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Advances in Electromagnetic Methods for Hydrocarbon Applications

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Summary

For hydrocarbon related applications, seismic has been the workhorse of the industry. In the borehole, electromagnetic (EM) methods play a dominant role as they are mostly used to determine oil reserves and to distinguish water-bearing zones from oil-bearing ones. Throughout the past 60 years we had several periods with an increased interest of the oil industry in EM. This interest got stronger with the success of the marine EM industry and now EM methods are being considered for many new applications. India has unique geologic challenges (sub-basalt and carbonate intrusions) that can only be solved with electromagnetics.

The classic electromagnetic methods are borehole, onshore and offshore and airborne EM methods. Airborne is not covered in the review because it is covered elsewhere (Smith et al., 2008; Smith, 2012). Marine EM material is readily available from the websites and I thus only mention some future technical directions as they will be important to Indian exploration applications.

The marine success is now being carried back to the onshore market, fueled by geothermal and unconventional hydrocarbon applications. Oil companies are now including EM in the decision workflow but still are hesitant to go through the learning exercises as early adopter. This is changing. 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 is costly and inefficient. EM will allow novel seismic methods to be applied.

In the borehole, anisotropy measurements, now possible, establish the missing link from surface measurements to ground truth. 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 improved geosteering including look-ahead-and-around the drill-bit is going on.

The overall importance of electromagnetics from India is increasing because it allows imaging through the basalts and also mapping of shale reserve depletion

Keywords: *Electromagnetics, hydrocarbon exploration, controlled source electromagnetic.*

Introduction

Electrical methods in applied geophysics started along with the other geophysical methods in the early 1900 with Wenner (1912), Schlumberger in 1922 (Gruner Schlumberger, 1982). Hydrocarbon applications are always driven by commercial interests and competitiveness and thus cyclical. Understanding the market values and how volumes drive the markets is almost as important as understand the technical benefits of the individual methods.

There are four principle areas for electromagnetics for hydrocarbon applications: Borehole, offshore, onshore and airborne. Airborne applications are covered by Smith (2012). For hydrocarbon exploration airborne EM is limited because of the depth of penetration. 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, derivative for logging-while-drilling (LWD) applications are presently being developed. After 2000, there was a general increase of marine electrical methods Eidesmo et al. (2002) and after the technical bubble burst the market is now stable with a slow growing trend. There has been little change in land applications and only recently there is increased interest. This is mostly driven by the marine success. New opportunity like monitoring

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and applications to shale reserves are on the horizon (Kumar and Hoveston, 2012; Strack, 2012).

Since seismic methods have made tremendous progress, we have sufficient 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, LWD, production logging, cross-well). This is the most important market area for electromagnetics (EM) as electrical logging tools are run in almost every well. Global annual market is 1 to 2 Billion US $ in services alone. In addition, there is a 50 to 100 Million $ hardware market.

- Marine applications are more recent and present a stable industry that has demonstrated its value to the oil company customers. Global market is 2012 approximately 200 Million US $.

- Airborne applications to hydrocarbon exploration are limited to 10 to 20 Million US $ annually because of the limited application scope

- Land applications, albeit growing, are only reaching approximately 50 Million US $ in 2012.

The EM related logging market is the only area that has continuously been growing and in market size and also in technology. This is related to improved technology (hardware and software) that allows us to get more signals from the noise and thus more resistor information (related to small signal) and directly in correlation is 'More Oil'. It thus makes sense to define the technology development phases as baseline and gage the other areas accordingly.

For the marine electromagnetics industry, we can see that we are almost at the end of the initial conception. Numerous marine technologies have been developed and only those that were operationally mature survive. There will be several more seismic integrated systems and the industry will have more than just one contractor. After the conception phase, will be the maturity, which mean routine acquisitions are being tendered. 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. For example we see tenders for shallow water integrated with seismic, marine magnetotellurics and even time domain electromagnetics while the market predominantly offers frequency domain controlled source electromagnetics. Needless to say the market will respond to demands and not only to offerings. In open competition, we will always reach a balance between technical and business aspects.

