# An innovative methodology based on Low Frequency Passive Seismic data analysis to map geothermal reservoir steam saturated areas

A. Kazantsev[1,4], P. Egermann[1], Irvan Ramadhan[2], F. Huguet[1],
C. Formento[1], M. Peruzzetto[1,4], H. Chauris[4], J.-P. Metaxian[3]
[1]Storengy (Engie group)
[2]Supreme Energy
[3]Institut de Recherche pour le Développement (IRD)
[4] MINES ParisTech

alexander.kazantsev@storengy.com, irvan-ramadhan@supreme-energy.com, frederic.huguet@storengy.com,
catherine.formento@storengy.com, marc.peruzzetto@mines-paristech.fr, jean-philippe.metaxian@ird.fr,
herve.chauris@mines-paristech.fr

Keywords: geothermal, steam, exploration, monitoring, geophysics, low frequency passive seismic

## ABSTRACT

In the context of exploration, development and monitoring, it is highly valuable to have access to the steam saturated regions of a geothermal resource. During exploration phase, it consists of a strong evidence that a sufficiently hot system is still present before the drilling decision. Then it allows to identify the best locations for the future exploration and development wells. During the production phase, it is important to monitor the steam saturated area extension due to the field depletion (production induced reservoir pressure decrease) in order to optimize the positioning of the make-up wells. This work presents an innovative methodology to detect relevant reservoir steam saturated areas which can be applied at different stages of high enthalpy geothermal projects. A field survey was recently conducted in the Muara Laboh geothermal field. The obtained results were in complete agreement with observations made on all the exploration wells. They enable to map the extension of the potential steam saturated region at the top of the structure and also to identify another potential steam area associated with a secondary top. The identified steam cap extension remains to be confirmed by the development wells which will be drilled and tested during the course of this year. These preliminary results have demonstrated the applicability and the potential of this promising new steam detection method for high enthalpy geothermal resources.

## CONTEXT AND INTRODUCTION

A new reservoir characterization technique based on the interpretation of ambient, natural, low frequency passive seismic signal meets currently a growing success to detect subsurface reservoirs saturated with multiphase fluids. It has been used in various domains such as hydrocarbon detection and volcanic eruption prediction (Ferrick et al., 1982). This technique was also successfully evaluated by Storengy on a natural gas storage asset using an advanced and innovative workflow developed internally (under patent procedure since 2016). As the spectral anomaly is related to the presence of several coexisting phases in a reservoir and the basic properties of a gas/water and steam/brine system are of the same order in terms of surface tension, density and viscosity, there is no fundamental reasons why this technique could not be applicable also in the geothermal context to detect steam saturated areas.

An accurate mapping of geothermal reservoir two-phase regions is of primary importance to guide the targeting of development and even exploration wells. On a longer term, it is also very important to map the extension of the steam area related to the reservoir depletion in order to guide the drilling of future make-up wells. Unfortunately, mapping two-phase regions is usually difficult in geothermal fields since the top reservoir is picked from the MT data whose vertical resolution is low, even though the steam/water interface is identified in some exploration wells. Therefore, it is highly valuable to develop new techniques to access this information directly in an accurate and cost effective manner. This is the main objective of this paper.

The first part of the present paper explains the principle of the methodology which relies on the acquisition and the analysis of Low Frequency Passive Seismic (LFPS) data. This approach was originally used and further developed by Storengy to monitor gas saturation in the context of natural gas storage activity (Lavergne, 2015). Ocean waves permanent activity generates coherent noise (seismic surface waves) at the ocean bottom, which then propagates across continents. This so called Ocean Wave Peak (OWP), or *microseism* for seismologists, provides us with a natural diffuse seismic source which interacts with multi-phase inclusions in subsurface leading to a modification of the energy spectrum. In the geothermal context, volcanic tremors can be an additional natural source at the same frequencies.

The interest of extending the application of such a technology in the context of high enthalpy geothermal reservoirs is tackled in the second part of this paper and illustrated through a LFPS field survey recently conducted in the Muara Laboh geothermal field (Situmorang et al., 2016).

