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Optimized array electromagnetics
for
Hydrocarbon/ Geothermal Exploration &
Reservoir monitoring

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Optimized array electromagnetics for Hydrocarbon/ Geothermal Exploration and Reservoir monitoring

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Keywords

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Summary

Over the past decade we optimized new generation of electromagnetic hardware/software that can be used for land, marine and borehole applications allows us to get better and more dense data. Further the optimization includes target resistivity and choice of component/sensors. The system uses a seismic-like architecture with nodes, each of which can be expanded with sub-arrays. It combines for the first time electromagnetic and microseismic data recording in a single box on the same time base. The modular architecture allows a fit-for-purpose configuration tailored to the specific exploration / monitoring target. It is not limited by number of channels or components to-be-recorded. For geothermal applications, depending upon the user requirements we define four different configurations suitable: Advanced MT, Broadband MT, *Mini MT* with AMT, and MT with TDEM. For hydrocarbon applications the independent node concept is more efficient. System characterization and a geothermal field and monitoring examples underline the technical features.

The entire system includes for the different methods processing and 3D inversion software, streamlining the workflow significantly.

Introduction

Over the past 30 years magnetotellurics has been the ‘work horse’ in geothermal exploration with geophysical methods. Standard magnetotelluric [MT] systems (operating at a frequency range from 0.001 Hz to 1 kHz) and audio-magnetotelluric [AMT] systems (operating at a frequency range from 1 Hz to 20 kHz) are routinely used. While the methodology and technology has stabilized, they are limited by cost and limited number of data sites. Little innovation regarding operational and interpretational workflow and cost optimization (Strack, 2014) could be found. The main purpose of going to an array architecture is to get more data of better quality at lower cost and utilize the strength of spatial redundancy of geophysical data.

At the same time, combining the acquisition of microseismics and controlled source EM lets us explore the use of the technology for reservoir monitoring

A broader range of sensors and state-of-the-art electronics yield several fit-for-purpose system configurations and applications that can greatly simplify operations and hardware cost by being tailored to the users need and experience.

System Parameters

Paramount for a successful field application is that the hardware is operated at a low cost and runs efficiently and reliably. This is our key development goal and gives us the flexibility to adjust system complexity and cost to the user’s need.

Over the past 8 years, we have developed a complete new generation of electromagnetic hardware that can be used for land, marine and borehole applications. The system uses architecture like a seismic nodal system (Jiang et al., 2015) and for the first time combines electromagnetic and microseismic recording capabilities in a single box with unlimited number of channels or components. Figure 1 shows a picture of the MT version of the system. Depending on user requirements we define four different configurations suitable for geothermal applications:

- **Advanced MT:** This configuration includes the standard MT frequency band (frequency range from 0.001 Hz to 1 kHz) with the option of additional AMT (frequency range from 10 Hz to 20 kHz) sensors. It has maximum flexibility and connectivity. AMT sensors can be run independently to have continuous acquisition with the MT sensors.
- **Broadband MT:** In this system part of the AMT sensor is combined with the MT sensors (0.00025 Hz to 10 kHz). This reduces cost and simplifies operation, but while the AMT is recorded there will be a gap in the MT data.
- **Mini MT and AMT:** This configuration is targeted as introductory system for easy operation. The low frequency fluxgate sensors record for a long time while the AMT band is recorded with a roving receiver. It gets deep and shallow structures and avoids burying of the long induction coils.
- **MT and TDEM:** This is the standard configuration used over the past decade with a standard MT system and a second TEM system for near surface information and static shift. This requires two separate instruments, measurements and interpretation and can be in many instances replaced by the AMT measurements (not always).

Figure 1: The main components of the array system: 1) KMS-820 digital acquisition system, 2) LEMI-120 low frequency magnetometer, 3) LEMI-701 electrodes, 4) KMS-831 sub-acquisition controller, 5) KMS-029 fluxgate magnetometer, 6) KMS-410 lithium ion battery, and 7) miscellaneous connection cable

All of the systems assume that the data are interpreted using a 3D inversion algorithm as it is commonly used.

In addition, a reservoir monitoring version has been field tested which includes approximately 200 channels and a high power controlled source of 100 KVA. It allows new signal focusing methods and to image the information directly below the receiver site.

