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Future Directions of Electromagnetic Methods for Hydrocarbon Applications

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Abstract For hydrocarbon applications, seismic exploration is the workhorse of the industry. Only in the borehole, electromagnetic (EM) methods play a dominant role, as they are mostly used to determine oil reserves and to distinguish water from oil-bearing zones. Throughout the past 60 years, we had several periods with an increased interest in EM. This increased with the success of the marine EM industry and now electromagnetics in general is considered for many new applications. The classic electromagnetic methods are borehole, onshore and offshore, and airborne EM methods. Airborne is covered elsewhere (see Smith, this issue). Marine EM material is readily available from the service company Web sites, and here I will only mention some future technical directions that are visible. The marine EM success is being carried back to the onshore market, fueled by geothermal and unconventional hydrocarbon applications. Oil companies are listening to pro-EM arguments, but still are hesitant to go through the learning exercises as early adopters. In particular, the huge business drivers of shale hydrocarbons and reservoir monitoring will bring markets many times bigger than the entire marine EM market. Additional applications include support for seismic operations, sub-salt, and sub-basalt, all areas where seismic exploration is costly and inefficient. Integration with EM will allow novel seismic methods to be applied. In the borehole, anisotropy measurements, now possible, form the missing link between surface measurements and ground truth. Three-dimensional (3D) induction measurements are readily available from several logging contractors. The trend to logging-while-drilling measurements will continue with many more EM technologies, and the effort of controlling the drill bit while drilling including look-ahead-and-around the drill bit is going on. Overall, the market for electromagnetics is increasing, and a demand for EM capable professionals will continue. The emphasis will be more on application and data integration (bottom-line value increase) and less on EM technology and modeling exercises.

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1 Introduction

Electrical methods in applied geophysics started along with the other geophysical methods in the early 1900s with Wenner (1912), Schlumberger in 1922 (Gruner Schlumberger 1982) and early patents by Schilowsky (German patent 322040 assigned 1913), and Blau (US patent 1911137 assigned 1933 to Standard Oil Development Corp.). Countless patents have been filed since then, and the interest in electromagnetics has been growing steadily except for onshore applications, where the interest was cyclical and a new cycle is just starting. Hydrocarbon applications are always driven by commercial interests and competitiveness and are thus cyclical. Understanding the market values and where values drive the markets is almost as important as understanding the technical benefits of the individual methods, because in many instances the market drives the technical priorities.

There are four principal areas for electromagnetics for hydrocarbon applications: borehole, offshore, onshore and airborne. Airborne applications are covered by a separate review paper (see Smith, this issue). For hydrocarbon exploration, airborne EM is limited because of the depth of penetration although the depth has been extended to several hundred meters in the past few years. A future market is its use for seismic static corrections. During the 1990s, a revival in borehole electrical methods could be seen, and while these technologies are now mature in the market place, derivatives for logging-while-drilling applications are presently being developed. After 2000, there was a general increase in marine electrical methods (Eidesmo et al. 2002) and after that technical bubble burst. The market is now stable with a slowly growing trend. This is witnessed by stable profitable business of the single dominant remaining market participant and only much smaller acquisition participants and several interpretation shops. There has been little change in land applications until recently, when interest increased. We now have at least 5 global service providers (Europe, Russia, China, and North America) that can handle small to large land acquisition surveys. This is mostly driven by the marine success and establishing slowly the value of EM to address problems to seismic acquisition. This is witnessed by the fact that three of the large EM land contractors are part of largest global seismic service companies. New opportunities like monitoring and applications to shale reserves are on the horizon (Kumar and Hoversten 2012; Strack and Aziz 2012).

Following in part from the tremendous progress in seismic methods, we have a great deal of new technology (electronics, computing and workflow) at our fingertips. It thus is reasonable to first understand the markets, starting with the most developed one:

- Borehole applications including all logging methods (wireline, logging-while-drilling, production logging, cross-well). This is the most important market area for electromagnetics (EM) as electrical logging tools are run in almost every well. The global annual market is 1–2 billion US $ in services alone. In addition, there is a 50–100 million $ hardware market.
- Marine applications are more recent and present a stable industry that has demonstrated its value to oil company customers. That global market in 2012 is approximately 200 million US $.
- Airborne applications to hydrocarbon exploration are limited to 10–20 million US $ annually because of the limited application scope (see Smith, R, review paper this issue).

- Land applications, albeit growing, are only reaching approximately 50 million US $ in 2012 (excluding China and Russia).

The EM-related logging market is the only area that has continuously been growing in market size and also in technology. This is related to improved technology (hardware and software) that allows us to get more signal from the noise and thus higher reliable resistor values (related to smaller signal) and directly in correlation is ‘More Oil’. Specifically, operational decisions and reserve estimates are driving the use of EM. It thus makes sense to define these technology development phases as baseline and gauge the other areas accordingly.

Clear phases in borehole applications can be distinguished (Luthi 2001).

1921–1927 Conceptual phase
1927–1949 Acceptance phase
1949–1985 Maturity phase
1985–now Reinvention phase… maybe we are at its end

During the conceptual phase, the technology was invented and initially tested. Success came only after it was taken to different countries from France and put on a broader basis. During the acceptance phase, most electrical logging tools were developed in their basic form and its use refined during the maturity phase. Then came logging-while-drilling, which challenged the leadership of one company. The luster of having developed all logging tools was destroyed by tools being developed under oil company sponsorship. (In fact, many of the wireline tools during the 1980s and 1990s were developed with oil company mentorship.) This is the direct result of the customer learning how to use the technology and wanting his or her own implementations. Parallel to the development of new wireline tools, logging-while-drilling tools were developed, but mostly on the basis of getting a slight competitive advantage. Thus, in the logging-while-drilling market, the dominance of an individual company is limited. Around 2010–2012, there is clearly a shift happening, and it appears that we are entering a new era of acceptance of the technology developed in the past 20 years.

Using this analogy for the marine electromagnetics industry, we can see that *we are almost at the end of the conceptual phase*. Numerous marine technologies have been developed, and only those that were operationally mature survive. Before the end of the conceptual phase, there will be several more seismic integrated systems and the industry will have more than just one contractor. This is because globally we see tenders from oil companies that are requiring exactly what they need, which is not always what the service industry provides or markets. Tenders for shallow water integrated seismic, marine magnetotellurics and even time domain electromagnetics are on the market while the offering is predominantly frequency domain controlled-source electromagnetics. Needless to say, the market will respond to demands and not only to offerings. In open competition, the market always reaches a balance between technical and business aspects.

For onshore electrical methods, we already had two conceptual phases and are now in the start of the third: One in the 1950s and one in the 1980s (during the latter period, most presently used technology was developed). For hydrocarbon applications, only magnetotellurics made it to an acceptance and now into maturity. At the same time driven by the success of the marine EM market and the borehole EM innovations, many novel market players and novel applications are revisiting land technology. Most likely several of them will become successful. Judging from the history in the borehole and marine (also airborne) fields, the winning player will be a newcomer.

