Game changing technology in seismic imaging applied to geothermal industry.

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ABSTRACT

Reflection seismic for geothermal exploration has proven its value over many years and in many places mainly in the form of 2D surveys. Although limited in size due to budget constraints, 3D geothermal seismic is now a reality in the Bavarian molassic basin and in the upper Rhine graben.

The development of efficient wireless recorders together with a dramatic increase in the source productivity allow seismic surveys to be run more efficiently and to better fit within typical geothermal exploration budgets.

This game-changing solution which uses single vibroseis sources and wireless single sensor receiver point, allows the deployment of equipment almost everywhere, and at any time, to record much more subsurface ray path coverage, within a given time period. The unequalled acquired trace density per km² allows the imaging of geothermal reservoirs with high resolution and a high signal-to-noise ratio over a large range of geological scales.

This increase in recorded source-receiver pairs is achieved within the economic constraints of typical projects through a drastic source productivity increase, thanks to the combination of single vibrator fleets acting independently without mutual activation constraints. In conventional seismic, vibrator fleets may contain up to four vibrators, and these fleets are sequentially activated one after the other with time and distance separation rules. Although the introduction of the slip sweep technique (Wams J, and Rozemond J., 1998) in the early 2000's has allowed the reduction of the time delay between the activation of two consecutive sources, it did not permit production rates higher than 1,000 VP per day in typical European terrain. The newly introduced SRS (Simultaneous Random Sweep) solution which involves single vibrator fleets emitting unique, encoded sweeps has no such time or distance separation rules. Consequently it allows productivity levels to reach 3000 VP's per day in Europe. A side benefit of single vibrator fleets is that it allows access to more positions and to double or quadruple the number of source fleets compared to conventional surveys, without additional equipment.

The SRS encoded broadband vibroseis sweeps are designed to cover 7 frequency octaves, while being mutually uncorrelated, which enables the fleets to act independently (i.e. unconstrained) without fear of interference. This technology allows clearer and higher-resolution subsurface imaging, without additional equipment and without additional acquisition time.

This broadband, unconstrained seismic acquisition technology has been demonstrated in relevant environments for mining projects since 2014. Trials were made for geothermal projects with 2D in the Netherlands and in 2018 the first commercial deployment on a 100km² 3D survey was achieved in Germany, South of Munich, in a mixed densely urbanized and forested environment. Results of fast track processing show very good seismic image quality.

1. INTRODUCTION

In Europe the identification of geothermal exploration sites rely on geological and geophysical potential surveys combined with vintage oil and gas reflection seismic reprocessing (mostly 2D). The issues of structural mapping and fluid content of the "reservoir" to de-risk the drilling are often addressed by small new 2D seismic surveys, and rarely 3D surveys, except in Germany. The main reason for this being economic limitations.

Conventional vintage 2D or 3D seismic have used a lot of geophones (in arrays) per recorded channel, a choice historically driven by the limited number of channels available on the recording system. Geophone field arrays were required at that time to apply anti-aliasing protection in an analogue fashion to the signal prior to its sparse digitisation. On the source side, to mimic high energy dynamite sources, vibrator fleets where composed of several heavy vibrators acting simultaneously over the spread of the source array. A low productivity and therefor a low density of acquired source-receiver pairs for a given acquisition budget was the end result. The cost of such a survey is high and it faces a quality bottleneck as even for new surveys there is often little difference with what was done in early 80's (except spatial sampling).

Recent developments on the seismic sensing side with autonomous wireless recorders (Dean, T., and

Sweeney, D., 2019) connected to broadband, high-sensitivity single geophones, combined with recent developments on the seismic source side with unconstrained single broadband vibrator sources, allows the boosting the acquisition rate (productivity) of source-receiver pairs which drive the overall seismic information value. This technology allows access to high quality 3D images of the subsurface within the geothermal exploration-specific constraints related to permitting, community acceptance, mix of urban, agricultural, protected areas, timing and geothermal budget.

In the Middle East, modern crews now typically record some 20,000 VP’s per day, compared to an average of 1,000 VP’s par day in Europe with legacy slip sweep technology. The only source restriction is the number of vibrators mobilized; it has to be balanced between the size of the survey and the targeted productivity.

