Marine EM,
the Past, the Present, and the Future

Steven Constable

Scripps Institution of Oceanography

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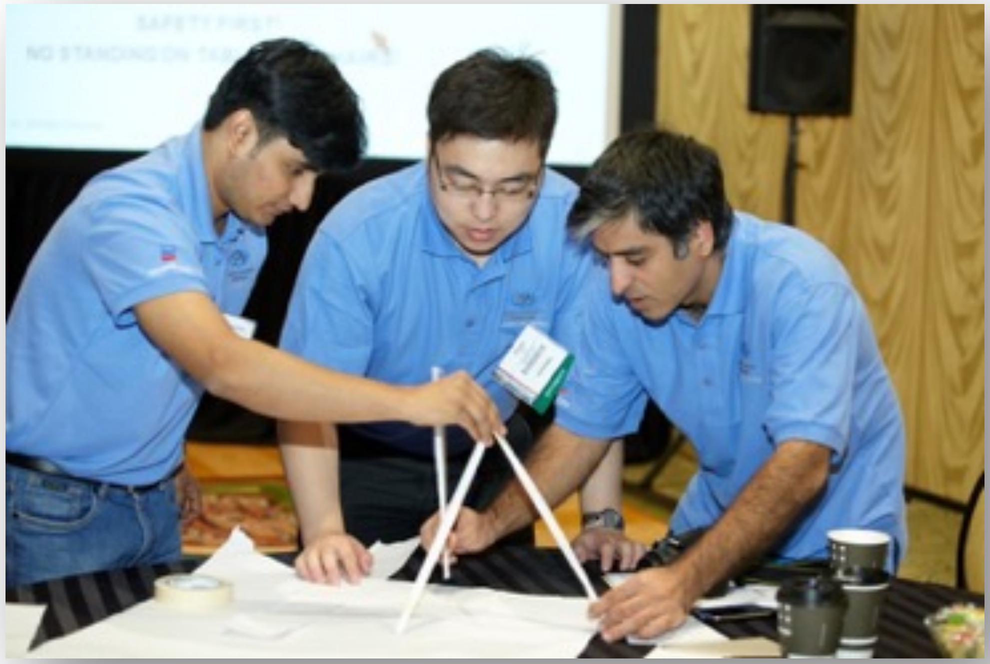

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THE WALL STREET JOURNAL.

DOWJONES TUESDAY, AUGUST 17, 2004 - VOL. CCXLIV NO. 33 - ★★★★ $1.00 ★★★★ WSJ.com

Turn of the Screw

In Tepid Job Scene, Certain Workers Are in Hot [illegible]

'Swiss Style' Machinists Doing Ultra-[illegible] Typify Shortage of Skills

Mr. Schrader Gets Courted

By Timothy [illegible]

HOLYOKE, Mass.—Two years ago, Robert Schrader got a call from a recruiter trying to lure him from his job in New Hampshire to opportunities as far away as Florida. He eventually took a new position in Massachusetts, after he had negotiated a raise, an expense-paid move and better health coverage. Since then, his old boss in New Hampshire has tried to woo him back.

Mr. Schrader isn't a hotshot young executive with a Harvard MBA. He's a factory worker.

That group in recent times has been associated more with unemployment lines than with the corporate recruiting circuit. But Mr. Schrader isn't your average blue-collar worker. He is a "Swiss style" machinist, a specialty developed more than a century ago to make tiny, very precise gears and shafts for the European watch industry. More recently, Swiss-style machining has been married with advanced computer technology to become essential in the precision manufacture of a wide range of products, from bone screws to roller balls for Bic pens. Mr. Schrader's employer in Holyoke, Marox Corp., makes medical implants and instruments.

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Business and Finance | World-Wide

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(Articles on Pages A3 and C5)

* * *

■ Stocks rose on bargain hunting and a drop in oil prices. The Dow industrials gained 129.20, or 1.31%, to 9954.55; the Nasdaq climbed 1.46% to 1782.84.

(Article on Page C1)

* * *

■ Tyson Foods said the SEC staff plans to recommend a civil action against it for allegedly failing to fully disclose perks for its ex-CEO.

(Article on Page A3)

* * *

■ Foreign investors increased purchases of U.S. securities in June to $71.8 billion, enough to finance the current-account deficit.

(Article on Page A4)

* * *

■ Hurricane Charley may damp U.S. employment in August. The storm hit during the week in which payrolls are measured.

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Bush told the VFW he plans to bring 70,000 troops back from abroad over the next decade. Aides said that includes two divisions from Germany. U.S. presence in places like Poland, Romania and Uzbekistan would rise.

* * *

■ Venezuela said President Chávez soundly defeated a bid to recall him at referendum Sunday, with 58% of voters favoring letting him complete the remaining two years of his term. International observers found no evidence of fraud or vote-rigging, and Carter urged the opposition to accept the result. Coming days will tell the tale in the oil-rich nation. (Page A3)

* * *

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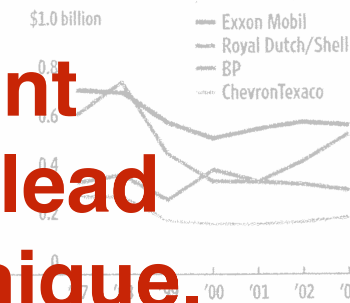
Midway through the set, a portly club official took the stage and ordered the crowd to sit down. The band ignored him and kept playing, and around 50 of the roughly 200 fans remained standing. The official ended the concert and angrily escorted the band off the stage. Faisal Talal, the band's singer and rhythm guitarist, shouted a string of profanities, drawing cheers from the crowd.

