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Future directions of Electromagnetic Methods for Hydrocarbon Applications

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3 **Future Directions of Electromagnetic Methods** 4 **for Hydrocarbon Applications**

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

A1 IAGA 21st EM induction workshop Review Paper, Darwin, Australia, 2012.

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33 **Keywords** Electromagnetics · Hydrocarbon exploration · Electrical geophysics

34

35 **1 Introduction**

36 Electrical methods in applied geophysics started along with the other geophysical methods
37 in the early 1900s with Wenner (1912), Schlumberger in 1922 (Gruner Schlumberger
38 1982) and early patents by Schilowsky (German patent 322040 assigned 1913), and Blau
39 (US patent 1911137 assigned 1933 to Standard Oil Development Corp.). Countless patents
40 have been filed since then, and the interest in electromagnetics has been growing steadily
41 except for onshore applications, where the interest was cyclical and a new cycle is just
42 starting. Hydrocarbon applications are always driven by commercial interests and competi-
43 tiveness and are thus cyclical. Understanding the market values and where values drive
44 the markets is almost as important as understanding the technical benefits of the individual
45 methods, because in many instances the market drives the technical priorities.

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

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

- 68 • Borehole applications including all logging methods (wireline, logging-while-drilling,
69 production logging, cross-well). This is the most important market area for
70 electromagnetics (EM) as electrical logging tools are run in almost every well. The
71 global annual market is 1–2 billion US \$ in services alone. In addition, there is a
72 50–100 million \$ hardware market.
- 73 • Marine applications are more recent and present a stable industry that has demonstrated
74 its value to oil company customers. That global market in 2012 is approximately 200
75 million US \$.
- 76 • Airborne applications to hydrocarbon exploration are limited to 10–20 million US \$
77 annually because of the limited application scope (see Smith, R, review paper this
78 issue).



- 79 • Land applications, albeit growing, are only reaching approximately 50 million US \$ in
80 2012 (excluding China and Russia).

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

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

89 1921–1927 Conceptual phase

90 1927–1949 Acceptance phase

91 1949–1985 Maturity phase

92 1985–now Reinvention phase... maybe we are at its end

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

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

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



126 Looking at these different phases explains why the reviewers of this subject matter in
127 the recent past (this means mostly for onshore) focused on a small aspect of hydrocarbon
128 applications as they were filling in the gap. The last broader hydrocarbon review was
129 written in a series of papers by Spies and Nekut (Nekut and Spies 1989; Spies 1983; Spies
130 and Frischknecht 1991). Other reviews focus on electrical methods in general and to a
131 small degree on hydrocarbon applications (Nabighian and Macnae 2005; Sheard et al.
132 2005). Numerous review papers have been offered on marine electromagnetics (Constable
133 and Srnka 2007; Constable 2010). The best source for review is presently the Web sites of
134 the marine contractors, which give links to the scientific papers about the technology they
135 use. Further information can be found in various reviews (i.e., Srnka et al. 2006; Constable
136 and Srnka 2007; Constable 2010).

137 I will here go through the applications in the above sequence and point out the
138 developments; I derive by considering the direction in which the industry might be
139 heading. I will combine business, history and technical aspects to derive market directions.
140 This path builds on the success of EM in the borehole, which is attributed to the solution of
141 real problems. The success of 3D induction log technology can be directly translated to
142 finding more reserves and not only the measurements delivering more complete images.
143 The same is true for marine Controlled-Source ElectroMagnetics (CSEM). On the other
144 side, Hesthammer has been advocating its use for making drilling decisions (Hesthammer
145 et al. 2010) and recently reported the confirmation of drilling results (Hesthammer et al.
146 2012) while not being a commercial success. In the context of drilling cost and decision,
147 the use of CSEM, even at low resolution using EM, is justifiable. Only for onshore
148 hydrocarbon applications have we yet to reach that point that has been reached several
149 times already in the conceptual phase.

