Monitoring deep geothermal reservoirs using ambient noise and coda wave interferometry; a feasibility study at Rittershoffen

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Background

Geophysical monitoring is of major interest for deep geothermal reservoirs. Firstly, it provides information about the natural evolution of hydrothermal systems. Secondly, it can be used to prevent risks such as induced seismicity or surface deformations. The analysis of induced seismicity is generally a preferred tool for monitoring deep geothermal sites. However, this tool is not suited to detect aseismic changes of the subsoil. Over the past decade, ambient seismic noise has emerged in seismology as a new tool to study the evolution of a medium over time. This method known as “Passive Image Interferometry” (Sens-Schönfelder and Wegler, 2006) has been successfully applied in various contexts such as active volcanic systems, where the seismic velocities are likely to change due pressure variations in the magmatic chamber (e.g. Brenguier et al., 2008a; Duputel et al., 2009), or in large faulting regions, where the seismic velocities can be modified during and after an earthquake (Brenguier et al., 2008b). Ambient seismic noise is continuous over time and can be recorded in a similar way at any place on Earth. Thanks to this property, we can theoretically follow the evolution of a medium despite the lack of seismic events and between the stimulation periods.

In this study we analyze the feasibility of such noise-based monitoring techniques near the industrial site of Rittershoffen installed in early 2012 and which is about to enter its operational phase in December 2016 (ECOGI Project). During the installation of this site, two boreholes were drilled. During summer 2014, the first borehole (GRT1) was stimulated to enhance the permeability of the reservoir and to provide acceptable heat productivity. This stimulation was accompanied by a moderate seismicity whose most energetic event reached a magnitude ml=1.6 that could reflect a change of the medium at that time.

Data

The two geothermal sites of Rittershoffen and Soultz-sous-forêts are monitored permanently and in real time by two networks designed to observe the induced seismicity. Together, they form a network of 12 short period stations equipped with 1 or 3 component 1Hz-L4C sensors and digitizers sampling at rates from 100 to 200 Hz. These stations provide high quality continuous recordings and are available since summer 2009 for the Soultz-sous-Forêts network (figure 1, red squares) and since 2012 for the Rittershoffen network (figure 2, blue squares).

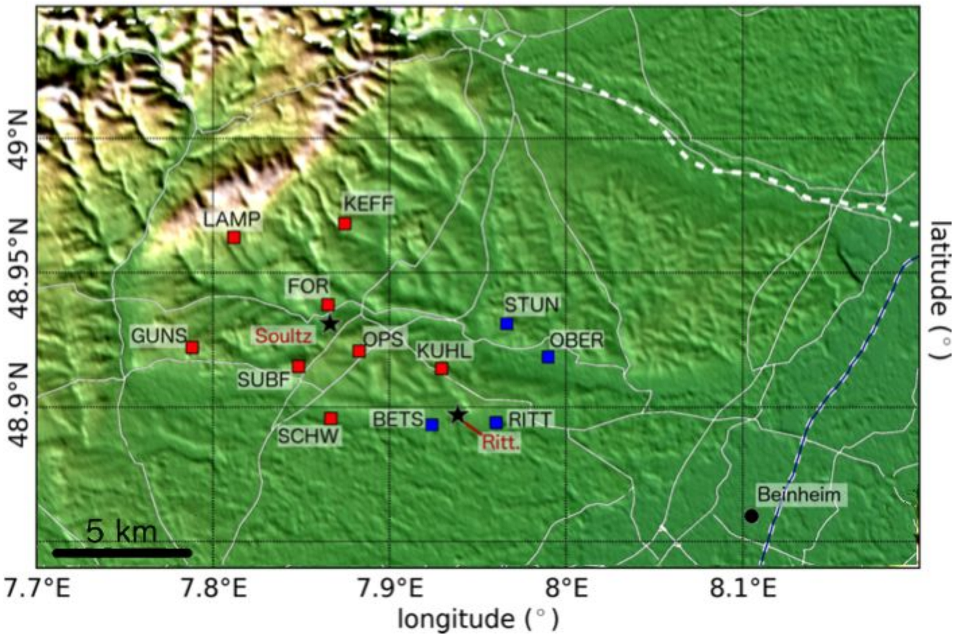

Figure 1 : Map showing the two deep geothermal sites of Soultz-sous-forêts ("Soultz"), Rittershoffen ("Ritt") and the industrial site of Beinheim who should receive the heat generated by the future plant Rittershoffen.