For onshore electrical methods we already had two periods of concept developments and are now in the start of the third: One in the 1950s and one in the 1980s (this when presently used technology was developed). For hydrocarbon applications only magnetotellurics made it to an acceptance and now well into commercial 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), the winning player will be a newcomer.

Looking at EM technology from this angle, 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).

Finally, I will draw conclusions based on proven success and technical potentialities of the methods using an onshore and offshore model.

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 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 1990 and 2000 (Strack et al., 1998). Concurrent to the wireline development, Logging While Drilling (LWD) tools progressed and today almost all wireline resistivity measurements are available as LWD tool. 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 locking 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 slowly. Intellectual property, in particular patents protected this position. In fact, the strategy and cultures that exist today in the geoscience industry comes from the logging world. Patents are used as business tools and to protect investment more than to enforce a technical point.

For illustration of the value of the 3D induction logging tool, Figure 1 shows an example of a 3D induction log interpretation. While the problem was well known (Klein, 1993), the first 3D induction-logging tool was developed by Baker Atlas under mentorship and funding of Shell (Kriegshaeuser et al., 2000, Strack et al., 2000). It allows the measurement of horizontal and vertical resistivities in vertical borehole, 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 yields tensor 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 and thus higher hydrocarbon saturation or more oil. The average reserve increase of 20% (and more) justified the development of this tool. In Figure 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 petro-physical equation, oil saturation is calculated. Note the oil saturation is significantly higher from the vertical resistivities. When we carry out controlled source EM (CSEM) measurements with a grounded dipole, we measure predominantly the vertical resistivity. This means calibration of surface dipole CSEM measurements can now be done as it was previously not reliably possible.

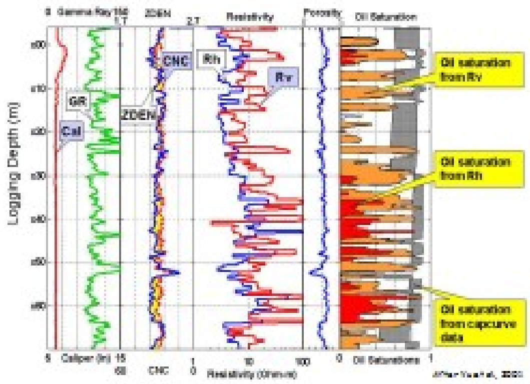

Figure 1: Example of an interpretation of a 3D induction logs interpretation (Yu et al., 2001). The tracks from left to right show: natural gamma ray for shale content, gamma-gamma density and neutron density for gas zone indicators, 2D inverted vertical and horizontal resistivities, interpreted porosity and interpreted oil saturation.

One of the key issues in placing the wellbore inside the reservoir is to predict ahead and around the bit. Rabinovich et al. (2012) try 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. It is a time domain system with short transmitter-to-receiver spacing and multi-components (Strack, 2003a & 2003b). The systems were developed through proof-of-concept phase and sideways and look ahead capability to tens of meters demonstrated (Banning et al., 2007, Hanstein et al., 2003).

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 Controlled Source Electromagnetics (CSEM). For the summary on 3D CSEM acquisition and interpretation technology if refer to EMGS's website:
http://www.emgs.com/technical_papers/.

Present state-of-the-art is that acquisition should be mostly done in 3D and large system. 2-D, 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 (tCSEM™) (Allegar at al., 2008; Holten et al., 2009, Strack et al., 2011)
- Focused resistivity marine EM (Davydycheva and Rykhlinski, 2009)
- Marine induced polarization (Davidenko et al., 2009; Legeydo et al., 2009)

Because this area is well published, I only show examples where still more work is required. I selected an example from a sub-basalt imaging problem in the North Sea because sub-basalt and sub-salt imaging are still important exploration issues. Basalt layers can be very this in the marine environment (several kilometers) and make it extremely difficult to allow 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 is well known to be able to delineate the sediments below the basalt. Figure 2 shows an example where marine magnetotellurics was inverted together with gravity and seismic data. 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 is from the Faroe Islands. It shows a sedimentary basis below the basalt layer. This type of joint tomographic imaging will be more common in the future (Zerilli and Roslov, 2003).