It was a classic moment of rock 'n' roll rebellion, but such gestures come at a high price in Iraq. The venues that Acrassicauda—which may be Iraq's only heavy-metal band—played before the war are now government compounds or off-limits because of street crime. The staid Iraqi

Sunk Costs

Major oil companies' total spending on research and development*



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Deregulation Deadlines Highlight Disparities Between Customers, Utilities

By Rebecca Smith

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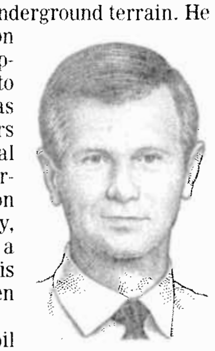
Since the 1970s when he'd studied the moon for NASA, Dr. Srnka had been fascinated by the prospect of using the electromagnetic properties of earth, water and rock to decipher underground terrain. He was hired by Exxon in the 1980s to apply the method to finding oil but was stymied for years by technological and funding hurdles. Finally, on this January day, Dr. Srnka got a chance to test his theory in a proven offshore oil field.



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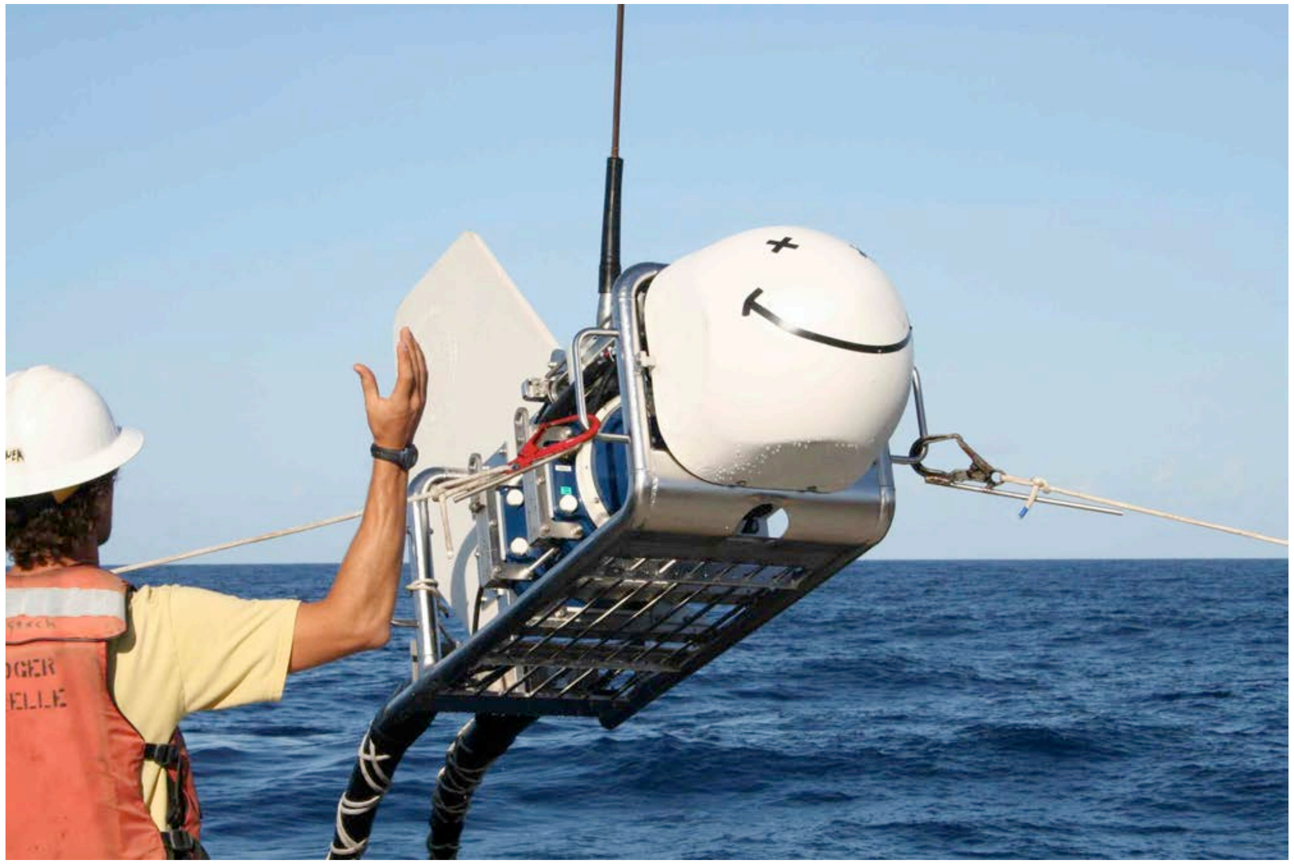
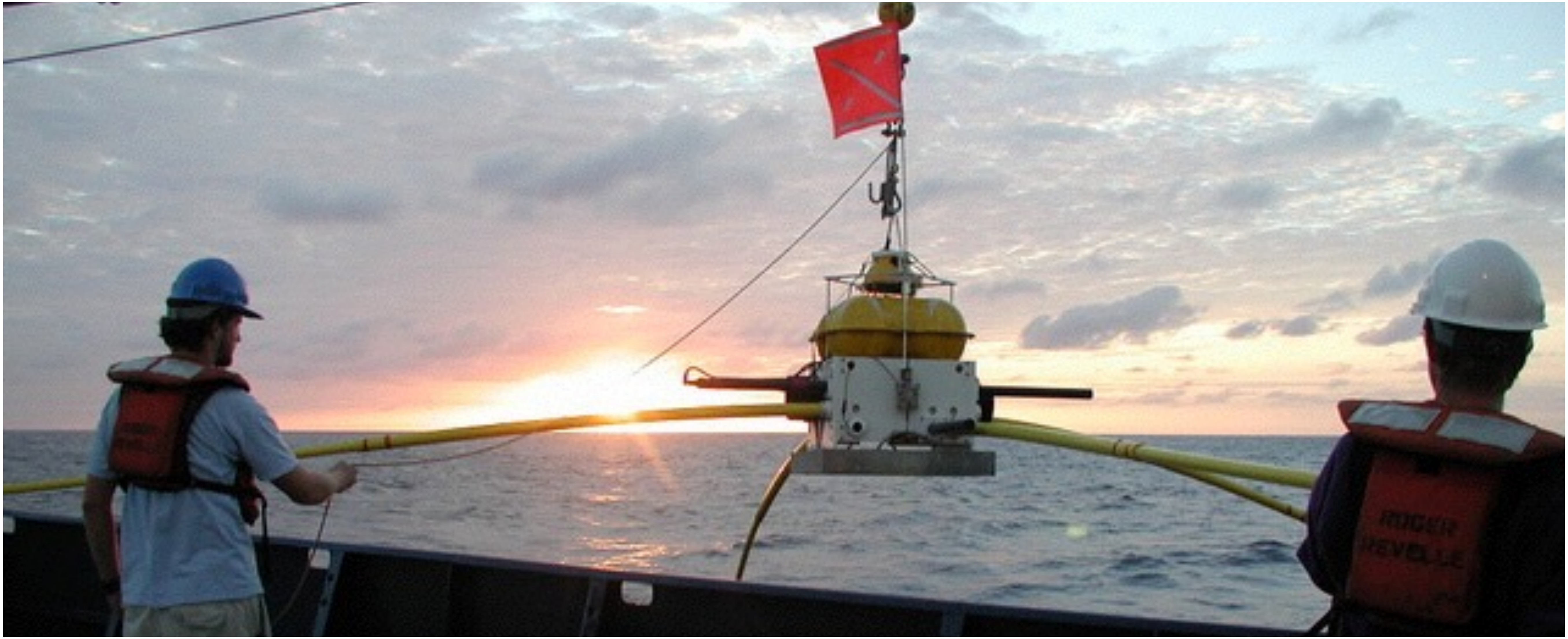
Len Srnka

