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Cloud-Based Array Electromagnetics Contributing to Zero Carbon Footprint

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Abstract

Fluid imaging technologies are used in a wide range of E&P applications. Among geophysical methods, electromagnetics (EM) determines subsurface resistivities and thus respond to fluid changes. On the path to zero CO_2 footprint, the biggest potential for EM lies in monitoring geothermal, carbon capture utilization and storage (CCUS), and enhanced oil recovery (EOR) of hydrocarbon reservoirs. For EOR of hydrocarbon reservoirs, EM methods also increase the recovery factor. At the same time, usage of CO_2 for flooding can help reaching zero carbon footprint faster.

In geothermal applications EM is a standard geophysical method. Monitoring is often carried out in compliance with induced seismicity monitoring to better understand the fluid movement inside the reservoir – here we suggest adding EM. For carbon capture applications, only recently EM methods have become of interest because there is a strong resistivity contrast between CO_2 saturated fluid and normal reservoir fluids.

We designed a new EM acquisition architecture that combines novel technologies and addresses the need of calibrating surface and borehole data with each other. This is necessary to obtain reservoir scale parameters. We also add various borehole receivers to the system to improve image focus and resolution. Our array acquisition system applies multiple electromagnetic methods as well as microseismic in ONE layout. This reduces operational cost and provides synergy between the methods. In a production scenario, using multi-component EM allows resolving oil and water-bearing zones equally well, as well as obtaining fluid flow directions. The modular architecture allows a fit-for-purpose configuration tailored to specific exploration/monitoring targets (in terms of depth, frequency range, and sensitivity required). The entire system combines hardware with processing and 3D modeling/inversion software, streamlining the workflow for the different methods.

Acquiring and interpreting in combination with artificial intelligence and Cloud-based data transmission and quality assurance achieves near real-time operations. The biggest value is in faster operations and making decisions at a time when they can impact acquisition data quality. We use a multi-layered Cloud solution, for acquisition, processing, and interpretation. This acceleration then opens new doors for the breakthrough of this technology from exploration to production and monitoring. It also allows the application envelope to be enlarged to much noisier environments where real time feedback allows for better noise compensation methods.

Once all components are commercialized, this could become a real game changer by providing near real-time 3-dimensional subsurface images because of a reduction of operational cost and by reducing the carbon footprint per barrel produced.

Introduction

During the energy transition, geophysics needs to focus on new applications. One key application is the imaging of reservoir fluids of geothermal reservoirs, CO_2 injection in old reservoir and adequate storage formations, and reducing the carbon footprint of existing hydrocarbon producing fields. In all cases proper imaging of the fluid changes results in a reduction of operating expense and allows to avoid safety/environmental issues with the reservoirs (like a reservoir seal breach).

For geothermal reservoirs, better operating efficiency is obtained when we image the temperature variation in the producing zones and optimize production. At the same time monitoring induced seismicity related to a possible reservoir seal failure is important.

While we transition to renewable energy sources, we also must address carbon reduction by either lower carbon footprint (of existing oil production) or by reinjection of CO_2 in the reservoir. Combining these two is called enhanced oil recovery (EOR +), where we now use CO_2 to drive the enhanced oil production and thus increase the recovery factor.

Thermal EOR is one of the secondary recovery methods that produces the largest environmental impact. In fact, the production of one barrel of heavy oil releases to the atmosphere about 10 kg of carbon dioxide equivalent per barrel (CO_2e/bbl) (assuming the boiling of 3.5 bbls of water for each bbl produced). Optimizing the steam oil ratio (SOR) needed for thermal EOR by 1% using CSEM (typically improvements are much larger), it is possible to reduce emissions up to 300 tons of CO_2e/day (for a global production of 3 MM bbl/day).

Fluid variations in reservoirs are best imaged with electrical methods. In our case, we are proposing to use a combination of surface and borehole electrical (electromagnetic EM) methods. The importance of using geophysical methods to image the fluids is described by Passalacqua and Strack (2020) and shows that electromagnetics (EM) has an important contribution to make during the energy transition and how it can reduce the carbon footprint in heavy oil production scenarios.