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

153 2 The Methods

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

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



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

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

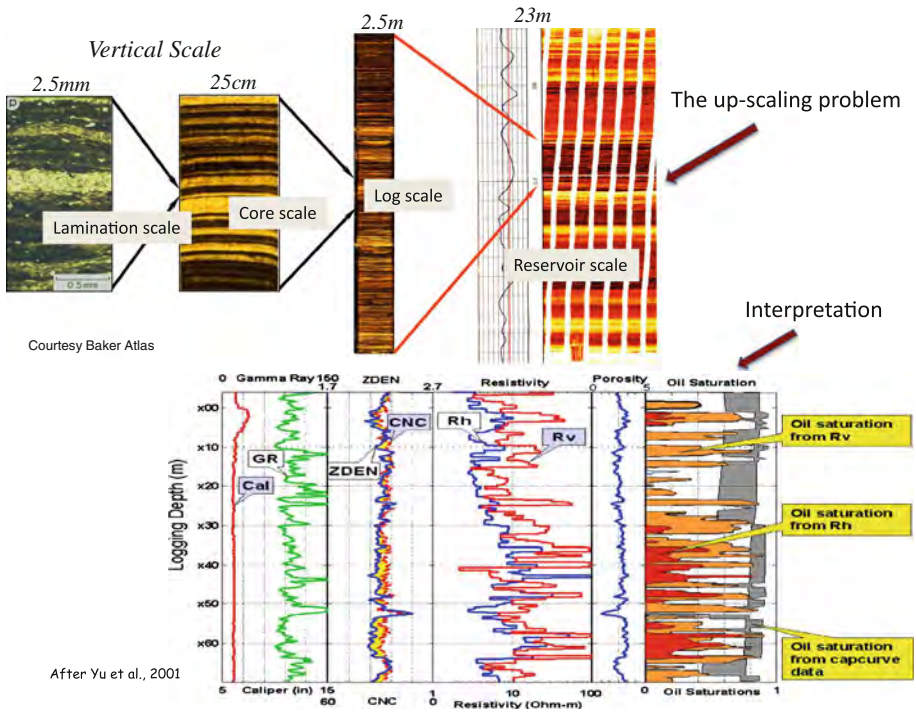


Fig. 1 Images of borehole anisotropy and its interpretation. The *top* shows various core/section images at different scales. Each of them clearly shows the anisotropic layers with the sands in the *light colors* and the shales in the *dark colors* (courtesy Baker Atlas). The *bottom* shows an example 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

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

- 229 • Marine magnetotellurics (MMT) (Constable et al. 1998; Hoversten et al. 1998; Zerilli
 230 1999)
- 231 • Controlled source electromagnetics (CSEM) (Constable 2010; Johnstad et al. 2005)
- 232 • Time domain CSEM (Allegar et al. 2008; Holten et al. 2009; Strack et al. 2011;
 233 Ziolkowski et al. 2011; Jang et al. 2012; Helwig et al. 2013; Garina et al. 2013)
- 234 • Focused resistivity marine EM (Davydycheva and Rykhliniski 2009)
- 235 • Marine induced polarization (Davidenko et al. 2008; Legeydo et al. 2009)

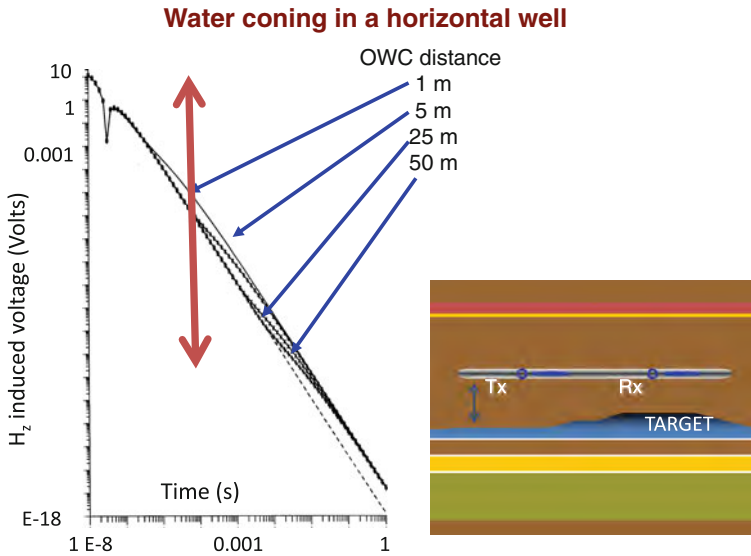


Fig. 2 Synthetic modeling example for a horizontal well and a single well time domain system using a 3-component (3C) transmitter and a 3C receiver. The different curves are for different distances to the water flood (oil–water–contact OWC) front cone depicted on the *right side* on the figure. The target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

236 Because this subject area is well published, I only show examples where still more work
237 is required. Sub-basalt and sub-salt imaging are still important exploration issues. Basalt
238 layers can be *thick* in the marine environment (several km) and make it extremely difficult
239 for controlled source energy to penetrate. Often the targets are also conductive, namely
240 perspective sediments below the basalt, and the exploration target is the thickness of the
241 sediments. Magnetotellurics (MT) is well known to be able to delineate the sediments
242 below the basalt (Beamish and Travassos 1992; Morrison et al. 1996; Virgilio et al. 2009;
243 Heincke et al. 2012). Figure 3 shows an example where MMT was inverted together with
244 gravity and seismic data (Jegen et al. 2009). The seismic data were used as constraint. The
245 top of the figure shows the 2D gravity and 1D MT inversion and the bottom after seismic
246 constraints were integrated into the inversion. The data are from the Faroe Islands. It shows
247 a sedimentary basin below the basalt layer. The body superimposed on the seismic section
248 is the same confined body that can be seen in the resistivity section, and now the depth has
249 been converted to two-way travel time. The next example in Fig. 4 shows the results from
250 a modeling experiment where seismic and EM are combined with the purpose of joint
251 imaging. This type of joint tomographic imaging will be more common in the future
252 (Zerilli and Roslov 2003). Another example is from time domain measurements, in this
253 case fixed array electric field time domain measurements applied to reservoir monitoring
254 (Hu et al. 2008). Figure 5 shows data examples with 5-s-long signals. The data are
255 unprocessed to avoid processing influence in the time-lapse sense (as it was felt that
256 filtering the map would allow better control over geological changes). The data are a
257 4-month time-lapse from a Chinese oil field with the target being around the 500 m depth
258 range. Here, we look at only repeatability. Later in this paper (Fig. 12), we will discuss the
259 time-lapse results.