## LOW FREQUENCY PASSIVE SEISMIC PRINCIPLE

The method is based on measuring the interaction between low frequency ambient waves and multi-phase inclusions in subsurface. Permanent activity of the ocean waves generates seismic ambient noise at the ocean bottom, which then propagates across continents mainly in the form of Rayleigh waves. The main sources of this noise have been investigated by different authors (Schimmel, 2011; Ardhuin et al., 2011). The left panel in Figure 1 (after Ardhuin et al., 2011) illustrates their distribution on the globe in 2008.

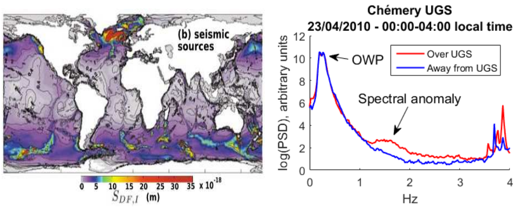

Figure 1: Source zones of seismic ambient noise (after Ardhuin et al., 2011) - Typical spectra of seismic signals outside (blue) and over (red) an Underground Gas Storage

Though these waves have most of their energy contained into the [0.1-0.2] Hz spectral band, they are still visible on the spectra up to 1-2 Hz. As we noted on various datasets, other sources can be active even at low frequencies. Human activities, such as industry and traffic, usually become visible above 1 Hz, and mainly contain surface waves. As it will be illustrated below, in the geothermal context, a volcanic system can be source of body waves dominating the ambient wavefield at frequencies as low as 1 Hz, and even lower. Whatever its origin, characterizing and exploiting a natural source avoids using costly artificial sources in seismic acquisition surveys.

Natural waves are likely to be scattered when crossing geological formations containing multi-phase inclusions because of the effective elastic and anelastic contrasts. The spectral content is modified, giving rise to an anomaly that can be mapped over the zone with multi-phase inclusions. Dangel et al. (2003) observed spectral anomalies above more than ten oil and gas fields around the world. In Figure 1 (right), the anomaly of the vertical component power spectral density (PSD) is observed above the Chémery natural gas storage in France. The aforementioned forward modeling approach based on scattering is currently being developed by Storengy and presented in more detail in Kazantsev et al. (2017). We must stress out that this approach is at reservoir scale, unlike the pore scale interface oscillation model proposed by Holzner et al. (2006) in order to explain the spectral anomaly in the hydrocarbon context.

A typical survey consists of deploying an array of three-component seismic sensors installed into 50 cm deep holes over the zone of interest (Figure 2). The recording should last at least 24 hours under good weather conditions. The array can be shifted from one day to another to improve the spatial resolution of the resulting map. Some reference sensors must stay at the same location during the whole survey. The band pass of the sensors should be at least [0.1–10] Hz. This light protocol enables to cover a large surface in a short period of time which makes it cost-effective compared to standard seismic surveys.

Figure 2: Typical sensor and its deployment

The analysis / interpretation process includes several steps:

- Pre-processing of the data to remove all the time windows where the signal was affected by external perturbations,
- Processing through the calculation of the energy spectra and the source signal propagation direction,
- Interpretation using several attributes representative of the spectral anomaly modification due to a multi-phase reservoir.

The method has been tested and validated over the Chémery natural gas storage by a consortium involving Gaz De France (now Engie). Following the preliminary results from Spectraseis in charge of the interpretation (Duclos et al., 2011), Storengy has developed its own improved processing workflow from the raw data, which has yielded very promising results (Kazantsev, 2015). Figure 3 shows the anomaly map in Chémery, compared to the gas accumulation computed by a flow simulation using a 3D reservoir model matched on 50 years of production data.

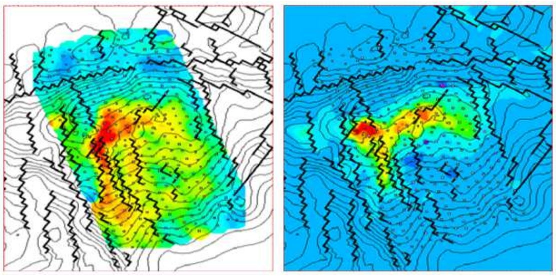

Figure 3: Spectral anomaly (left) compared to the simulated gas accumulation (right) [after Kazantsev (2015)]

A very good consistency can be observed between the two maps. As the gas distribution in the reservoir model, the spectral anomaly appears very sensitive to the presence of N-S faults located in the southwestern part of the storage (bold black lines in Figure 3 left). Moreover, the maximum spectral anomaly corresponds very well to the structural tops of the reservoir where the maximum gas column height is located.