Methodology

Mapping fluid dynamics is best done with EM since different fluids have different water concentrations. In saline water, the free electrons are responsible for strong electron flow and low resistivties. In the geothermal case, temperature variations drive fluid mobility and electron flow. When a geothermal reservoir cools, its mobility lowers and resistivity increases (Yu et al., 2009). For the CO_2 storage monitoring case, CO_2 in solution causes larger molecules to form (Boerner et al., 2015) that obstruct the electron flow resulting in higher resistivities for dissolved CO_2. For Enhanced Oil Recovery (EOR), mobility of the oil results in increased electron flow and reduced resistivity (Passalacqua et al., 2018).

We selected the Controlled Source EM method (in time domain) as our method of choice due to its high coupling to the resistivity of the subsurface (Strack, 1992, 2014). To improve the signal-to-noise ratio and the response from the subsurface we inject an electromagnetic signal as shown in Figure 1. This signal diffuses downward and outward with increasing time. In the figure, the injected current flows perpendicular to the contour lines (of equal charge density), causing secondary electromagnetic fields to be measured at the surface at various receiver locations by multi-component receivers measuring both magnetic and electric fields. Measuring the microseismic signal at the same time is optional. From the receiver the data is sent directly into the Cloud for real-time quality assurance and further processing.

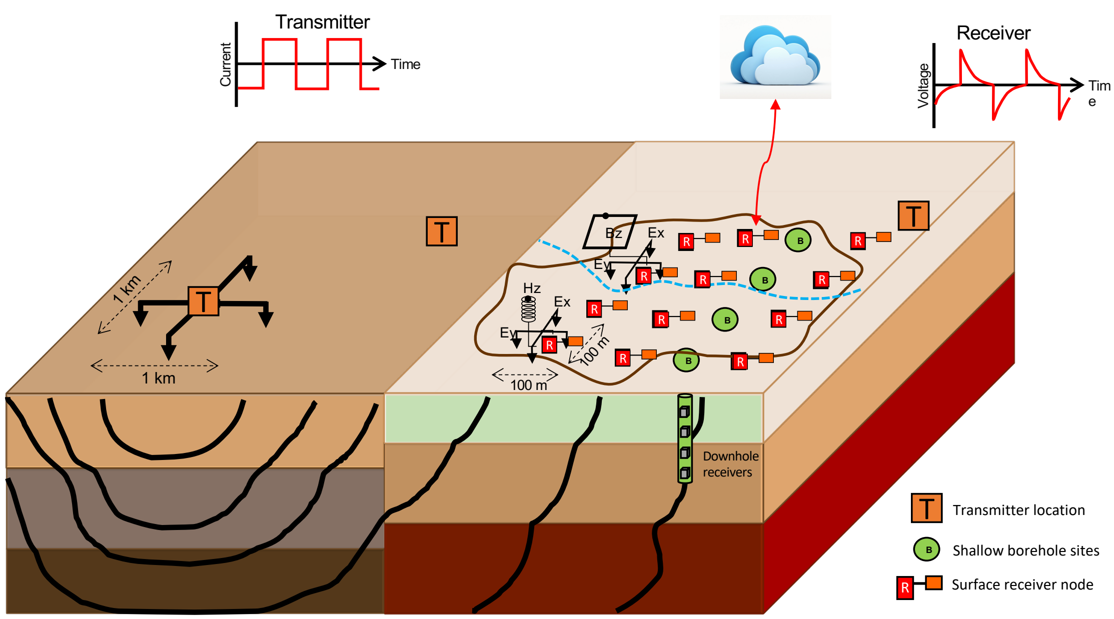

Figure 1: Controlled Source EM survey layout showing transmitter, receivers, and shallow borehole sensors. Each sensor can have muli-components in electric and magnetic fields as well as 3-component seismic sensors. The contour lines represent lines of equal current densities for progressing time.

