ADVANCING EARTH AND SPACE SCIENCE

Perspectives of Earth and Space Scientists

FEATURE ARTICLE
10.1029/2019CN000123

Perspectives on Marine Electromagnetic Methods

Steven Constable[1]

[1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

Key Points:
- Marine electromagnetic methods form important tools for the study of plate boundaries and other offshore geology
- The development of marine electromagnetic methods benefited greatly from their use in offshore hydrocarbon exploration
- Today, almost any land-based use of electromagnetic methods can be taken offshore

Correspondence to:
S. Constable,
sconstable@ucsd.edu

Citation:
Constable, S. (2020). Perspectives on marine electromagnetic methods. *Perspectives of Earth and Space Scientists*, *2*, e2019CN000123. https://doi.org/10.1029/2019CN000123

Received 22 AUG 2019
Accepted 30 APR 2020

Abstract Marine electromagnetic methods form important tools for the study of offshore geology, particularly at plate boundaries such as mid-ocean ridges, subduction zones, and the boundary between the lithosphere and asthenosphere, because electrical conductivity is strongly dependent on water content, partial melt, and temperature. Very early development of electromagnetic methods in the oceans was driven by military interest in marine communication and detection, and geological applications soon followed. Around the turn of the century, what was originally a niche discipline expanded dramatically when the hydrocarbon industry embraced magnetotelluric and controlled-source electromagnetic methods as aids to deep-water exploration, driving a significant improvement in instrumentation and interpretation software. This greatly enhanced the imaging capabilities of these methods, and led to an expansion of their academic use both in plate boundary studies and newer applications such as gas hydrate studies, offshore groundwater mapping, and others.

Plain Language Summary Although geophysical electromagnetic (EM) methods have long been used extensively on land to study and explore continental geology, widespread offshore use of EM methods only started early this century, largely as a consequence of huge investments by the oil and gas industry. Although industry use of marine EM prospecting has recently contracted, it has left a lasting legacy of equipment and software being used for academic studies spanning plate boundary tectonics, permafrost and gas hydrate, groundwater, geothermal resources, and other applications. The author was involved in much of this story and relates it in this contribution to Perspectives of Earth and Space Scientists.

1. Introduction

Because electrical conductivity varies by many orders of magnitude in crustal and mantle rocks, and is sensitive to the nature of pore fluids, temperature, and mineral chemistry, geophysical methods using natural and man-made sources of electromagnetic (EM) energy have been in use for almost a century. Although EM methods have intrinsically lower resolution than seismic methods, they can image geology that has little or no seismic signature and are the tool of choice for mineral, geothermal, and groundwater exploration, among other things. Electrical conductivity can tell you a lot about the rocks beneath the surface: how porous, how hot, how molten, how frozen, and how saturated with hydrocarbons they are. Geophysical EM methods can be divided into the magnetotelluric (MT) and controlled-source (CSEM) techniques. The energy source for the MT method is the natural fluctuation of Earth's external magnetic field caused by the solar wind. In CSEM measurements a man-made source of EM energy is used. Magnetic transmitters are often used on land, but in the ocean it is easiest to pass an electric current through the seawater. In both cases magnetic and electric fields are measured by recorders (receivers) in the air, on land, or on the seafloor, the recorded fields being proportional to electrical conductivity. Figure 1 illustrates these two approaches as used in the marine environment.

Although the earliest marine EM studies were driven by military interest in vessel and mine detection, among other things, the geophysical story starts in the 1970s, when an oceanographer called Charles (Chip) Cox wanted to know the electrical resistivity of the oceanic crust and upper mantle, in order to convert seafloor electric field measurements to ocean water flow (he needed to calibrate how much induced electric current stays in the seawater, and how much leaks into the seafloor). To do this Chip developed the first instruments to make seafloor MT and CSEM measurements. Within a few decades, the oil and gas industry was spending hundreds of millions of dollars a year using Chip's methods in the search for offshore hydrocarbons, and today marine EM techniques are considered part of the standard tool kit for the study of offshore geology. I joined Chip as a postdoc only a few years after he made the first marine CSEM measurements, so although I was not quite around from the very beginning, I have had a front-row seat as