Other successful applications of similar techniques can be found in the literature for hydrocarbon detection before drilling exploration wells (Holzner et al., 2005; Graf et al., 2007; Riahi et al., 2013) and for volcanology to monitor the low frequency tremors attributed to the magmatic chamber activity evolution before eruption (Ferrick et al., 1982; Ripepe and Gordeev, 1999).

## ACQUISITION OVER A GEOTHERMAL SITE

The LFPS methodology has been tested on the Muara Laboh geothermal field (West Sumatra) which was extensively described by Situmorang et al. (2016). PT Supreme Energy Muara Laboh (SEML) drilled six full diameter exploration wells which yielded an estimation of temperature distributions, resource size, permeable structures, and hydrology of the system. The conceptual model relies on a hot geothermal fluid upwelling from the deep part of the resource in the southern part. The fluid then flows globally to the northern direction. The reservoir fluid temperature ranges between 200°C to 310°C. In the most part, the reservoir contains a single liquid phase but a small extension steam cap was detected at the shallowest part of the reservoir from wellpad A as shown in Figure 4.

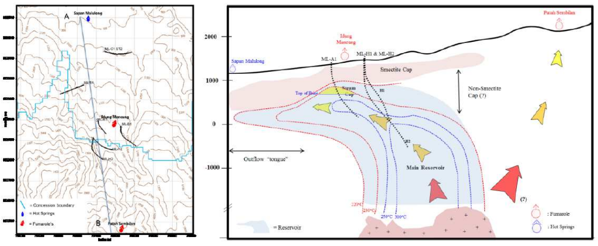

Figure 4: North-south cross section showing conceptual model of Muara Laboh field (Situmorang et al., 2016)

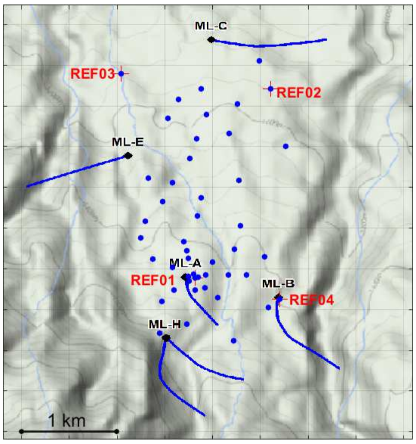

Figure 5 : Broadband seismic network deployed in Muara Laboh. Each blue location corresponds to 48 hours of available recording

11 low frequency 3-component broadband seismometers (Güralp 6TD 30s) were deployed from 31/05/2016 until 14/06/2016. Three of them (REF01, REF02, REF03) remained at permanent locations. Another 7 stations were deployed in a circular configuration whose location changed every two days. This configuration enables the array processing of the ambient noise in order to characterize the incident wavefield. The network is shown in Figure 5. Another permanent station (REF04) was added on 15/06/2016. The permanent stations remained installed until 14/08/2016 in order to check the stability of the measured attributes.

## RESULTS

After pre-processing, the power spectral density (PSD) was estimated on all the 3 components. An example is shown in Figure 6.

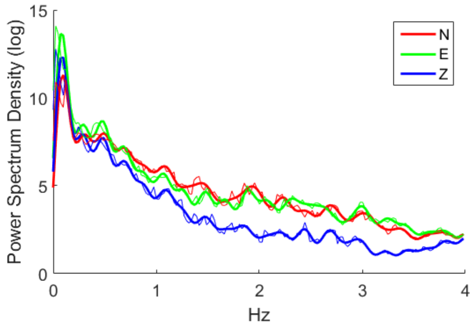

Figure 6 : Example of spectra estimated for the REF03, 03/06/2016. Bold curve : smoothed spectra.