Looking at these different phases explains why the reviewers of this subject matter in the recent past (this means mostly for onshore) focused on a small aspect of hydrocarbon applications as they were filling in the gap. The last broader hydrocarbon review was written in a series of papers by Spies and Nekut (Nekut and Spies 1989; Spies 1983; Spies and Frischknecht 1991). Other reviews focus on electrical methods in general and to a small degree on hydrocarbon applications (Nabighian and Macnae 2005; Sheard et al. 2005). Numerous review papers have been offered on marine electromagnetics (Constable and Srnka 2007; Constable 2010). The best source for review is presently the Web sites of the marine contractors, which give links to the scientific papers about the technology they use. Further information can be found in various reviews (i.e., Srnka et al. 2006; Constable and Srnka 2007; Constable 2010).

I will here go through the applications in the above sequence and point out the developments; I derive by considering the direction in which the industry might be heading. I will combine business, history and technical aspects to derive market directions. This path builds on the success of EM in the borehole, which is attributed to the solution of real problems. The success of 3D induction log technology can be directly translated to finding more reserves and not only the measurements delivering more complete images. The same is true for marine Controlled-Source ElectroMagnetics (CSEM). On the other side, Hesthammer has been advocating its use for making drilling decisions (Hesthammer et al. 2010) and recently reported the confirmation of drilling results (Hesthammer et al. 2012) while not being a commercial success. In the context of drilling cost and decision, the use of CSEM, even at low resolution using EM, is justifiable. Only for onshore hydrocarbon applications have we yet to reach that point that has been reached several times already in the conceptual phase.

Here, I caution the reader to take initial drilling success or failure as scientific proof as more than just one method or approach contributes to drilling decisions: Only longer term statistics can be the judge when complex decision trees are involved.

2 The Methods

In the 1980s, the basic borehole methods included induction logs (also known as conductivity tools) and laterologs (also known as galvanic tools or resistivity tools). After the introduction of the array induction tool at the end of the 1980s, numerous alternatives were developed. The innovation spirit spilled over to array laterologs, log inversion, through-casing resistivities and 3D induction. All of these were developed in the 1990 and came on the market through the 1990s and 2000s (Strack et al. 1998). Concurrent with the wireline development, logging-while-drilling tools progressed, and today almost all wireline resistivity measurements are available as logging-while-drilling tools. The advantage of this lies in getting the information from the borehole before a drilling mud invaded zone is built up. The next challenge lies in looking ahead and around the drill bit and placing a borehole correctly in the three-dimensional space.

The borehole tool market has for 60 years been driven by dominance of a single company. Only with the introduction of new technology, namely logging-while-drilling in the 1980s, this situation changed. Intellectual property, in particular patents, protected this position. In fact, the strategy and cultures that exist today in the geoscience industry come from the logging world. Patents are used as business tools and to protect investment more than to enforce a technical point. This means that one may wait for a while before claiming patent infringement just to make sure there is enough financial benefit to be gained.

For illustration of the value of electrical anisotropy and the 3D induction-logging tool, I use an illustration of sand/shale sequences as they occur in many basins and its interpretation. Figure 1 shows at the top images of borehole anisotropy and at the bottom an example of a 3D induction log interpretation. The top images are (from the left) an electron microscope image, 2 core images, and an electrical resistivity plot. All are at different scale from 2.5 mm (electron microscope scale) to 23 m (seismic/reservoir scale) vertical scale. The light colors represent sand content and the dark ones shale content. Clearly, the natural layering and thus transverse isotropic anisotropy are everywhere. This problem was well known (Klein 1993). Baker Atlas developed the first 3D induction-logging tool under mentorship and funding of Shell (Kriegshäuser et al. 2000; Strack et al. 2000). It allows the measurement of horizontal and vertical resistivities in vertical borehole, specifically, and in general, the determination of the tensor resistivity. The motivation lies in a large amount of resistive oil trapped in thin laminations between conductive shales. Standard induction logs only yield horizontal resistivities, which are dominated by the shales (Yu et al. 2002), resulting in significantly underestimated hydrocarbon reserves. Obviously, this tool does not only apply to thin laminations, but also to any dispersed shales and, with the appropriate petrophysical analysis, it yields tensor water/oil saturation. Higher transverse isotropic resistivities (resistivities are the same on horizontal direction and different in vertical direction) result, in most cases, in higher vertical resistivities. If the model and measurements are correct, they are commonly interpreted as higher hydrocarbon saturation or more oil. The average reserve increase of 20 % (and more) justified the development of the 3D-induction-logging tool. In Fig. 1, we have a natural gamma ray log on the left, indicating shale content. To its right is gamma–gamma density and neutron density curves followed by 2D inverted resistivities (vertical, Rv; and horizontal, Rh). Together with the porosity track that follows and the appropriate petrophysical equation, oil saturation is calculated. Note the oil saturation is significantly higher from the vertical resistivities. When we carry out CSEM measurements with a grounded dipole, we measure predominantly the vertical resistivity. This means calibration of surface dipole CSEM measurements can now be done that was previously not possible reliably.

One of the key objectives in placing the wellbore inside the reservoir is to predict ahead of and around the bit. Rabinovich et al. (2011) tried to clarify the scientific aspects and commercial implementation of the first technologies for this application. Present technology can only look a few meters to the side. Zhou et al. (2000) proposed technology that could actually do this. This is a time domain system with short transmitter-to-receiver spacing and multi-components (Strack 2003a, b). The systems were developed through proof-of-concept phase for sideways and look ahead capability to tens of meters, demonstrated by Banning et al. (2007). In order to remove the effect of the drill string, special deconvolution methods needed to be applied (Hanstein et al. 2003). Figure 2 shows an example of simulations for such a time domain system for a horizontal well when water is being coned by production. It can be seen that the signal varies significantly with distance from the wellbore. The curves display the measured voltage from a 3-component receiver system. The arrow in red in the figure symbolizes the large dynamic range required (13 decades in voltage). Test measurements were carried out (not shown here) with a proof-of-concept tool and demonstrated that this can actually be done. Banning et al. (2007) showed some results where sideways and look-ahead capabilities were demonstrated. Since the data are proprietary, it cannot be shown here but what can be said is that the field data confirmed the theoretical predictions and a range of at least 50–100 m is possible from inside the wellbore (Banning et al. 2007).

