would simulate likely conditions in which larger post-shut-in events could occur and thus provide an explanation for the mechanism involved. Close analysis of an extensive suite of such models should make it possible to identify the features required for this phenomenon to occur. Laboratory acoustic-emission work would greatly help in this effort, by complementing the numerical studies and helping to calibrate the models utilized.

2. What are the source parameters and mechanisms of induced events? The issue of stress drop versus fault size and moment is important. There is some evidence that large stress drops may be occurring on small faults, resulting in larger-magnitude events than the conventional models would predict (Brune and Thatcher, 2002; Kanamori and Rivera, 2004). It was pointed out that stress heterogeneity may be a key to understanding EGS seismicity. There are results to support this hypothesis (Baria et al., 2005). For example, the regional stress field must be determined before any stability analysis is done, which (it was concluded) requires integration of various techniques such as borehole stress tests and source mechanism studies. It was also found that induced seismicity does not prove that the rock mass is close to failure; it merely pinpoints local stress concentrations (Cornet et al., 1995). In addition, it was determined that, at Soultz, it took a 4 to 5 MPa pore-pressure increase over the in situ stress, at around 3500 m depth, to induce seismicity in a freshly created fault, ignoring large-scale, pre-existing fractures. Finally, it is difficult to identify the failure criterion of large-scale, pre-existing faults, many of which do not have significant cohesion.

3. Can experiments be designed and performed to shed light on the key mechanisms causing EGS seismicity? Based on years of observing and studying induced seismicity in geothermal fields, many different mechanisms have been suggested: pore-pressure increase, thermal stresses, volume change, hydrothermal alteration, stress redistribution, and subsidence, to name just a few. Are repeating events a good sign or not? Does similarity of signals provide clues to overall mechanisms? One proposed experiment is to study the injection of hot water versus cold water to determine whether thermal effects are the cause of seismicity. If we could come up with a few key experiments to either

eliminate or determine the relative effects of different mechanisms, we would be heading in the right direction.

4. How does induced seismicity differ in naturally fractured systems from hydrofracturing environments? The variability of natural systems is quite large, from systems such as The Geysers to low-temperature systems, each differing in geologic and structural complexity. Do similar mechanisms apply, will it be necessary to start afresh with each geothermal area, or can we learn from each system, such that the seismicity of other sites will be easier to address?

5. Is it possible to mitigate the effects of induced seismicity and optimize production at the same time? In other words, can EGS fracture networks be engineered to have both the desirable properties for efficient heat extraction (large fracture surface area, reasonable permeability, etc.) and yet be generated by a process in which the associated induced seismicity does not exceed well-defined thresholds of tolerable ground shaking? The traffic light system developed by Bommer et al. (2006) goes some way to achieving this end, but the idea of fracture network engineering, as introduced in Hazzard et al. (2002), should be further investigated. Microearthquake activity could be a sign of enhanced fluid paths, fracture opening/movement, and possibly permeability enhancement (especially in hydrofracturing operations) or a repeated movement on an existing fault, or parts of a fault. The generation of seismicity is a measure of how we are perturbing an already dynamic system as a result of fluid injection or extraction.

6. What levels of induced ground motions are tolerable, in terms of amplitude and duration, and also frequency of occurrence, for exposed populations? At what levels of shaking do the motions become a threat to buildings and to the safety of their occupants? Robust answers to these questions will require that ground motions be expressed in more complex forms than single parameters such as PGV, and will probably require the simultaneous use of two or more parameters in vector combination.

7. Does a geothermal reservoir reach equilibrium? Steady state may be the wrong term, but energy can be released in many different ways. Extraction of geothermal fluids (steam/hot water) releases energy, as does seismicity, creep, subsidence, etc. (local and regional stress are the energy inputs or storage). It has been pointed out that, while the number of events at The Geysers is increasing, the average energy release (as measured by cumulative seismic moment of events) is actually constant or slightly decreasing (Majer and Peterson, 2005). If this decrease in energy occurs as the result of many small events, then it is a good thing, but if it occurs as the result of a few big events, it would be undesirable. Hence the need to understand seismic magnitude distribution in both space and time.

11. Summary and conclusions

Three international workshops have been convened to date to address the issue of EGS-induced seismicity. The learnings from a number of EGS projects should provide a firm foundation on which to build a clear understanding of, and a protocol for dealing with, induced seismicity associated with EGS operations. To date there is no known instance of any large seismic event associated with EGS projects having caused any major damage or injury. However, the Soultz and Basel cases demonstrate that non-damaging but perceptible motions can impede the development of this technology for as long as the exposed population is not adequately informed and convinced of the cost-benefit balance between a green energy source and the inconvenience of occasional, but non-threatening, ground shaking. Indeed, in the case of the Basel project, the events that caused disquiet among the city inhabitants were a long way from the thresholds for onset of damage. This, however, contrasts with a small number of cases in which seismicity induced by damming (Koyna, India), hydrocarbon production (Gazli, Uzbekistan) and waste disposal activities (Rocky Mountain Arsenal, USA) caused significant damage.

It is clear that there is no case for complacency in managing the EGS-induced seismicity issue. It appears that the occurrence of felt events may be a characteristic of EGS operations and it remains to be seen how such systems will behave seismically over the long term, after the initial period of stimulation. This is as yet unchartered territory since no EGS project has yet gone into long-term production. Additional research and experience as well as the adoption and application of accepted best practices are required to prevent induced seismicity from delaying or hindering the acceptance of EGS.

During these workshops, scientists and engineers working on EGS seismicity have developed short- and long-term guidelines. In the short term we have to ensure that there is open communication between the geothermal energy producer and the local population and authorities. This involves early establishment of a monitoring and reporting plan, communication of the plan to the affected community, and diligent follow-up in the form of reporting and meeting commitments. The establishment of good working relationships between the geothermal producer and the local inhabitants is essential. Education in terms of the nature of MEQs and the difference between perceptible and damaging ground motions is an important feature of this outreach. Adoption of best practices from other industries should also be considered. For example, in the Netherlands gas producers adopt a good-neighbour policy, based on a pro-active approach to seismic monitoring, reporting, investigating and, if necessary, compensating for any damage (NAM, 2002). Similarly, geothermal operators in Iceland have consistently shown that it is possible to gain public acceptance and even vocal support for field development operations by ensuring that the local population sees the direct economic benefit of the field activities (Gudni Axelsson, pers. comm., September 2006).

For the long term we must aim at achieving a step-by-step inprovement in our understanding of the processes governing induced seismicity, duly acknowledging any benefits and mitigating any risks along the way. At the same time, our final objective is to engineer subsurface fracture networks with the desired properties. Seismicity is a key item of information for understanding subsurface fracture networks and is now being used routinely to understand the dynamics of fracturing and the all-important relationship between fractures and fluid behaviour. Future research efforts will reap the benefits of international cooperation through data exchange, sharing the results of field studies and research at regular meetings, and engaging industry in the research projects. Additional experience, and application of the practices discussed above, will provide further knowledge, helping us to successfully utilize EGS-induced seismicity and achieve the full potential of the enhanced systems.