There are two geothermal applications for the same technology: The first is during the exploration phase in finding the geothermal reservoir and the second is the monitoring of the geothermal reservoir and its temperature variations during production. Figure 2 shows an interpretation example from an electromagnetic survey (magnetotellurics) with the purpose of finding hydrothermal targets in a sedimentary basin in Hungary (Yu et al., 2009). The exploration workflow started with the analysis of existing seismic data and geology and subsequent magnetotelluric and gravity measurements. These were then interpreted independently and then integrated as 2-dimensional sections to produce consistent models. The result is shown in Figure 2. The top section shows the anomalous target zone in the center where we have a zone of low resistivity and low density. Low density means higher water content (porosity) and low resistivity means warmer saline fluids. With this, the geologic interpretation of the seismic data was reinterpreted and zones where fracture zones could be seen in the seismic data that were at the same location became a target of higher priority. The interpreted model was based on 3-dimensional modeling to ensure data-to-model consistency. This loop was reiterated several times already during the drilling process to get the best prediction. The well drilled subsequently yielded 4 MW geothermal power.

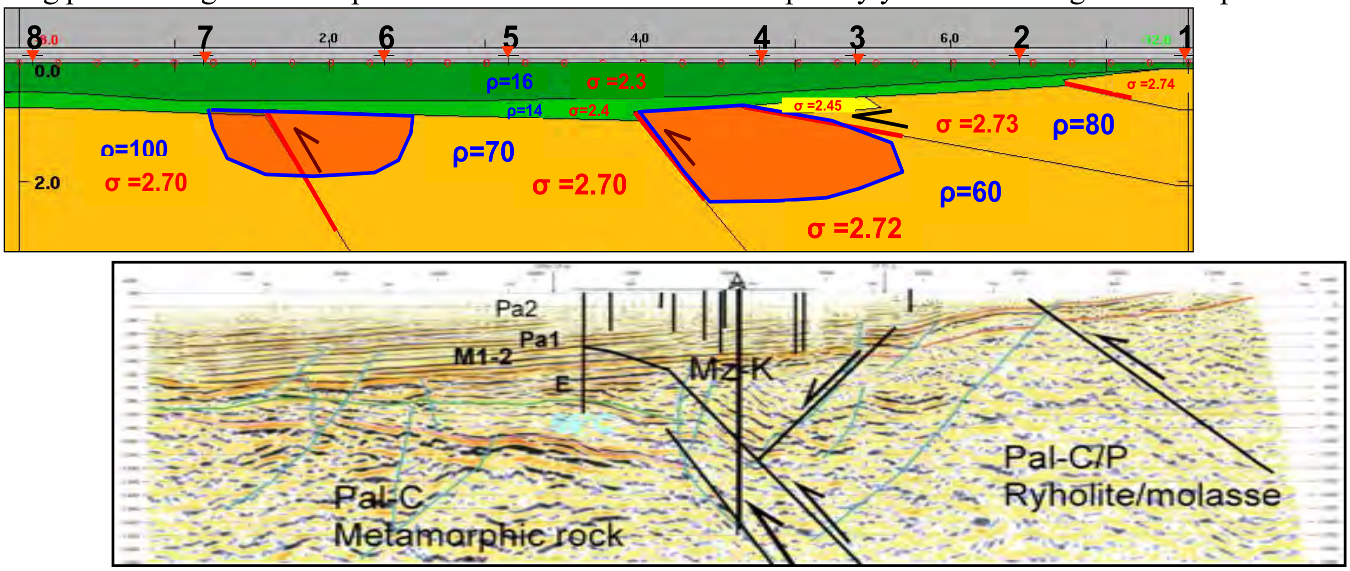

Figure 2: Example of a mulit-physics interpretation of electromagnetics to geothermal applications. The top section shows the gravity and electromagnetics (magnetotelluric) interpreted model where low rock density and low resistivity coincide in the anomaly in the center. The bottom shows further integration results with the reflection seismic and the drill location in the center that produces in the first days already 4 MW geothermal power (modified after Yu et al., 2009).

Monitoring of injected CO_2 is becoming more and more important to reduce CO_2 but also to obtain carbon credits. After the CO_2 is captured, it gets directly injected into the reservoirs and over time combines with the in-situ fluids (mostly water/brine). In that combination, the larger resulting clusters block electron flow and the fluid resitivity increases by a factor of 5 to 40 (Boerner et al., 2015). Figure 3 shows a model section where the reservoir is at 1-5 km depth and CO_2 is injected in several reservoir layers with adequate porosity and fluid content. Before injection, baseline measurements are being carried out that are subsequenty used for reference. Repeat measurements are then carried out every few years. The CO_2 spreads from the injection points into the formation at a rate of 100 to 200 m per annum. On the right side are the response curves for CSEM measurements at these different points in time. Here, we have the induced voltage in magnetic field sensor. We can see that the signal decays faster with time which means the fluid is more resistive – compared to the baseline measurements. An example of such CO_2 monitoring survey is given by Barajas-Olalde et al. (2021).