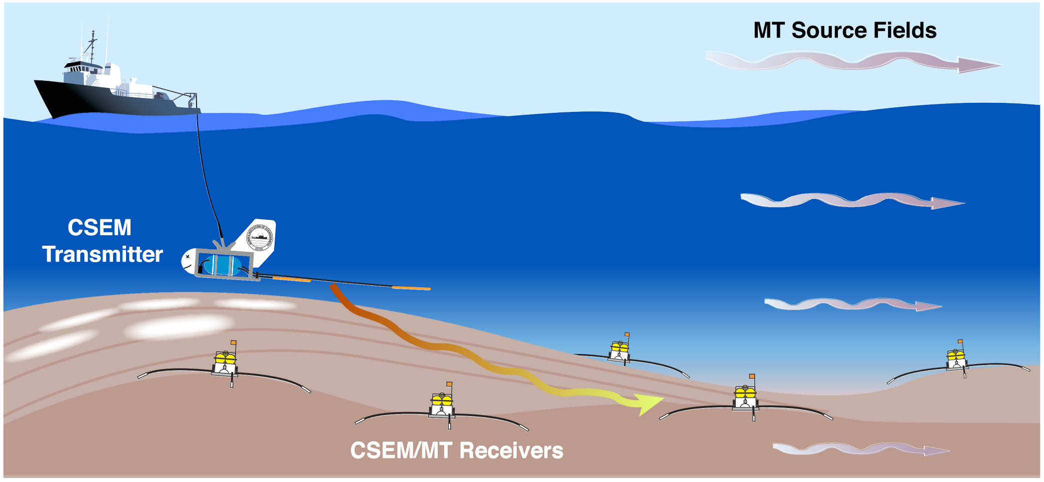

Figure 1. Concept diagram for marine EM methods: Magnetotelluric (MT) fields originate in the ionosphere and magnetosphere and propagate into the ocean and seafloor, inducing electric fields as they dissipate. Seafloor measurements of fluctuations in the magnetic and electric fields provides a measure of conductivity. Man-made (CSEM) EM signals are produced using a transmitter, which is towed close to the seafloor to prevent loss of signals in the conductive seawater. EM energy propagates through the seafloor to the receiver instruments, again providing a measure of conductivity.

marine EM methods have blossomed from obscurity to, at one point, stardom. Here I will tell you this story. It is a personal story, not a complete history or a comprehensive review—I have covered much of that in my academic papers. Although incomplete, my story touches on most of what transpired, and I hope the reader will find it enlightening and possibly entertaining. When we write our work up for scientific journals, we pretend that our science is an orderly process of hypothesis-experiment-conclusion, even though we all know that is mostly rubbish. Science is a result of accident, opportunity, luck, circumstance, who will fund you, who will work with you, and so forth. This story is about that part of science.

2. Beginnings

My career in marine EM methods was perhaps not entirely accidental, but close to being so. It certainly was not well planned. I suspect this is more often the case than not, even if people think they are in control of their destinies. Two events in particular served to steer me in the direction I ended up taking.

I did my undergraduate degree in geology at the University of Western Australia (1975–1979), but having grown tired of peering down a petrological microscope, I took a fair number of physics classes, and for my honors project collected and interpreted gravity data under the guidance of the resident geophysicist, a seismologist named Hugh Doyle. I became interested in paleomagnetism, so I decided I wanted to do a PhD at the Australian National University (ANU) under Michael (Mike) McElhinny, one of the grandfathers of paleomagnetism. I landed a scholarship and Cathy Constable, my fiancée at the time, and I headed to Canberra in my Morris Mini.

When I arrived at ANU and met my future PhD advisor, Mike gave me a list of potential projects, maybe a dozen of them, all paleomagnetism except the top one, which was deep crustal electrical sounding. Mike said that he was worried that his palaeomagnetism students were not finding jobs, and although I could choose any project, he hoped I would work on electrical sounding. I figured I would get more support doing the project my advisor wanted over what I wanted, so I went along with it. That was event number one.

Mike knew very little about electrical methods—the project was based on something a friend of his in South Africa had done—so I was largely on my own to develop and build all the equipment and software, but this was good training and, indeed, Mike supported me generously with money and technician time. The then Director of the Research School of Earth Sciences, Ted Ringwood, took a dim view of Mike supervising this project, but he figured that Ted Lilley, a faculty member who worked in MT methods, would help make things work. Later, Phil McFadden, another paleomagnetist, joined Mike at ANU and was also helpful.

Things did work, but slowly, and during my qualifying exam, one of my examiners, Anton Hales, said that I "might become one of those rare birds, PhD (failed)." Toward the end of my studies, about the time I was thinking about postdocs (late 1982), Ted Lilley came back from a conference he had attended in Canada and dropped an index card on my desk taken from the message board at the meeting. On it was a hand-written note saying that Charles Cox was looking for a postdoc to work on marine electromagnetism at the Scripps Institution of Oceanography. This was event number two.

I had barely heard of Scripps and knew nothing about marine EM. I could find only one paper on the subject (Young & Cox, 1981), written by Chip and a student, in a new journal I had never heard of, called *Geophysical Research Letters*. Our library did not carry it. Cathy by then *had* become a paleomagnetist after doing a masters with Mike, and Scripps was in the process of hiring a paleomagnetist named Lisa Tauxe, who presumably would be a good person for Cathy to do her PhD with (it did not happen that way: Perhaps one day Cathy will tell her story in this journal). I applied for and got the postdoc. I learned later that Anton Hales had written me a very supportive letter, which carried a lot of weight since he was well respected at Scripps, thus making up for his earlier skepticism of my future potential.