The only remaining bottleneck in productivity is the capacity to roll receivers (from the back of the spread to the front of the spread during the survey) even in case of single phones because of the high cost of personnel in Europe and limitations related to HSE exposure. This is overcome by acquisition designs putting more emphasis on the source side rather than receiver side.

2. SRS TECHNOLOGY

In the SRS (Simultaneous Random Sweep) blended acquisition solution, autonomous vibrators operate independently and are not synchronized by the recording system anymore. Sweeps are not emitted at specific time slots or with a distance-separation constraint. Each vibrator emits its unique encoded sweep when ready at its position. If needed, SRS could be combined with dynamite infill (in areas vibrators cannot access) simultaneously alongside the vibroseis acquisition.

As vibrators sweep when they are ready, it is mandatory to record data continuously.

The encoded sweeps are designed in such a way that they can overlap, and even be emitted at the same time by various vibrators, with SRS technology having the ability to successfully separate the resulting mixed signal so that it is free from interference. The source separation is performed in the field through multi-source deconvolution using the permanently recorded ground forces (instead of the sweep pilot used when performing the traditional correlation). Final data is delivered according to industry-standard formats.

The encoded sweeps are designed based on the technique of pseudorandom sweeps (Sallas J. et al., 2011) which uses a set of weakly-correlated pseudorandom sequences in a way to minimize the cross-talk interference between sweeps. A set of conventional linear sweeps could not fulfil these requirements.

The pseudorandom sweeps are not output from vibrator's controller. They ensure that cross-talk between sweeps are minimized and is calibrated in such a way that its energy matches that of the standard linear sweeps (low energy level is a well-known drawback of standard pseudorandom sweep).

The SRS vibroseis high-productivity acquisition technique is well suited for surveys carried out in terrain with a mix of urban, industrial and agricultural obstacles, which traditionally prevent efficient seismic acquisition. SRS allows the acquisition of data in a cost-effective manner, under tight timelines and with minimum environmental footprint.

With SRS, eliminating the common time and/or distance separation shooting rules, which are particularly stringent using standard high-productivity techniques, allow an unprecedented degree of freedom.

3. BROADBAND

EmphaSeis™ (Saleh A. *et al.*, 2017) broadband technology is a sweep method that extends the frequency bandwidth of vibroseis data. It does this by using the vibrator mechanical and hydraulic specifications to optimally design the output force and the variable sweep rate, without posing a risk to the sweep fidelity or the mechanical systems of the vibrator. This ensures the maximum drive level possible at each frequency (Tellier N. and Ollivrin G., 2019). The customized non-linear sweeps are designed to build up energy at low and high frequencies while keeping in the vibrator operating well within its capabilities.

Once converted into the SRS encoded sweep, potentially harmful resonant frequencies are eliminated, allowing closer safe access to buildings and underground infrastructure.

The broadband sweep used in Pullach is based on single vibrator with a Σ1 60s length encoded sweep, 3-96Hz, 250/250ms tapers. It provides higher vertical resolution and better definition of reflection events compared to the legacy datasets using 12-96 Hz 12s Σ9 with 3 vibrators and arrays of 12 geophones, 3 km north of Pullach survey.

4. WIRELESS RECORDING

Wireless recording field solutions can be classified according to their capacity for equipment QC and seismic data transmission in real-time (Dean T., and Sweeney D., 2019). The basic nodal systems have very limited, or zero QC capacity. The immediate advantage of this approach is their long battery life but at the expense of dynamic range and with noise performance, as poor as 116dB and 2.84μV compared to the highest standard of wireless industry at 131dB and 0.45μV (WTU-508). The basic nodal systems have only internal single geophones, while some others can connect any number of geophone strings.
At the other end, some systems claim to be able to

harvest seismic data in real time but with a bottleneck in wireless communications technology and battery autonomy.

The Sercel Unite system used for the Pullach survey (Figure 1) is an intermediate technology allowing harvesting of QC attributes and occasional check of seismic data at the field recording control truck. It has been used within the limits of its internal battery life due to the high rate of acquisition allowed by the SRS blended technology. The harvesting of QC attributes allows permanent visibility and control of the equipment/spread and can even be performed by AVD (drone) (Tellier N. and Wilcox S., 2018). The latest generation of Sercel WTU-508 would even allow real time transfer of QC attributes and ambient noise alarms to any gateway.