When we apply this technology to EOR, we have also two application options: First, direct EOR where we use fluid imaging to increase the recovery factor by 20-50% (based modeling using 3D anisotropic reservoir models). This reduces the carbon footprint per barrel produced. Second, the use of CO_2 as the driving fluid instead of steam or water. This method is called EOR + and yields the additional benefits of removing CO_2 from the athomsphere. Figure 4 illustrates such a scenario using a real field example for a water driven EOR pilot. The reservoir is at approximately 2 km depth and the resistivity models results from the petrophysical analysis of the resistivity logs. The water flood is shown in blue in the figure. On the right are two measured response curves, taken several days apart: One before and one after water injection. Below on the right is anomaly displayed as a percentage change, showing a water flood effect of an approximately 30% change in resistivity.

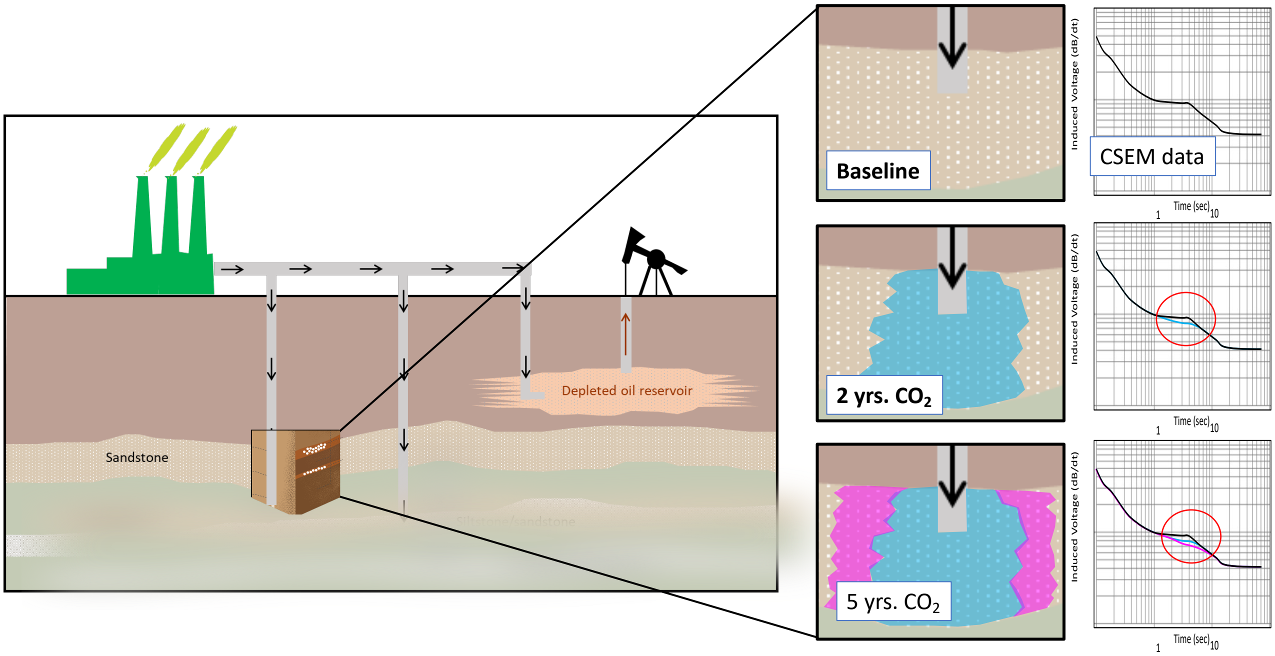

Figure 3: CO_2 Earth model, reservoir model, and CSEM data response curve for different time steps after injecting CO_2 into the reservoir.