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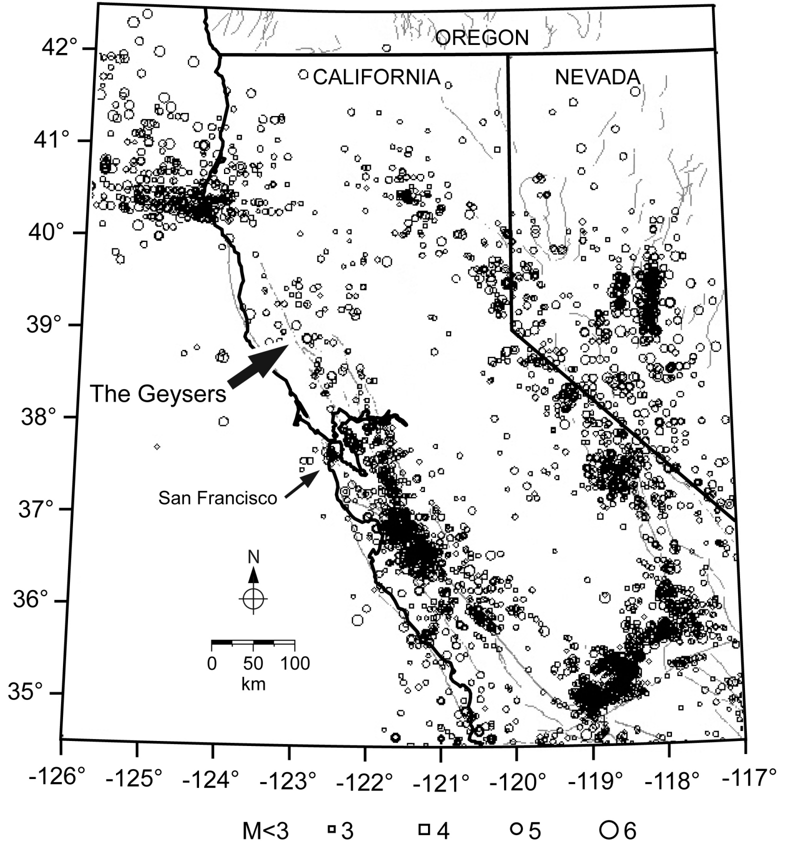
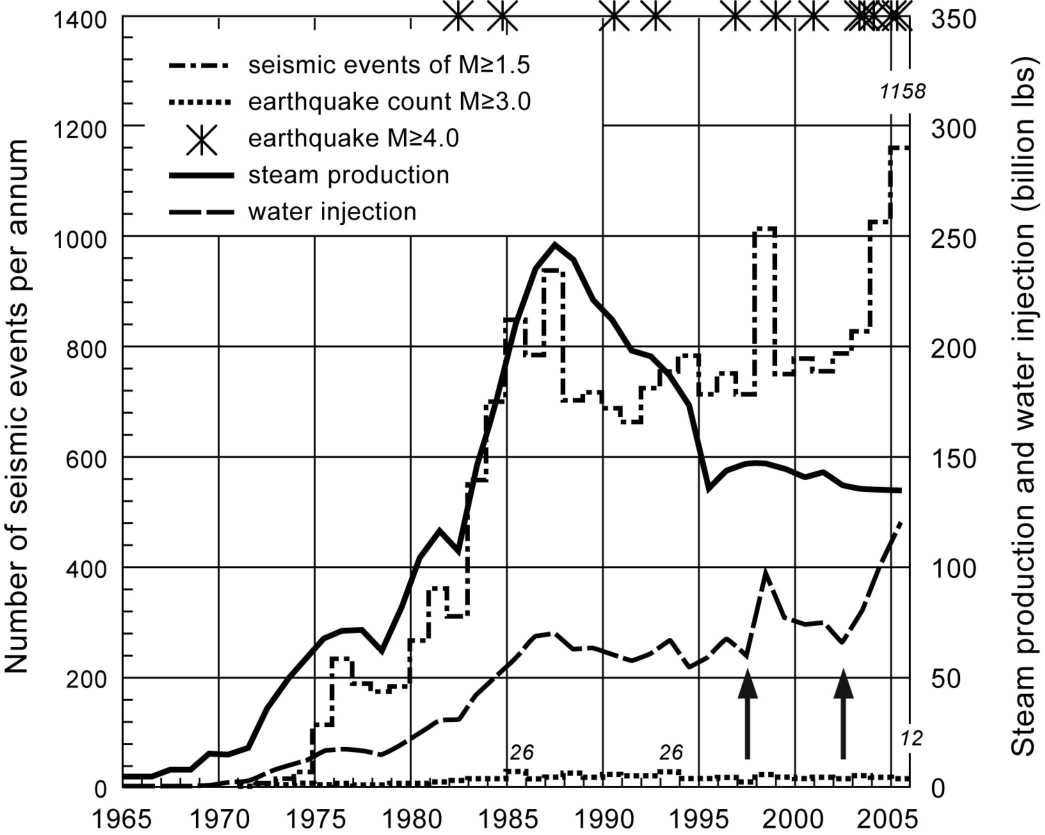