3. Scripps

Apart from my family's emigration from England to Australia when I was 9 years old, I had never traveled internationally, and relocation to California in 1983 was a big leap. I would not say that everything was new—the eucalyptus groves planted all through the university campus were reassuringly familiar—but there was an awful lot to learn. We knew one person in all of San Diego, a chemist who was a contemporaneous undergraduate at UWA, but people were nice and we adjusted well enough. I quickly started to learn the ropes (literally) from Chip (nobody used Charles), everything from tying a bowline to time series analysis (he once told me in passing that he had developed the fast Fourier transform before Tukey did, but had not bothered to publish it—I think this was likely true). As a once-geologist, now surrounded by physicists and mathematicians turned oceanographers and geophysicists, I was somewhat out of my depth. When I first walked the halls of the Institute of Geophysics and Planetary Physics (IGPP), I read the door name plates of Robert (Bob) Parker, George Backus, and Freeman Gilbert, all in a row. Having struggled, unsuccessfully, to understand Backus-Gilbert inverse theory as a student, I was completely caught off guard and in awe. This was how little I knew of Scripps.

Although my mathematical abilities were wanting, I was good at building stuff, which was pretty much the stage of Chip's work at the time. Part of Chip's funding came from the Navy to study the propagation of EM energy through the oceanic lithosphere and the marine acoustic noise environment, both relevant to submarine operations. We carried out a successful experiment in 1984 that achieved the first of these goals, showing that the lithosphere was more resistive than previously thought, which resulted in my first, and for a very long time only, *Nature* paper (Cox et al., 1986). Getting Chip to follow through and submit revisions to get it published was quite a struggle—see the comment on the FFT above. There are at least two papers that Chip submitted but never revised, one of which was the original description of his marine CSEM instrument system, which I later got permission to put online (Cox et al., 1981).

Our 1984 results showed that Chip, and others using EM measurements for ocean current transport, did not have to worry much about their signals leaking into the seafloor, but another aspect of our results was a little contentious. Chip and others had shown that the effect of coastlines on marine MT data extended a distance offshore that was proportional to the resistivity-thickness product of the oceanic lithosphere (Cox, 1980). When you plugged in the numbers from our study, you get a distance of thousands of kilometers—essentially all the ocean is subject to the coast effect. There was a concern that this would negatively impact funding for marine MT, and so no mention of this was made in the *Nature* paper. During a visit to ANU, a few years later, I worked on this issue with Graham Heinson, then a student of Ted Lilley's. We modeled the coast effect for ocean basins and compared the results to published marine MT data, which indeed suggested that the data were influenced by the distant coastlines (Heinson & Constable, 1992). This did not go down well with the established marine MT community (Constable & Heinson, 1993; Tarits et al., 1993). Although contentious at the time, once this effect was recognized it could be included in the interpretation, and marine MT methods have flourished in spite of these early concerns.

Chip got involved in marine EM through oceanography, and by coming to work with him, my Scripps position was in Physical Oceanography. After a few years it became clear to me that I had no future in the oceanography division at Scripps and that Chip was not the sort of person to engage in the politics needed to

10.1029/2019CN000123

change that. In one of my few active career decisions, early in a 3-week cruise for which John Orcutt, then IGPP Director, was chief scientist, I asked John if I could move to IGPP. I got no immediate reply, but just before the cruise ended John asked me how much lab space I would need. I moved to IGPP in 1988 and became its director in 2016.

4. Cambridge and Southampton

Sometime in the mid-1980s Martin Sinha, from the University of Cambridge, visited Scripps to learn about our marine EM program. Martin was a seismologist who studied mid-ocean ridges, and he had decided that using marine EM methods made a lot of sense if you are looking for magma chambers and hydrothermal systems. To this end, he was able to get a Natural Environment Research Council (NERC) 5-year proposal funded to develop the appropriate equipment in the United Kingdom. One important difference from the Scripps gear was the way the deep-towed EM transmitter was built. Chip's transmitter was designed to be dragged on sedimented seafloor, the closest of which was about 20 km from the ridges. Martin designed a transmitter that could be "flown" above the seafloor, and thus could be operated over the rugged outcrops of volcanic rock at the ridge axis (Sinha et al., 1990). The last use of Chip's transmitter was in 1988, on the "PEGASUS" experiment, which again addressed the resistivity structure of the oceanic lithosphere (Constable & Cox, 1996). After PEGASUS, our marine EM experiments were a series of collaborations between Scripps and Cambridge, and later Southampton Oceanography Center after Martin moved there. These projects targeted mid-ocean ridge structure and were carried out on the East Pacific Rise, the Reykjanes Ridge, and Lau Basin between 1989 and 1995, using a combination of the UK transmitter and UK and Scripps receiver instruments, with funding from NERC and (sometimes) the U.S. National Science Foundation (NSF). Lucy MacGregor joined Martin's group as a PhD student in 1993 and worked on the Reykjanes Ridge data, graduating in 1997. After a brief postdoc with me at Scripps to work on the Lau Basin data, during which time she developed the first practical two-dimensional CSEM inversion code, Lucy returned to positions as a research fellow in Cambridge and then as a NERC research scholar in Southampton. Among other things, Lucy then worked with Martin on developing ideas for subbasalt imaging using marine CSEM methods, a difficult seismic target, as part of the LITHOS consortium of oil companies. We shall return to Lucy and Martin later.

