Géosciences pour une Terre durable
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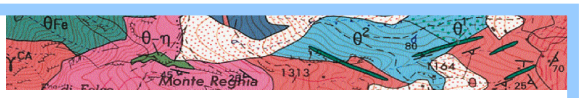

Broadband seismology for monitoring and exploring hydrothermal systems

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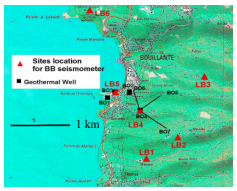
BRGM has been involved for many years in the study of the Bouillante geothermal system (Guadeloupe, West Indies). Bouillante has been used as a natural laboratory to test, validate and improve geophysical and geochemical methodologies aimed at improving our understanding of both the structure and dynamic behaviour of a hydrothermal system under controlled depressurisation (there is no re-injection of cold fluid). Marine seismic and terrestrial geophysical surveys performed by the BRGM have improved our knowledge of the 3D structure of this hydrothermal system.

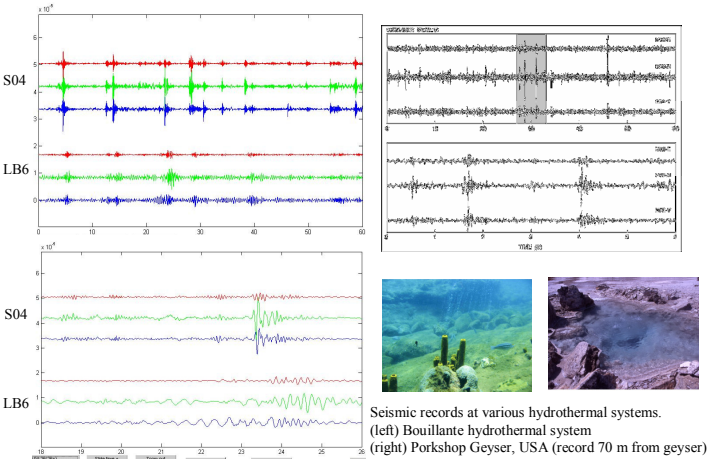
Géothermie Bouillante has been exploiting the Bouillante hydrothermal system since 1988 for local power supply. In October 2004, the extraction rate of the hydrothermal fluids was increased up to 15 MWe to reach 10% of the electrical power supply needs of Guadeloupe. To monitor possible seismicity induced by stress changes, BRGM started the operation of a network of 5 Güralp CMG-40T broadband seismometers (0.02 - 60 s) in August 2004. Data recorded with this network reveal various types of signals, none of which show a clear relationship to the geothermal field. The data mainly consist of local seismicity and regional tectonic earthquakes, including aftershocks of the Mw 6.3 earthquake of 21 November 2004 near the Island of Les Saintes.

Interestingly, however, the records obtained at the northernmost station in the Bouillante network reveal the existence of events of small amplitudes with an average repeat time of ~30s, whose spectra are characterized by dominant frequencies in the range 0.5 - 10 Hz. Cross-correlation analyses performed on a record of several days duration show that these events are highly repeatable in time, which is suggestive of a stable source location and non-destructive source mechanism. Most events display resonant signatures reminiscent of long-period events seen in other hydrothermal systems. To better characterize the origin of the events seen at Bouillante, we carried out a survey in a 1 x 1 km area in the immediate vicinity of the northernmost station of the permanent network. During this survey, 20-min-long records were obtained with a single broadband seismometer temporarily deployed at 19 sites within the selected area. Each period of observation common to the permanent and temporary stations is marked by the presence of events that are clearly recorded at the permanent station, but which are not always recorded by the temporary station. Based on the highly repeatable character and frequency of occurrence of the events, we infer their source location by using event arrival times measured at individual stations, combined with polarity analyses and temporal and spectral amplitude measurements. We discuss possible mechanisms at the origin of the events and their implications in light of the known tectonic features and available geochemical data. We also compare these data with similar events observed at Yellowstone, U.S.A.



Topographical map with location of the network of the broadband (BB) stations

Installation and orientation of a Güralp seismometer CMG-40T (60 s) in a 1 m deep hole.