For land electromagnetic applications, Nekut and Spies wrote their review paper (1989, and a more general review in 1991 (Spies and Frischknecht, 1991), the applications of electromagnetics included:

1. Sub – basalt exploration (Wilt et al., 1989)
2. Sub – salt exploration (Hoveston et al., 2000)
3. Messy overburden (Christopherson, 1991)
4. Porosity mapping (Strack et al., 1988)
5. Induced polarization applications (Sternberg & Oehler, 1984)

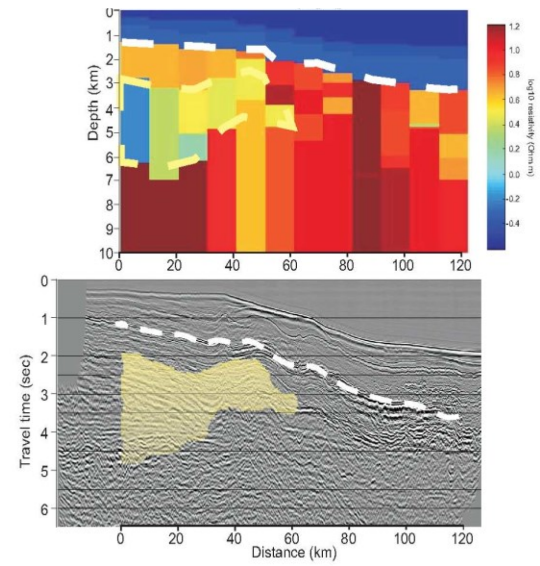

Figure 2: Example of joint inversion of magnetotelluric, gravity and seismic data (Jegen at al., 2009). The top diagram shows the joint inversion of gravity and magnetotelluric data and the bottom after seismic was used to constrain the inversion.

Application are well published with some of the more recent sub-basalt ones being 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 electromagnetics to improve seismic statics and various other operational concerns such as shot hole depth optimization (Zerilli, 2002; 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 magnetotellurics in complex topography. An example is shown in Figure 3 where the top shows the magnetotellurics and the bottom the high resolution DC resistivity. The DC resistivity measurements were used to control the statics caused by complex terrain on the magnetotellurics data. This is becoming a more common application of electromagnetics where the type of methods used is tailored to providing a value added solution.

I selected a sub-basalt example for the marine as future application of importance to India, sub-salt is an important for land as there are many salt provinces, seismic has difficulties and gravity lacks the resolution. New acquisition systems can handle the noise better and thus there will be renewed interest in sub-salt, in particular in the United States (because of the easier business environment that allows small independents to explore and produce oil quickly). Figure 4 shows a sub-salt interpretation from Northern Germany (Buehnemann et al., 2002), near Bremen where there is strong cultural noise present.

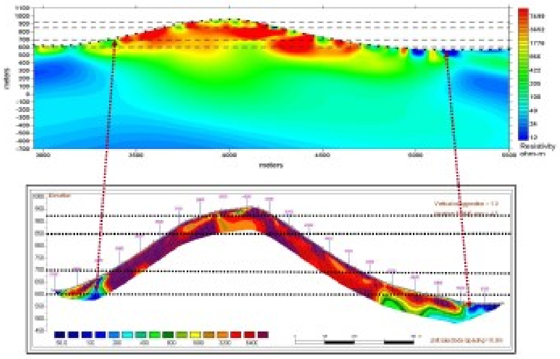

Figure 3: Examples section of magnetotellurics and DC resistivity data for complex terrain (Zerilli, 2002). The top shows the magnetotellurics section and the bottom the DC resistivity section.