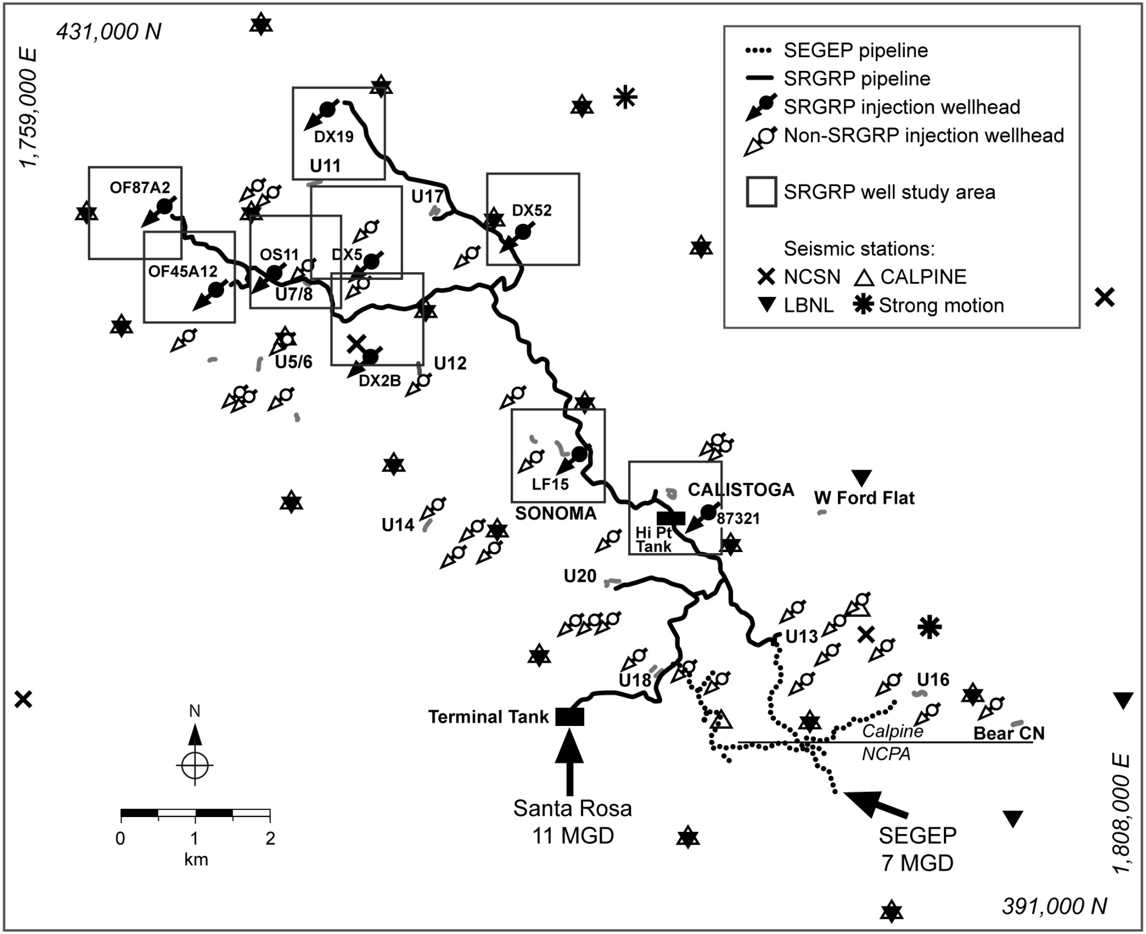
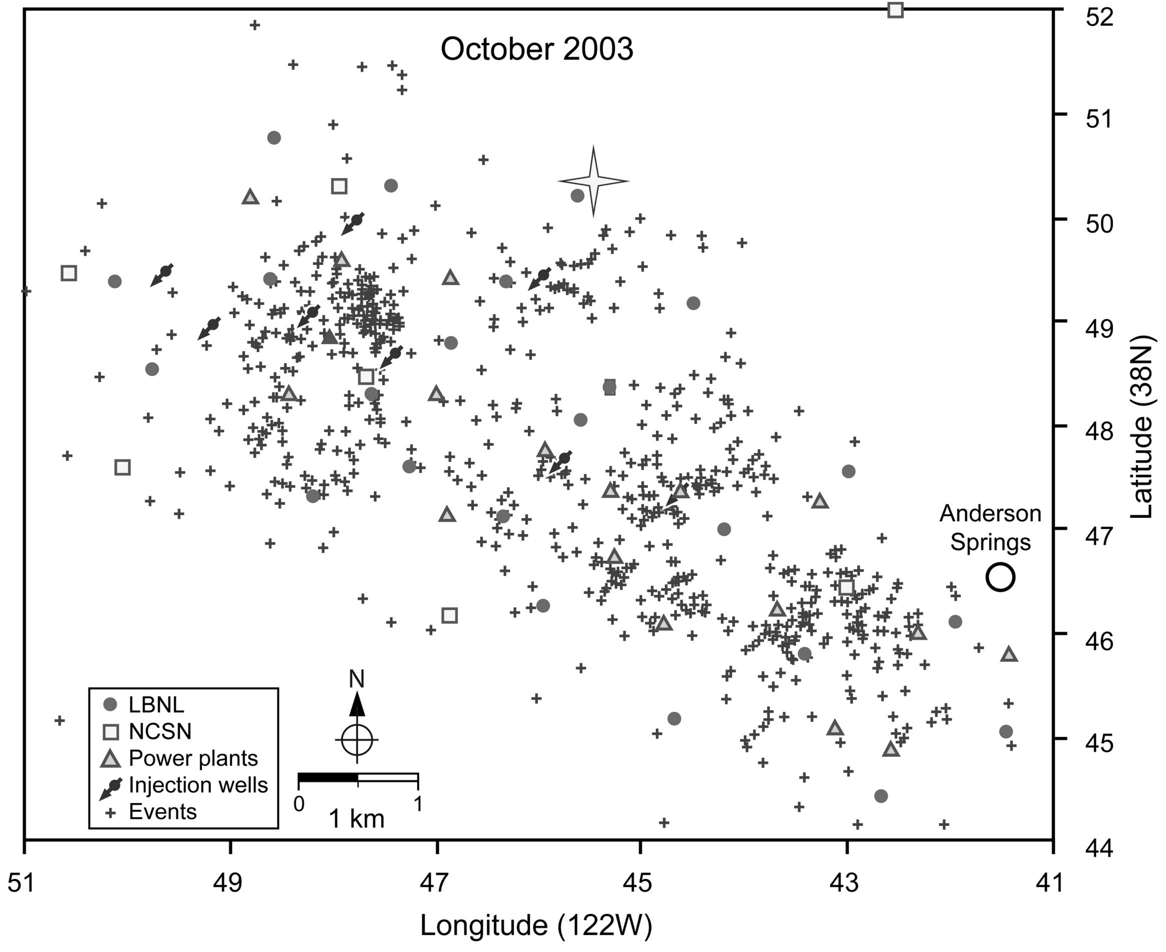
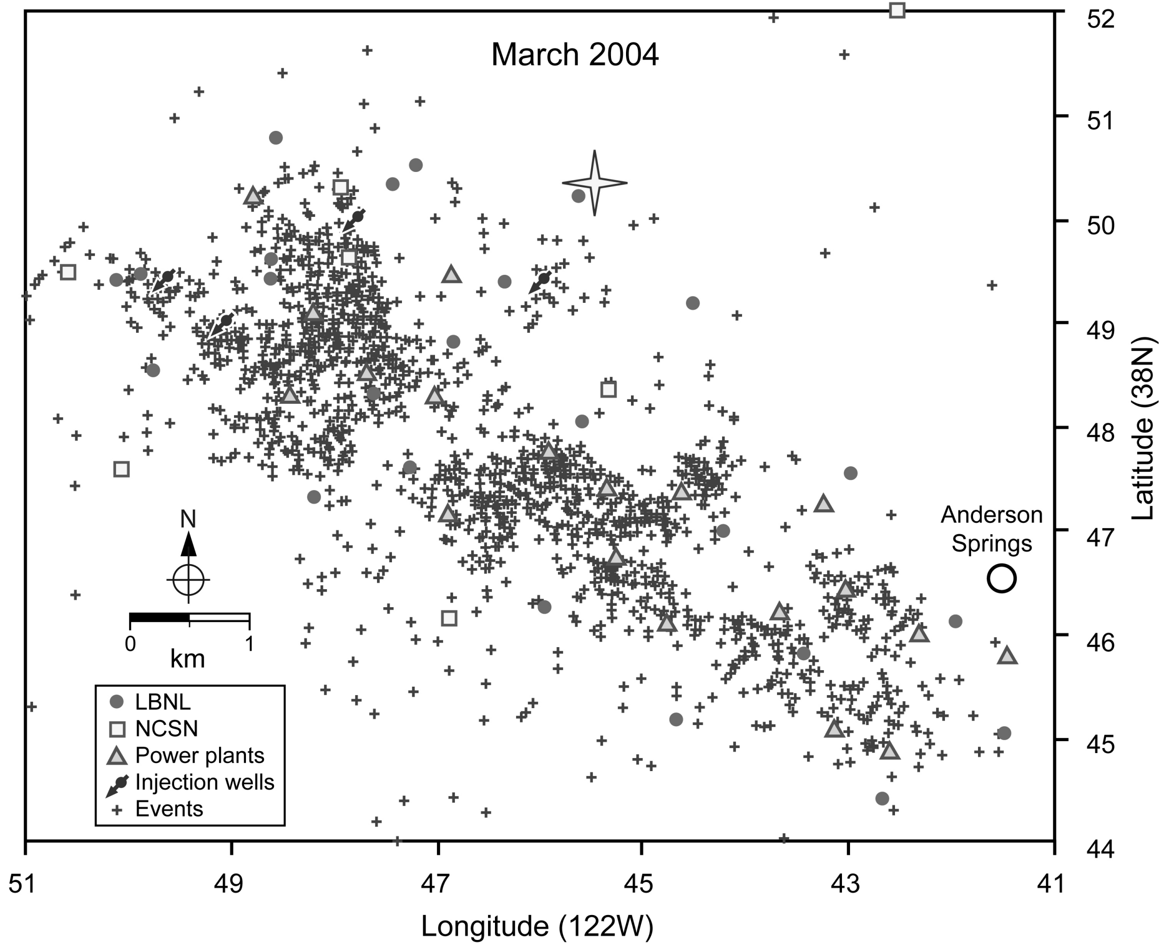
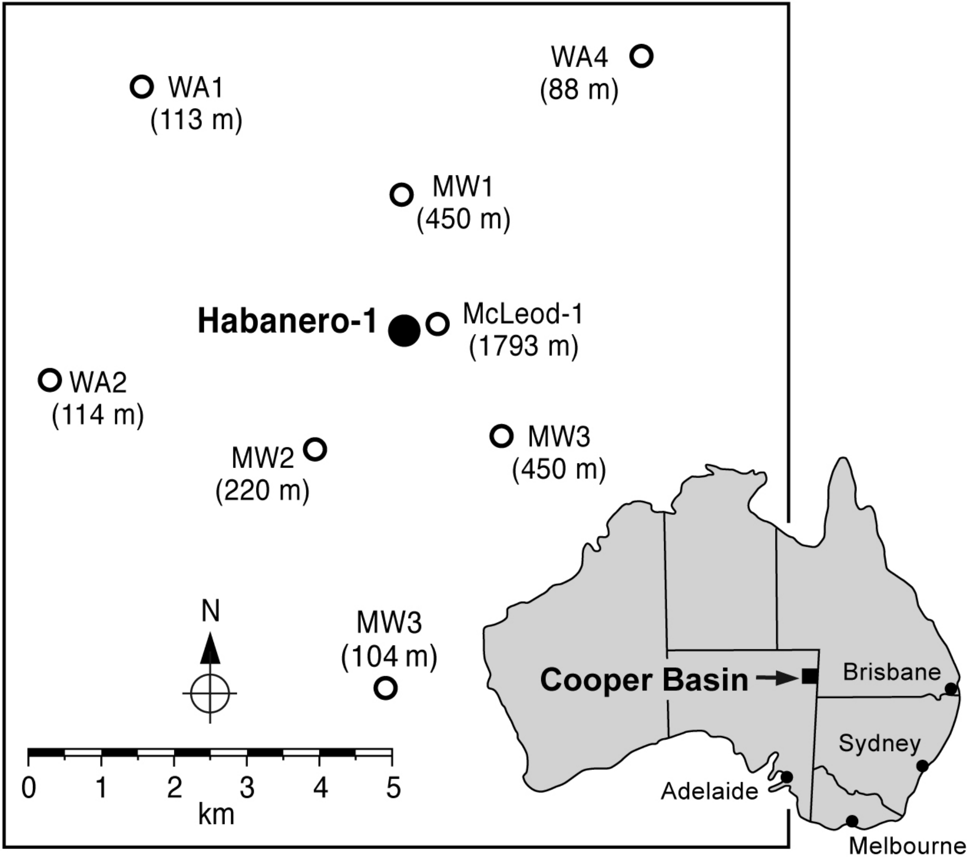