Advanced MT

Traditional geothermal electromagnetic applications include standard magnetotelluric [MT] systems and audio-magnetotelluric [AMT] systems. For this application the standard broadband induction coil magnetometer LEMI-120 is used; the wide bandwidth from 0.0001 Hz to 1 kHz and low noise characteristic (e.g., < 0.1pT/√Hz) makes it an ideal single-MT sensor. The sensors are lightweight (approximately 10 lbs.) and compact (approximately 4 ft.). If the application does not require the full high frequency range, an alternate option is the use of an even shorter coil with the LEMI-121 (0.0001 Hz to 500 Hz). At less than 2 ft. and less than 8 lbs. deployment is made even easier. The AMT band is adequately covered with the LEMI-118, which offers an application range from 1 Hz to well over 70 kHz.

Overall this configuration could allow for deep penetration in excess of 10 km with a minimum in hardware deployed in the field. Its advantage is maximum flexibility in the MT band and its disadvantage lies in limitation at the high frequencies, which – depending upon target geoelectric section – could require the use of loop source TEM for static corrections, Cummings and Mackie (2010). While AMT high frequency measurements can in many cases be used for static correction, there is no 100% guarantee because the measurements could also be exhibiting static effects at higher frequencies. This makes the complete set of sensors and measurements the largest of all proposed system. Thus this is the most expensive option.

Broadband MT

For geothermal applications one often requires limited high and low. For this, one can cover the operating range of the frequency band from 0.00025 Hz to 20 kHz in a single sensor configuration, the LEMI-152 broadband coil.

The advantage is that the operator needs to carry much less equipment in the field and the broader frequency band is recorded automatically. Disadvantage can be that the separate band recordings are never perfectly done synchronous [Note: *different sampling rates are used for recording different frequency bands, e.g., record at a sampling rate of 1 kHz for 1-6 hours and at 40 Hz overnight*] and while you are recording high frequencies you are not getting low frequency data. Also the frequencies may not be high enough to handle the static shift and you may require separate TEM loop source measurements for static shift correction.

In summary, you are accepting some technical trade-offs for less equipment (and cost).

Mini MT and AMT

For a more efficient and easier operation at even lower cost and at the same time yielding a larger data volume we can combine multiple low frequency systems with a high frequency system, taking advantage in size and cost. As an estimate, you will get approximately four acquisition systems for the same price as three broadband systems.

The low frequency systems include 3-component fluxgate sensors, we call *Mini MT* (DC to 180 Hz). They are coupled with one AMT system. This combination is very fast to set-up as the sensors are small, require less site preparation (e.g., less digging of sensor holes), and yet deliver a full spectrum application. The AMT frequency range is covered by the LEMI-118 broadband magnetometer or a smaller and lighter design (i.e., 1 ft., < 1 lbs., 1 Hz – 500 kHz; LEMI-142). The low frequency band is covered by the 32-bit KMS-029, a sensor containing a three-component fluxgate magnetometer.

In such operating scenario the AMT system records for only a few minutes and is moved from site to site. The *Mini MT* records for at least 6 hours or a full day and the magnetic fields from the fluxgate sensor and the coil are then matched and correlated to establish continuity in the frequency band.

This configuration has the advantage of easy and fast operation and low cost. At the same time, because of the lower frequencies it can be used for crustal applications with longer recording times. This could be useful when an unknown exploration area is targeted. The disadvantage lies in the overlapping frequency band where our special correlation technique only works in 90% of the cases (due to the characteristics of flux gate sensors). This is only an issue when the target lies exactly in that frequency.

MT and TEM

Finally in a combination using standard MT and transient EM [TEM or time domain EM – TDEM] measurements the system allows for traditional EM exploration and monitoring. There are two modes that have been used: TEM for static shift correction and TEM to complement the entire exploration depth using a grounded dipole.

For static shift correction with the TEM method a primary field is typically generated by a loop transmitter, Pellerin and Hohman (1990), Cummings and Mackie (2010). This has become standard for geothermal applications though more recently also AMT measurements combined with careful field calibration and statistical averaging has been used, Yu et al. (2010a & 2010b).

Advantage in using loop-source TEM for static shift lies in the best depth adjustment for the MT measurements (static shifts are caused by the electrode contact resistance variation). Since loop-source TEM is unaffected, one can trust the data. The cost is operational efficiency and the need of a second set of equipment. Given that interpretation is done in three dimensions, the static shift information will also be contained in the model (theoretically).