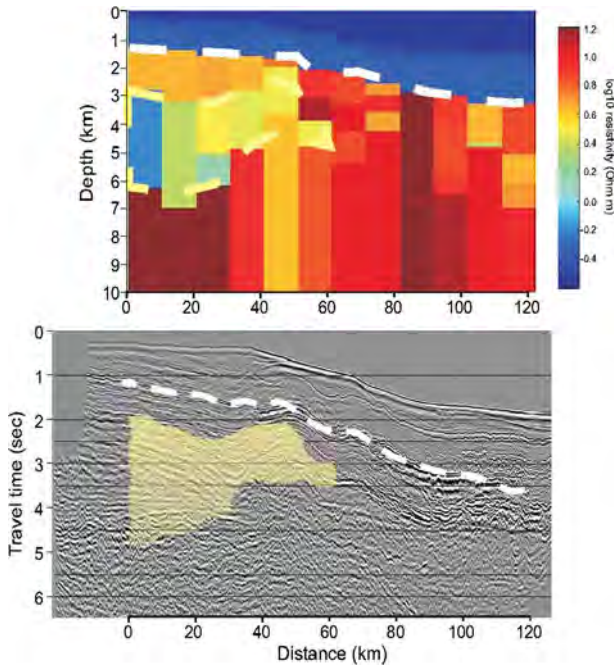


Fig. 3 Example of joint inversion of magnetotelluric, gravity, and seismic data (Jegen et al. 2009). The top diagram shows the joint inversion of gravity and magnetotelluric data and the bottom after seismic data was used to constrain the inversion

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

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

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

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

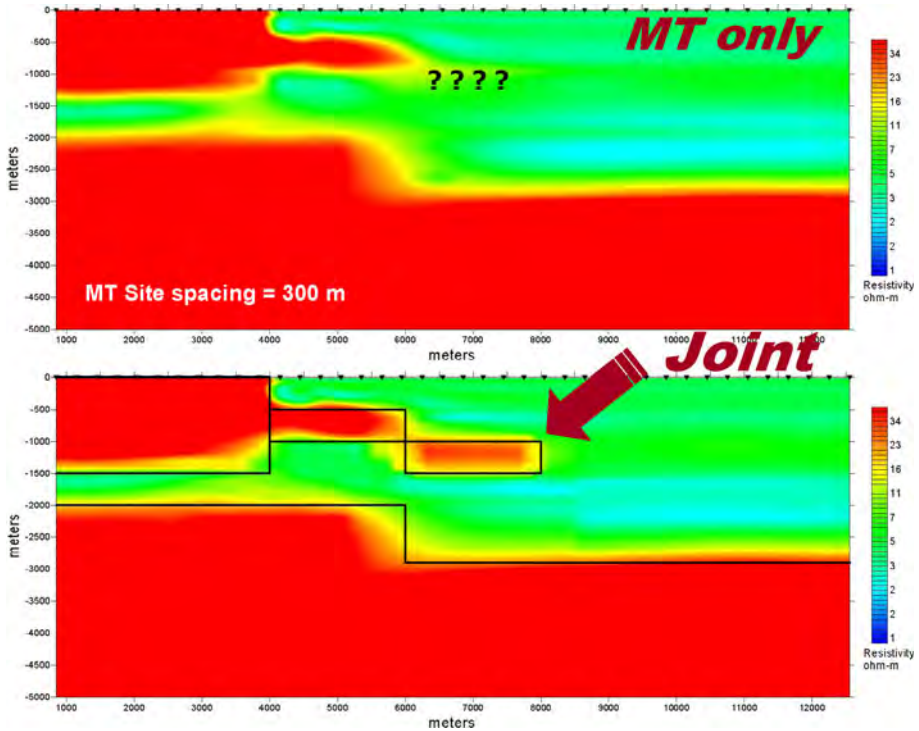
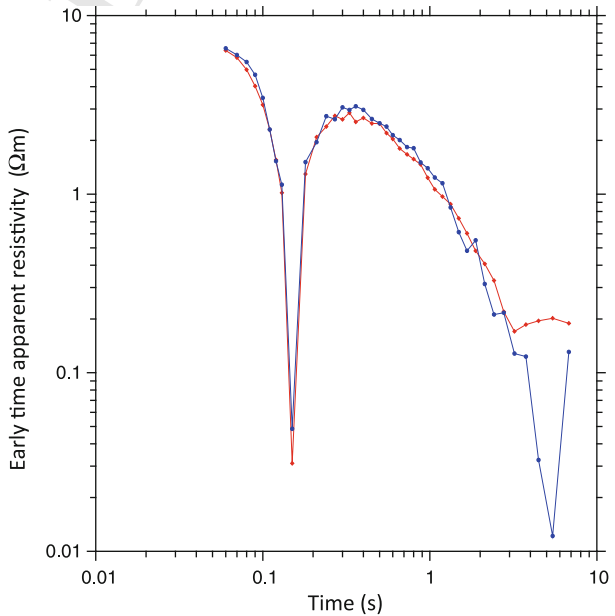