OREGON
CALIFORNIA
NEVADA
The Geysers
San Francisco
N
0
50
100
km
42°
41°
40°
39°
38°
37°
36°
35°
-126°
-125°
-124°
-123°
-122°
-121°
-120°
-119°
-118°
-117°
M<3
3
4
5
6

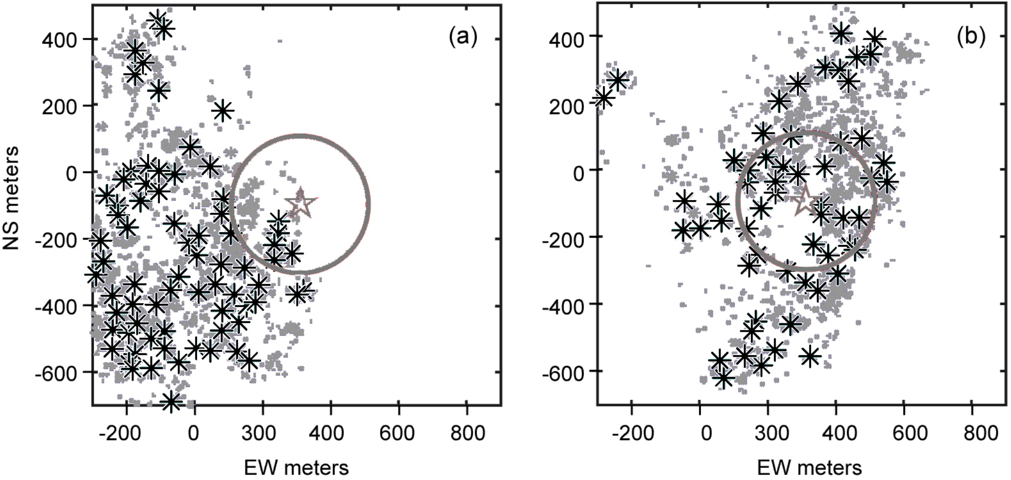

seismic events of M≥1.5
earthquake count M≥3.0
earthquake M≥4.0
steam production
water injection
1158
26
26
12
Number of seismic events per annum
Steam production and water injection (billion lbs)
0
200
400
600
800
1000
1200
1400
0
50
100
150
200
250
300
350
1965
1970
1975
1980
1985
1990
1995
2000
2005

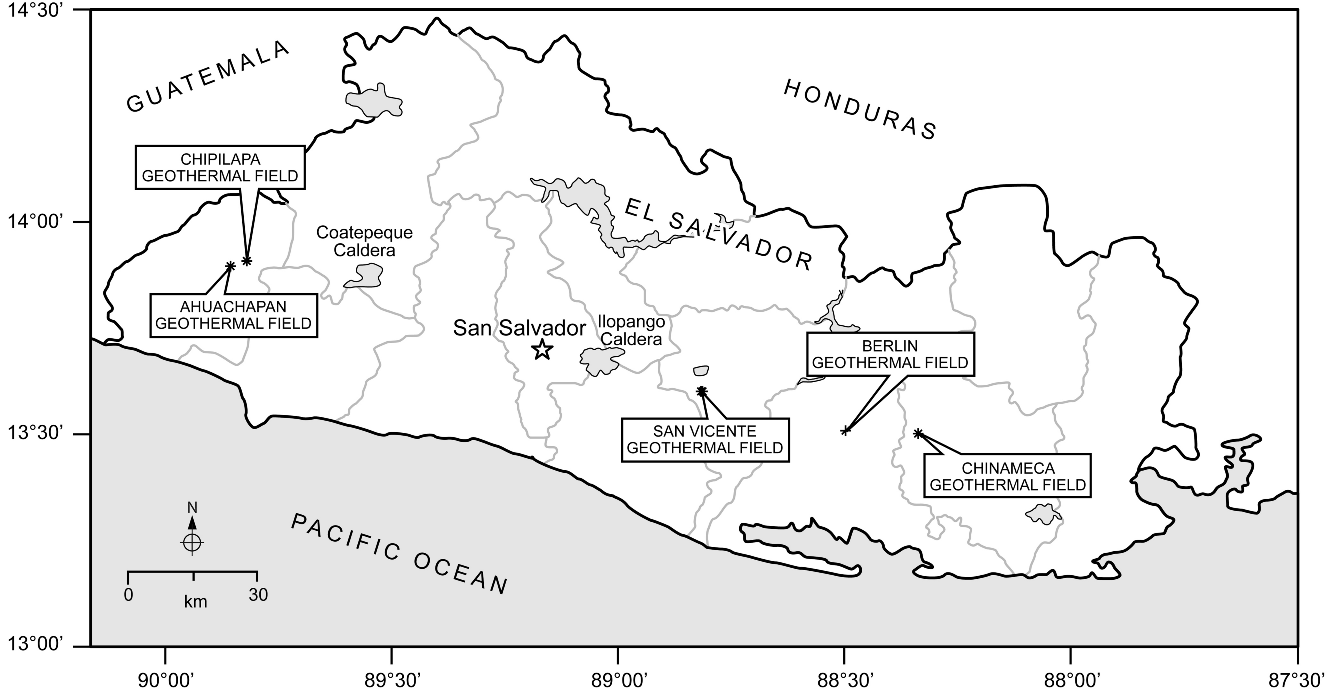

431,000 N
1,759,000 E
SEGEP pipeline
SRGRP pipeline
SRGRP injection wellhead
Non-SRGRP injection wellhead
SRGRP well study area
Seismic stations:
NCSN
CALPINE
LBNL
Strong motion
DX19
U11
OF87A2
U17
DX52
OS11
DX5
OF45A12
U7/8
U5/6
U12
DX2B
LF15
SONOMA
CALISTOGA
W Ford Flat
87321
Hi Pt Tank
U14
U20
U13
U18
U16
Terminal Tank
Calpine
NCPA
Bear CN
N
0
1
2
km
Santa Rosa
11 MGD
SEGEP
7 MGD
1,808,000 E
391,000 N

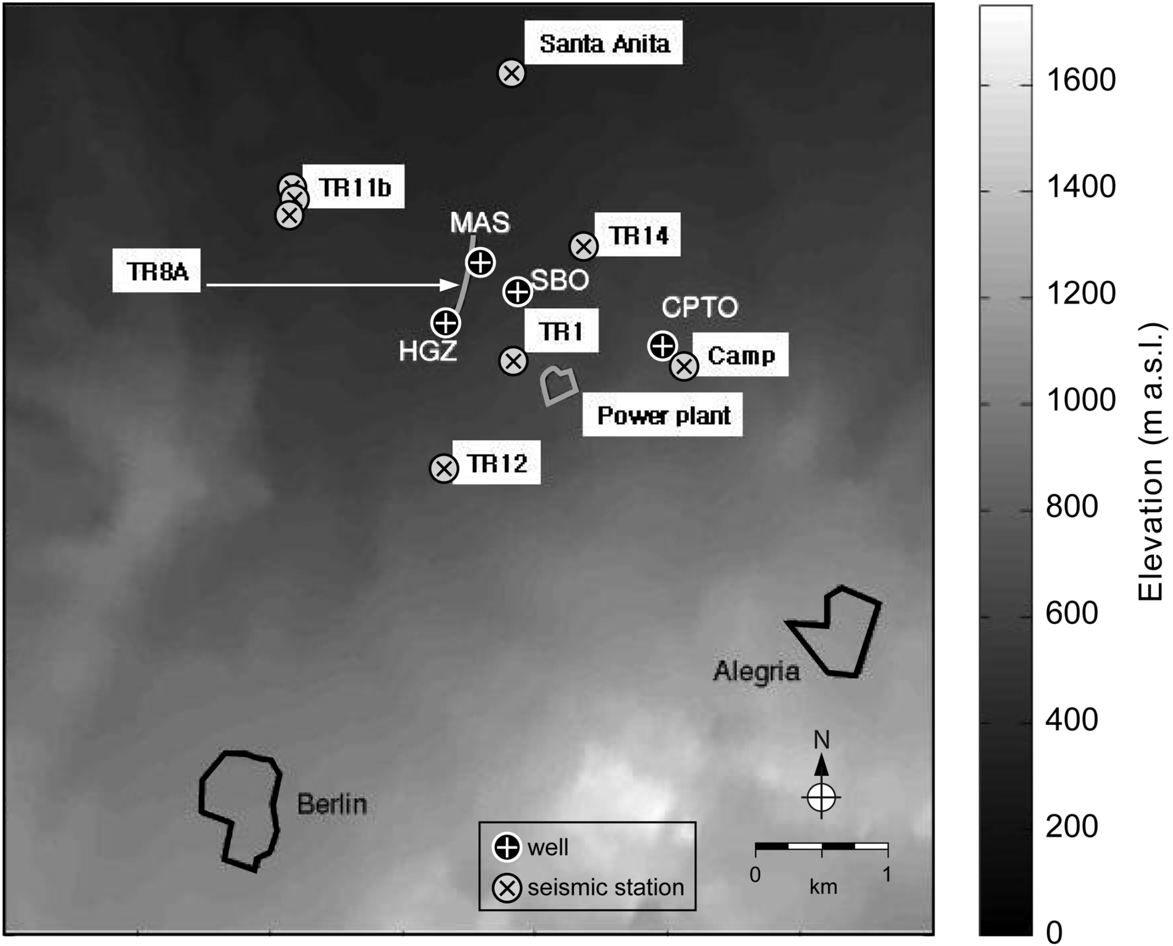

October 2003
Anderson Springs
LBNL
NCSN
Power plants
Injection wells
Events
N
0
1
1 km
51
49
47
45
43
41
Longitude (122W)
52
51
50
49
48
47
46
45
44
Latitude (38N)