To complement the MT measurements one can also use grounded-dipole TEM, Keller et al. (1984), Strack (1992). The signal transmitted by the dipole consists of a series of alternating step functions that create a collapsing field that in turn induces electric and magnetic fields in the subsurface. Subsurface properties and features at great depths can be detected by recording these fields at increasing distances from the transmitter during the off-times, Strack and Vozoff (1996). Using this methodology in addition to MT can help in areas with higher cultural noise and when more detail coupling to the subsurface resistivity is required.

Reservoir Monitoring

Monitoring geothermal reservoir is often a matter of compliance. In most case microseismic monitoring is used. When the target is the fluid movement in the reservoir, electromagnetics is a much more suitable method as the signal measures directly the fluid movement in the pore space as strong resistivity variation usually results from such movement.

The most suitable methods for this is a controlled source method in most cases in the time domain. Our system has approximately 200 channels including 3 component electric and magnetic field and 3C seismic sensors. The transmitter is a high power 100 KVA time domain transmitter that can operate autonomous. We have carried out numerous 3D feasibilities including in-field noise measurements and conducted a field pilot for a water flood.

Processing and Interpretation

For a successful interpretation the workflow should always consider the 3D geometry of the target. The software workflow is shown in Figure 2. It includes mandatory 3D-type interpretation. As an advantage of this approach we can easier take care of any static shift, e.g., use the AMT data for statics or CSEM data or standard loop source time domain electromagnetics. In doing so we use less hardware and less interpretational effort.

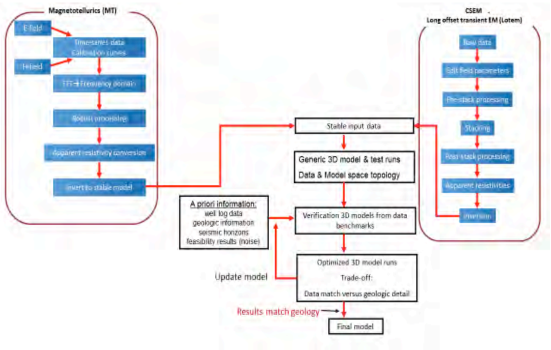

Figure 2: A schematic diagram of various processing workflows including processing and interpretation to final 3D model.

Applications

Besides lower cost and more efficient and flexible operation for traditional exploration applications, the system is increasingly used for other applications including reservoir monitoring environment. The following examples illustrate the system capabilities and approach for reservoir monitoring.

Establishing monitoring system characteristics

To establish system performance and show confidence in the interpretation extensive field tests were performed. The field tests included a variety of hardware, transmitter and system layouts. These were then followed by feasibility studies yielding system and methodology design. We carried out feasibility studies for fields in the Middle East, North America, Asia and Europe. Over the last few years we have also carried out a successful field test in an oil field.

Usually, a feasibility assessment starts with the derivation of an equivalent resistivity model. This requires a resistivity log from which we derive an anisotropic resistivity section. In combination with the geologic information and sometimes seismic horizons, we perform a complete 3-dimensional modeling study and generate 3D synthetic data. In addition, we carry out noise tests that allow us to estimate how various sensors perform for specific reservoir target parameter variations. The field data from the noise test are compared with 3D modeling results. Figure 3 shows an example of the layout for monitoring (at the top) and the modeling response. The model at the top of the figure refers to seismic horizon 3 which was used to constrain the models. During this feasibility project extensive 3D modeling was performed in order to evaluate anomaly characteristics such as relative signal difference, depth influence, overall detectability and resolution capabilities.

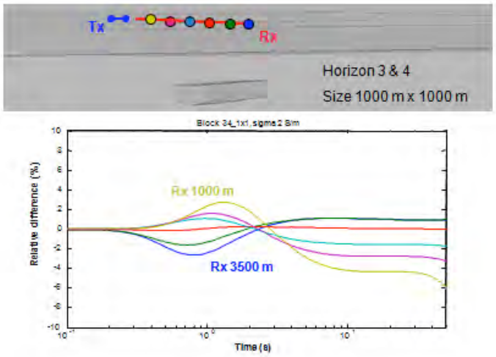

Figure 3: Example for a 3D reservoir modeling Feasibility. The model combines three-dimensional seismic horizons and state-of-the-art 3D electromagnetic forward models. The surface transmitter is a dipole and the receiver offset is varied from 1,000 m to 3,500 m with respect to the model shown at the top.