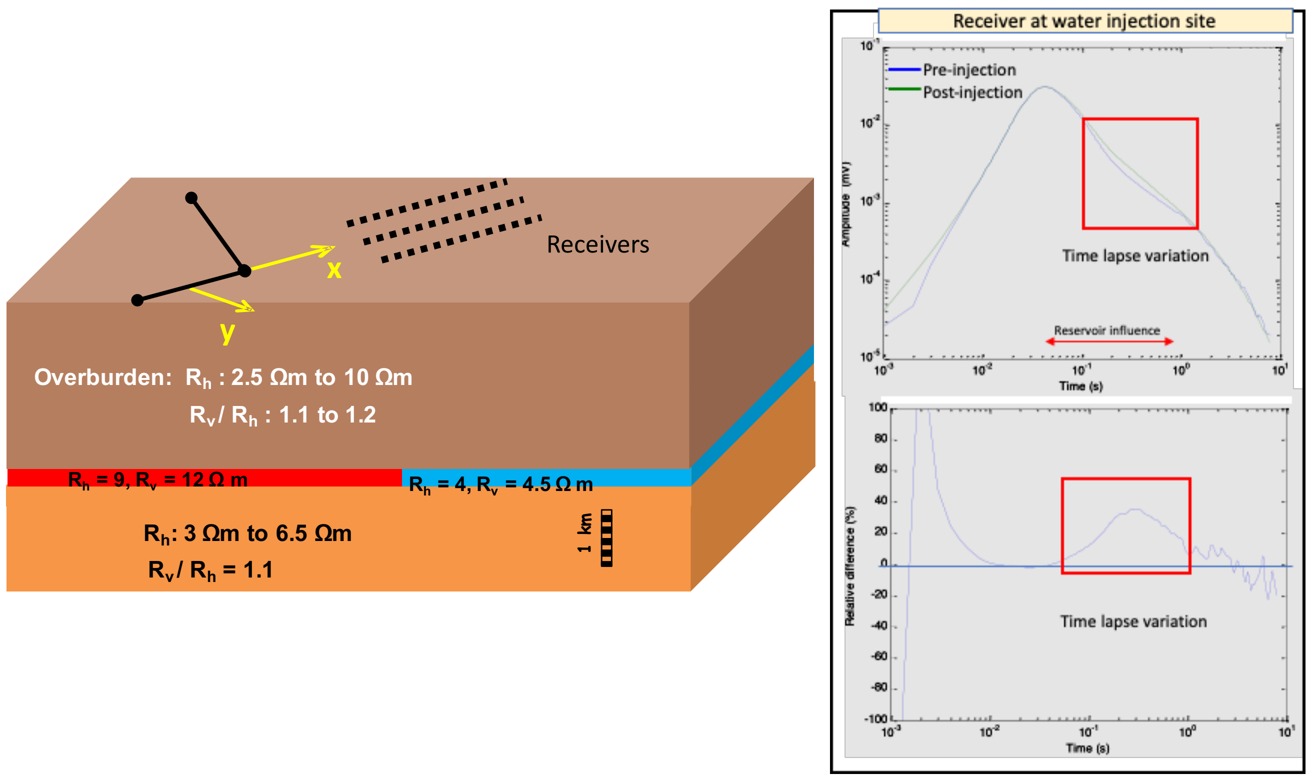

Figure 4: EOR model with anisotropic resistivities and real data CSEM time lapse data response (3 days of water-flooding).

Cloud implementation

The technical progress in technology which makes the application of geophysical fluid imaging possible is Cloud-enabled data transmission and Artificial Intelligence (AI) and Machine Learning (ML). This allows us to provide operational decisions in near-real time to reduce operational cost/time and move the use of this technology from R&D to a point where it can provide operational decisions. Figure 5 shows the workflow and tasks for geophysical reservoir monitoring. Shown are the time estimates for each step and the most time-consuming technical task are written in bold. During a recent CO_2 monitoring survey, we could already provide 'Quality Assurance via the Cloud' before the receivers were moved to a new location. This reduced repeat site occupation by 90% and survey time by 20%. The 1-dimensional inversion of the MT data was delivered in 2 days, the 2-dimensional inversion in 5 days and the 3-dimensional inversion in 2 weeks after acquisition while field operation was still ongoing. These times can be significantly reduced because the 3D modeling steps are still time consuming and with more use of AI/ML this will be going toward near-real time.