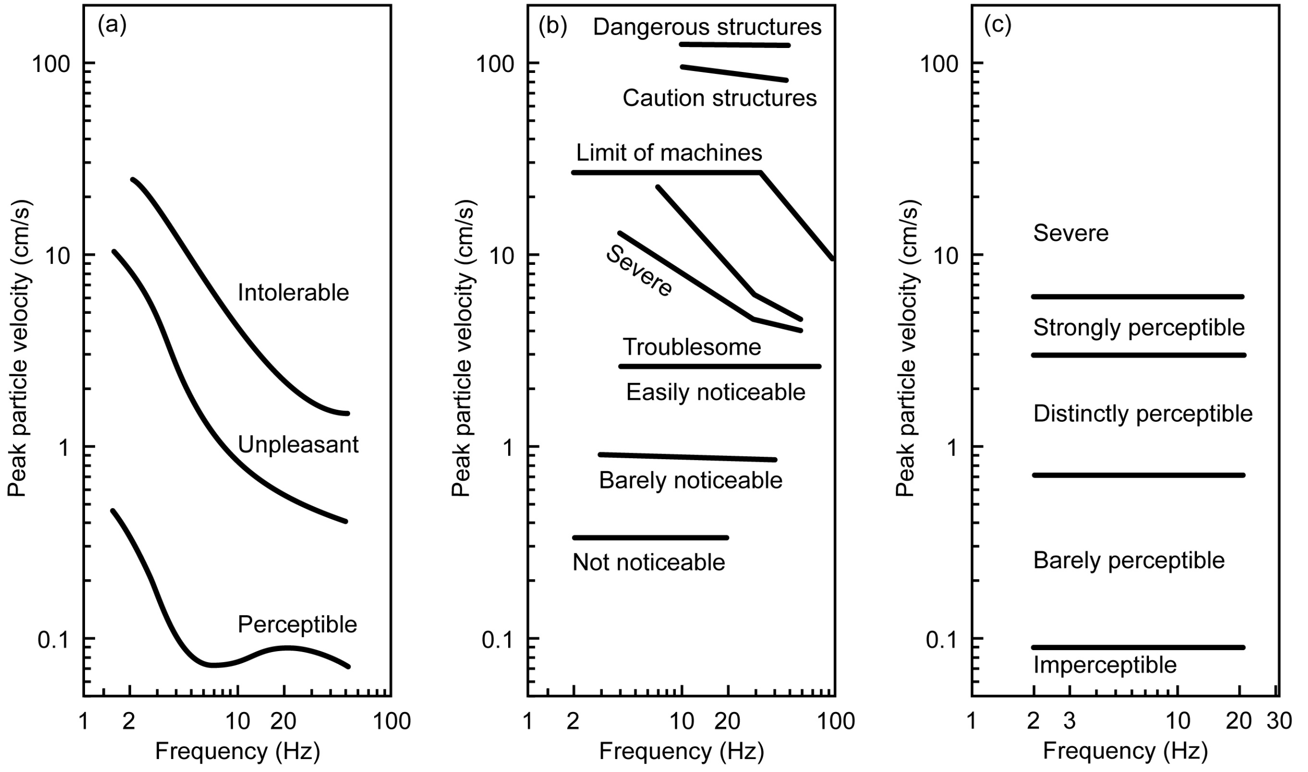

March 2004
Anderson Springs
N
0
1
km
● LBNL
☐ NCSN
△ Power plants
Injection wells
+ Events
51
49
47
45
43
41
Longitude (122W)
52
51
50
49
48
47
46
45
44
Latitude (38N)

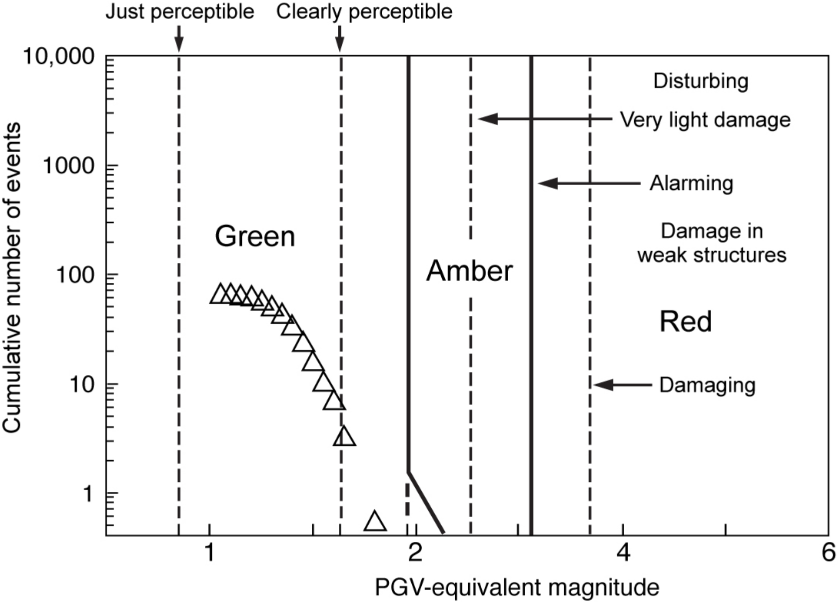

WA4
(88 m)
WA1
(113 m)
MW1
(450 m)
Habanero-1
McLeod-1
(1793 m)
WA2
(114 m)
MW3
(450 m)
MW2
(220 m)
N
MW3
(104 m)
0
1
2
3
4
5
km
Cooper Basin
Brisbane
Sydney
Adelaide
Melbourne

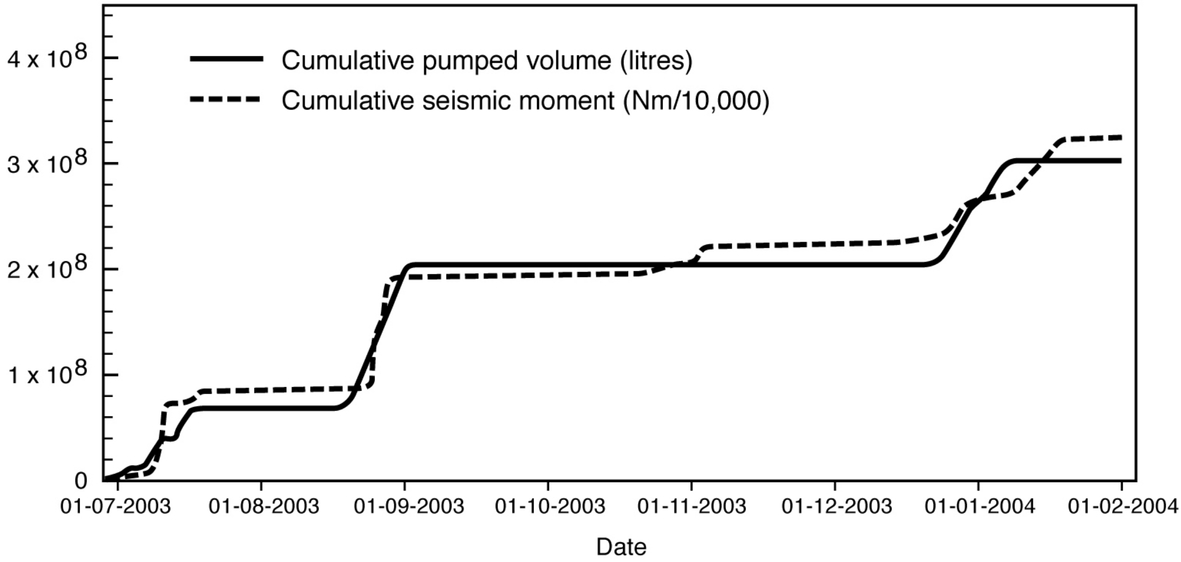

(a)
(b)
NS meters
EW meters
EW meters
400
200
0
-200
-400
-600
-200
0
200
400
600
800