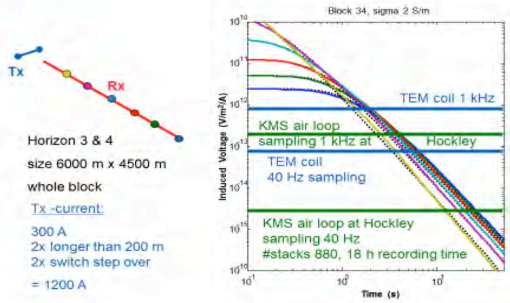

Figure 4: Transient signal for target reservoir parameter variations with sensor noise levels superimposed.

As part of the project the environmental noise was evaluated in detail at the field site. Different sensor responses were compared including noise levels. Figure 4 illustrates some transient responses of typical TEM coils and the KMS air loop at different sampling frequencies in relation to expected noise levels.

Data flow is a key operational element. We integrate multiple data flow options in the system. First that data is stored on SD card (hot swappable), then the system can be connected during recording via USB cable, LAN or via various Wi-Fi options including a webserver that allows control of the unit by smart phone/tablet. To avoid the interference between Wi-Fi transmission and sensors, we add an almost noise-free Wi-Fi device that backup the data onto an autonomous webserver (via LAN or cell phone).

While MT is the most common electromagnetic method for exploration, for reservoir monitoring applications a higher coupling of the measurements with the subsurface resistivity is required and thus the use of a controlled source EM (CSEM) is recommended. This allows us to obtain more detail than we could obtain with MT. An example of a CSEM experiment design can be found in Passalacqua et al. (2016).

The integration with microseismic monitoring to monitoring reservoir production and induced seismicity can also be done. The data can be recorded in the same acquisition system.

Since this Feasibility, we have carried out more feasibilities and even a field test where we could see the water flood after only a few days.

Example of geothermal exploration

Following is an application for a geothermal evaluation performed in Hungary, where nearly thirty areas have been investigated using an integrated approach with well logs, seismic, gravity and AMT/MT data. We showcase results from one area near the small town of Szentlörinc that was successfully drilled and is producing hot water. A more detailed account of the overall survey can be found in Tulinius et al. (2010).

Figures 5 and 6 summarize general pre-survey knowledge of the exploration area, respectively a geological and seismic cross sections parallel to the survey line. Notably, the pre-existing seismic data where initially targeted for oil and gas exploration at shallower depths than the geothermal reservoir. Main target for geothermal utilization is the pre-Tertiary basement rock, mainly limestone/dolomite layers of Mesozoic age. Additionally, fractures play a major role in geothermal development and the deeper fault system is also acting as a path for the deep heat source to reach the surface. Feasibility studies frequently suggest the use of EM methods to define these features, Singharajwarapan et al. (2012).

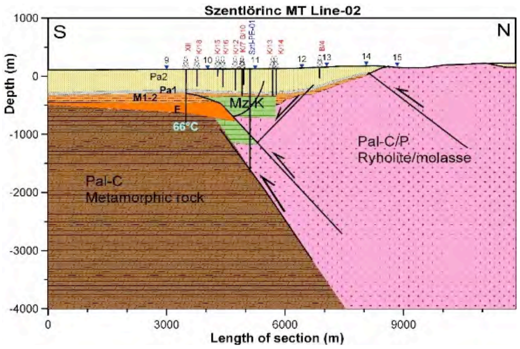

Figure 5: Geological cross section parallel to the AMT/MT/gravity line near Szentlörinc.

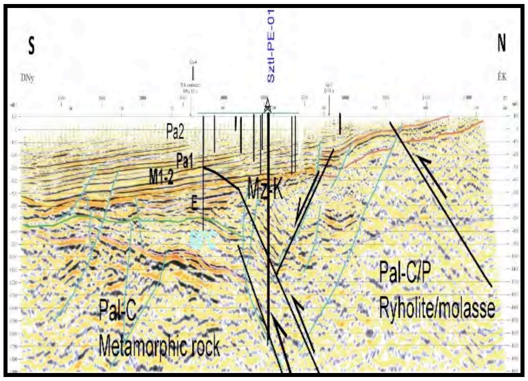

Figure 6: Seismic cross section parallel to the AMT/MT/gravity line near Szentlörinc.