Outline:

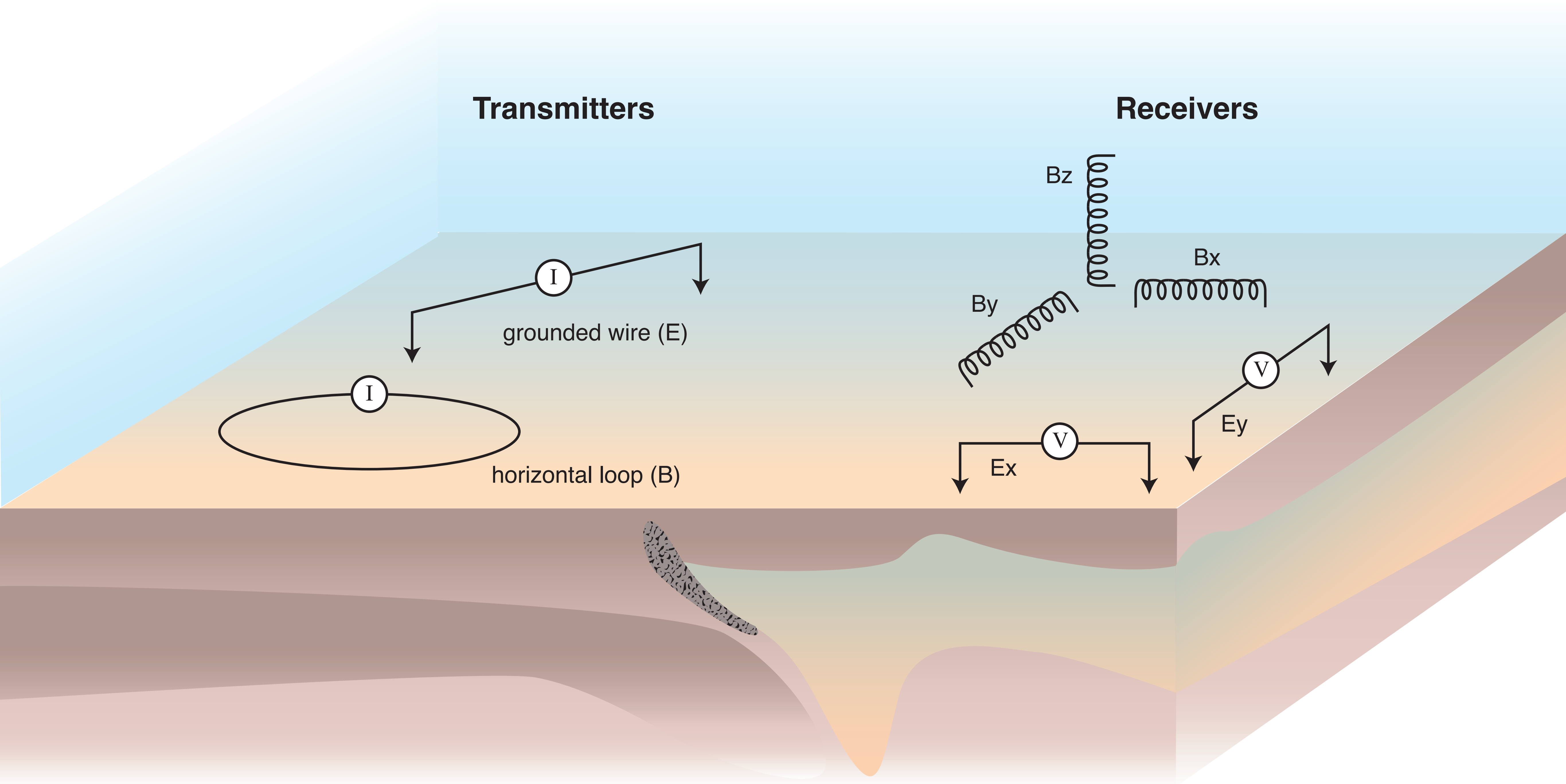
- Basics of the EM methods
- Early history of marine EM
- Commercialization
- 10 things you need to know
- The future