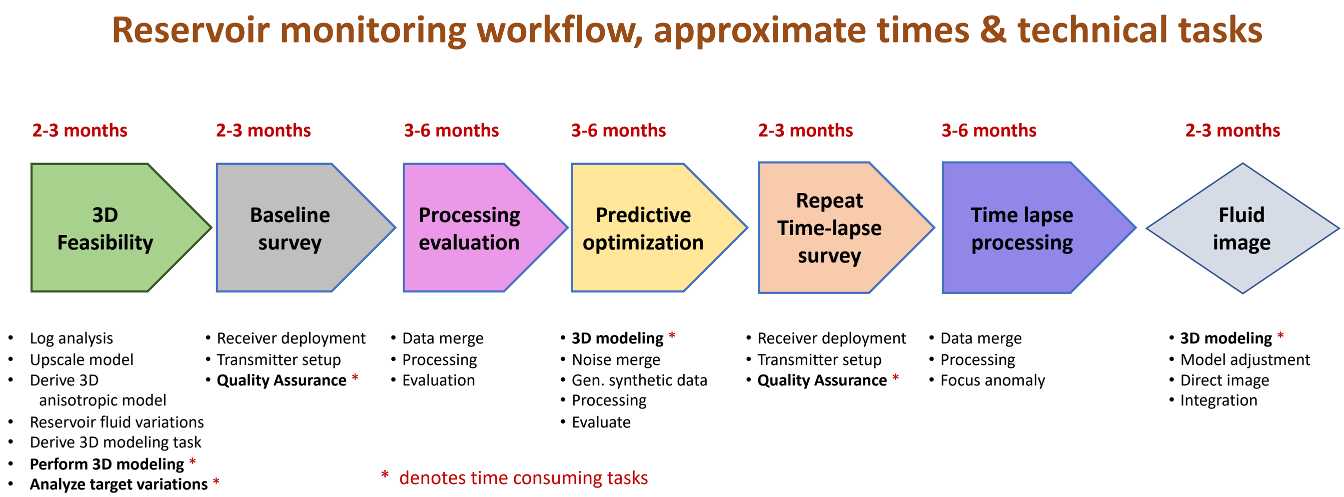

Figure 5: Tasks and workflow for a monitoring project. The tasks are covering the CSEM efforts and the time consuming (costly) tasks are bolded (after Strack et al., 2021)

A key element in applying this is the verification of the results. We usually carry out a 3-dimensional feasibility pre-survey which gets coupled with in-field noise measurements to design the best possible 3-dimensional a priori model that is consistent with the petrophysics of the existing well logs. This model is used during the survey to estimate if the results are within the range of expectations. Figure 6 shows an example of applying this together with Cloud-based data delivery/Quality assurance. The scientist feeding this process were located at 4 locations (in 4 time zones) on 2 continents. In the figure, we have a magnetotelluric (MT) data set on the left that was delivered via the Cloud in the evening (US time) and processed in Europe and returned back to the field crew in the morning before the next crew change. On the left we see the standard MT data displayed as apparent resistivity and phase and on its right the inversion model is compared with the verified borehole model. While the model match is already good, there is still a data mismatch in the frequency domain as noted in the figure. We then used two remote reference sites (one was 300 km and the other 3500 km away). We used standard remote reference processing and obtained the results shown on the right of the Figure 6. Note that the data match between inverted response and data is now much better since the local noise was significantly reduced. Also, the borehole verification model is better matched by the inversion results. Having this type of information available in the field significantly increases the confidence in the ongoing acquisition and the related quality assurance process.