AMT/MT measurements are used to estimate the resistivity at depth along a preselected survey line, resulting in a two-dimensional section along that profile line. The AMT/MT measurements comprised of four components, i.e., the X and Y components of both magnetic and electrical field data. In order to identify currents flowing along a structure, i.e., transverse electric (TE) mode, or currents flowing crossing a structure, i.e., transverse magnetic (TM) mode, the strike was calculated in the frequency range between 10 kHz and 0.001 Hz in each survey area. A remote reference was used to improve data quality applying the multiple-station technique, Egbert (1997). To get better constrains a gravity survey was also performed along the profile lines with a (much denser) spacing of 250 m.

A total of 468 AMT/MT sites and close to 1,900 gravity stations were measured along 45 line in 27 areas.

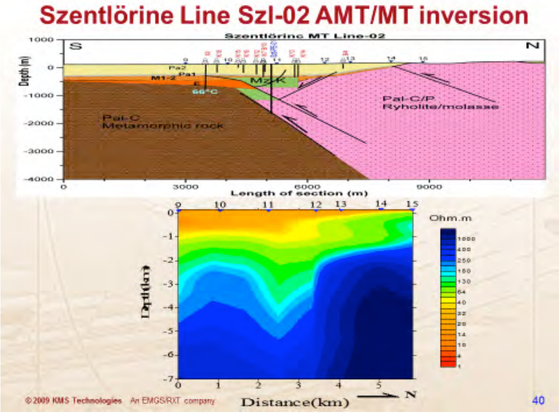

Figure 7: Sample AMT/MT inversion result along with a geological cross section.

Figure 7 shows a sample AMT/MT inversion profile along with the respective geological cross-section. The geologic model was derived from the interpreted seismic data and the data was inverted in 3D, then a regional model was derived followed by a regional anomalous model.

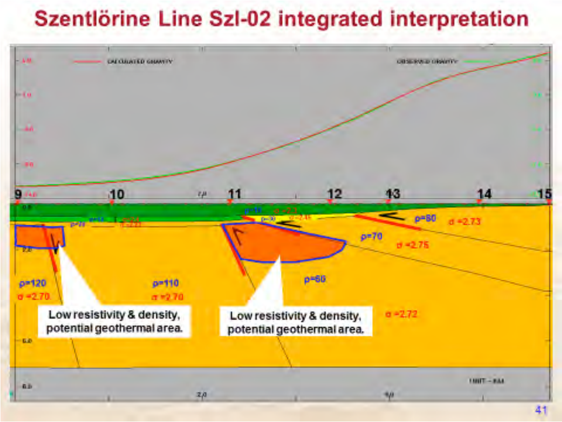

Figure 8: Sample gravity profile and integrated interpretation.

Figure 8 depicts a sample gravity profile together with an integrated density interpretation cross section based on the original geologic model. Where low resistivity and low density anomalies coincide we see potential for geothermal development because lower resistivity give higher temperature and lower density indicates more pore space filled with fluids.

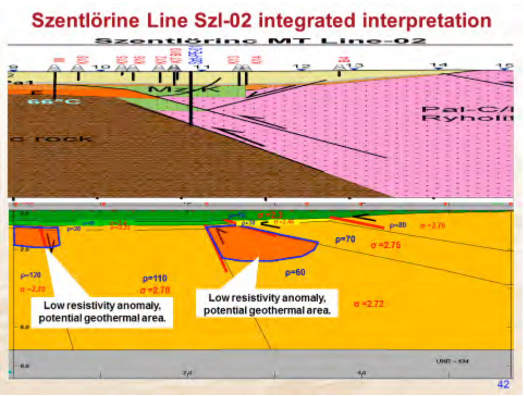

Figure 9: Sample of an integrated interpretation section along with a geological cross section.

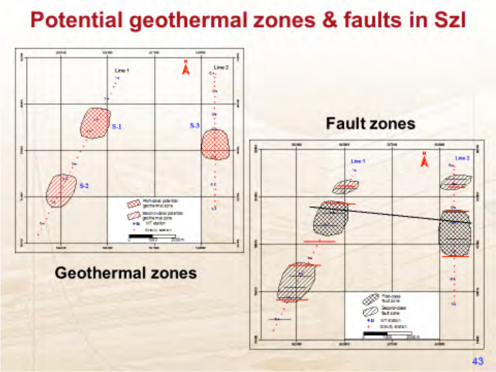

Figure 10: Map view of potential geothermal zones and faults near Szentlör

Figure 9 illustrates the integrated interpretation section along with a geological cross section. Next, we define fracture zones from the seismic data and map them with the electrical/density anomalies. Where they overlap, we have a likely drilling target. As result, Figure 10 shows a map view of potential geothermal zones and faults of the chosen survey location near Szentlörinc.