Fig. 4 Example of a joint tomographic inversion of seismic and magnetotelluric data using synthetic models. The top is the magnetotelluric interpretation alone, and the bottom is based on a joint inversion (after Zerilli 2002)

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)



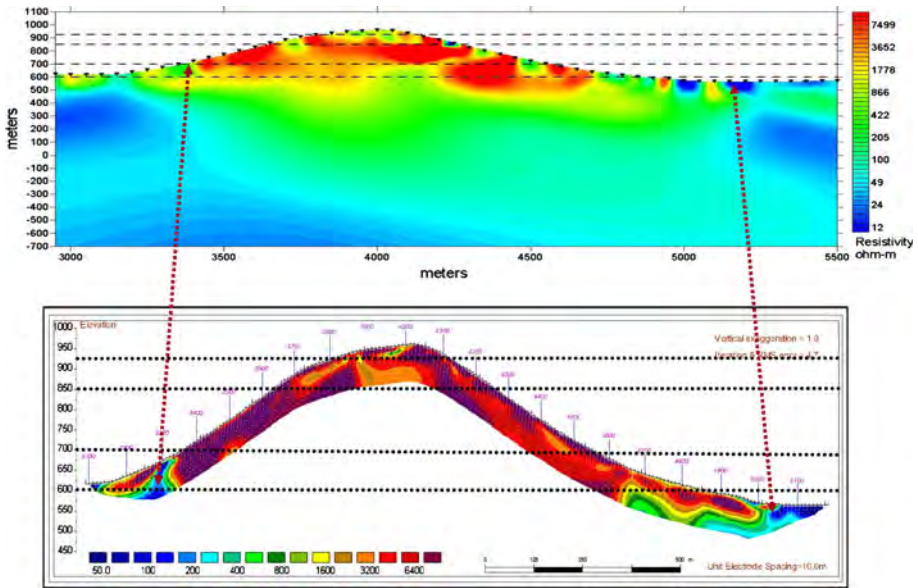


Fig. 6 Examples section of MT and DC resistivity data for complex terrain (Zerilli 2002). The top shows the MT section and the bottom the DC resistivity section, which was used to define near-surface variations to place shot points with better coupling to the subsurface

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

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

295 3 The Drivers of Technology

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

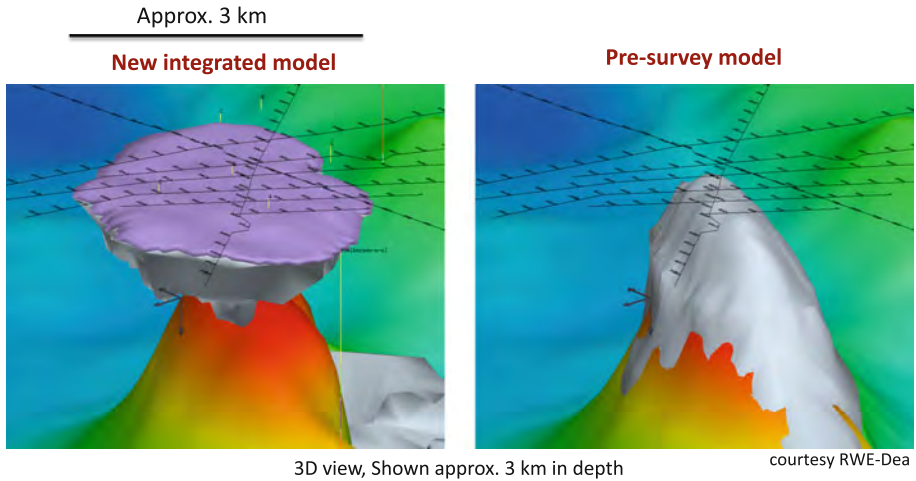


Fig. 7 Example of a subsalt interpretation using MT. On the *right side* is the interpretation without the MT and on the *left* after the MT survey, interpretation and integration (after Buehnemann et al. 2002)