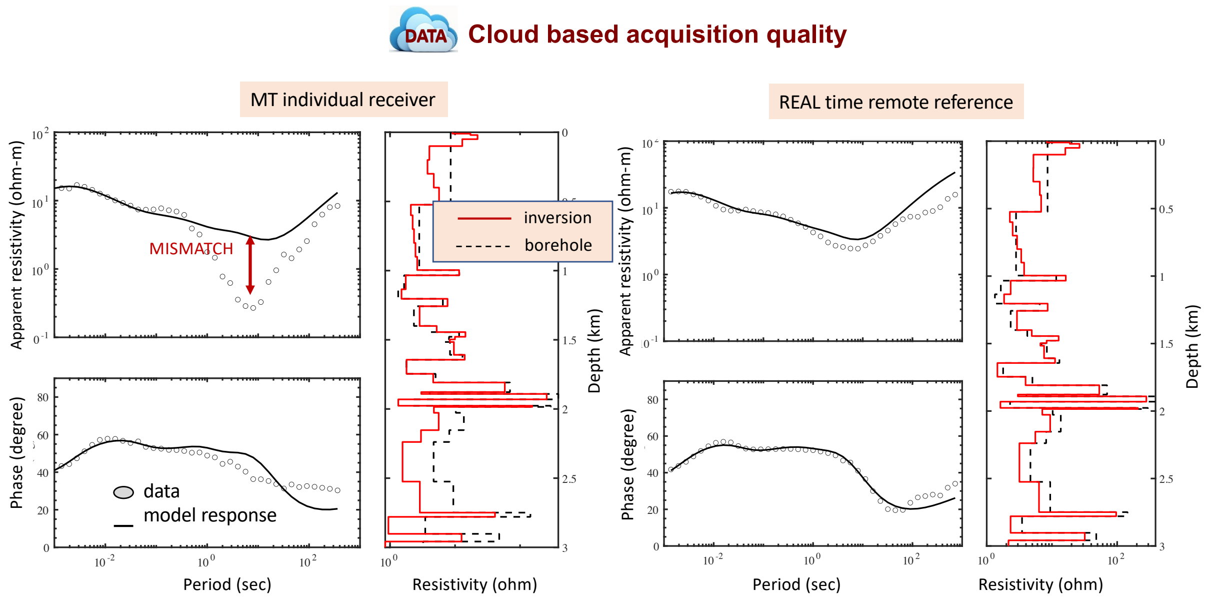

Figure 6: Example EM data set using Cloud-enabled data exchange. On the left is an EM (magnetotelluric) data set using only the data available at the recording site. On the right are the results of the same data but using remote reference receivers (a few hundred km away) to reduce the noise. Note that the mismatch in the apparent resistivity curve is greatly reduced. To the right of the data plots are also the inversion models compared with the actual log data. The match with Cloud-based remote reference processing is greatly improved (after Strack et al., 2021).

Benefits & conclusions

The here presented Cloud-based technology provides better quality data at a lower price alreadyduring operations. This reduces operating time and cost, helps avoid the need for repeats, and gives more confidence in the data. The specific value for each of the three applications is different:

- For the geothermal applications electromagnetic fluid imaging allows us to image during the exploration phase in an environmentally friendly way the geothermal zone (here hydrothermal). Once a geothermal reservoir is being produced, we can map the temperature variation resulting from production and thus optimize production. This allows us to control the geothermal producing zone and produce more efficiently and at higher output. Further, with geothermal reservoirs induced seismicity is often an issue and together with microseismic monitoring, EM will allow for a swift response to potential seal or rock breakages.
- For CO_2 storage monitoring, we can map the movement of the fluid that is injected and stored in the reservoir. We can verify the seal integrity during the injection process, with added improvements when combining with microseismics. Injected CO_2 is rapidly serving as carbon offset credit and has the potential to significantly drive the economics of the energy transition.
- For EOR applications, an energy-efficent improvement of the recovery factor (typically 20-40%) and hence reduction of carbon footprint per barrel produced is one benefit of the here proposed monitoring and interpretation system. The use CO_2 as HC fluid displacement driver of course provides an economic benefit beyond that related to its carbon credits. For shallow reservoirs, reservoir seal failure is always a concern and as above this should be monitored with EM and microseismic in combination.

Over the last 20 years we have assembled the here summarized complete reservoir monitoring technology workflow. The journey starting with exploring fundmental concepts, continued via fine tuning the methodology and designing and building the necessary hardware. It concluded with developing interpretation software and skills. We have applied this technology successfully in the USA, Asia and the Middle East. Within the context of transitioning to renewable energy our approach not only supports the development of more sustainable energy supplies but also allows existing HC production to approach a much lower carbon footprint faster and at lower cost.

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