The East Pacific Rise cruise in 1989 was the last marine EM cruise that Chip participated in. He returned to his first love, wave microstructure at the ocean surface, which he worked on until his death in 2015. Chip had started working on marine EM in the 1960s, had pioneered both marine MT and marine CSEM methods, supported my entry into the field for about a decade, then left me to my own devices. I consider myself most fortunate to have been given that support, and then that freedom.

5. Industry MT

In the 1990s it became extremely hard to fund my work from the NSF, perhaps because of Chip's retirement, but probably because of a failed attempt by me to develop a seafloor tiltmeter instrument with NSF funding. This was a problem, because until 2015 my Scripps position was partially soft money, and of course my students and techs needed support as well, so when in early 1994 I received calls from both Arnold (Arnie) Orange and Michael (Mike) Hoversten, separately inquiring about my ability to carry out marine MT measurements on the continental shelf for oil industry targets, I was quick to engage. Arnie was a land geophysical contractor who had been asked by a client if offshore data collection was possible, and Mike, who had worked for BP but was then working at Lawrence Berkeley National Laboratory, had run some model studies which suggested that MT data could help find the base of salt in the Gulf of Mexico, which at the time was difficult to do with seismic data alone.

Jean Filloux, an ex-student of Chip's, had continued his marine MT studies, and because it seemed clear that U.S. funding would not support more than one group, I had not worked in marine MT myself. I did, however, collaborate with Graham Heinson, who was then working with Antony White at Flinders University, South Australia, to do a few marine MT projects. I had some of Graham's fluxgate instruments in my lab at the time Arnie and Mike approached me, but it became apparent that the industry targets needed higher-frequency data than the current marine MT instruments could collect. I figured we needed induction coil sensors and was able to borrow some from EMI Inc., a company that Mike was associated with, and Arnie provided money to build seafloor pressure cases for them. We fitted the magnetometers to a Scripps seafloor electric field CSEM receiver and in April 1994 deployed it on an opportunistic cruise in the San Diego Trough, a testing ground in easy reach of Scripps, with a land reference instrument installed at IGPP's Piñon Flat Observatory. The results were good, and we took them to Chevron and Texaco, which funded continued development of the method.

The timing was right. I had recently started working with John Orcutt, who had Navy funding to develop a new generation of seafloor seismic data logger. We called this the L-CHEAPO (Low-Cost Hardware for Earth Applications and Physical Oceanography), which aimed to reduce the size, cost, complexity, and power of previous instruments. It was during the first test of the L-CHEAPO that we were able to deploy the prototype MT instrument described above. With industry funding as part of the mix, we developed the L-CHEAPO into a versatile, dual-use instrument that could be used both for MT and seismic data collection.

There is a lot more to a functional MT instrument than the data logger, and between initial funding in 1995 and our final data acquisition in 2001, it took repeated trips to a salt body on the Gemini prospect in the Gulf of Mexico to develop a viable marine MT instrument. Our industry sponsors were patient and kept funding us as long as there was some progress to be seen, something hard to do with NSF support. Bill Abriel of Chevron was our champion within the consortium of companies we had put together (BP and BHP Petroleum came in later), and he kept the pressure on to keep the funding flowing. We had another supporter, Andrea Zerilli of Agip, Milan, who was an enthusiastic proponent of marine MT and funded two surveys offshore Sicily in 1995 and 1996 to map carbonates in the Mediterranean, yet another geological target that was difficult to study using seismic methods alone.

Arnie licensed the MT instrument and rented equipment from Scripps to offer proprietary surveys to the oil industry through his company, Arnold Orange Associates (AOA). I used the rental revenue to build more instruments, and in this way bootstrapped a reasonable-sized instrument fleet, but it was a slow process and AOA could not take on big or simultaneous contracts. In an effort to capitalize the instrumentation, AOA sublicensed the MT receiver to EMI, in the hope that this company, which built land MT gear, would invest in a fleet that AOA could rent. But EMI did not want to invest until AOA had the contracts. So there was a stalemate that went nowhere and eventually AOA took the sublicense back.

It is notable that industry approached Scripps to develop commercial marine MT, rather than the other way around, and given that marine MT had been around for some time, one might ask why only then. The answer is probably that deep-water (>1,000 m) drilling only started around 1995, and deep-water drilling is very expensive, measured in hundreds of millions of dollars, so there was some incentive to have a new type of data in areas where the seismic method was prone to difficulties, such as salt, carbonate, and volcanics.