The MT station density was 50 m for the ‘X’ profile and 100 m otherwise. The data was processed and interpreted, first independent 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 magnetotellurics data and clearly the salt overhand is not even visible. The client of this survey drilled subsequently and the entire material including feasibility is under preparation for publication.

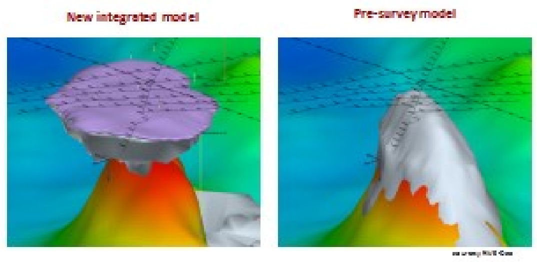

Figure 4: Example of a subsalt interpretation using magnetotellurics. On the right side is the interpretation without the magnetotellurics (MT) and on the left after the MT survey, interpretation and integration (After Buehnemann et al., 2002).

The Drivers of Technology

‘What drives 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 is 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 part that of this is the business opportunity and the markets. If the markets exist and are financially strong than the financial support will follow. This is the main reason for the marine EM market: as exploration cost rise and risks increase the industry is desperately looking for alternatives.

Where will the next markets be? I predict it will be in the shale reserve area. Already we know that the shale reserves are very large and can carry us for an additional 100 years. Thus the market is there. Shales reserves means in many cases thin laminated sand shale sequences or turbidites. In logging terms these used to be called ‘low resistivity – cow contrast pays’. The 3D induction log allows no to quantify them. This means that shale plays require electrical anisotropy measurements and since the sands are thin and resistive, it will require an electric dipole transmitter. The laminations are usually 1 cm to 1 inch thick so far below the resolution. The sand holds the oil and they can be seen though 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 is confirmed by seeing that already one contractor is applying DC resistivity and magnetotellurics to the problem.

We selected the Bakken shale oil play as example, reduced a model from the well log shown in Figure 5 using the cumulative conductance/transverse resistance averaging described by Keller and Frischknecht (1967), selected Lotem inline electric field layout and modeled first full fluid substitution from oil to brine (Strack and Aziz, 2012 and 2013). This yielded an anomaly of 6% (see Figure 6; Strack and Aziz, 2013) and clearly showed the thin resistive layer effect shown in Passalacqua (1983) and Eadie (1980) that is the basis for the marine EM Direct Hydrocarbon Indicator (DHI) anomaly.

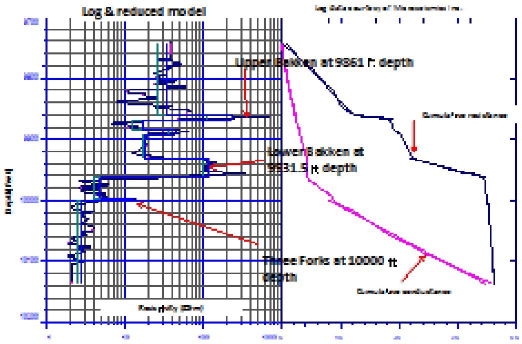

Figure 5: Exemplary Bakken well log (courtesy of Microseismic Inc.) showing the reservoir layers. All of them are clear resistors. On the right are the cumulative conductances and resistance used to derive the layer boundaries.

Details of the shale application and monitoring applications can be found in Strack and Aziz (2013).

The problem with populating this 3D cube is cost of data acquisition, resolution of the electromagnetic methods, and information value as their 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 them and follow the same trend, namely using array nodal system. We are now in the second attempt (Rueter et al., 1995, Strack and Aziz, 2012) to reduce the cost of EM hardware. In addition, we need to add as much information as possible like borehole measurements. This means system design in terms of system architecture and data flow and integration is 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, the approach of integrating with seismic is clearly getting traction in the market place, which is confirm by more seismic/EM tenders showing up in the market. Again cost reduction is the driver as most logistics for seismic or EM is the same and the cost in incurred only once in this mode.