Method

The Passive Image Interferometry method requires computing the cross-correlation of the continuous noise records between each pair of sensors of the network. This method allows us to extract the coherent component of the random-looking seismic noise. The obtained correlation functions reproduce the Green's function between each pair of sensors. In other words, the cross-correlation function of ambient noise records between a pair of receivers converges toward the seismogram that would have been recorded at one station if an impulsive source had occurred at the other one (Weaver and Lobkis, 2001; Shapiro and Campillo, 2004). Thanks to the continuity of the seismic noise, each seismological station of the network behaves as a permanent seismic source, and highlights the structures continuously. The cross-correlation function is computed on a sliding time window (figure 2). Any change of the medium is expected to affect the temporal stability of the noise cross-correlation function. More precisely, a uniform change of the seismic velocity is expected to result in a stretching of the correlation function, while a local change of the medium will only affect the temporal stability of the shape of the cross correlation function. The temporal stability of the cross-correlation function is analyzed by comparing the time windowed correlation function (figure 2, colored signal) to a reference waveform (figure 2, black correlation function). For each time window centered at time *t*, a stretching coefficient (noted $\epsilon(t)$) as well as the coherency coefficient (noted *X(t)*) are measured. The temporal evolution of ϵ and *X* are used as indicators of the evolution of the medium over time t (e.g. Weaver et al., 2011).

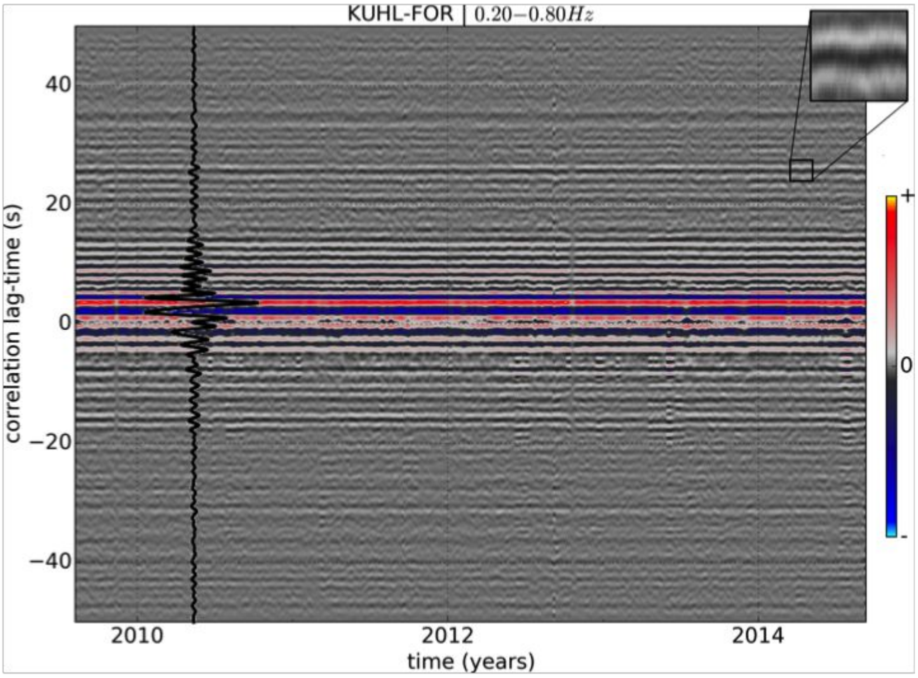

Figure 2 : Evolution of the cross-correlation function of ambient seismic noise computed between a pair of stations (named KUHL and FOR) over a 10-days sliding time window. The black signal corresponds to the average correlation function. The colored signal represents the evolution over time of the correlation function. The closeup square highlights small variations of the phase of the correlation function.