6. Industry CSEM

In April 1984, shortly after I had arrived at Scripps, Chip hosted a meeting for oil industry representatives with a view to developing marine CSEM methods for exploration. Four companies (Amoco, Arco, Elf, and Sohio, all now defunct) funded our work but quickly abandoned the project when the price of oil collapsed in 1986. This was probably just as well. Water depths for exploration at that time were only a couple of hundred meters, and Chip had built some new equipment for use in shallow water, but the frequency of operation (64 Hz) was too high to reach very far into the seafloor sediment.

In late 1998, Terje Eidesmo and Svein Ellingsrud, two scientists from Statoil in Trondheim, visited Scripps to talk about marine EM, ostensibly our marine MT work, and we bounced around ideas for doing a subbasalt MT survey off the Faroe Islands. Things took a different turn in late 1999, when they invited me to visit Trondheim as a consultant to review an internal research program. When I got to Trondheim I discovered that they had worked out that one could use marine CSEM to directly detect oil and gas reservoirs. They were new to EM methods and were unaware of a CSEM modeling code that was freely available at that time. I had a version of this code on my laptop, which I ran to show that their conclusions were basically correct, which is what I told them in my report. They were keen to take the idea into the field, so I suggested that with Martin Sinha's transmitter and my receivers, which included the new continental shelf MT instruments, we could collect the appropriate data. This got the ball rolling, and in a year we were sailing south from Tenerife to Angola on the research vessel *RRS Charles Darwin*.

Meanwhile, I was also talking to Leonard (Len) Srnka of ExxonMobil, again about subbasalt MT off the Faroes, which again switched to CSEM when Len got an internal marine EM project funded as a reincarnation of EM research started by him in 1979. By November 2000 we were planning to build a fleet of 30 newly designed CSEM receivers for ExxonMobil tests off Angola in early 2002, again using the *Charles Darwin* and again using Martin's transmitter. ExxonMobil was running 3-D forward simulations of reservoir targets using a modification of Greg Newman's EM modeling code.

The Statoil and ExxonMobil projects off Angola were successes. The Statoil survey over a known oilfield called Girassol produced the expected factor of 10 increase in electric fields over the reservoir. ExxonMobil surveyed several drilled and undrilled prospects to verify the CSEM method, one a major discovery called Kissanje and an undrilled exploration commitment in a nearby block. Kisannje, like Girassol, produced the expected response. The predrill prospect produced a response consistent with a dry hole, which indeed it was when drilled soon after.

Statoil published results in 2002, with articles in *First Break* and *Leading Edge,* two industry monthlies (Eidesmo et al., 2002; Ellingsrud et al., 2002), and an abstract for the EAGE conference in Florence. This represented the beginning of a gold rush—that same year three contractor companies were formed to provide commercial CSEM services: EMGS, which was spun out of Statoil; OHM Surveys, which was spun out of Southampton with Lucy MacGregor as one of the founders; and AOA Geomarine Operations (AGO), which was spun off Arnie's company AOA. AGO had a contract with ExxonMobil that gave them access to the 30 receivers that Scripps had built, and still had the license to the Scripps MT receiver (which was built from a CSEM receiver, you may recall). OHM built versions of the Southampton CSEM receivers developed for the mid-ocean ridge work, which were originally based on the Scripps design. EMI, which had access to Scripps circuit diagrams and machine drawings when it had the AOA sublicense, provided instruments to EMGS. Scripps also commissioned a new CSEM transmitter that year, with funding from ExxonMobil. Like Southampton's, it was designed to fly above the seafloor, and AGO started to build a much larger transmitter based on this design, which would be called Orca. OHM had access to Martin's transmitter, and EMGS contracted Siemens, the power electronics company, to build a 1,000 amp transmitter for them.

It was not hard to predict that the market for commercial marine EM was not going to support three contractors, but that did not stop anyone, and the next 5 years were heady times. In 2004, ExxonMobil's marine EM program made the front page of the *Wall Street Journal,* complete with a picture of Len. MorganStanley predicted that CSEM revenues might reach better part of a billion dollars in a few years, and AGO was bought by Schlumberger, the large oilfield services firm. Several custom-designed ships were built. I went to one Society of Exploration Geophysicists (SEG) meeting and had a tiny taste of what being a rock star might be like, with people I had never met recognizing my name tag. The first time I presented marine EM at a SEG meeting in 1986, my talk was attended by perhaps half a dozen people, most of whom were speaking in that session. Now we had a special session on marine EM that packed the largest conference room available. Over cocktails I was offered crazy amounts of money to consult for a company that had recently started business (I chose to keep my academic job). It was quite wild, and a lot of fun, while it lasted.

