KMS Technologies

A Fit-for-purpose electromagnetic system for Reservoir Monitoring & Geothermal Exploration

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Fit-for-Purpose Array Electromagnetic Methods for Geothermal Applications

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Magnetotelluric [MT] method, Transient electromagnetic [EM] method, controlled source electromagnetic [CSEM], audio-magnetotelluric [AMT] method, geothermal application, reservoir monitoring, 3D interpretation, microseismic

ABSTRACT

We present a completely new generation of electromagnetic hardware that can be used for land, marine and borehole applications. The system uses architecture like a seismic nodal system and for the first time combines electromagnetic and microseismic data recording in a single box. The modular architecture allows a fit-for-purpose configuration, not limited by number of channels or components to-be-recorded. Depending upon the user requirements we define four different configurations suitable for geothermal applications: Advanced MT, Broadband MT, *Mini MT* with AMT, and MT with TDEM. – System characterization and testing as well as a geothermal field example are also shown.

1. Introduction

Over the past 30 years electromagnetic methods, especially magnetotellurics, have become the tool of choice in geothermal exploration. 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 10 Hz to 20 kHz) are routinely used. While the methodology and technology has stabilized, they are applied with little innovation regarding operational and interpretational workflow and cost optimization, Strack (2014).

By combining a broader range of sensors and state-of-the-art electronics, we can derive 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.

2. System Parameters

Paramount for a successful field application is that the hardware is operated at a low cost and runs efficiently. 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 decade, 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. The modular architecture allows for a fit-for-purpose configuration, not limited by number of channels or components to-be-recorded. Figure 1 shows a picture of the system. Depending upon the user requirements we can define four different configurations that can be 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).

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

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

2.1 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.

2.2 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).

2.3 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 you 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 lower 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.

2.4 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.

3. Processing and Interpretation

For a successful interpretation the workflow should always consider the 3D geometry given by the Earth. Hence, our software workflow, shown in Figure 2, 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. In doing so we use less hardware and less interpretational effort.