Then the V/H spectral ratio was calculated as

$$\chi_{V/H} = \frac{PSD_z}{\sqrt{\frac{1}{2}(PSD_N^2 + PSD_E^2)}}$$

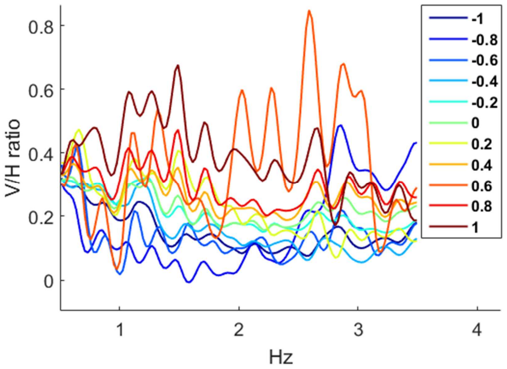

Figure 7 : Result of the V/H spectral curves classification

Following the patented procedure, an automated classification was applied to the recorded V/H spectral curves according to their shape. The classification output is quasi-continuous between -1 and 1. The spectra with values close to 1 exhibit a stronger V/H ratio between 1 and 2.5 Hz (Figure 7). The evolution of the mean V/H ratio between 1 and 2.5 Hz recorded by the reference stations during two months following the survey is shown in Figure **8**. It can be seen that the high V/H ratio at REF01 is a stable feature over time.

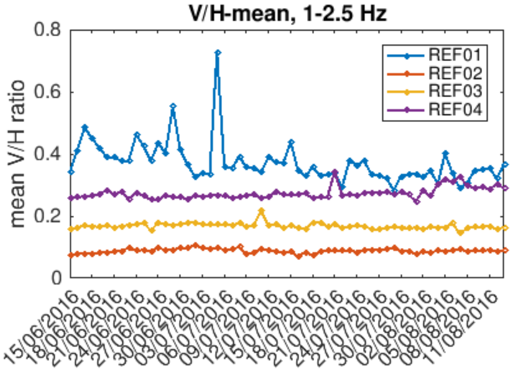

Figure 8 : Mean V/H ratio evolution in [1-2.5] Hz over a two-months recording period

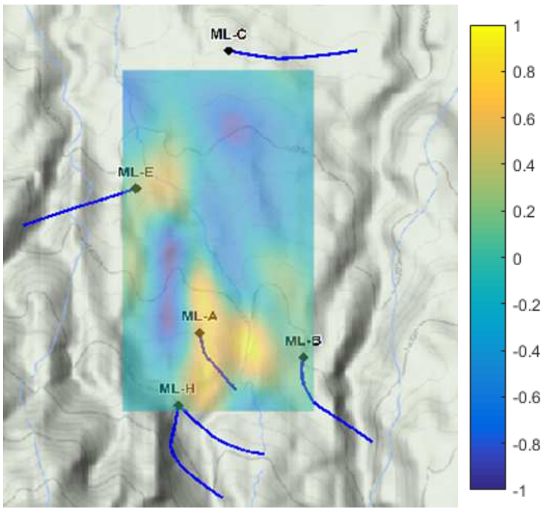

Figure 9 : Final anomaly strength map after classification and kriging

The classification results were then mapped onto the surveyed area by kriging, taking into account the uncertainties related to the time variability of the spectra (Figure 9). This map shows two “anomalous” zones characterized by a high V/H ratio (classification output close to 1) : a stronger one in the south of the field close to the well A, and a weaker one in the eastern vicinity of the well E.

Our current hypothesis is that these zones are generated by the scattering of the ambient wavefield on the steam bearing zones. The ambient wavefield was analyzed with two arrays of different apertures to address 2 frequency bands : [1-2] Hz and [5-7.5] Hz (see Figure 10 for configuration and response functions).

MUSIC algorithm (Schmidt 1986) was applied to retrieve histograms of apparent slowness and back-azimuth over overlapping 5 minutes time windows. The results shown in Figure 11 suggest that there is no consistent velocity decrease with frequency in the [1-2] Hz band (array 2) as it would be expected for surface waves. Moreover, the values of apparent velocities range from 1500 to 3000 m/s, which is more typical for body waves at these frequencies.