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

307 Where will the next markets be? I suspect one will be in the shale reserves area, and I
308 will outline my reasoning as follows. Already we know that the shale reserves are very
309 large and can provide the USA with energy for an additional 100 years. Thus, the market is
310 there. Shales reserves means in many cases thin laminated sand–shale sequences or tur-
311 bidities. In logging terms, these used to be called ‘low resistivity–low contrast pays’. The
312 3D induction log allows now to quantify them by measuring electrical anisotropy. This
313 means that shale plays require electrical anisotropy measurements. Since the sands are thin
314 and resistive, and resistive thin layers are found with electric dipole CSEM only, it will
315 require an electric dipole transmitter. If laminated, the laminations are usually 1 cm to 1
316 inch thick, so far below the resolution. This means the shale package must be sufficiently
317 thick (let us say several 10 s of meters at least) to be seen by surface methods. The sand
318 holds the oil, and the resistive sands can be seen through vertical current flow only. In an
319 exploration scenario, there is often no well and one must derive educated estimates and
320 update them as information becomes available. This concept is confirmed by the fact that
321 already one contractor is applying DC resistivity and MT to the problem.

322 We selected the Bakken shale oil play as an example, where we wanted to demonstrate
323 the value of measuring EM and concluding reservoir behavior from it. We reduced a model
324 from the well log shown in Fig. 8 using the cumulative conductance/transverse resistance
325 averaging described by Keller and Frischknecht (1967), selected Long Offset Transient
326 ElectroMagnetic (LOTEM) with inline electric field layout and modeled first full fluid
327 substitution from oil to brine (Strack and Aziz 2012). This yielded an anomaly of 6 % and
328 clearly showed the thin resistive layer effect in Passalacqua (1983) and Eadie (1980) (the
329 same effect is the basis for the marine EM direct hydrocarbon indicator (DHI) anomaly).
330 The survey layout parameters used were: 9 km offset between transmitter and receiver,
331 source length—500 m, source current 150 Ampere, and receiver dipole length 1 m. A



332 horizontal well scenario is the standard way of developing a shale reservoir. In order to
333 significantly improve the production from the low permeability zone as in gas shale and
334 tight gas reservoirs, accurate well bore positioning is crucial to optimizing the production
335 while keeping drilling cost at minimum. This key problem requires extensive use of
336 logging-while-drilling modeling and advanced geosteering technique based on electro-
337 magnetic methods. The data include gamma ray, resistivity, density-neutron and sonic. The
338 real-time data are compared with the model to produce a cost-effective solution in driving
339 the well bore to the target and keeping it within the tight and dispersed reservoir. The
340 availability of high-resolution azimuthal resistivity logging-while-drilling imaging tool
341 along with 100 % borehole coverage has brought the fracture characterization and for-
342 mation evaluation to a higher level in unconventional plays.

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

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

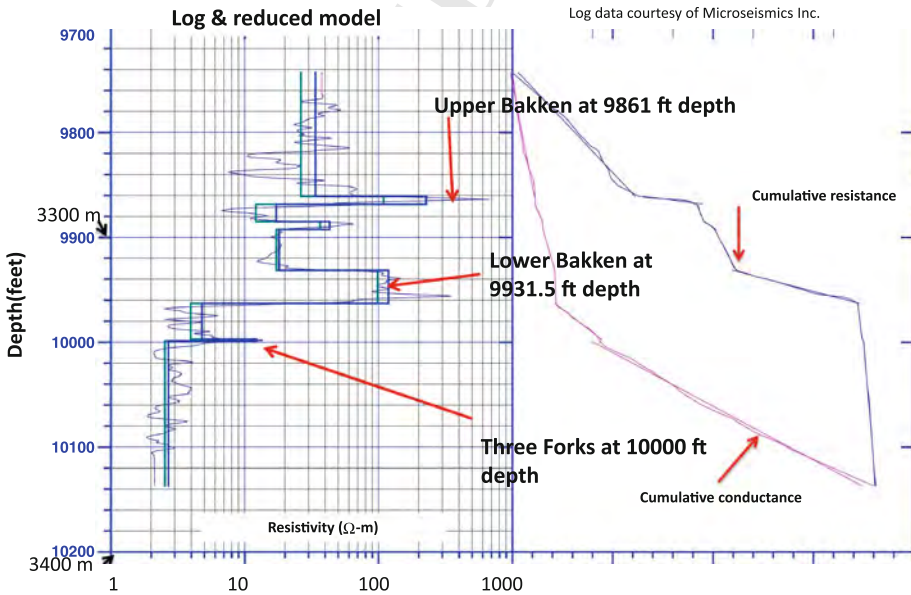


Fig. 8 Example Bakken well log (courtesy of Microseismic Inc.) showing the reservoir layers. All of them are clear resistors. On the right are the cumulative conductances [$\text{Sum}(\text{conductivity} \times \text{thickness})$] and resistance [$\text{Sum}(\text{resistivity} \times \text{thickness})$]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