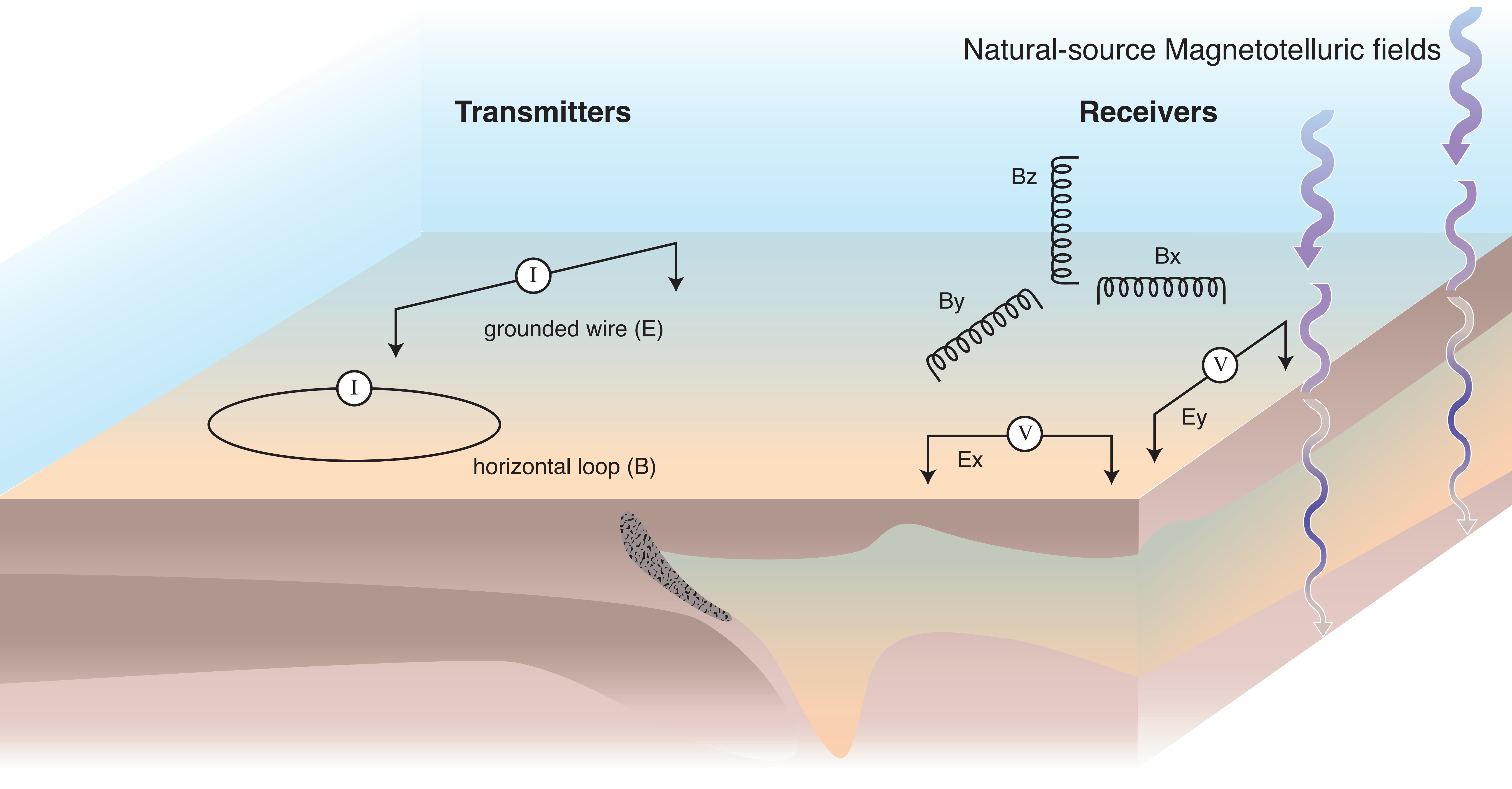
What is CSEM?

Controlled **S**ource **E**lectro**M**agnetic sounding has been used since the 1930's to map sub-surface geology through the proxy of electrical conductivity. On land it is mainly used for mining exploration (shallower, conductive ore bodies), but has been used for map geological structure for oil exploration.



What is MT?

CSEM is related to another EM technique called **MagnetoTelluric (MT)** sounding, which uses similar receivers to measure Earth's natural magnetic field variations and the induced electric currents. MT signals are either part of a useful complementary method or a source of noise for CSEM.