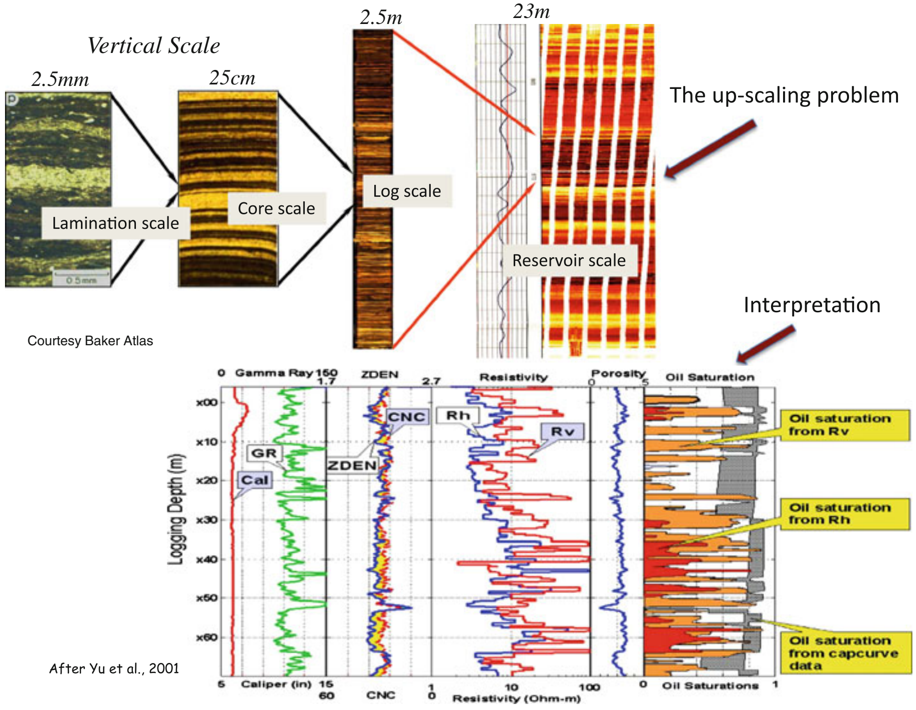


Fig. 1 Images of borehole anisotropy and its interpretation. The *top* shows various core/section images at different scales. Each of them clearly shows the anisotropic layers with the sands in the *light colors* and the shales in the *dark colors* (courtesy Baker Atlas). The *bottom* shows an example of an interpretation of a 3D induction logs interpretation (Yu et al. 2001). The tracks from *left* to *right* show natural gamma ray for shale content, gamma–gamma density and neutron density for gas zone indicators, 2D vertical and horizontal resistivities from inversion, interpreted porosity, and interpreted oil saturation

Marine electromagnetics is the newest and fastest growing application of electrical geophysics. Many review papers have been written recently (Hoversten et al. 2000; Constable and Srnka 2007; Constable 2010; Key 2012). Presently, there is a strong emphasis on CSEM. For the best summary on the present state-of-the-art 3D CSEM acquisition and interpretation technology, refer to Weiss and Constable (2006) or Zerilli et al. (2011). Present state of the art is that acquisition should be mostly done in 3D and large systems (Gabrielsen et al. 2012). In 2D line, acquisition is still common and the oil companies are pushing for more shallow water and transition zone surveys as well as ultra deep water and sub-basalt surveys (thick layers). Among the marine methods are:

- Marine magnetotellurics (MMT) (Constable et al. 1998; Hoversten et al. 1998; Zerilli 1999)
- Controlled source electromagnetics (CSEM) (Constable 2010; Johnstad et al. 2005)
- Time domain CSEM (Allegar et al. 2008; Holten et al. 2009; Strack et al. 2011; Ziolkowski et al. 2011; Jang et al. 2012; Helwig et al. 2013; Garina et al. 2013)
- Focused resistivity marine EM (Davydycheva and Rykhlinski 2009)
- Marine induced polarization (Davidenko et al. 2008; Legeydo et al. 2009)

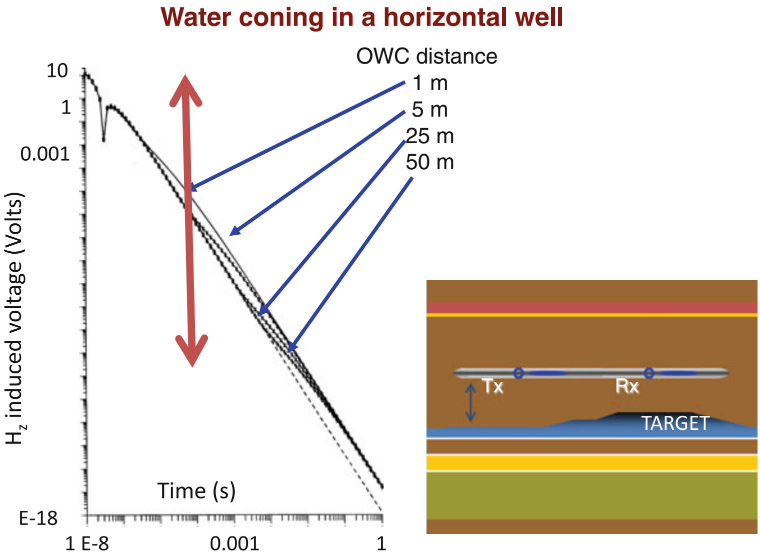


Fig. 2 Synthetic modeling example for a horizontal well and a single well time domain system using a 3-component (3C) transmitter and a 3C receiver. The different curves are for different distances to the water flood (oil–water–contact OWC) front cone depicted on the *right side* on the figure. The target marks the water flood

Because this subject area is well published, I only show examples where still more work is required. Sub-basalt and sub-salt imaging are still important exploration issues. Basalt layers can be *thick* in the marine environment (several km) and make it extremely difficult for controlled source energy to penetrate. Often the targets are also conductive, namely perspective sediments below the basalt, and the exploration target is the thickness of the sediments. Magnetotellurics (MT) is well known to be able to delineate the sediments below the basalt (Beamish and Travassos 1992; Morrison et al. 1996; Virgilio et al. 2009; Heincke et al. 2012). Figure 3 shows an example where MMT was inverted together with gravity and seismic data (Jegen et al. 2009). The seismic data were used as constraint. The top of the figure shows the 2D gravity and 1D MT inversion and the bottom after seismic constraints were integrated into the inversion. The data are from the Faroe Islands. It shows a sedimentary basin below the basalt layer. The body superimposed on the seismic section is the same confined body that can be seen in the resistivity section, and now the depth has been converted to two-way travel time. The next example in Fig. 4 shows the results from a modeling experiment where seismic and EM are combined with the purpose of joint imaging. This type of joint tomographic imaging will be more common in the future (Zerilli and Roslov 2003). Another example is from time domain measurements, in this case fixed array electric field time domain measurements applied to reservoir monitoring (Hu et al. 2008). Figure 5 shows data examples with 5-s-long signals. The data are unprocessed to avoid processing influence in the time-lapse sense (as it was felt that filtering the map would allow better control over geological changes). The data are a 4-month time-lapse from a Chinese oil field with the target being around the 500 m depth range. Here, we look at only repeatability. Later in this paper (Fig. 12), we will discuss the time-lapse results.