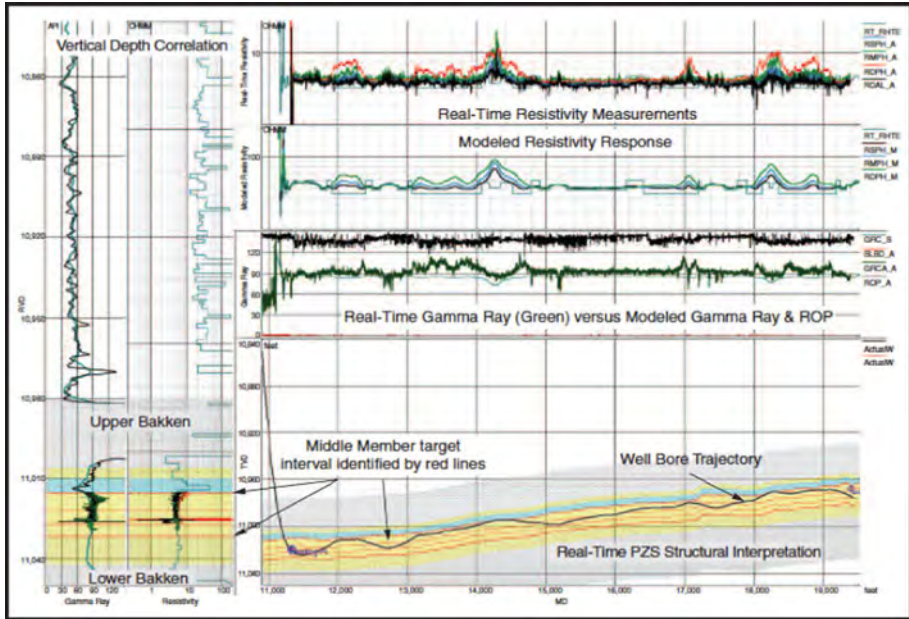


Fig. 9 Correlations displaying logging-while-drilling measurements utilized for geosteering decision at Bakken formation. The measurements along with other geological information from offset wells assist in placing the well bore in the right position along the trajectory without drilling into the limestone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

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

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

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



CSEM time lapse: ALL 3 reservoirs, 10% depleted, horizontal well

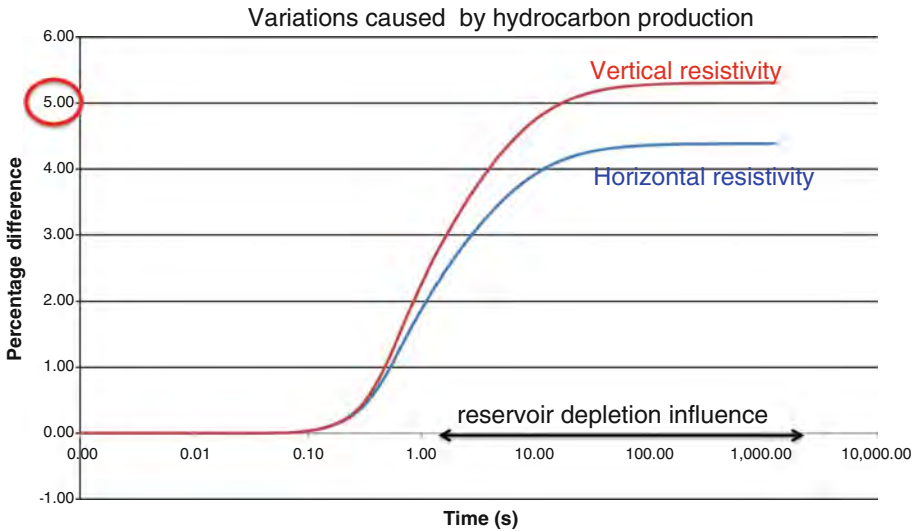


Fig. 10 Percentage difference for vertical and horizontal resistivities for a horizontal well in the Bakken after 10 % depletion. The anomalous response between oil saturated and depleted is still in the order of 5 % as marked in the figure

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

385 Only limited case histories have been published (Wirianto et al. 2010, Ziolkowski 2010)
 386 as the industry had over the past 20 years difficulties to harness a new business model
 387 where the oil companies own the equipment and services are provided locally (Strack
 388 2010). One of the examples with field data is from Hu et al. (2008). They monitored with
 389 time domain the flooding of a reservoir. The results are shown in Fig. 12. There we have
 390 the difference in apparent resistivity displayed in percentage.

391 In this case, the reservoir was shallow and surface methods worked. In many cases, the
 392 time-lapse anomaly from the surface is very small and this forces us to go to the borehole
 393 (Strack 2003a, b, 2004). When including the borehole, you may ask yourself whether you
 394 prefer receiver or transmitter in the borehole. Clearly, for signal-to-noise considerations,
 395 you will want to move the receiver as far away from the noise as possible. Also, in a desert
 396 environment, making electric field measurements may become tricky. Colombo et al.
 397 (2010) showed that, in principle, you could design a project that would map water flood in
 398 a 2.8-km-deep reservoir with intermittent thick resistive anhydrite layer. The difference
 399 section (bottom images) and reservoir flood snapshots in time are shown in Fig. 13. The
 400 survey setup is shown on the right of the figure. The color difference plots between of
 401 predicted (from reservoir simulator) flood fronts are shown at the bottom of the figure. It
 402 can be seen that the anomaly moves along with the oil front movement (the red maximum
 403 moves to the right where the oil remains). Again, this is an area of increased market
 404 activities (Dutta et al. 2011), and we can expect in the near future some case histories.