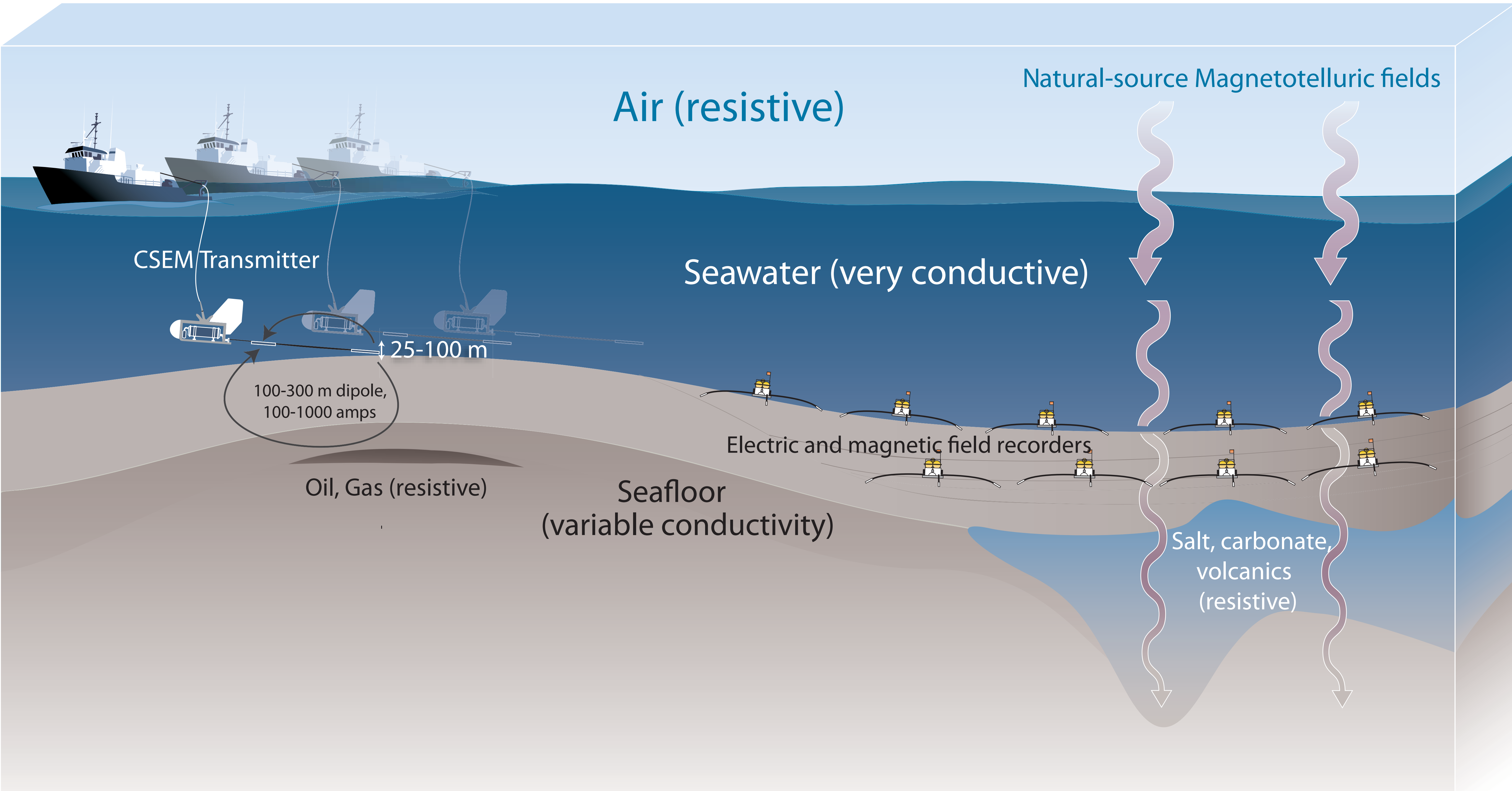


Both can be used in the marine environment:

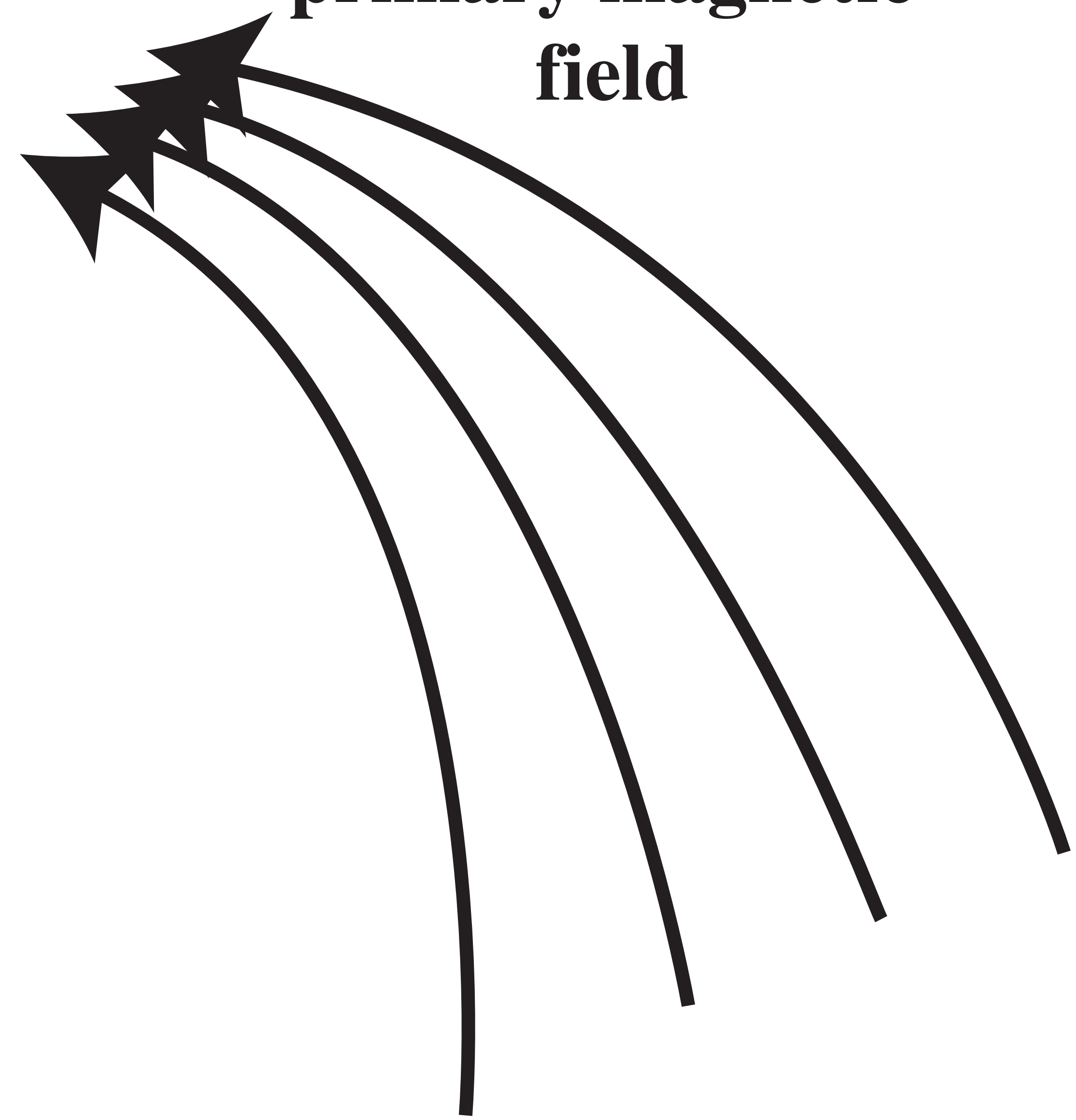
Marine CSEM
more sensitive to
resistive rocks