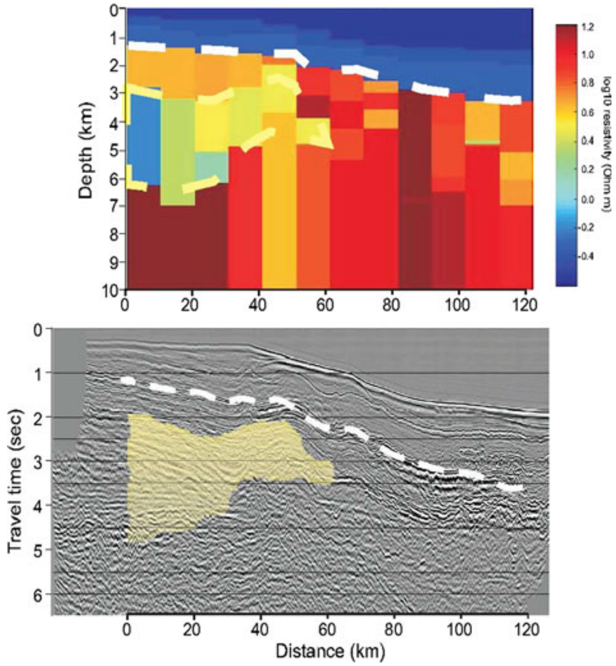


Fig. 3 Example of joint inversion of magnetotelluric, gravity, and seismic data (Jegen et al. 2009). The top diagram shows the joint inversion of gravity and magnetotelluric data and the bottom after seismic data was used to constrain the inversion

For land electromagnetic applications, Keller et al. 1984 summarized land CSEM and Nekut and Spies wrote their review paper (1989) and a more general review in 1991 (Spies and Frischknecht 1991), and the applications of EM included:

1. Sub-basalt exploration (Wilt et al. 1989; Beamish and Travassos 1992)
2. Sub-salt exploration (Hoversten et al. 2000; De Stefano et al. 2011)
3. Messy overburden (Christopherson 1991)
4. Porosity mapping (Strack et al. 1989)
5. Induced polarization applications (Sternberg and Oehler 1984)

More recent papers on sub-basalt exploration were those by Strack and Pandey (2007) and Colombo et al. (2012). Colombo already derived different products from the data, namely adjustments to seismic velocities and thus improved seismic images.

New applications include application of EM to improve seismic statics and various other operational concerns such as shot hole depth optimization (Zerilli 2002 and 2005; Dawoud et al. 2009). In addition to defining optimized shot holes, Zerilli also used high-resolution DC resistivity measurements to constrain the near surface in MT in complex topography. An example is shown in Fig. 6 where the top shows the MT and the bottom the high-resolution DC resistivity. The DC resistivity measurements were used to control the near-surface statics caused by complex terrain on the MT data. In this case, the near-surface correction was used for better shot point location for the seismic acquisition. This is becoming a more common application of EM where the type of methods used is tailored to providing a value-added solution to another costly application.

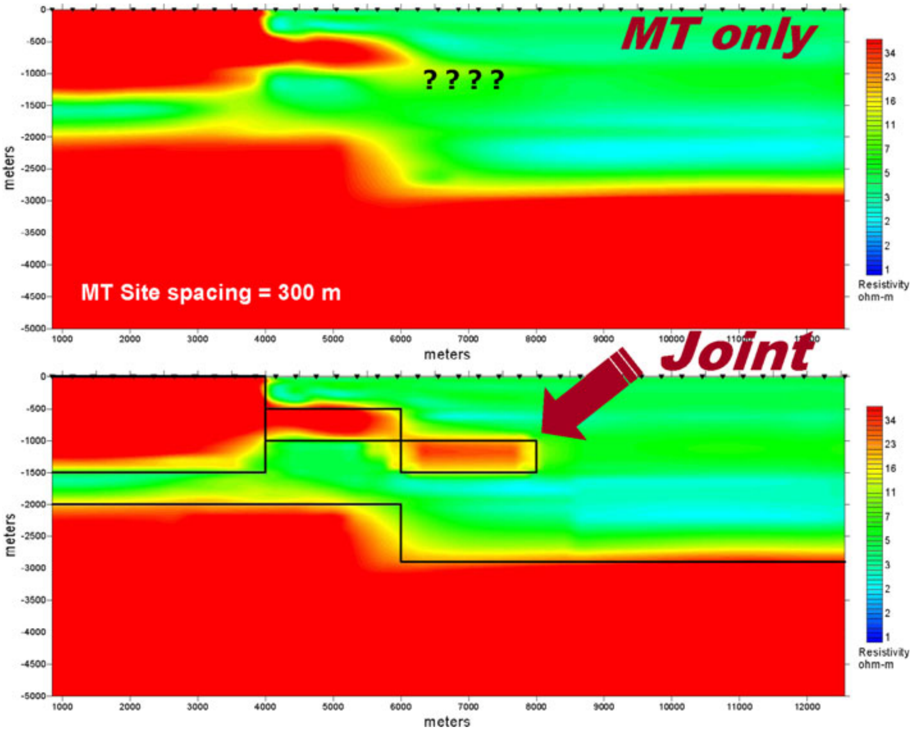
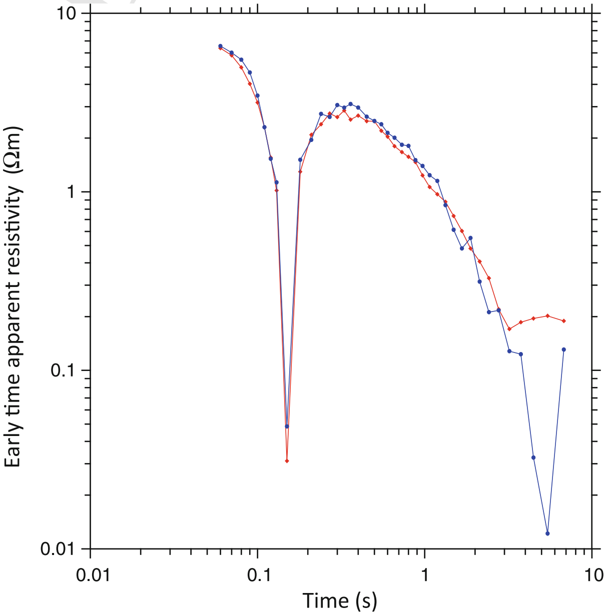


Fig. 4 Example of a joint tomographic inversion of seismic and magnetotelluric data using synthetic models. The top is the magnetotelluric interpretation alone, and the bottom is based on a joint inversion (after Zerilli 2002)

Fig. 5 Data examples from a fixed array electric field time domain survey. The *different curves* represent different survey times, 4 months apart (after Hu et al. 2008)