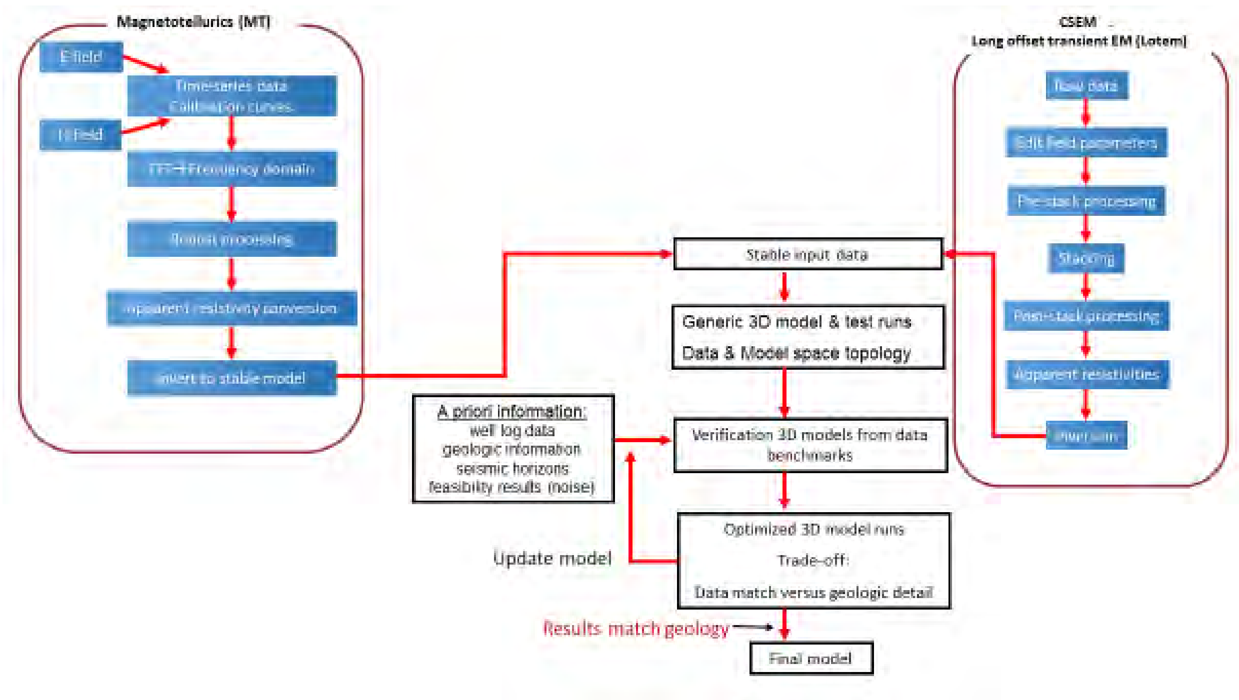

Figure 2: A schematic diagram of various processing workflows including processing and interpretation to final 3D model.

4. Applications

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

4.1 Establishing monitoring system characteristics

In order 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 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.

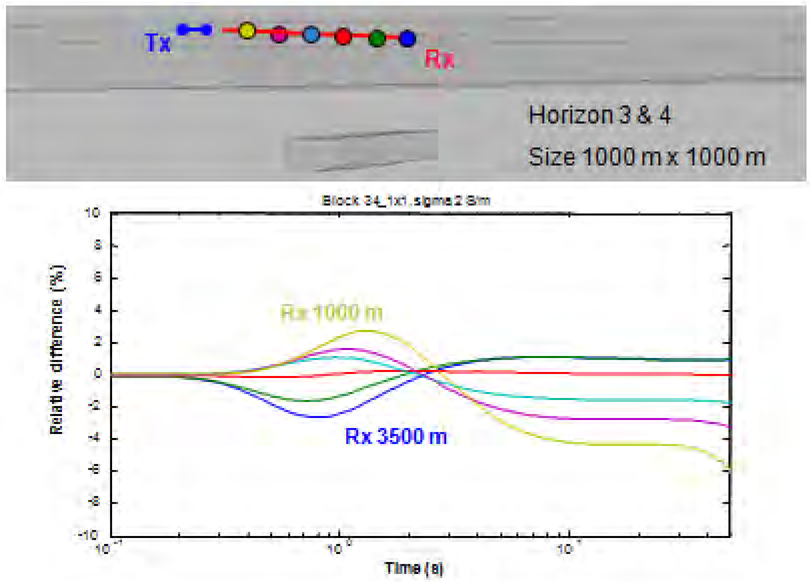

Figure 3: **Example for a 3D reservoir modeling Feasibility. The model combines three-dimensional seismic horizons and state-of-the-art 3D electromagnetic forward models. The surface transmitter is a dipole and the receiver offset is varied from 1,000 m to 3,500 m with it layout with respect to the model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

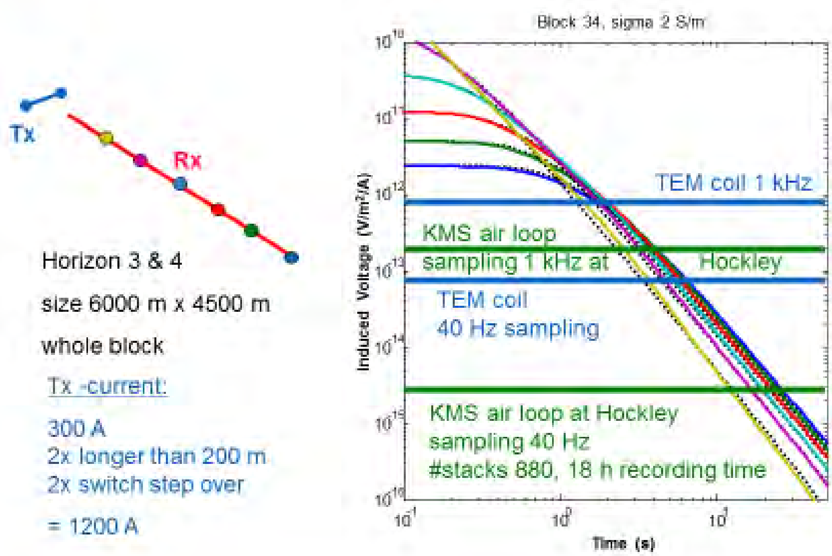

Figure 4: Transient signal for target reservoir parameter variations with sensor noise levels superimposed.