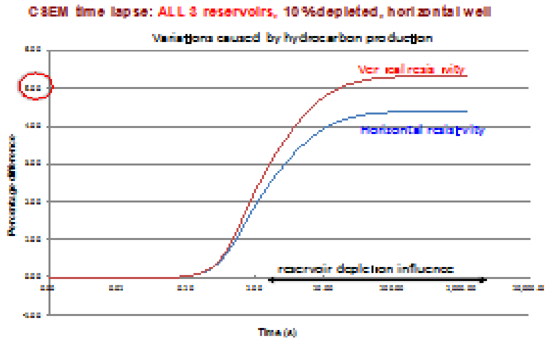

Figure 6: Percentage difference for vertical and horizontal resistivities for a horizontal well in the Bakken with 10% depletion. The anomalous response is still in the order of 5%.

I address at technical/business enablers that are based on market opportunities. If you had a large fund you could probably influence the market for a short while and then automatically would come a bust followed by a revival if the product offerings are sound or a complete busts if you have not managed to stabilize your product. Thus, money alone is not all that is needed.

Inhibitors of Technology

What is slowing down technology development in general and electromagnetics in particular? If we have ONE super successful event , like Numar (a company that developed NMR logging tools) selling to Halliburton for over $300 Million or EMGS (a marine EM service company) doing their IPO for over 1 Billion US $, everyone will want to copy and many will mobilize scientists and engineers to do so. Some will win and some will loose. This means we must include business drivers but use caution not rely on luck alone. We can increase the progress of electromagnetics 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 electromagnetics 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 geophysics does 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 we everything takes so long and does not work. You overcome this with repeated dry runs.

- *Integration:* We often pride ourselves with 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 honor only ONE EM data set.

- *Geology or geologic noise:* In some case, the geology is too complex or the geologic noise masks the wanted response. This is usually rare, though we often use it as an excuse when we do not understand or hardware or software.

- *Cost and integration:* We often reduce cost and ignore integration. Integration comes AFTER interpretation. Integration costs often as much as interpretation. Unfortunately, as the common EM geophysicist knows mostly only EM, this is outside of his/her scope. This means we need to plan for this.

- *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 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). A perfect example for this is by Kumar and Hoversten (2012). As this is a professional experience issue, always seek advise from experience colleagues.

Note: I am not including lack of opportunity or funding as for experience researchers, overcoming this is the opportunity on hand.

Future

We ask ourselves where is the future? First, I think we should look at other field. 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 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 system cost by 60%. Another 50% and more is needed to make EM attractive to seismic geophysicists. Driver will be that we need more data.

- *Denser measurements* and higher data redundancy. Parallel to seismic the spatial sampling must go much higher that Nyquist. It does not help to look with MT for 50 m intrusions with 1 km station spacing (this mean we are still under-sampling).

- *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 their problem. Pilot demonstration is outstanding, but I have no doubt this will happen in the next 12 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 afterwards.

- The *marine environment* will further mature, but we will see a trend to services integration as it 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, but geographic loops hole will become less important as violators will be caught in different jurisdictions.

- There will be more *integration with seismics* forthcoming shortly as little has happened since 1990 (Strack and Vozoff, 1996).

Applying all of this to India's onshore and offshore challenges with respect to electromagnetics. Learning from the power of integration and industrial development of the instruments, workflows and tools we should be using:

- For onshore Deccan trap related issues magnetotelluric surveys in combination with controlled source measurements should be carried out in an array mode that allows full EM integration. If possible the basalt layers should be undershot by long offset seismic or refraction and combined in a tomographic sense.

- For offshore the approach should be in 2 stages: First, integrated long offset seismic OBS with MMT. Second, a follow up with CSEM. Careful site selection and onboard QC should be done to ensure best data quality and to obtain 3D data.

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