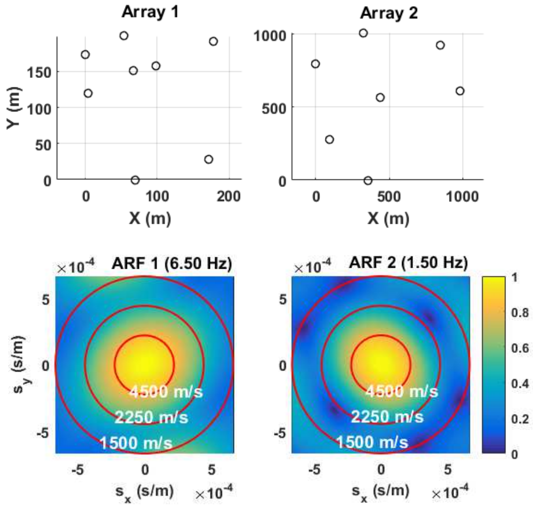

Figure 10 : Geometry of the two arrays (top) and their response functions at the relevant frequencies (bottom)

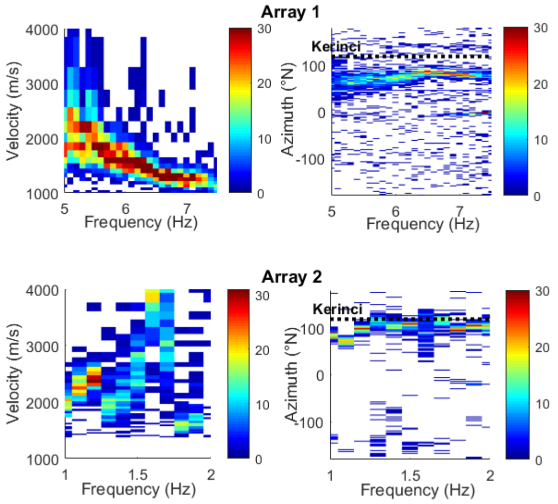

Figure 11 : MUSIC : velocity-frequency and back-azimuth histograms over analyzed windows

The results of the array 1 exhibit velocities between 1000 and 2000 m/s into the [5-7.5] Hz band, which again seems too high for surface waves, though a decrease over frequencies is observed. Finally, the back–azimuth is stable over frequencies and is close to the Kerinci volcano’s direction, as shown in the back-azimuth histograms in Figure 11. This leads us to conclude that the wavefield in the frequency band of interest is dominated by body waves originating from volcanic tremors. The next step of the work will consist of modeling the scattering of such waves by a contrast intended to mimic a steam-bearing zone.

## DISCUSSION

The results obtained by the empirical LFPS approach presented above are in complete agreement with the observations made on all the exploration wells (Figure 12). They enable to map the extension of two steam saturated regions :

- The main one at the top of the structure (A wellpad) were the most prolific exploration well have been drilled with a steam production under bottom hole conditions.
- In the northern part near the area of wellpad E. This latest steam anomaly is less intense and could be associated with a shallow steam zone. This is suggested by the heating-up temperature profiles recorded after drilling which are showing a significant temperature anomaly behind the casing at shallow depth (Figure 12).

Although the identified steam cap extension remains to be confirmed by development wells in the course to be drilled and tested this year, these first results are very encouraging and very consistent with the current knowledge of this geothermal reservoir.

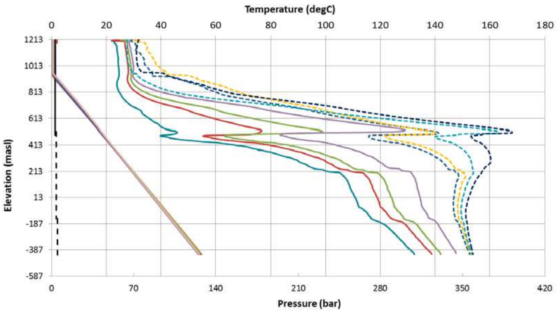

Figure 12: Anomaly in temperature recovery behind casing observed on E1 well that could be attributed to shallow steam

## CONCLUSIONS

A new methodology based on the acquisition and the analysis of Low Frequency Passive Seismic (LFPS) data has been successfully tested on the Muara Laboh geothermal reservoir to map the steam saturated areas.

The protocol for data acquisition is simple and the survey can be conducted over a short period of time which makes it a cost effective solution. The data analysis and interpretation consist of the key part to obtain accurate energy spectra and relevant attributes representative of the spectral anomaly modification due to steam saturated reservoir areas.