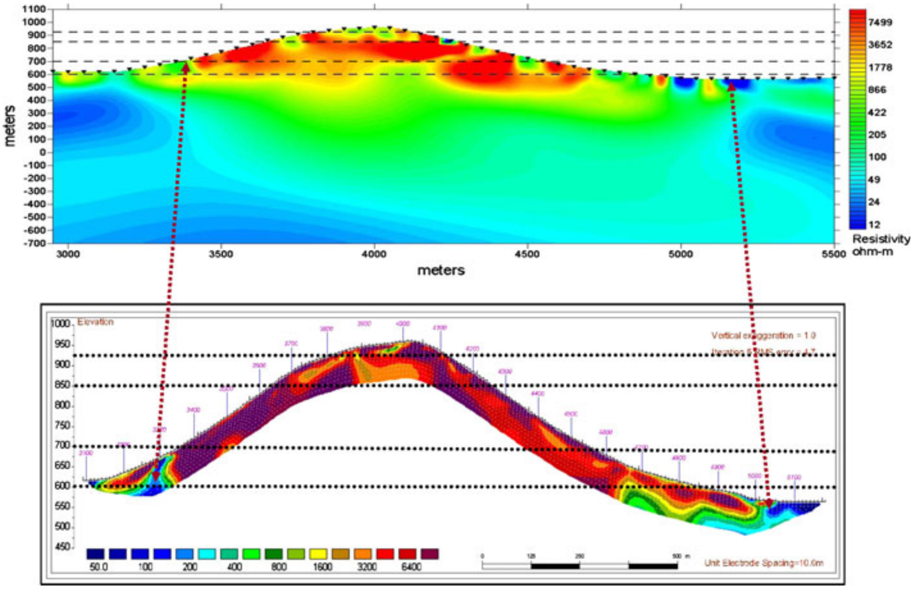


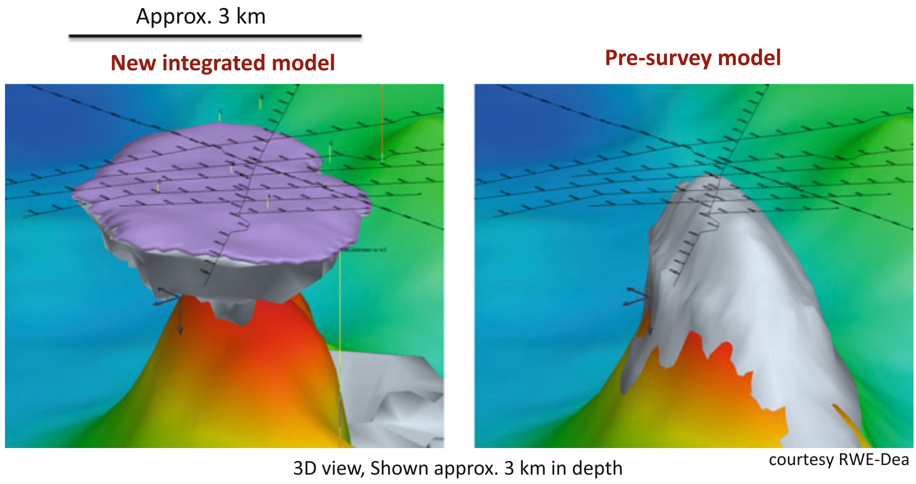
Fig. 6 Examples section of MT and DC resistivity data for complex terrain (Zerilli 2002). The *top* shows the MT section and the bottom the DC resistivity section, which was used to define near-surface variations to place shot points with better coupling to the subsurface

While I selected a sub-basalt example for the marine as future application, sub-salt is an important feature for land as there are many salt provinces, seismic has difficulties, and gravity lacks the resolution. Both sub-salt and sub-basalt are serious problems to seismic imaging onshore and offshore. New systems can handle the noise better and thus there will be renewed interest in sub-salt, in particular in the USA, because of the easier business environment that allows small independents to explore and produce oil quickly. Figure 7 shows a sub-salt interpretation from Northern Germany (Buehnemann et al. 2002), near Bremen where there is strong cultural noise present.

The MT station density was 50 m for the profile that crosses in the center and 100 m otherwise. The data were processed and interpreted, first independently and then integrated with gravity and seismic resulting in the image on the left side of the figure. On the right is the interpretation without the MT data, and clearly the salt overhang is not even visible. The client of this survey drilled subsequently and the entire material including feasibility is under preparation for publication.

3 The Drivers of Technology

'What drives the development of a technology?' Is it the technology itself, the business opportunity or the people? The answer lies in the combination of all: You need the right technology and the right people and combine it with the opportunity and the financial backing. The development of many of the Norwegian startup companies are the best examples where technology, qualified geophysicists, and market demand and funding come together in a country with less than 5 million people (which is less than the greater Houston area). The most important parts of this are the business opportunity and the



courtesy RWE-Dea

Fig. 7 Example of a subsalt interpretation using MT. On the *right side* is the interpretation without the MT and on the *left* after the MT survey, interpretation and integration (after Buehnemann et al. 2002)

markets. If the markets exist and are financially strong, then the financial support will follow. This is the main reason for the marine EM market: As exploration costs rise and risks increase, the industry is desperately looking for alternatives to reduce expenses, high-grade prospects and reduce risks.

Where will the next markets be? I suspect one will be in the shale reserves area, and I will outline my reasoning as follows. Already we know that the shale reserves are very large and can provide the USA with energy for an additional 100 years. Thus, the market is there. Shales reserves means in many cases thin laminated sand–shale sequences or turbidities. In logging terms, these used to be called ‘low resistivity–low contrast pays’. The 3D induction log allows now to quantify them by measuring electrical anisotropy. This means that shale plays require electrical anisotropy measurements. Since the sands are thin and resistive, and resistive thin layers are found with electric dipole CSEM only, it will require an electric dipole transmitter. If laminated, the laminations are usually 1 cm to 1 inch thick, so far below the resolution. This means the shale package must be sufficiently thick (let us say several 10 s of meters at least) to be seen by surface methods. The sand holds the oil, and the resistive sands can be seen through vertical current flow only. In an exploration scenario, there is often no well and one must derive educated estimates and update them as information becomes available. This concept is confirmed by the fact that already one contractor is applying DC resistivity and MT to the problem.

We selected the Bakken shale oil play as an example, where we wanted to demonstrate the value of measuring EM and concluding reservoir behavior from it. We reduced a model from the well log shown in Fig. 8 using the cumulative conductance/transverse resistance averaging described by Keller and Frischknecht (1967), selected Long Offset Transient ElectroMagnetic (LOTEM) with inline electric field layout and modeled first full fluid substitution from oil to brine (Strack and Aziz 2012). This yielded an anomaly of 6 % and clearly showed the thin resistive layer effect in Passalacqua (1983) and Eadie (1980) (the same effect is the basis for the marine EM direct hydrocarbon indicator (DHI) anomaly). The survey layout parameters used were: 9 km offset between transmitter and receiver, source length—500 m, source current 150 Ampere, and receiver dipole length 1 m. A horizontal well scenario is the standard way of developing a shale reservoir. In order to significantly improve the production from the low permeability zone as in gas shale and tight gas reservoirs, accurate well bore positioning is crucial to optimizing the production while keeping drilling cost at minimum. This key problem requires extensive use of logging-while-drilling modeling and advanced geosteering technique based on electromagnetic methods. The data include gamma ray, resistivity, density-neutron and sonic. The real-time data are compared with the model to produce a cost-effective solution in driving the well bore to the target and keeping it within the tight and dispersed reservoir. The availability of high-resolution azimuthal resistivity logging-while-drilling imaging tool along with 100 % borehole coverage has brought the fracture characterization and formation evaluation to a higher level in unconventional plays.

Figure 9 shows how the application of geosteering improves the decision of placing the well bore at the right location and maintaining it within the Bakken formation. The figure shows logging-while-drilling measurements along with other geological information from offset wells coming into play in placing the well bore in the right position along the trajectory of the thin (15 feet/5 m thick) Middle Bakken without drilling into the limestone, despite the arduous interpretation. The geological interpretation between the tight limestone and the Lower Bakken was formidable because the resistivity and the gamma ray information in the Middle Bakken do not show any distinguishing characteristics for the geosteering decision-making (O'Connell et al. 2012).