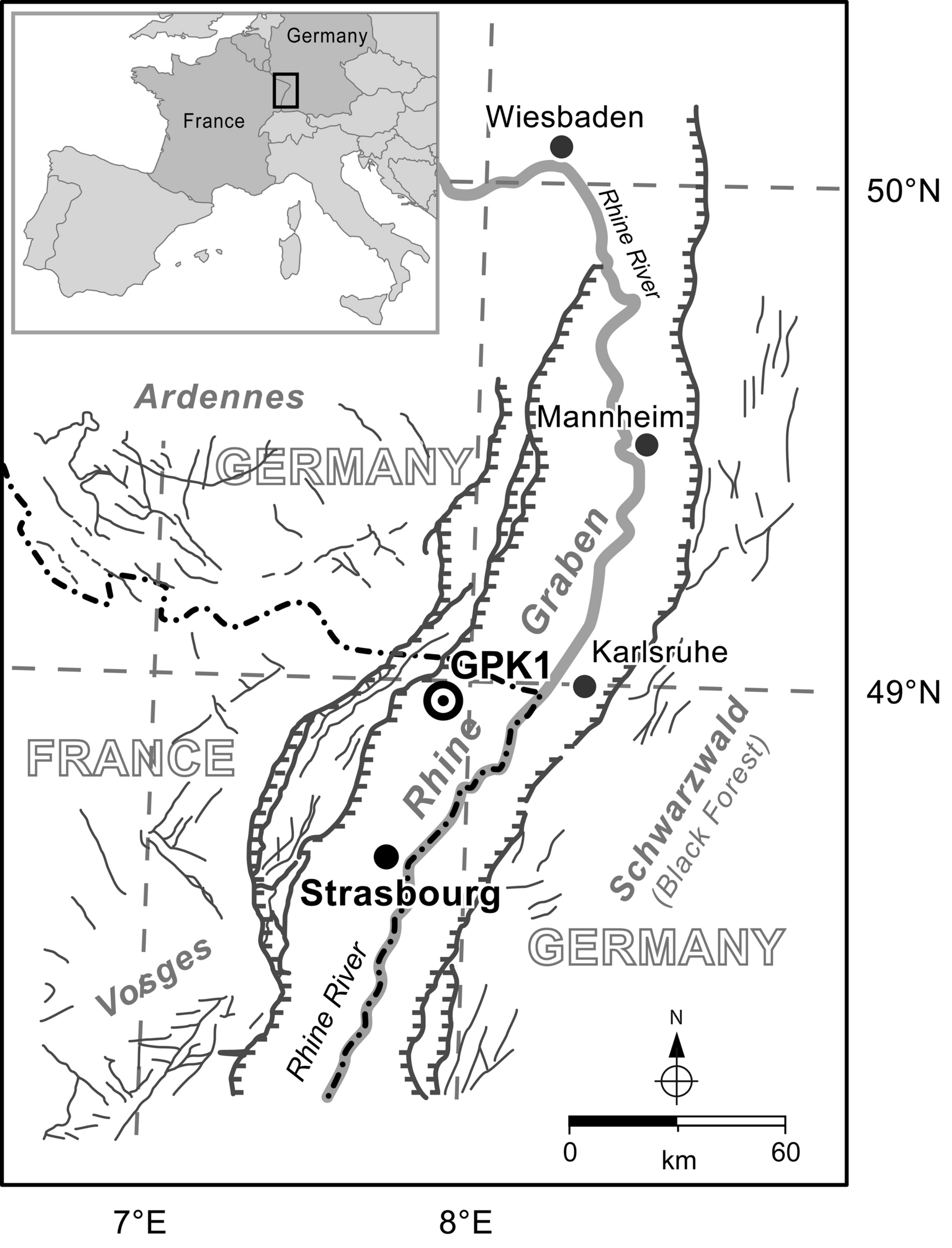

14°30’
14°00’
13°30’
13°00’
90°00’
89°30’
89°00’
88°30’
88°00’
87°30’
GUATEMALA
HONDURAS
EL SALVADOR
PACIFIC OCEAN
CHIPILAPA GEOTHERMAL FIELD
AHUACHAPAN GEOTHERMAL FIELD
Coatepeque Caldera
San Salvador
Ilopango Caldera
SAN VICENTE GEOTHERMAL FIELD
BERLIN GEOTHERMAL FIELD
CHINAMECA GEOTHERMAL FIELD
N
0
km
30

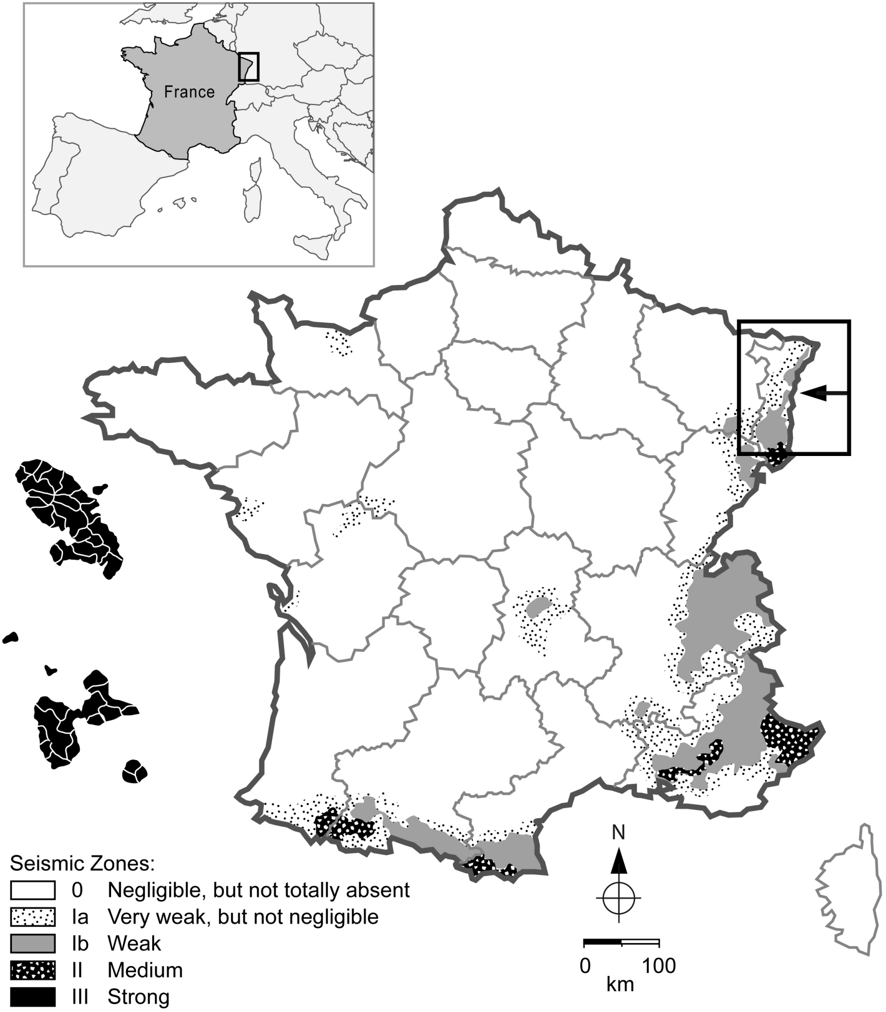

Santa Anita
TR11b
MAS
TR14
TR8A
SBO
CPTO
TR1
HGZ
Camp
Power plant
TR12
Alegria
Berlin
N
well
seismic station
0
km
1
1600
1400
1200
1000
800
600
400
200
0
Elevation (m a.s.l.)

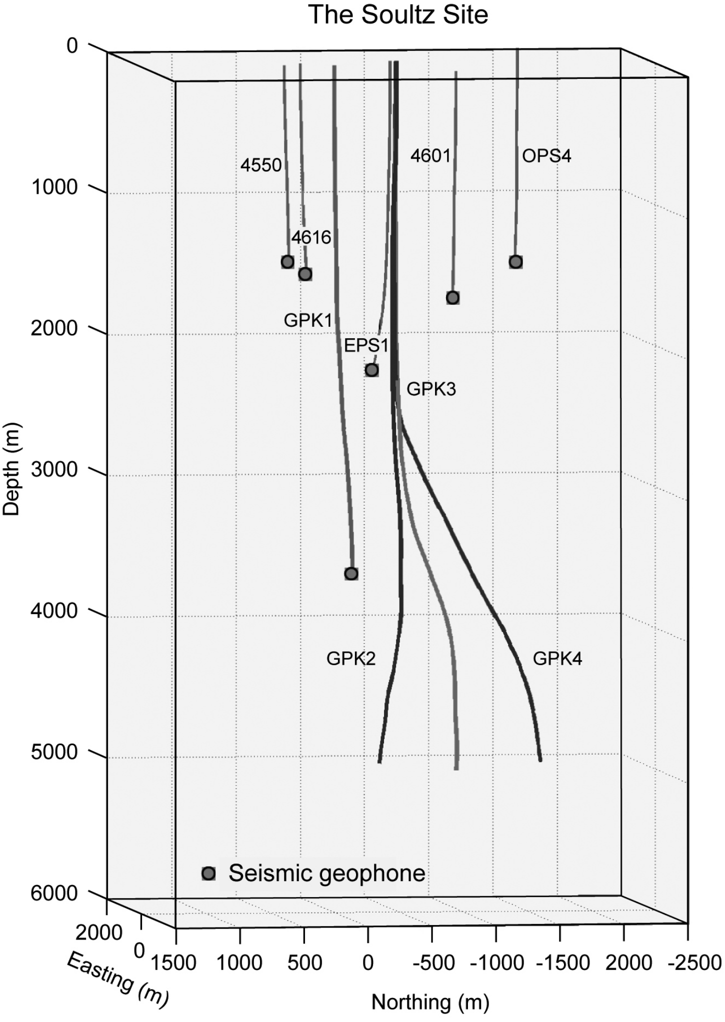

(a)
(b)
(c)
Peak particle velocity (cm/s)
100
10
1
0.1
Frequency (Hz)
1
2
3
10
20
30
100
Intolerable
Unpleasant
Perceptible
Dangerous structures
Caution structures
Limit of machines
Severe
Troublesome
Easily noticeable
Barely noticeable
Not noticeable
Severe
Strongly perceptible
Distinctly perceptible
Barely perceptible
Imperceptible