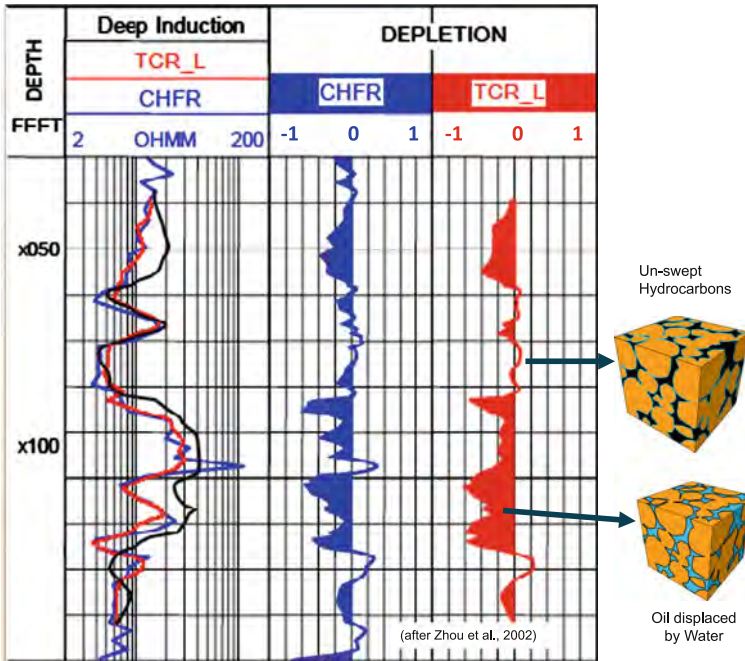


Fig. 11 Example of time lapse through-casing resistivity measurements (after Zhou et al. 2002). On the *left side* are the through-casing resistivity measurements [TCR_L (through-casing resistivity—long spaced) and CHFR (cased hole formation resistivity)] in addition to the deep induction log, which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

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

412 4 Inhibitors of Technology

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

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

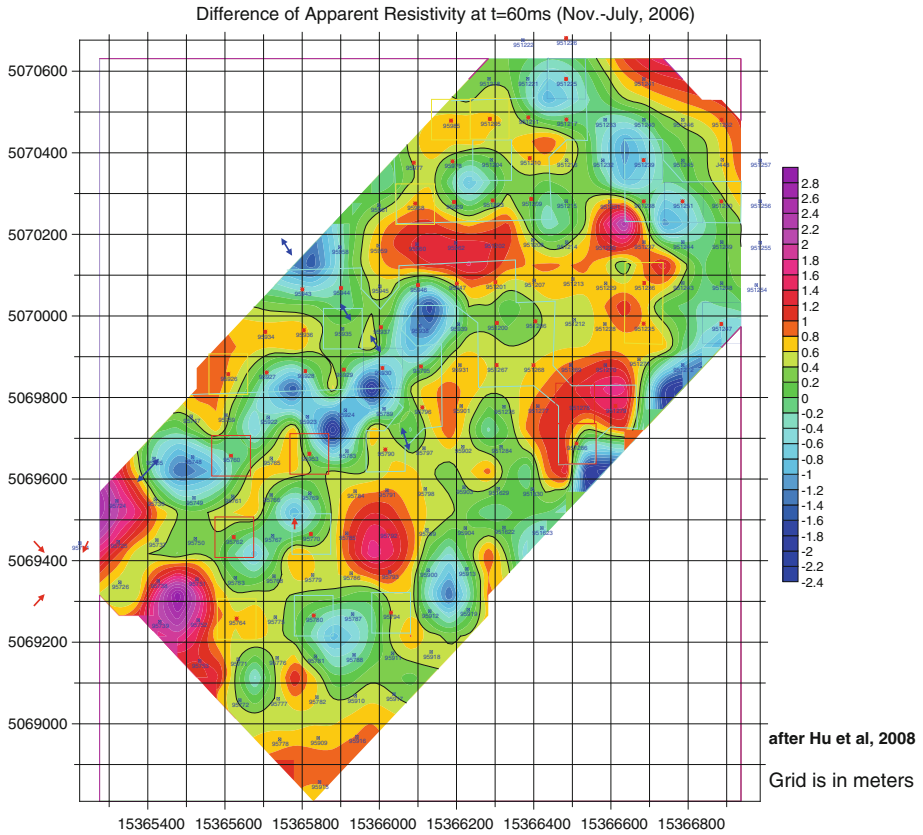


Fig. 12 Percentage difference of time domain electromagnetic time-lapse measurements (Hu et al. 2008)