In Fig. 10 is the percentage anomaly as function of time for changes in vertical and horizontal resistivity after the reservoir has been depleted by 10 %. In this case, the saturation in all three Bakken reservoirs in Fig. 8 was varied, yielding up to 5 % changes from its status before depletion. Note that the changes are measurement time dependent

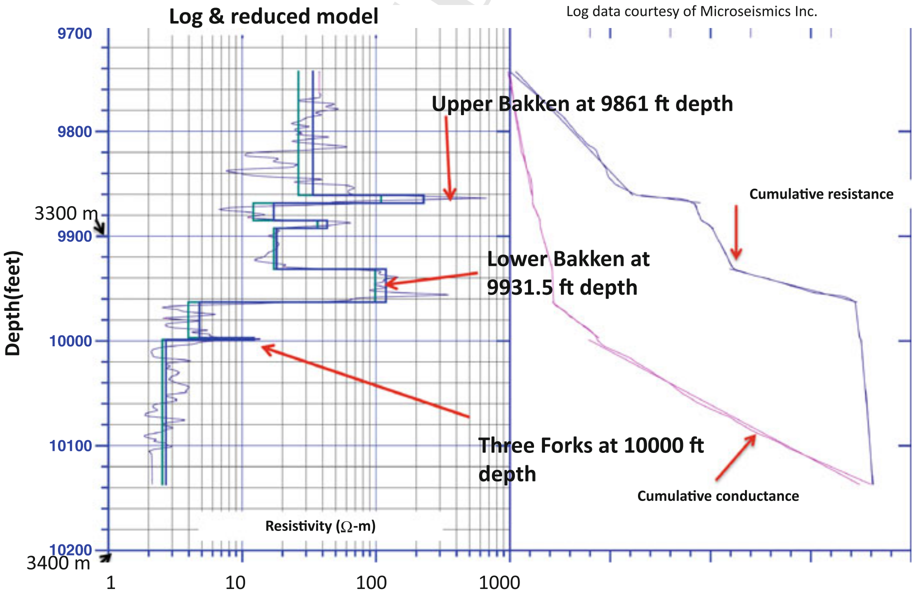


Fig. 8 Example Bakken well log (courtesy of Microseismic Inc.) showing the reservoir layers. All of them are clear resistors. On the right are the cumulative conductances [Sum(conductivity × thickness)] and resistance [Sum(resistivity × thickness)] used to derive the layer boundaries

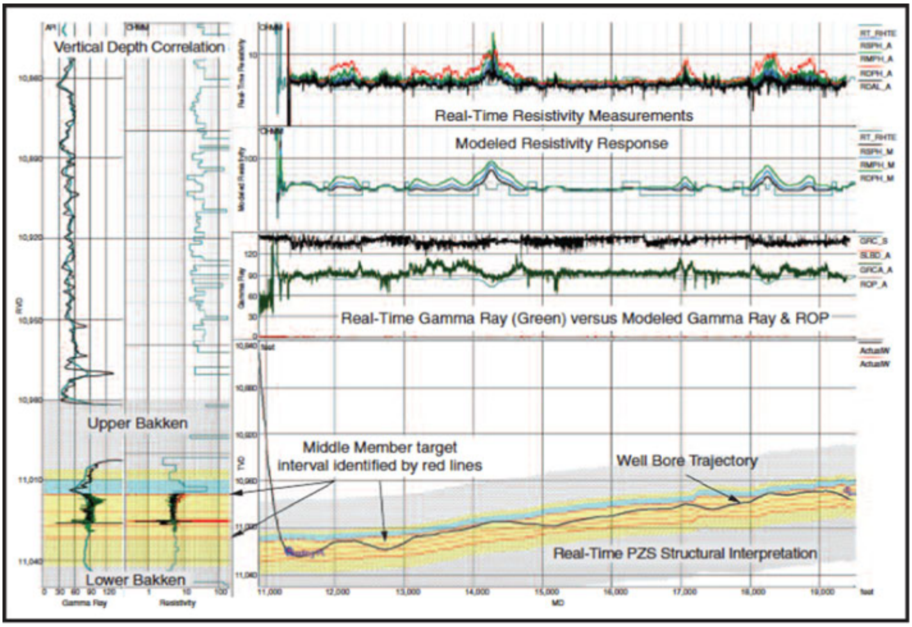


Fig. 9 Correlations displaying logging-while-drilling measurements utilized for geosteering decision at Bakken formation. The measurements along with other geological information from offset wells assist in placing the well bore in the right position along the trajectory without drilling into the limestone despite (O'Connell et al. 2012). For reference scale, the upper Bakken is at 3.3 km depth

while the maximum changes are at the DC level (late measurement times). The time-lapse changes are only marginally less when varying only one of the 3 reservoirs.

The problem with populating the 3D seismic cube around the reservoir is cost of EM data acquisition, resolution of the electromagnetic methods, and information value as EM sensitivity decreases with distance from the source. Since EM methods and equipment are in many cases custom adjusted/made, the cost is still many times higher than for surface seismic. This means we need to learn from our seismic colleagues about operational cost and efficiency. The easiest way is to align with the seismic industry and follow the same trend, namely using an array nodal system. We are now in the second attempt (Rüter and Strack 1995; Strack and Aziz 2012) to reduce the cost of EM hardware. In addition, we need to add as much information as possible, such as borehole measurements. This means that system design in terms of system architecture and data flow and integration are important. For borehole measurements, the cost is a secondary issue because the information value of placing a borehole in the subsurface is significantly higher than the EM measurement cost. Today, integration of EM with seismic (from acquisition view point) is clearly getting traction in the market place, which is confirmed by more seismic/EM tenders showing up in the market. Again, cost reduction is the driver as most logistics for seismic or EM are the same and the cost is incurred only once in this mode.

Another potential big driver of technology is the application to reservoir monitoring. When oil, which is resistive, is replaced with brine, commonly a huge resistivity drop occurs as electron mobility is increased. Figure 11 shows one of the few available logs that show a resistivity reduction from oil production. Here, we have several resistivity logs from the same borehole. On the left side, we have the same style through-casing resistivity measurements