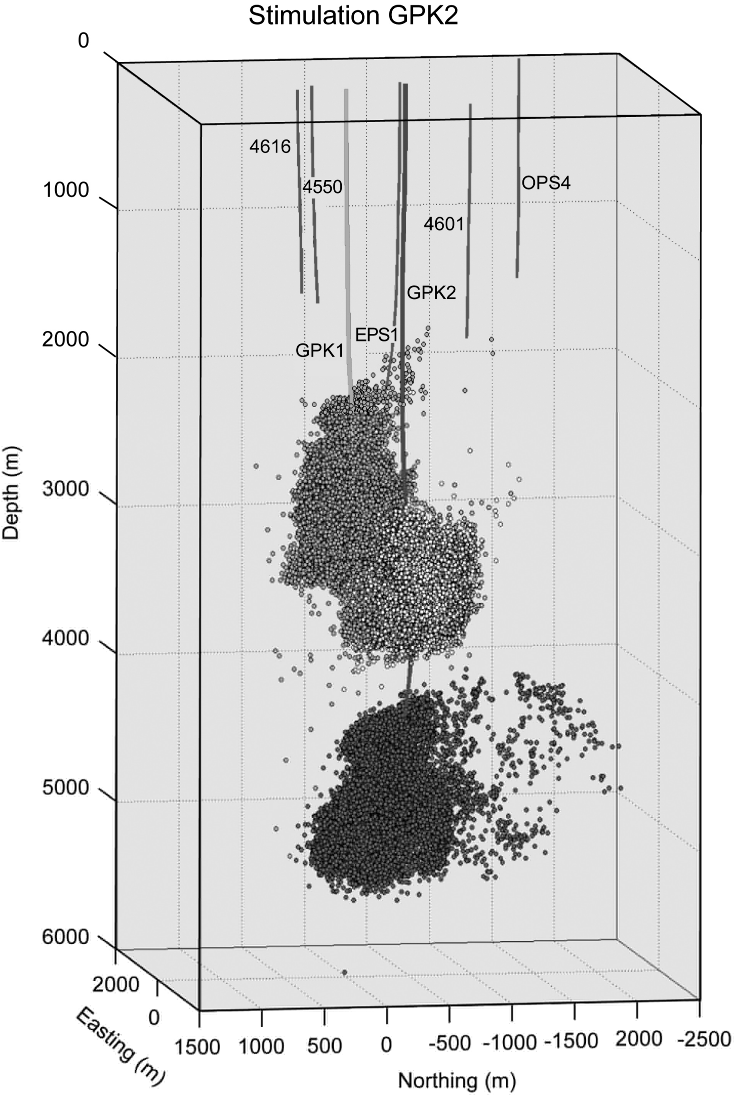

Just perceptible
Clearly perceptible
10,000
1000
100
10
1
Cumulative number of events
Green
Amber
Red
Disturbing
Very light damage
Alarming
Damage in weak structures
Damaging
1
2
4
6
PGV-equivalent magnitude

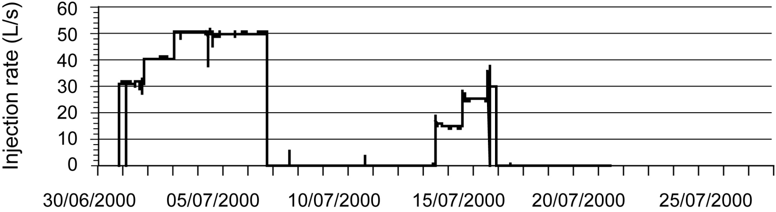

Cumulative pumped volume (litres)
Cumulative seismic moment (Nm/10,000)
4 x 10^8
3 x 10^8
2 x 10^8
1 x 10^8
0
01-07-2003
01-08-2003
01-09-2003
01-10-2003
01-11-2003
01-12-2003
01-01-2004
01-02-2004
Date

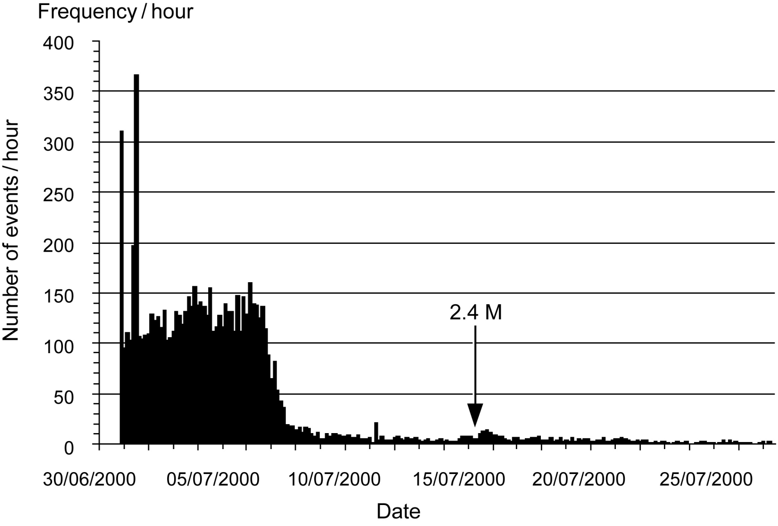

Germany
France
Wiesbaden
50°N
Rhine River
Ardennes
Mannheim
GERMANY
Graben
Karlsruhe
GPK1
49°N
FRANCE
Rhine
Schwarzwald
(Black Forest)
Strasbourg
GERMANY
Vosges
Rhine River
N
0
km
60
7°E
8°E

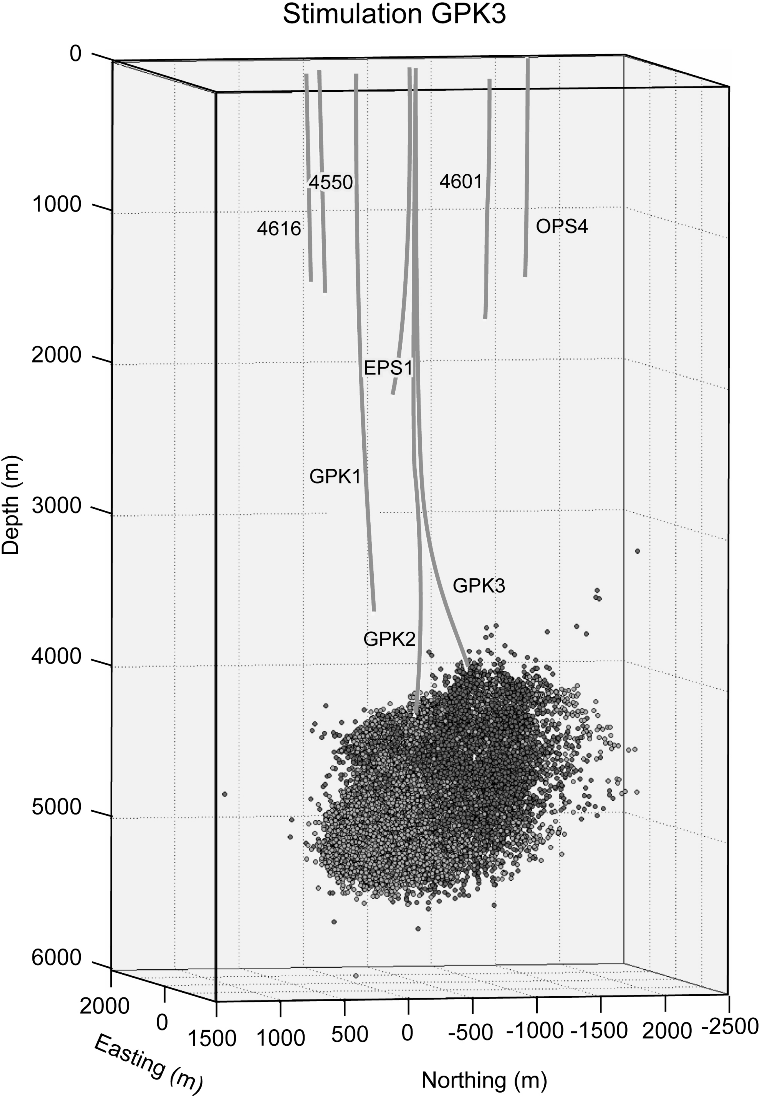

France
Seismic Zones:
0 Negligible, but not totally absent
Ia Very weak, but not negligible
Ib Weak
II Medium
III Strong
N
0
100
km