Results and discussions

The imperfect repeatability of the noise sources is responsible for small temporal variations of the correlation functions (figure 2, close-up window) reducing our ability to detect changes of the medium. In the period range 0.2s to 5s, where the noise is dominated by the local to regional anthropogenic activity (0.2s to 1s) and by the secondary micro-seismic peak (1 to 5s), we estimate that the lowest relative velocity change that could be detected using the available networks ranges from 0.1% near 0.2s to 1% near 5s. These detection thresholds have not been reached during the drilling of the two boreholes of the Rittershoffen site (GRT1 and GRT2) and during the stimulation of the well GRT1. However, near 3s of period we observe a significant loss of coherency of the cross-correlation functions that follows the chemical and hydrological stimulation of the reservoir at Rittershoffen (figure 2, black arrow). This signal is not accompanied by a speed variation at ±0.5%, which suggests that it is due to a local change of the medium. Similar observations have been made near the geothermal site of S^{t}-Gallen (Switzerland; Obermann et al., 2015). In our case, further investigations are required to confirm that it is not related to a change in the seismic noise.

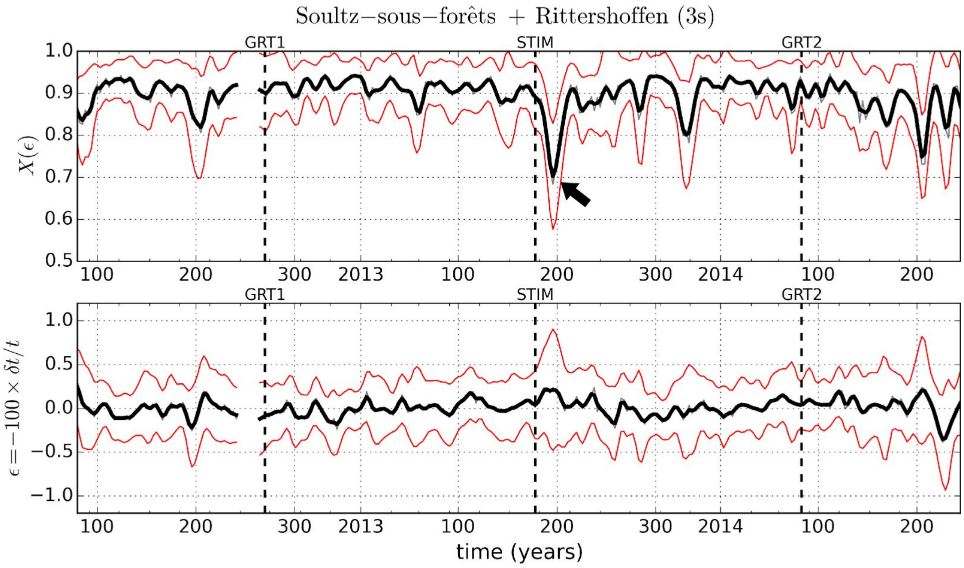

Figure 3 : Evolution of the noise cross-correlation functions at period 3s during the installation phase of the Rittershoffen geothermal power plant. The dashed lines indicate the drilling of the well GRT1, the stimulation of the reservoir and the drilling of the well GRT2 respectively. Top : Evolution of the cross-correlation coherency X. The red line represents the uncertainty on the measurements. The black arrow indicates a sudden drop of the cross correlation coherency. Bottom : relative variations of the seismic velocity as a function of time expressed in percent. The observed variations are lower than the estimated uncertainties (red curves) and are therefore not significant.

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