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.

4.2 Example of geothermal exploration

In this example we show an application for geothermal exploration using the array system. In recent years, the magnetotelluric method has proven to be a successful exploration tool in Northern Thailand's geothermal systems, Amatyakul (2015). A most recent example is found in Amatyakul et al. (2016).

The 3D MT survey over the Fang geothermal system (FGS) is the most recent exploration effort in the area which has been probed for geothermal use since 1977. The FGS is a low temperature system powered by a deep, hot igneous body (< 500^{o} C) which heats deep, trapped groundwater. The hot fluid rises up along fractures and weathered rock associated with fault zones, mixing with colder groundwater to reach an equilibrium at temperatures up to 160^{o} C. At shallow depth the fluid is also trapped along fractures and weathered rocks to form low-temperature systems (< 100^{o} C) Feasibility studies frequently suggest the use of EM methods to define the narrow fracture and weathered zones within the granite rocks, Singharajwarapan et al. (2012). The objective is to map the batholith heat source as high resistivity body and the weathered rocks and fluid-filled sediments at moderate resistivities. Hot fluids along fractures might image as conductive zones.

The survey covered a 6 km by 8 km area. 33 MT stations were deployed with a typical spacing of 500 m, mostly over sedimentary basin with only a few on granite, limestone or sandstone due to site accessibility. Four sets of KMS-820 MT equipment that record electric fields (Ex and Ey) and magnetic fields (Hx, Hy, and Hz) were deployed for 20 hours to acquire broadband data up to 1,000 s. A remote reference at 600 km South was used to improve data quality applying the multiple-station technique, Egbert (1997). In order to also acquire high-frequency magnetic field data (> 1 kHz) the broadband magnetic coils were replaced by high-frequency coils for some 30 minutes recording time. Processing and self-imposed quality criteria, e.g., noise, reduced the data (impedance tensor and vertical magnetic transfer function) to a usable period from 3 kHz to 300 s for each site. The 3D inversion (Siripunvarapron and Egbert, 2009) used 16 periods per site at regular intervals on a $\log_{10}$ scale.

A cross-sectional view of the final inverted resistivity model perpendicular to the fault zone is shown in Figure 5. Four main structures are interpreted: 1) a high resistivity (> 300 Ohmm) structure labeled R, a moderate resistivity structure (30-300 Ohmm) labeled M, 3) a transition zone between 1 and 2 stretching from shallow depth to great depth, likely associated with the presence of the major and minor faults in the area, and 4) two conductive anomalies (labeled C1 and C2 where the resistivity is less than 30 Ohmm). Both anomalies also carry evidence of hot fluids found in the area.