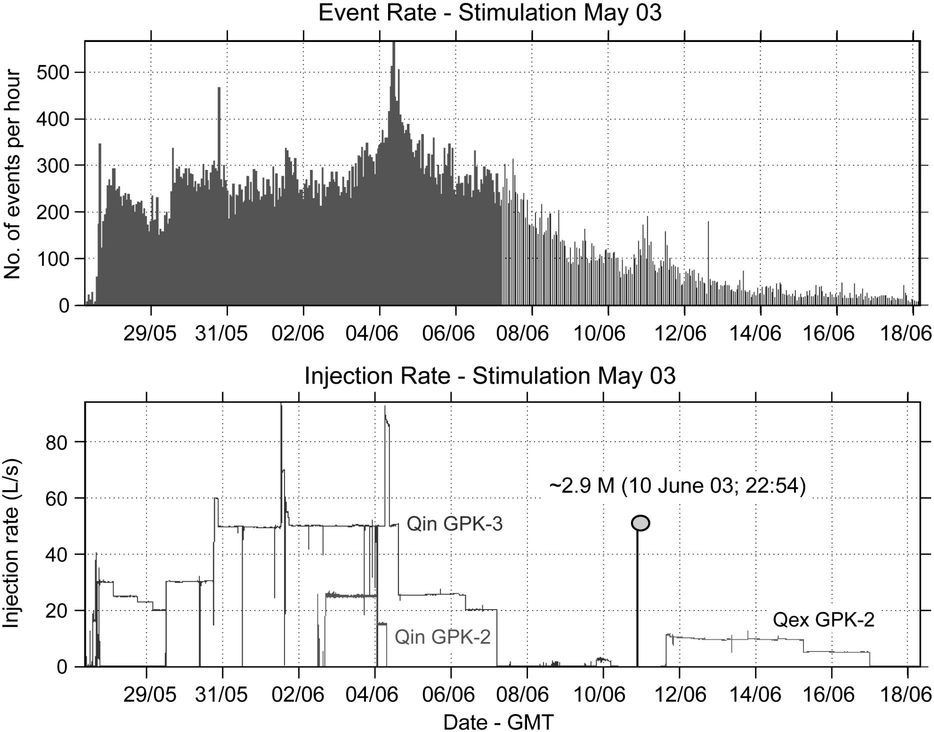

The Soultz Site
Depth (m)
0
1000
2000
3000
4000
5000
6000
4550
4616
GPK1
EPS1
4601
OPS4
GPK3
GPK2
GPK4
Seismic geophone
Easting (m)
2000
0
Northing (m)
1500
1000
500
0
-500
-1000
-1500
2000
-2500


Stimulation GPK2
0
1000
2000
3000
4000
5000
6000
Depth (m)
4616
4550
GPK1
EPS1
GPK2
4601
OPS4
2000
0
Easting (m)
1500
1000
500
0
-500
-1000
-1500
2000
-2500
Northing (m)


Injection rate (L/s)
60
50
40
30
20
10
0
30/06/2000
05/07/2000
10/07/2000
15/07/2000
20/07/2000
25/07/2000


Frequency / hour
Number of events / hour
400
350
300
250
200
150
100
50
0
2.4 M
30/06/2000
05/07/2000
10/07/2000
15/07/2000
20/07/2000
25/07/2000
Date


Stimulation GPK3
0
1000
2000
3000
4000
5000
6000
Depth (m)
4550
4616
4601
OPS4
EPS1
GPK1
GPK3
GPK2
2000
0
Easting (m)
1500
1000
500
0
-500
-1000
-1500
2000
-2500
Northing (m)


Event Rate - Stimulation May 03

Injection Rate - Stimulation May 03

Figure captions

Figure 1. Location of seismic events in northern California with magnitudes greater than 3.0 and less than 5.0, from January 1900 to mid-May 2004. M: local magnitude (source: The Berkeley Seismographic Laboratory, Northern California Earthquake Data Center; NCEDC)

Figure 2. Historical seismicity from 1965 to October 2006 at The Geysers. Data are from the Northern California Earthquake Data Center (NCEDC). The two arrows indicate the increases in fluid injection in 1997 and 2002 (Bill Smith, pers. comm., June 2006). M: local magnitude; 1 billion lbs ~ 454 x 10^6 tons

Figure 3. Location of seismic stations, pipelines, and injection wells at The Geyers. SEGEP: South East Geysers Effluent Project; SRGRP: Santa Rosa Geothermal Reinjection Project; NCSN: Northern California Seismic Network of the U.S. Geological Survey (USGS); CALPINE: Calpine Corporation; LBNL: Lawrence Berkeley National Laboratory; MGD: million gallons per day (1 gallon = 3.785 liters).

Figure 4. Location of all seismic events in The Geysers field in October 2003, two months prior to start of injection of treated Santa Rosa waste waters. Squares: locations of injection wells. Large star: approximate location of the magnitude 4.4 event of 18 February 2004. LBNL: Lawrence Berkeley National Lab; NCSN: Northern California Seismic Network of the USGS.

Figure 5. Location of all seismic events in The Geysers field in March 2004. The squares: injection wells; Large star approximate location of the magnitude 4.4 event of 18 February 2004. LBNL: Lawrence Berkeley National Lab; NCSN: Northern California Seismic Network of the USGS.

Figure 6. Location of Cooper Basin and of the seismic stations at the site. The 4421-m deep well Habanero-1 injection well is located at the origin of the local coordinate system (27º48'59" S/140º45'35" E). Legend annotates instrument depths (Baisch et al., 2006)

Figure 7. Plan view of seismicity at the Cooper Basin site associated with the injection of fluids. (a) Location of events before the M3 event (large star), (b) location after the M3 event. The size of the symbols (stars and dots) are correlated to magnitude. The circles are the radii of the source area of a magnitude 3 event (Asanuma et al., 2005b).

Figure 8. Location of the most important geothermal areas in El Salvador.

Figure 9. Berlín geothermal field. Location of wells, including the trace of injection well TR8A) and of seismic stations, and elevations in meters above sea level (Bommer et al., 2006).

Figure 10. (a) Levels of human sensitivity to vibration caused by blasting (USACE, 1972); (b) reference levels for traffic-induced vibration (adapted from Barneich, 1985); (c) thresholds for vibrations caused by pile-driving (Athanasopoulos and Pelekis, 2000; Bommer et al., 2006).

Figure 11. "Traffic light" boundaries superimposed on event recurrence defined in terms of magnitudes adjusted to produce the epicentral Peak Ground Velocity (PGV) if their focal depths were exactly 2 km. Triangles represent the cumulative recurrence data from the three episodes of fluid injection (totaling 54 days of pumping) normalized to a period of 30 days (Brommer et al., 2006); see text for further details.

Figure 12. Comparison of cumulative pumped (injected) fluid volume at the Berlín geothermal field and induced seismicity expressed in terms of cumulative seismic movement, using seismicity data from the immediate vicinity of injection well TR8A (Bommer et al., 2006)

Figure 13. Location and schematic geology for the Hot Dry Rock project at Soultz-sous-Forêts, Alsace, France. Concentric circles corresponds to well GPK1 (Baria et al., 2005)

Figure 14. Position of the Soultz Hot Dry Rock project (arrow) relative to seismically active zones in France

Figure 15. Layout of the boreholes at the Soultz Hot Dry Rock project in 2004 (Baria et al., 2005).

Figure 16. Seismicity induced by the hydraulic stimulation of borehole GPK2 at Soultz-sous-Forêts. Borehole traces are also shown (Baria et al., 2005)

Figure 17. Injection rates and microseismic data for the hydraulic stimulation of borehole GPK2 at Soultz-sous-Forêts. Arrow shows when the magnitude 2.4 event occurred. M: local magnitude (Baria et al., 2005).

Figure 18. Seismicity induced by the stimulation of borehole GPK3 at Soultz-sous-Forêts. Borehole traces are also shown (Baria et al., 2005).

Figure 19. Injection rates and microseismic data for the stimulation of borehole GPK3, Soultz-sous-Forêts (Baria et al., 2005).