There were some less pleasant aspects. Statoil had filed a few patents for the use of marine CSEM in hydrocarbon exploration and later started to exercise them to try and limit competition. The University of Southampton had filed patents too, with similar claims, and the ensuing court battles took an emotional toll on Martin Sinha, who was called to defend the Southampton patents, and he retired quite soon after that. Many, myself included, thought that what Statoil had patented was prior art, and Schlumberger tried to make that case in court, with mixed results. Colleagues from the academic EM community ended up on both sides of the courtroom as expert witnesses. I stayed out of the fray—I had friends on all sides.

The commercial marine EM market started to deflate in 2010 or so, the year when Schlumberger got out of the business and laid all their gear up. In 2012 OHM got absorbed by EMGS. PGS got into the game around 2010 with a surface towed, joint seismic and EM system, but then left in 2017. Why the boom and bust? Well, marine CSEM was clearly oversold during the early years of this century, but that is not uncommon with new technologies in the oil patch. I do not think the patent litigation helped, as it damped down competition based on cost and quality. But there may be underlying issues. The great value in marine CSEM largely comes from the fact that seismic methods often mistake small concentrations of gas (“fizz gas”) for a bona fide hydrocarbon reservoir, because a small amount of gas has a big effect on seismic velocity. It takes larger oil or gas fractions, however, to affect electrical resistivity, and so CSEM data can screen for these seismic false positives. This was the case with ExxonMobil's predrill exploration target, which was fizz gas. So marine CSEM does not make money so much as it saves money, which does not quite have the same impact. And it only saves money if you do not drill, and the companies often drill anyway for a variety of reasons. Nevertheless, marine CSEM continues to see steady use for exploration, helping to prioritize drilling targets and to provide baseline information in frontier basins. It is likely that CSEM has identified reservoirs that have been missed by seismic methods. Marine MT is still used to map geological structure as an aid to exploration.

7. Back to Academia

When marine CSEM took off, I turned the Gemini subsalt MT project into an industry consortium to help fund my academic program. I had worked out that a geophysicist in an average oil company could sign off on about $15,000 without seeking approval from management, so I set the yearly membership at this level, which is much lower than most other university consortia. What I lost in quality I made up in quantity—in its heyday we had over 30 members. This provided a great source of funding for students and postdocs, with some left over to try out new ideas. I endeavored, with some success, to remain nonpartisan with all the contractors, who were all members of my consortium, but inevitably because AGO had licensed the Scripps technology (and were paying royalties to the university), early on I spent a fair bit of my time helping AGO make things work, although this ended when Schlumberger bought it.

The revenue and return on overhead that resulted from renting and selling seafloor receivers to AOA/AGO I plowed back into more receivers, eventually resulting in a Scripps academic fleet of about 70 seafloor instruments. When Schlumberger pulled out of marine EM in 2010 I started lobbying it to donate the equipment to Scripps, and I was successful in 2014. This resulted in another 100 or so seafloor receivers, and a lot of other useful ancillary kit. Through sponsorship from ExxonMobil, I initially built two 200-amp transmitters, and then upgraded to two 500-amp transmitters, one of which used a topside power supply that had been donated by AGO. Between transmitters and receivers all this amounts to about 10 million dollars worth of equipment that was paid for without government support.

It did not hurt to remind the NSF of this industry leverage when writing proposals, and my NSF funding turned around in 2001 when we got a proposal funded to look at anisotropy in the oceanic lithosphere using, along with Southampton's transmitter, some of the first L-CHEAPO receivers. In 2004 we were funded to collect MT across the East Pacific Rise using 40 receivers built with industry support and an early version of the 200-amp CSEM transmitter. In 2010 we carried out an NSF-funded project to study the subduction zone off Nicaragua using 58 receivers and the second-generation 500-amp transmitters. We were also directly funded by industry to collect publishable, academic data, and in particular we carried out a comprehensive study of an Australian gas field supported by BHP Petroleum in 2009.

This was all good, but we were barely able to interpret these large MT and CSEM data sets using the available inversion tools. I had a 2-D MT Occam inversion code that worked in the marine environment, but its structured rectilinear mesh could only approximate bathymetry. We had no 2-D CSEM inversion tools (the one Lucy MacGregor had developed was not very portable), and had to make do with 1-D inversions. We made progress this way but were not achieving the full potential of the data sets. (Industry had 2-D and 3-D codes, but they were/are all proprietary.) However, Kerry Key, who had been with the Scripps EM group from undergraduate to faculty member, was working on a 2-D joint CSEM and MT inversion program under support from the industry consortium (Key, 2016). When this code came online around 2011, we began to achieve great things. We published two back-to-back papers in *Nature* in 2013, one on the East Pacific Rise mid-ocean ridge work (Key et al., 2013) and one on the Nicaraguan subduction zone MT data (Naif et al., 2013). These publications highlighted the power of marine MT to image melt in the oceanic mantle in ways that really helped our understanding of how plate tectonics worked, and the power of marine CSEM to show us where water resides in the crust and how it gets transported during subduction.