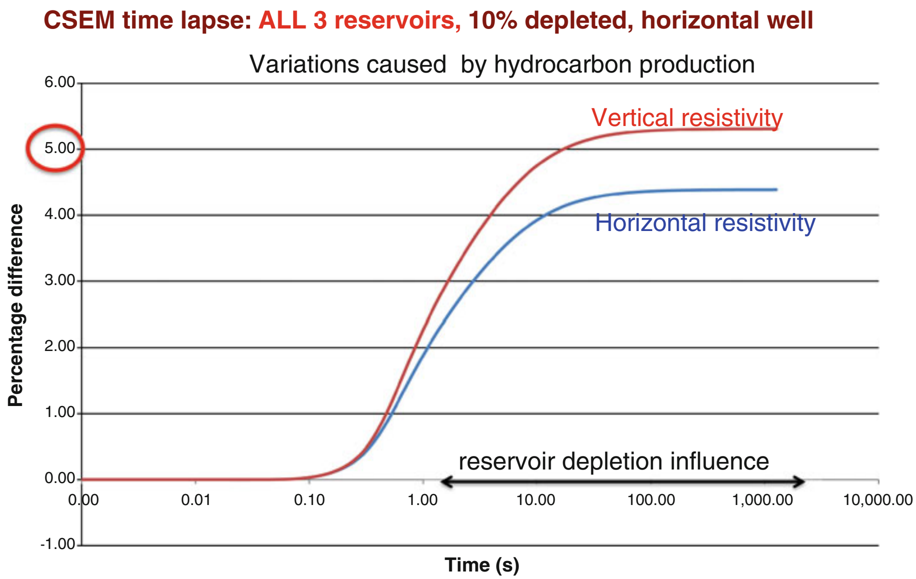
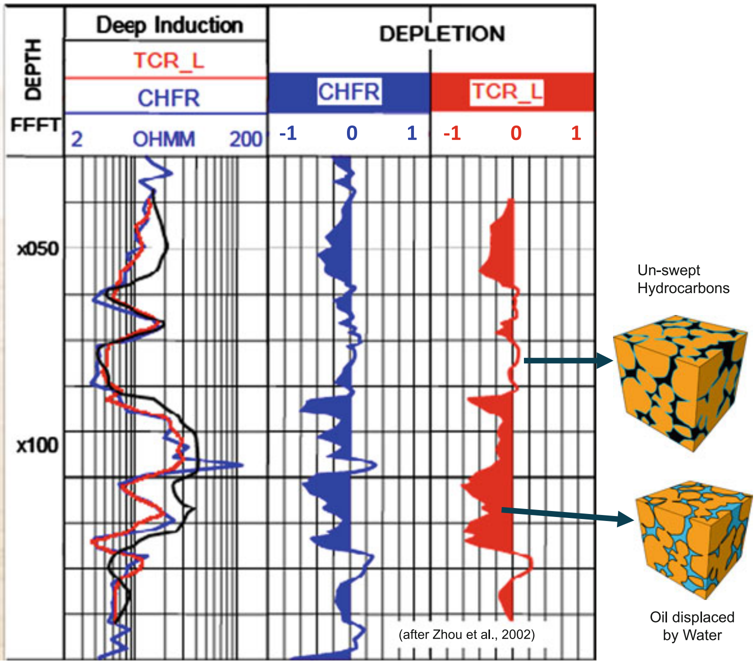


Fig. 10 Percentage difference for vertical and horizontal resistivities for a horizontal well in the Bakken after 10 % depletion. The anomalous response between oil saturated and depleted is still in the order of 5 % as marked in the figure

from 2 contractors (blue and red) overlain on the open whole induction log. Given the different measurement times, they match the open-hole results measured by the induction log. On the right side, we have the time-lapse fractional difference displayed for both measurements. They show very similar results. When the changes are negative, we clearly have oil depletion, and when it does not change, the oil remains in place. These zones are represented in the figure by the rock model cartoon showing either water or oil in the pore space.

Only limited case histories have been published (Wirianto et al. 2010, Ziolkowski 2010) as the industry had over the past 20 years difficulties to harness a new business model where the oil companies own the equipment and services are provided locally (Strack 2010). One of the examples with field data is from Hu et al. (2008). They monitored with time domain the flooding of a reservoir. The results are shown in Fig. 12. There we have the difference in apparent resistivity displayed in percentage.

In this case, the reservoir was shallow and surface methods worked. In many cases, the time-lapse anomaly from the surface is very small and this forces us to go to the borehole (Strack 2003a, b, 2004). When including the borehole, you may ask yourself whether you prefer receiver or transmitter in the borehole. Clearly, for signal-to-noise considerations, you will want to move the receiver as far away from the noise as possible. Also, in a desert environment, making electric field measurements may become tricky. Colombo et al. (2010) showed that, in principle, you could design a project that would map water flood in a 2.8-km-deep reservoir with intermittent thick resistive anhydrite layer. The difference section (bottom images) and reservoir flood snapshots in time are shown in Fig. 13. The survey setup is shown on the right of the figure. The color difference plots between of predicted (from reservoir simulator) flood fronts are shown at the bottom of the figure. It can be seen that the anomaly moves along with the oil front movement (the red maximum moves to the right where the oil remains). Again, this is an area of increased market activities (Dutta et al. 2011), and we can expect in the near future some case histories.



(after Zhou et al., 2002)

Fig. 11 Example of time lapse through-casing resistivity measurements (after Zhou et al. 2002). On the *left side* are the through-casing resistivity measurements [TCR_L (through-casing resistivity—long spaced) and CHFR (cased hole formation resistivity)] in addition to the deep induction log, which was measured before the sassing was set. To the right are the time-lapse fractional changes for these measurements

I have addressed the key technical/business enablers that are based on market opportunities. From the success and failures of small companies in the past 15 years, I observe: If you had large funds, you could probably influence the market for a short while and then automatically would come a bust (because the market is not yet stable and large enough) followed by a revival if the product offerings are sound or a complete bust if you have not managed to stabilize your product. Thus, money alone is not all that is needed, but it surely buys you the time it takes to refine your product.

4 Inhibitors of Technology

What slows down technology development in general and proof-of-concept in particular? If we have ONE super successful event, like the Numar (a company that developed NMR logging tools) sale to Halliburton for over $300 million or EMGS (a marine EM service company) doing their Initial Public Offering (IPO) for over 1 billion US $, many people will try to copy and will mobilize scientists and engineers to do so. Some will win and some will lose. This means we must include business drivers, but use caution not to rely on luck alone. We can increase the progress of EM utilization by avoiding common mistakes. Below, I have listed a number of the mistakes that I have encountered over the past 30 years.

- *Resolution:* Since EM is diffusive, it does not have the resolution of seismic. Caution in making promises and prediction is in order. We need to realize that the seismic trained

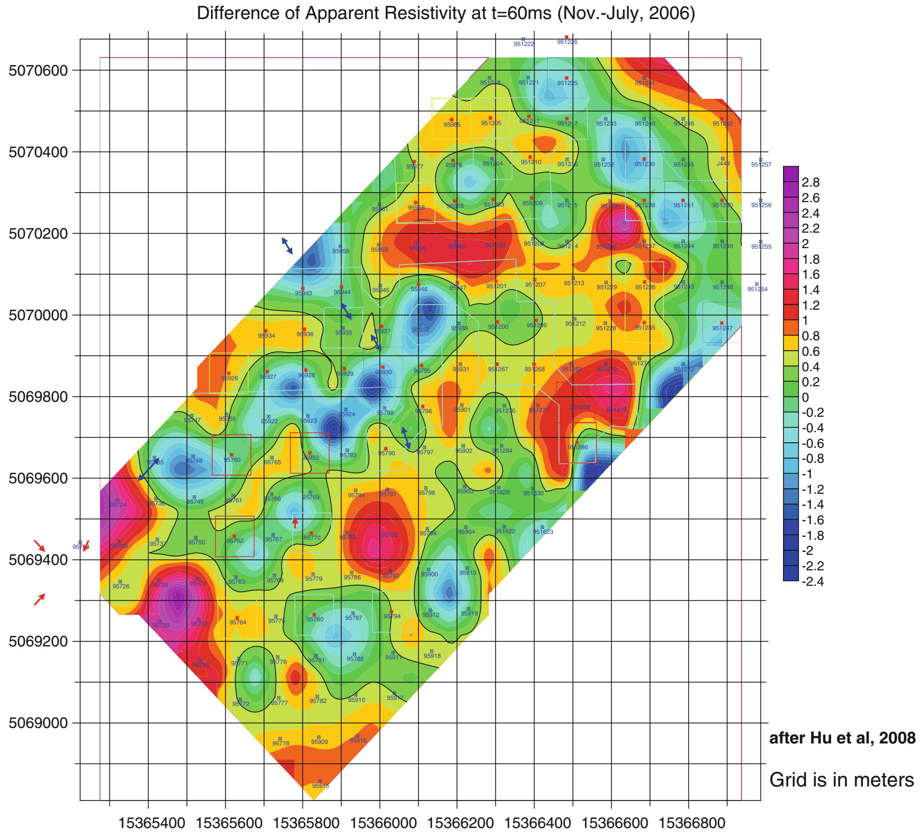


Fig. 12 Percentage difference of time domain electromagnetic time-lapse measurements (Hu et al. 2008)

geophysicists do not understand this and, if we are successful, he/she will immediately expect seismic resolution (or EM velocities).