The first results are very promising since already consistent with the current knowledge of the reservoir. The ongoing field development drilling campaign should enable to strengthen the accuracy of these preliminary results. The application of this new steam saturated areas detection method for high enthalpy geothermal resources is very promising for both the exploration and field development phases. It may improve the success ratio of the wells through a better targeting of the most prolific areas.

## REFERENCES

Ardhuin, Fabrice, Eleonore Stutzmann, Martin Schimmel, and Anne Mangeney. 2011. ‘Ocean Wave Sources of Seismic Noise’. *Journal of Geophysical Research* 116 (C9), doi: 10.1029/2011JC006952

Dangel, S, M.E Schaepman, E.P Stoll, R Carniel, O Barzandji, E.-D Rode, and J.M Singer. 2003. ‘Phenomenology of Tremor-like Signals Observed over Hydrocarbon Reservoirs’. *Journal of Volcanology and Geothermal Research* 128 (1–3), doi: 10.1016/S0377-0273(03)00251-8

Duclos, M., B. Artman, B. Birkelo, F. Huguet, J. F. Dutzer, and R. Habiger. 2011. ‘Low Frequency Seismic Survey at a Gas Storage Reservoir’. *73rd EAGE Conference and Exhibition incorporating SPE EUROPEC 2011,* doi: 10.3997/2214-4609.20149602

Ferrick, M. G., Anthony Qamar, and W. F. St Lawrence. 1982. ‘Fluid Dynamic Analysis of Volcanic Tremor’. *Cold Regions Research and Engineering Laboratory (U.S.)*

Graf, R., S. Schmalholz, Y. Podlachikov, and E. H. Saenger. 2007. ‘Passive Low Frequency Spectral Analysis: Exploring a New Field in Geophysics’. *World Oil 01/2007*, 47-52

Holzner, R., P. Eschle, M. Frehner, S. Schmalholz, and Y. Podlachikov. 2006. ‘Hydrocarbon Microtremors Interpreted as Oscillations Driven by Oceanic Background Waves’. *68th EAGE Conference and Exhibition Incorporating SPE EUROPEC 2006*.

Holzner, R., P. Eschle, H. Zürcher, M. Lambert, R. Graf, S. Dangel, and P. F. Meier. 2005. ‘Applying Microtremor Analysis to Identify Hydrocarbon Reservoirs’. *First Break* 23 (5).

Kazantsev, A., H. Chauris, P. Dublanchet, and F. Huguet. 2017. ‘Near-Field Elastic Scattering of Rayleigh Waves - A Model for Interpreting Hydrocarbon Micro-Tremors’. *79th EAGE Conference and Exhibition 2017,* doi: 10.3997/2214-4609.201700868

Kazantsev, Alexandre. 2015. ‘Extraction et Analyse l’anomalie Sismique Basse Fréquence Sur Le Site de Stockage de Chémery’. *Storengy report OI-CE/DESS-AKA-2015-00237.*

Lavergne, Damien. 2015. ‘Innovative Technology for Monitoring an Underground Gas Storage : Low Frequency Passive Seismic Analysis’. *World Gas Conference 2015,* Paris, France.

Riahi, N., A. Goertz, B. Birkelo, and E. H. Saenger. 2013. ‘A Statistical Strategy for Ambient Seismic Wavefield Analysis: Investigating Correlations to a Hydrocarbon Reservoir’. *Geophysical Journal International* 192 (1), doi: 10.1093/gji/ggs031

Ripepe, Maurizio, and Evgenii Gordeev. 1999. ‘Gas Bubble Dynamics Model for Shallow Volcanic Tremor at Stromboli’. *Journal of Geophysical Research: Solid Earth 104 (B5),* doi: 10.1029/98JB02734

Schimmel, M., E. Stutzmann, F. Ardhuin, and J. Gallart. 2011. ‘Polarized Earth’s Ambient Microseismic Noise: POLARIZED MICROSEISMIC NOISE’. *Geochemistry, Geophysics, Geosystems* 12 (7), doi: 10.1029/2011GC003661

Schmidt, Ralph O. 1986. ‘Multiple Emitter Location and Signal Parameter Estimation’. *IEEE Transactions on Antennas and Propagation* AP-34 (3).

Situmorang, J., R. Martikno, A. Perdana Putra, and Ganefianto, N. 2016. ‘A Reservoir Simulation of the Muara Laboh Field, Indonesia’. *41st Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, California.