Many papers using CSEM and joint MT/CSEM inversion quickly followed. To some extent, our work with industry had been largely invisible to the academic community outside applied geophysics and certainly those outside EM methods. With these high-profile publications and associated presentations at conferences, this started to change. We also had the resources to start expanding the marine EM toolkit beyond the deep-towed transmitter/seafloor receiver system that Chip pioneered, developing equipment tailored to the study of shallow seafloor and shallow water targets. Today, any land-based use of EM methods can now be taken offshore, including groundwater, geothermal, mining, permafrost, and tectonic applications. Some targets, such as hydrothermal vents and gas hydrate, represent purely offshore applications.

8. Musings

8.1. Who Was First?

A big issue during the patent lawsuits was that while marine CSEM clearly already existed, was applying it to the detection of hydrocarbons new and patentable, or not? When Chip died in 2015 I went through his office to make sure that Scripps did not lose anything of historical value. I came across the original copy of a research proposal by Chip, to Exxon, dated March 1981. In the proposal was the computed CSEM response for what I had taken to calling the canonical oilfield model. Interestingly, when we were seeking industry support in 1984 there was no mention of this. My memory is vague on the issue, but this was right after the famous Elf Aquitaine "oil sniffer" hoax made the news, and I think Chip did not want to be thought of as peddling electromagnetic snake oil. But clearly Chip, and Exxon, knew of the potential for direct hydrocarbon detection way back in the beginning of the 1980s.

8.2. Ignorance Is Bliss

This story is mainly about marine EM, but in working up the results from the 1984 experiment it became apparent to me that (a) nobody knew what the conductivity-temperature relationship for the upper mantle was, and (b) the parameterized inverse methods in use at that time were not satisfactory. To make progress I needed to address these two issues. For the first one I established a collaboration with Al Duba of Lawrence Livermore National Laboratory. Al had apparatus for measuring the electrical conductivity of single crystals, and I proposed putting a sample of mantle rock in it. Al told me that was crazy because there would be no way to control or even understand the reactions between the various mineral phases, but he did it anyway. To learn about the second issue I sat in on Bob Parker's inverse theory course, and one of the homework problems was about regularized inversion of a linear problem (gravity). I asked Bob if one could apply this technique iteratively to the nonlinear EM problem, and he told me that there was no convergence proof for nonlinear problems. Not really understanding, I tried anyway. Both of these rash exploits paid off. Putting a rock in Al's conductivity cell worked (Constable & Duba, 1990), and I have half a dozen well-cited papers on laboratory models of mantle conductivity. Iterative regularized inversion also worked, and the Occam's inversion paper with Bob and Cathy on this subject (Constable et al., 1987) is one of the most cited papers in the journal *Geophysics*. The morals of this story are (i) work with the very best people in the field if you get the chance, and (ii) sometimes it pays to be ignorant and try stuff anyway. It helped that the work with Al was funded from internal IGPP money, and I needed no extra funding to take Bob's class and write inversion code.

8.3. Sharing Code

It did occur to me that for a career in marine EM, where you had to build all your own equipment, write all your own code, and got ship time once a year if you were very lucky, it was a good idea to have a side gig such as lab work or theory to produce a few more papers. However, in those days I was blissfully ignorant of the rigors associated with academic advancement. During the 3 years prior to my 1990 promotion to associate level, the Occam paper is the only paper I published. Although I did not realize it at the time, this paper's early success (partly a result of me giving computer code to anyone who asked) probably saved my career.

8.4. Taking Risks

Although lack of government funding pushed me towards industry, and, indeed, without industry support I might well not have been able to remain in academia at all, taking this path involved some real risks. In the beginning I flew to Italy for a 1-day meeting with Agip to sell the idea of marine MT, using personal money for travel costs. On a number of occassions I committed to expensive field programs, which included chartering vessels, before the funding had been signed off. (The operators of the R.V. *Pelican*, in Cocodrie, Louisiana, were most helpful in this regard, and several times gave me access to the vessel on a verbal promise to eventually pay.)

8.5. Fossil Fuels

As expedient as it was, one does have second thoughts about working with the fossil fuel industry. I am as keen as anyone else to see the end of oil, and I drive an all-electric car powered by rooftop solar electricity. But the world still needs oil and gas, and will do so for some time as we make the transition to renewable energy. Although it is dangerous to argue that the ends justify the means, the instruments and software developed through my relationship with industry are being used to study blue-water tectonic problems, and also important environmental applications such as offshore groundwater, geothermal energy, melting permafrost, and gas hydrate destabilization.