Marine MT
more sensitive to
conductive rocks

But both methods can detect contrasts



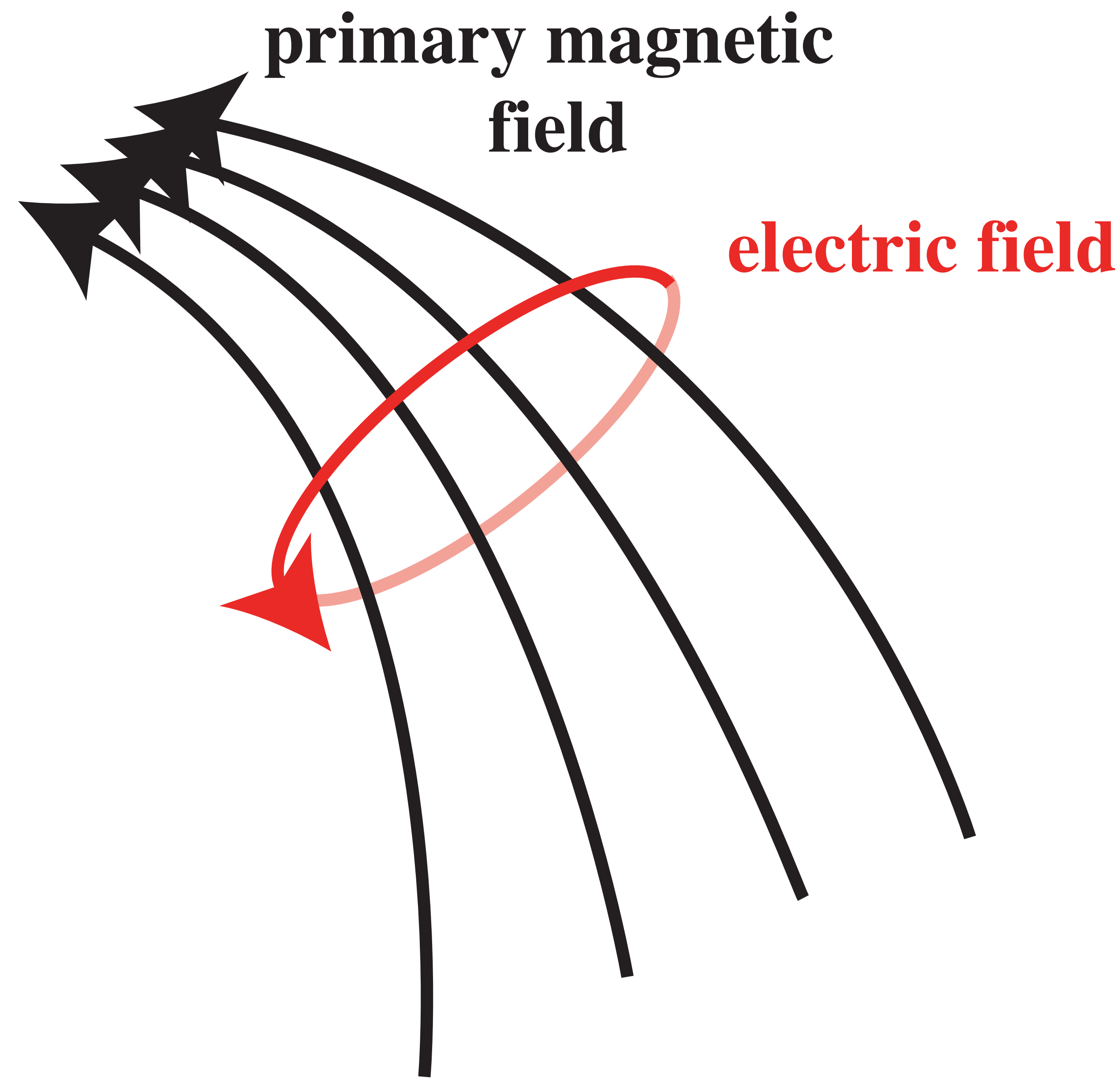
Both MT and CSEM sounding use **electromagnetic induction,** which describes what happens around a time-varying primary magnetic field:



Faraday's Law says that a time varying (or moving) magnetic field will induce electric fields:

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi}{dt}$$

(Φ is magnetic flux).