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

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

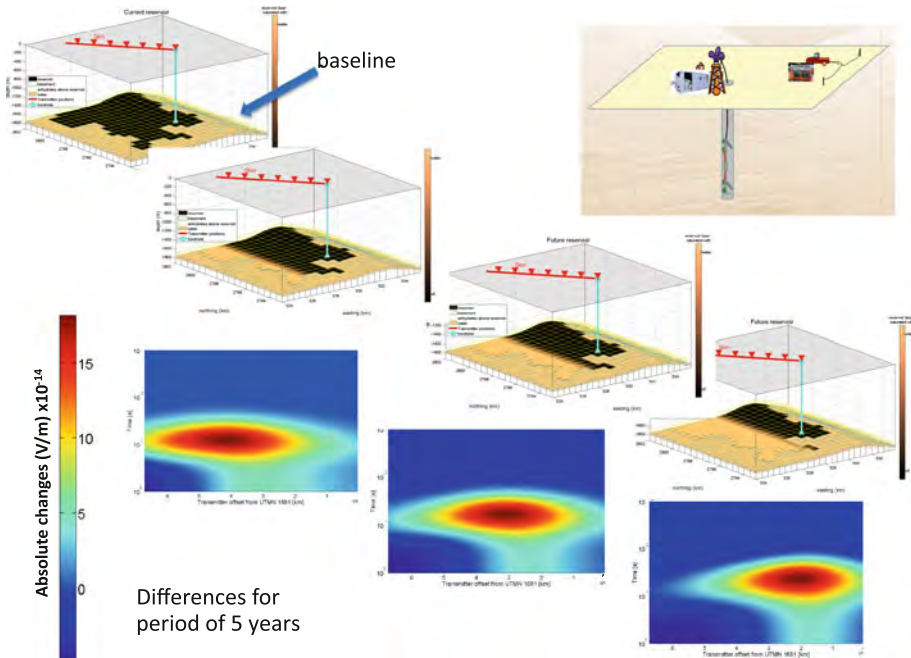


Fig. 13 Reservoir simulator results (*center*) and difference sections for surface-to-borehole experiment. The survey layout is on the *top right* (after Colombo et al. 2010). The reservoir is at about 2,800 m depth. In the center are horizontal slices through the reservoir shown in dark the movement 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)

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

450 Not included is lack of opportunity or funding as, for experienced researchers, over-
 451 coming this is the opportunity on hand.

452 5 Future

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



- 457 • Clearly *hardware cost* is coming down and will come down more. The past 2 years
458 reduced EM system cost by 60 %. Another 50 % and more is needed to make EM
459 attractive to seismic geophysicists. The driver will be that we need more data, which
460 means cost per data point must come down but total hardware expenditure will go up.
461 • *Denser measurements* and higher data redundancy. As with seismic, spatial sampling
462 must go much higher than the Nyquist frequency. It does not help to look with MT for
463 50-m intrusions with 1-km station spacing (this means we are still under-sampling).
464 Higher spatially oversampled measurements will be the standard.
465 • *Operational decisions* will drive EM applications, mainly to improve seismic
466 acquisition (static, complex structure and topography and shot hole optimization),
467 but also for site investigations, environmental certifications, etc. This will be a big
468 growth area as it immediately adds to the bottom line.
469 • *Shale applications*: Slowly, even the seismic geophysicists in oil companies are
470 realizing that EM could contribute to solving their problem. A pilot demonstration is
471 still outstanding, but I have no doubt this will happen in the next 12–24 months. The
472 potential benefits are simply too big.
473 • *Reservoir monitoring applications*: Slowly, we see the first case histories and some oil
474 companies are pushing this openly. The industry will adopt better business models to
475 match this, and the technology will be provided as it is already there.
476 • In the *borehole*, we will see even more emphasis on geosteering. The more information
477 we have close to drilling, the less formation evaluation we have to do afterward.
478 • The *marine environment* will further mature, but we will see a trend to services integration
479 as has happened everywhere else. 3D acquisition will be the standard, and full integration
480 of ALL EM methods will be the normal product (not just CSEM or electric fields).
481 • The *patent space* will become more diverse in terms of methods. Geographic loop holes
482 will become less important as violators will be caught in different jurisdictions as
483 globalization progresses.
484 • There will be more *integration with seismics* forthcoming shortly as some progress
485 happened since 1990 (Strack and Vozoff 1996). We still do not have routine joint
486 seismic/EM acquisition or processing and only limited proposals for integrated
487 interpretation. Given the increased request for this (Harris et al. 2009; Gao et al. 2011;
488 Ellis et al. 2011), we can only hope to see more integration in the next few years.

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

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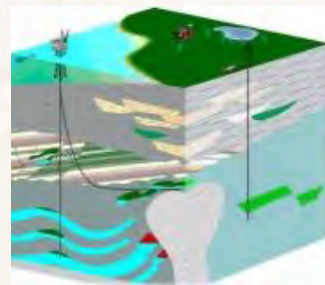
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