8.6. Monopolies

For about the first half of my career, Chip and I at Scripps, and Martin and Lucy at Southampton, were the only people who did deep-water CSEM experiments of the type described here. This is not the sort of monopoly you want. Few people really understood the science, and funding was hard to get. It is just as well that things worked out for me at Scripps, because my applications for positions at other universities were uniformly unsuccessful. While interviewing at a prestigious university, I was told by a very distinguished professor that "we will never learn anything about the Earth from marine EM" (needless to say, I was not offered a position). I think that this misunderstanding was common at the time, although most people were too diplomatic to expose it so bluntly. It is abundantly clear to me that I have been a lot better off since the field of marine EM expanded beyond Scripps and Southampton. Now there are marine EM groups in Woods Hole Oceanographic Institution, Lamont, Kyoto, Tokyo, Geomar and BGR in Germany, NTU in Trondheim, and elsewhere. My plan is to do my best to help marine EM expand even more in the time I have available.

Acknowledgments

Besides the people and companies mentioned here, I would like to thank all the other colleagues, sponsors, students, postdocs, technicians, engineers, captains, and crews who have helped me in my career. You are too numerous to mention, but you know who you are. Thank you.

References

Constable, S., & Cox, C. S. (1996). Marine controlled source electromagnetic sounding 2. The PEGASUS experiment. *Journal of Geophysical Research*, *101*(5), 519–5530.

Constable, S. C., & Duba, A. (1990). The electrical conductivity of olivine, a dunite, and the mantle. *Journal of Geophysical Research*, *95*, 6967–6978.

Constable, S. C., & Heinson, G. (1993). In defense of a resistive oceanic upper mantle: Reply to a comment by Tarits, Chave and Schultz. *Geophysical Journal International*, *114*(3), 717–723. https://doi.org/10.1111/j.1365-246X.1993.tb07000.x

Constable, S. C., Parker, R. L., & Constable, C. G. (1987). Occam's Inversion: A practical algorithm for generating smooth models from EM sounding data. *Geophysics*, *52*(3), 289–300. https://doi.org/10.1190/1.1442303

Cox, C. (1980). Electromagnetic induction in the oceans and inferences on the constitution of the earth. *Geophysical Surveys*, *4*(1-2), 137–156. https://doi.org/10.1007/BF01452963

Cox, C. S., Constable, S. C., Chave, A. D., & Webb, S. C. (1986). Controlled source electromagnetic sounding of the oceanic lithosphere. *Nature*, *320*(6057), 52–54. https://doi.org/10.1038/320052a0

Cox, C. S., Deaton, T. K., & Pistek, P. (1981). An active source EM method for the seafloor. Scripps Institution of Oceanography Technical Report, http://escholarship.org/uc/item/7dr96489, accessed 16 June 2019.

Eidesmo, T., Ellingsrud, S., MacGregor, L. M., Constable, S., Sinha, M. C., Johanson, S., et al. (2002). Sea bed logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas. *First Break*, *20*, 144–152.

Ellingsrud, S., Eidesmo, T., Johansen, S., Sinha, M. C., MacGregor, L. M., & Constable, S. (2002). Remote sensing of hydrocarbon layers by seabed logging (SBL): Results from a cruise offshore Angola. *The Leading Edge*, *21*(10), 972–982. https://doi.org/10.1190/1.1518433

Heinson, G., & Constable, S. C. (1992). The electrical conductivity of the oceanic upper mantle. *Geophysical Journal International*, *110*(1), 159–179. https://doi.org/10.1111/j.1365-246X.1992.tb00719.x

Key, K. (2016). MARE2DEM: A 2-D inversion code for controlled-source electromagnetic and magnetotelluric data. *Geophysical Journal International*, *207*(1), 571–588. https://doi.org/10.1093/gji/ggw290

Key, K., Constable, S., Liu, L., & Pommier, A. (2013). Electrical image of passive mantle upwelling beneath the northern East Pacific Rise. *Nature*, *495*(7442), 499–502. https://doi.org/10.1038/nature11932

Naif, S., Key, K., Constable, S., & Evans, R. L. (2013). Melt-rich channel observed at the lithosphere-asthenosphere boundary. *Nature*, *495*(7441), 356–359. https://doi.org/10.1038/nature11939

Sinha, M. C., Patel, P. D., Unsworth, M. J., Owen, T. R. E., & MacCormack, M. R. J. (1990). An active source EM sounding system for marine use. *Marine Geophysical Researches*, *12*(1-2), 59–68. https://doi.org/10.1007/BF00310563

Tarits, P., Chave, A. D., & Schultz, A. (1993). Comment on 'The electrical conductivity of the oceanic upper mantle' by G. Heinson and S. Constable. *Geophysical Journal International*, *114*(3), 711–716. https://doi.org/10.1111/j.1365-246X.1993.tb06999.x

Young, P. D., & Cox, C. S. (1981). Electromagnetic active source sounding near the East Pacific Rise. *Geophysical Research Letters*, *8*(10), 1043–1046. https://doi.org/10.1029/GL008i010p01043