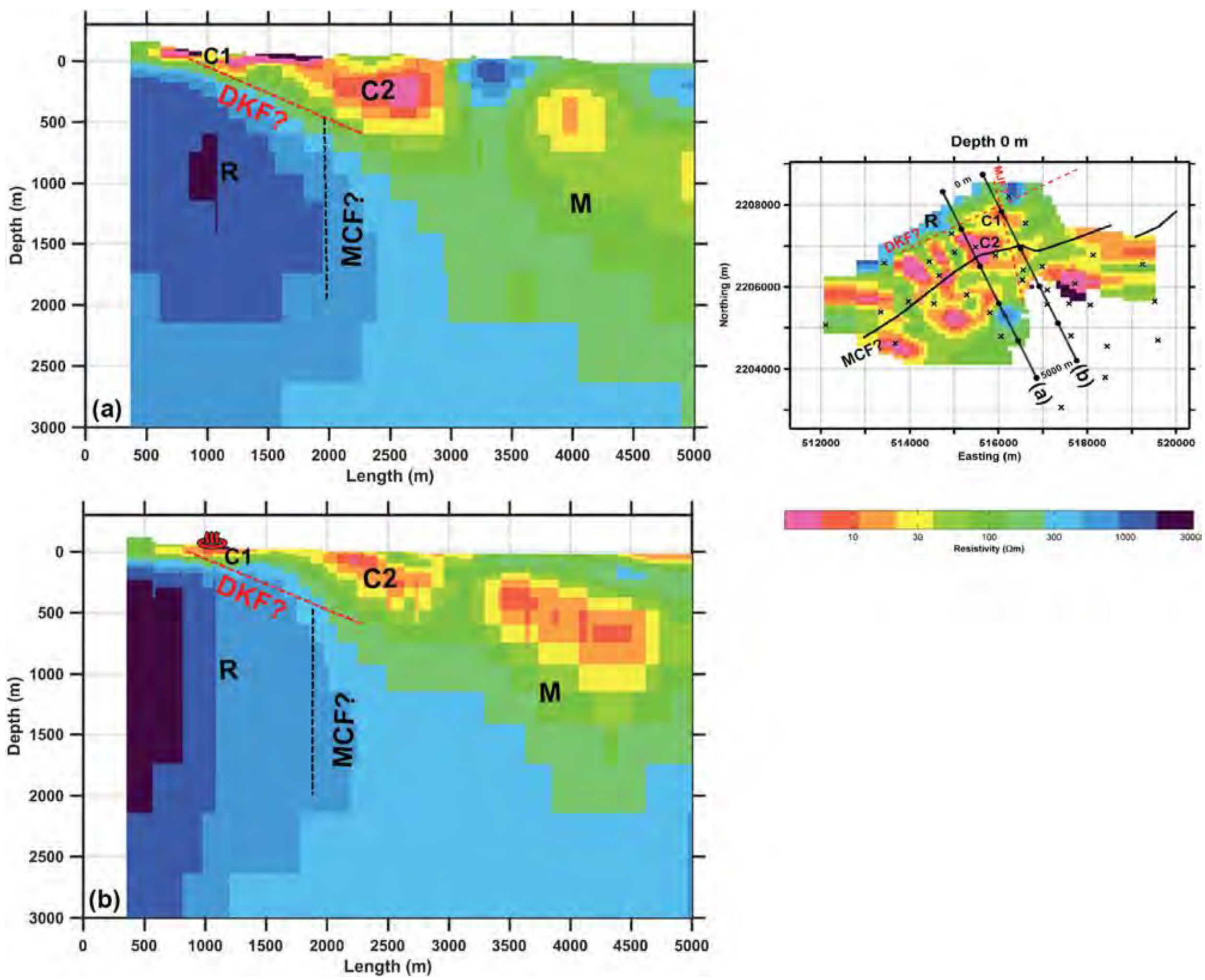

Figure 5: (a) and (b) are cross-sectional plots of the final inverted model from northwest to southeast perpendicular to the Mae Chan Fault (MCF) and the Doi Kia Fault (DKF). The red dashed lines are the estimated orientation of the DKF. The black dashed line shows the orientation of the MCF, Amatyakul et al. (2016)

This model is consistent with local surface geology: R represents crystalline granite rock, M corresponds to topmost few kilometers of the Fang sedimentary basin, the transition zone matches known fault locations, and C1 pinpoints the position of the Fang hot spring. The C2 conductor has not previously been discovered and presents an important target for future drilling and commercial expansion of the geothermal system.

Once a 3D model has been derived the results must be integrated with other geologic and geophysical information. This integration yields a reliable exploration target. An example can 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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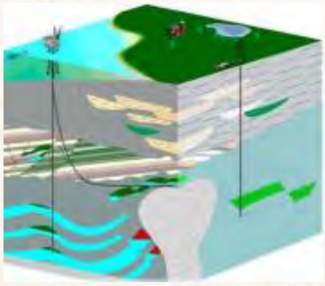

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