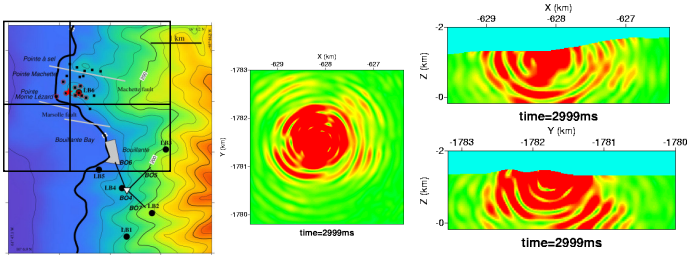
Seismic records at various hydrothermal systems.
(left) Bouillante hydrothermal system
(right) Porkshop Geyser, USA (record 70 m from geyser)

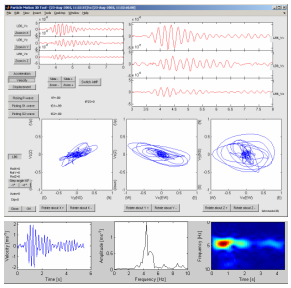
Location of earthquakse using 2 seismometers

As those events are recorded at station only, no accurate location and depth can be obtained without additional data.
It is possible to take advantage of the short repeat time between those similar events to design, test and perform a low-cost prospecting technique, which allows us to locate and possibibly estimate the source mechanism of those earthquakes.
At several locations (remote stations) around the permanent station, we recorded ground motion for 15 to 20 minutes using one additional mobile sensor (Güralp CMG-40T). For each period/location, we thus obtain 2 data sets: one at the permanent station and another one at the remote mobile station. At the permanent station, several similar LP earthquakes occurred as shown in the previous section. By analyzing the correspondence with the remote data set, we demonstrate that the extension of record of those earthquakes is limited in space. In addition, by analyzing travel times, relative amplitudes and polarization between signals at all pairs remote/permanent stations, we found the location and depth of the source.

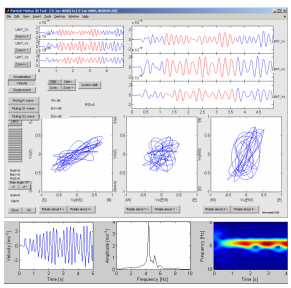
Main characteristics of those earthquakes:
1. Duration of about 1 to 5 seconds;
2. Amplitudes of about 1 to 5 10^{-6} m/s;
3. Frequency content ranging 0.5-10 Hz, up to 15 Hz in some cases;
4. Similarity in the waveforms for many events.
5. Those earthquakes are recorded at Morne Lézard only.

3D finite difference modelling



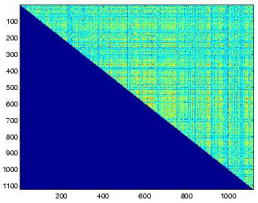


23/08/2005 – 11:32 – LB6

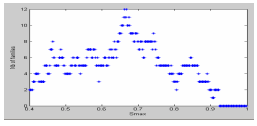


Model:
Fracture zone EW - L=300m;l=20m;W=150m
Depth=50m; Vp=1500 m/s; ρ=1100 kg/m^3
Elastic solid: Vp=3000m/s; Vs=1700 m/s; ρ=2800 kg/m^3

Statistical analysis: one principal source mechanim



Correlation matrix for the vertical component of more than 1100 earthquakes.



We analyse three periods ranging 24/09/2005 17:50 to 21:42 (232 minutes); 25/09/2005 16:57 to 22:07 (310 minutes) and 28/09/2005 15:17 to 21:36 (379 minutes). We employed a STA/LTA algorithm to detect automatically events. Each detected signal is extracted from the continuous data and stored as a 6-s long waveform. On the period considered, we detected 2129 earthquakes in 921 minutes, which corresponds to one event every 26 seconds on average. We applied a [1-20 Hz] pass-band filter. In order to classify earthquakes into families, we used the correlation matrix between waveforms, as a basis for classification. We computed a set of 3 correlation matrices(one of each component) between all events. Each value S_{jk} in the matrices is the maximum value of the cross-correlation between each pair (j,k) of detected signals. The matrices are quantitative measures of the degree of similarity between waveform pairs. In order to classify them, we use an equivalent class algorithm based on Eardley algorithm. The algorithm identifies groups of elements satisfying a commutative "sameness" condition and sorts them into similar trees. In our case, the sameness condition is chosen as Sjk > Smax. Smax is an arbitrary chosen value. Because of the competing processes of new cluster formation, and cluster coalescence, some value of Smax will produce a maximum number of clusters. In our data set, the difficulty of separating events into robust families may come from the low signal to noise ratio of the data set. Results strongly suggest that there is one principal mechanism, which generates those earthquakes.

Conclusion

At Bouillante geothermal system, small, repetitive, long-period earthquakes are recorded in an area of intense hydrothermal activity. There are indicative of the resonance of fractures in which hot boiling fluids circulate. The source mechanism may be the cavitation of bubbles entering a cooling area. This promising observation suggests that a relation between seismic data to heat flux within the geothermal system may be drawn.

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