- *General technology readiness:* We often underestimate what are required using scientific processes in the real world. Often we go to the field with unprepared equipment and workflow. Then, we are wondering why everything takes so long and does not work. You overcome this with repeated dry runs.
- *Integration:* We often pride ourselves on coming up with an answer based on our own data only. Mother nature is complex, and there are many ways to provide an answer. This means an answer that honors other data sets with a higher RMS error is often more reliable than an answer that honors only ONE EM data set.
- *Geology or geologic noise:* In some cases, the geology is more complex than expected or the geologic noise masks the wanted response. This is usually rare; we often use it as an excuse for something we do not understand (like hardware or software).
- *Cost and integration:* We often reduce cost and ignore integration. Integration comes AFTER interpretation. Integration often costs as much as interpretation. Unfortunately, as the common EM geophysicist knows mostly or only EM, this is outside of his/her scope. This means we need to plan for this.

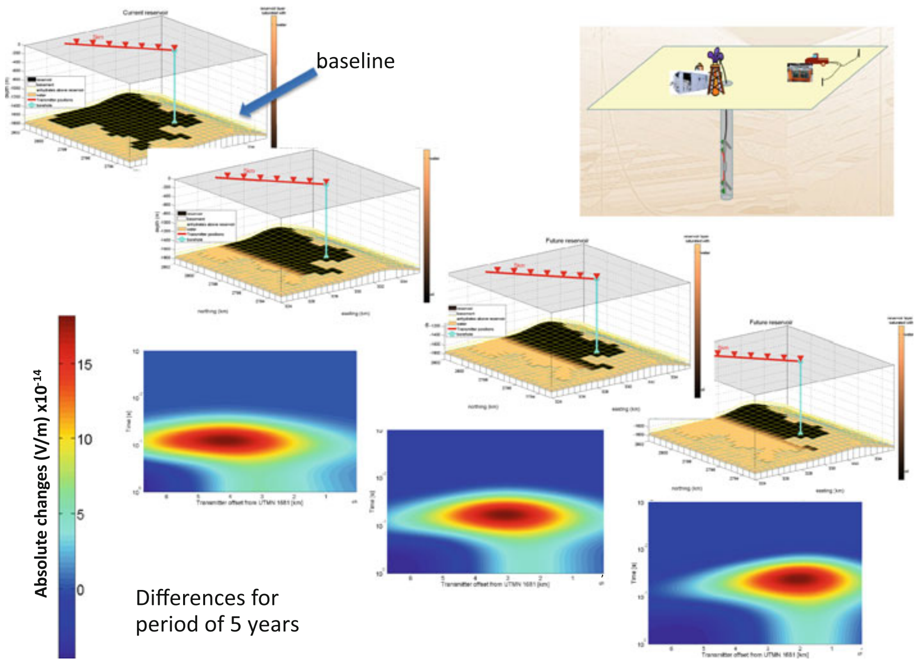


Fig. 13 Reservoir simulator results (*center*) and difference sections for surface-to-borehole experiment. The survey layout is on the *top right* (after Colombo et al. 2010). The reservoir is at about 2,800 m depth. In the center are horizontal slices through the reservoir shown in dark the movement of the oil. Below in color you see the differences between the different time steps (time on the vertical and transmitter offset on the horizontal)

- *Not-invented-here 'NIH'* (for industry) or scientific arrogance for academia. This is the most common pitfall. Many companies/researchers go a long way to use only things they developed or understand irrespective of the benefit to the customer or whether their solution provides the best answer.
- *Selection of wrong method*: An example is using electric dipole CSEM to find conductive sediments under a thick resistor because we only have an electric field receiver—the solution would be to add MT receivers. In academia, we often see the wrong method being applied to the problem (like using MT to delineate thin resistive reservoirs because that is the only thing the researcher knows). Not often enough can people look at problems with an open mind (when not experienced).

Not included is lack of opportunity or funding as, for experienced researchers, overcoming this is the opportunity on hand.

5 Future

What will happen in the future? First, I think we should look at other subjects. Today, the Internet Age is the future and it is part of our life. We have known about the powers of the Internet for more than 15 years. So using this analog, let us assume that the future is in *that area* where we already see progress today.

- Clearly *hardware cos*t is coming down and will come down more. The past 2 years reduced EM system cost by 60 %. Another 50 % and more is needed to make EM attractive to seismic geophysicists. The driver will be that we need more data, which means cost per data point must come down but total hardware expenditure will go up.
- *Denser measurements* and higher data redundancy. As with seismic, spatial sampling must go much higher than the Nyquist frequency. It does not help to look with MT for 50-m intrusions with 1-km station spacing (this means we are still under-sampling). Higher spatially oversampled measurements will be the standard.
- *Operational decisions* will drive EM applications, mainly to improve seismic acquisition (static, complex structure and topography and shot hole optimization), but also for site investigations, environmental certifications, etc. This will be a big growth area as it immediately adds to the bottom line.
- *Shale applications:* Slowly, even the seismic geophysicists in oil companies are realizing that EM could contribute to solving their problem. A pilot demonstration is still outstanding, but I have no doubt this will happen in the next 12–24 months. The potential benefits are simply too big.
- *Reservoir monitoring applications:* Slowly, we see the first case histories and some oil companies are pushing this openly. The industry will adopt better business models to match this, and the technology will be provided as it is already there.
- In the *borehole*, we will see even more emphasis on geosteering. The more information we have close to drilling, the less formation evaluation we have to do afterward.
- The *marine environment* will further mature, but we will see a trend to services integration as has happened everywhere else. 3D acquisition will be the standard, and full integration of ALL EM methods will be the normal product (not just CSEM or electric fields).
- The *patent space* will become more diverse in terms of methods. Geographic loop holes will become less important as violators will be caught in different jurisdictions as globalization progresses.
- There will be more *integration with seismics* forthcoming shortly as some progress happened since 1990 (Strack and Vozoff 1996). We still do not have routine joint seismic/EM acquisition or processing and only limited proposals for integrated interpretation. Given the increased request for this (Harris et al. 2009; Gao et al. 2011; Ellis et al. 2011), we can only hope to see more integration in the next few years.

Overall, the potential for a great career in electrical geophysics is there as long as we can follow the guidance of the problem on hand and strive for the best solution.

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