Figure 1: Unite equipment at Pullach basecamp.

5. PULLACH SURVEY

This acquisition is the first 3D survey recorded in Europe with such modern technology and for a geothermal objective.

The city of Pullach im Isartal is located south of Munich and is already providing geothermally-sourced district heating since 2005 through two wells at 3500m and 3445m TVD. As the demand is increasing, the production has been expanded in 2011 with a third well at 3505 m TVD. The district heating network is about 25km in length for 1000 houses and has a maximum energy of 10.4 MWth.

The 3D seismic survey located south of Munich City (Pullach) covered 103km² (9,700 VPs – Figure 2) with a source line interval of 424m, VP Interval of 17,67m and RP interval of 26,5m. The recording spread was one patch of 9,195 Sercel UNITE RAUex with a single SG5 geophone, optimal for broadband acquisition.

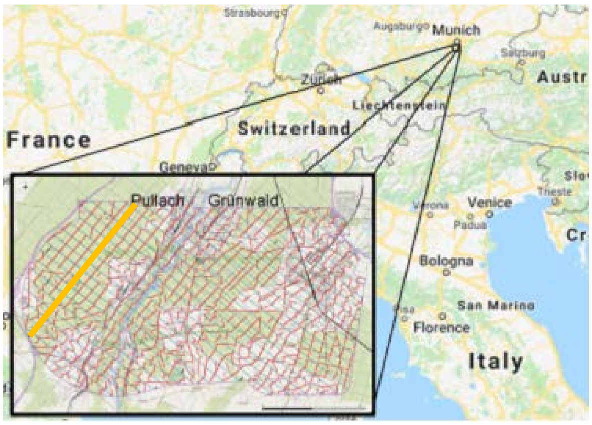

Figure 2: Location map of the 3D survey in Bavaria. (Red dots represent VP locations - Orange line is the XL2278 presented Figure 4).

The area of Pullach comprises a mixture of urban, suburban, agriculture and forest. The forestry is generally well managed with a substantial network of forestry roads (hence the 424m between lines). in the survey area.

There is a variety of different obstructions in the survey area. The valley of the Isar river runs through the project from South to North. The area is covered by a railway network, a main road , motorways which go along the western border and the North East corner of the prospect. There are also many sensitive ecological areas and protected waterways. The seismic survey was preceded and supported by an intensive public relations campaign. All district administrations concerned by the survey were informed far in advance.

The geological conditions around Munich are well known to be favourable to deep geothermal energy. At a depth from 2000 m to over 3000 m the Malm permeable limestone aquifer offers a temperature from 80°C to over 100°C. The Malm formation is some 500m thick and located below a clastic sequence. The Top Lithothmanienkalk reflector at 1.7s twt, (XL2278 - Figure 4 - marked with white arrows) is clearly visible on the fast-track PSTM cube. The Top Malm should be a few ms (2 or 3 wavelet phases) below. The carbonate formation is known to have sparse diffraction signatures and no strong reflections events.

SRS was implemented to ensure rapid acquisition. This new method uses vibrators in autonomous mode (here 45000 lb - Figure 3), each one using a unique encoded sweep where the frequencies are swept randomly. This enabled the overlapping in time of the 60 s sweeps between vibrators without any need of distance separation. The start time of each sweep is random, GPS clock coded and controlled by each vibrator. Recording is continuous throughout the day.

Figure 3: Vibrator used for Pullach survey.

CGG's highest productivity land seismic survey in Europe using legacy slip sweep technology (2003) passed the 1,000 VP/d mark in the early 2010's. With this latest SRS technology it recently passed the 3,000 VP/day on single shift in Alsace (Nord Alsace – ESGéothermie/EdS).
Timing of the Pullach survey was of critical importance due to environmental restrictions.

Immediately after the last VP was harvested, and before deblending was completed, a TeraMig™ PSTM cube (Cotton J. et *al., 2016*) (direct pre-stack time migration of raw field data, no FK, no velocity or mute optimization, AGC + elevation statics) was provided to the client (Figure 4).