The integrated approach using different data sets has proven to be a very effective way of locating the most promising areas for geothermal utilization in Hungary. Once a 3D model has been derived and integrated with other geologic and geophysical information, this yields reliable exploration targets. Further examples can also be found in Yu et al. (2010a & 2010b).

CONCLUSIONS

Using advanced electronics and data workflow, a new array data acquisition strategy can be derived. This allows us to build fit-for-purpose acquisition units as well and to customize the acquisition strategy while optimizing cost of hardware and operational aspects.

We propose an array acquisition system which has already been used in over 20 countries mostly for geothermal applications. The system can also be used for high-definition monitoring of geothermal reservoirs. Other geophysical measurements such as microseismic can easily be integrated because necessary hardware is already implemented.

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REFERENCES

Cummings, W., and Mackie, R., “Resistivity Imaging of Geothermal Resources Using 1D, 3D, and 3D MT Inversion and TDEM Static Shift Correction Illustrated by a Glass Mountain Case History.” *Proc. World Geothermal Congress*, (2010), Bali, Indonesia.

Egbert, G.D., “Robust Multiple Station Magnetotelluric Data Processing.” *Geophys. J. Int*., 130, (1997), 475-496.

Keller, G. V., Pritchard, J.I., Jacobson, J.J., and Harthill, J.N., “Megasource Time-Domain Electromagnetic Sounding Methods.”, *Geophysics*, 49, (1984), 993-1009.

Passalacqua, H., P. Boonyasaknanoon, and K. Strack, “Integrated Geophysical Monitoring for Heavy Oil.” SPE-184089, *Heavy Oil Conference*, (2016), Kuwait, Kuwait.

Pellerin, L., and G. Hohmann, “Transient Electromagnetic Inversion: A Remedy for Magnetotelluric Static Shifts.” *Geophysics*, 55, (1990), 1242–1250.

Jiang, J., Aziz, A.A., Liu, Y, and Strack, K.M., "Geophysical Acquisition System.” (2015), US Patent 9,057,801.

Singharajwarapan, F.S., Wood, S.H., Prommakorn, N., and Owens, L., “Northern Thailand Geothermal Resources and Development – A Review and 2012 Update.” *Trans. Geothermal Resources Council*, 36, (2012), 2-6.

Strack, K.M., “Future Directions of Electromagnetic Methods for Hydrocarbon Applications.” *Surveys in Geophysics*, 35, (2014), 157-177.

Strack, K.M., and Vozoff, K., “Integrating Long-Offset Transient Electromagnetics (LOTEM) with Seismic in an Exploration Environment.” *Geophysical Prospecting*, 44, (1996), 99-101.

Tulinius, H., Porbergsdottir, I.M., Adam, L., Zuzhi, H., and Yu, G., “Geothermal Evaluation in Hungary using Integrated Interpretation of Well, Seismic and MT Data.” *Proc. World Geothermal Congress*, (2010), Bali, Indonesia.

Yu, G., Gunnarsson, A., He, Z., and Tulinius, H., “Characterizing a Geothermal Reservoir using Broadband 2-D MT Survey in Theystareykir, Iceland.” *Proc. World Geothermal Congress*, (2010a), Bali, Indonesia.

Yu, G., Strack, K.M., Tulinius, H., Porbergsottir, I.M., Adam, L., Hu, Z.Z., and He. Z.X., “Integrated MT/Gravity Geothermal Exploration in Hungary: A Success Story.” *21st ASEG Conference and Exhibition*, (2010b), Sydney, Australia.

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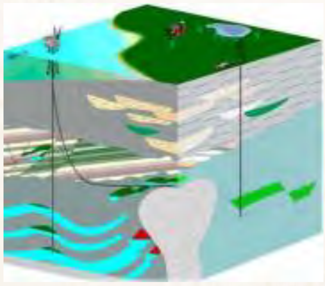

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