The Pullach survey was acquired using a true 5 octave broadband sweep (Emphaseis™) from 3 to 96 Hz with 500ms tapers, enabling higher resolution and better definition of subsurface reflectors. The bandwidth and resolution of this SRS/Broadband solution is clearly illustrated with a frequency band pass filter panel analysis (Figure 5).

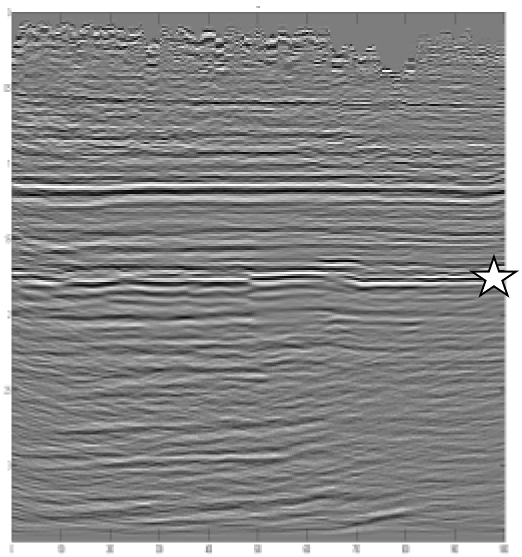

Figure 4: Inline brute PSTM TeraMig section – white star represent the target at time depth (location Figure 2).

After this successful survey in Germany, another 3D survey specially designed to image the geological structure down to the top basement at the full reservoir scale was recorded in France in the North Rhine graben over 180km². It is the first 3D seismic survey ever shot for geothermal prospecting in France and was only made economically using SRS solution with a single sweep 2-96 Hz, 48s, with single vibe on 6 geo).

6. CONCLUSIONS

Seismic in Europe, and especially in a suburban densely-populated environment, is a technical and operational challenge, but it is the best way to de-risk drilling targets when developing a deep geothermal project in a sedimentary basin context.
It was proved by this 3D seismic survey recorded in Pullach that despite the constraints of the environment, road traffic and a high noise level, an excellent broadband seismic volume can be obtained at an economical cost due to the very high productivity levels offered by this acquisition technology. However, the seismic survey is only possible if the local population is well informed about the purpose of the survey and has a positive attitude to the use of geothermal energy.

The enablers of this novel, highly effective solution are many fold. To list the most important ones:

- Continuous wireless recording;
- Unconstrained simultaneous sources;
- Broadband source encoding;
- Source meta data recording including GPS time-stamping and ground force;
- Multi-source designature.

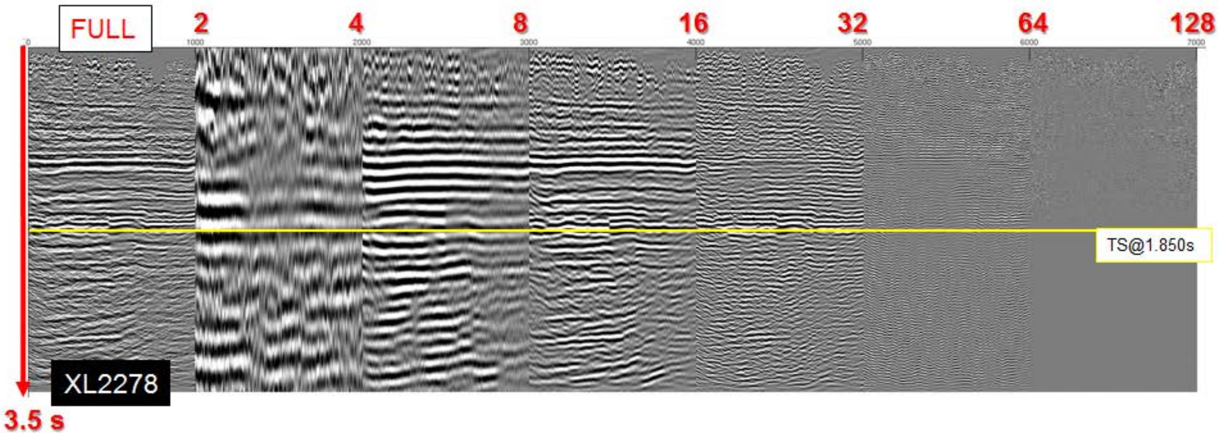

Figure 5: Octave decomposition of XL 2278.

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