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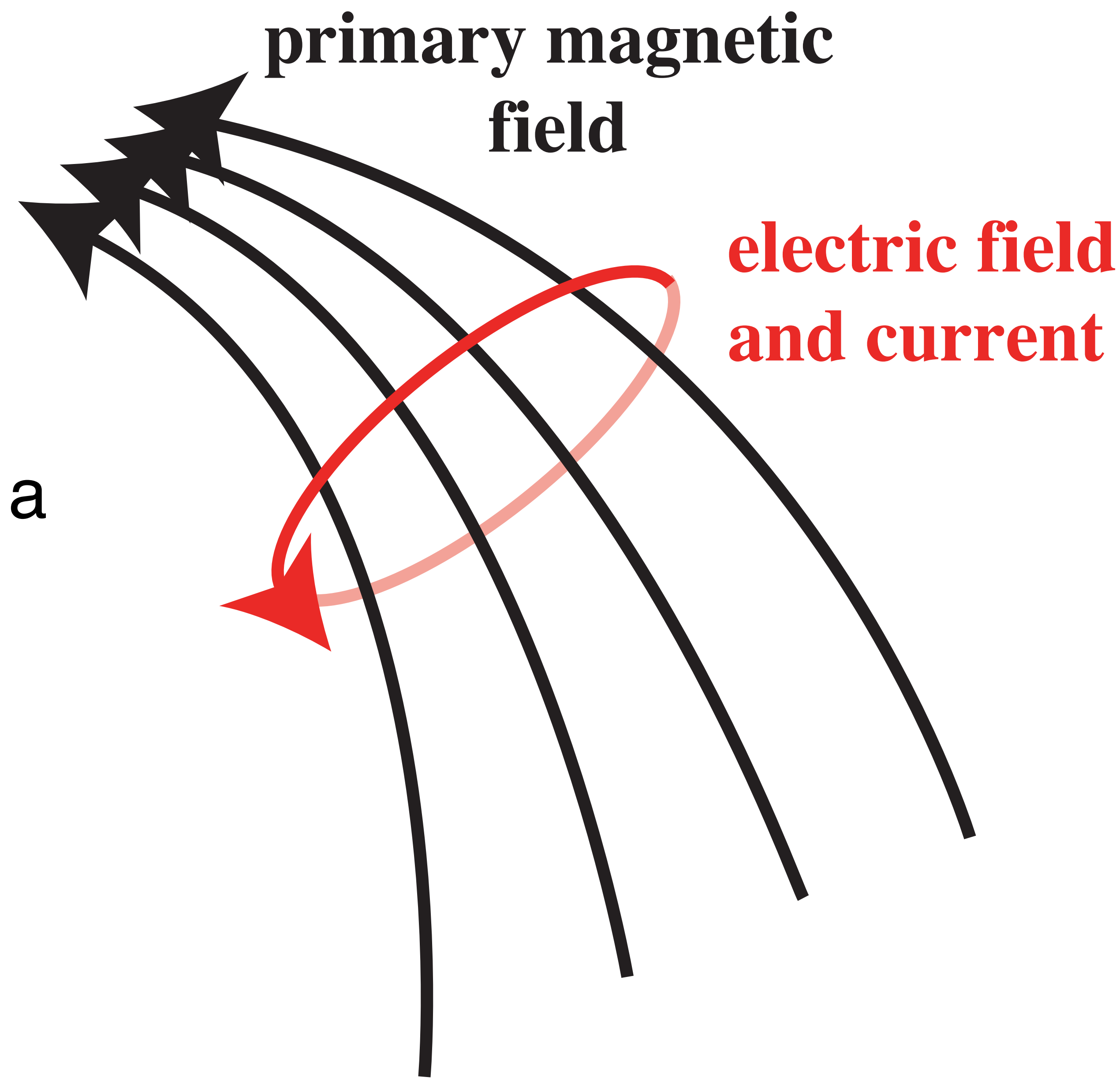

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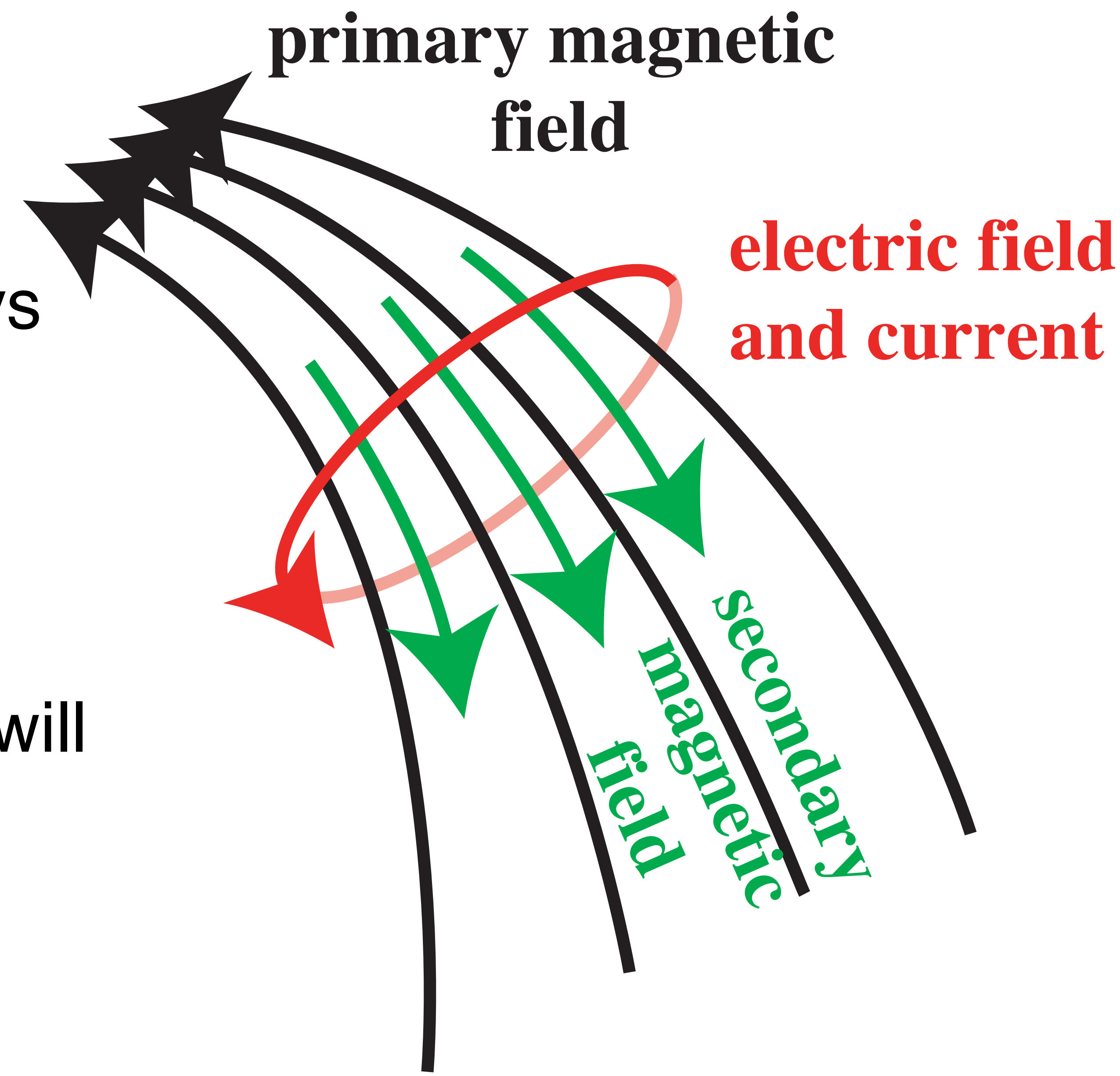
(Φ is magnetic flux). Ohm's Law says that $\mathbf{E}$ will generate a current $\mathbf{J}$ in a conductor:

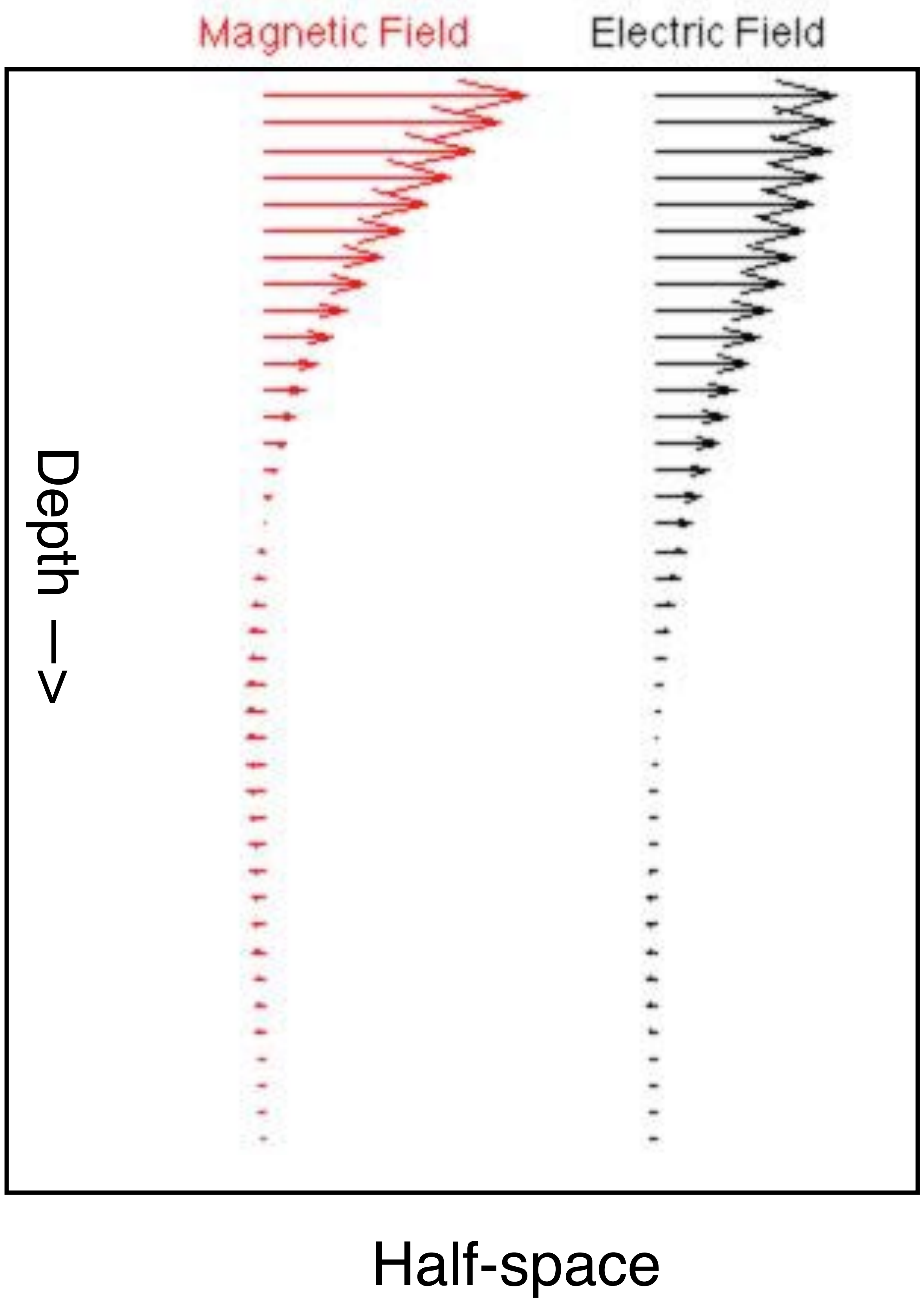
$$\mathbf{J} = \sigma \mathbf{E}$$

Ampere's Law says that the current will generate a secondary magnetic field:

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu I$$



The secondary field opposes the changes in the primary field. The consequence of this is that conductive rocks absorb variations in EM fields more than resistive rocks.



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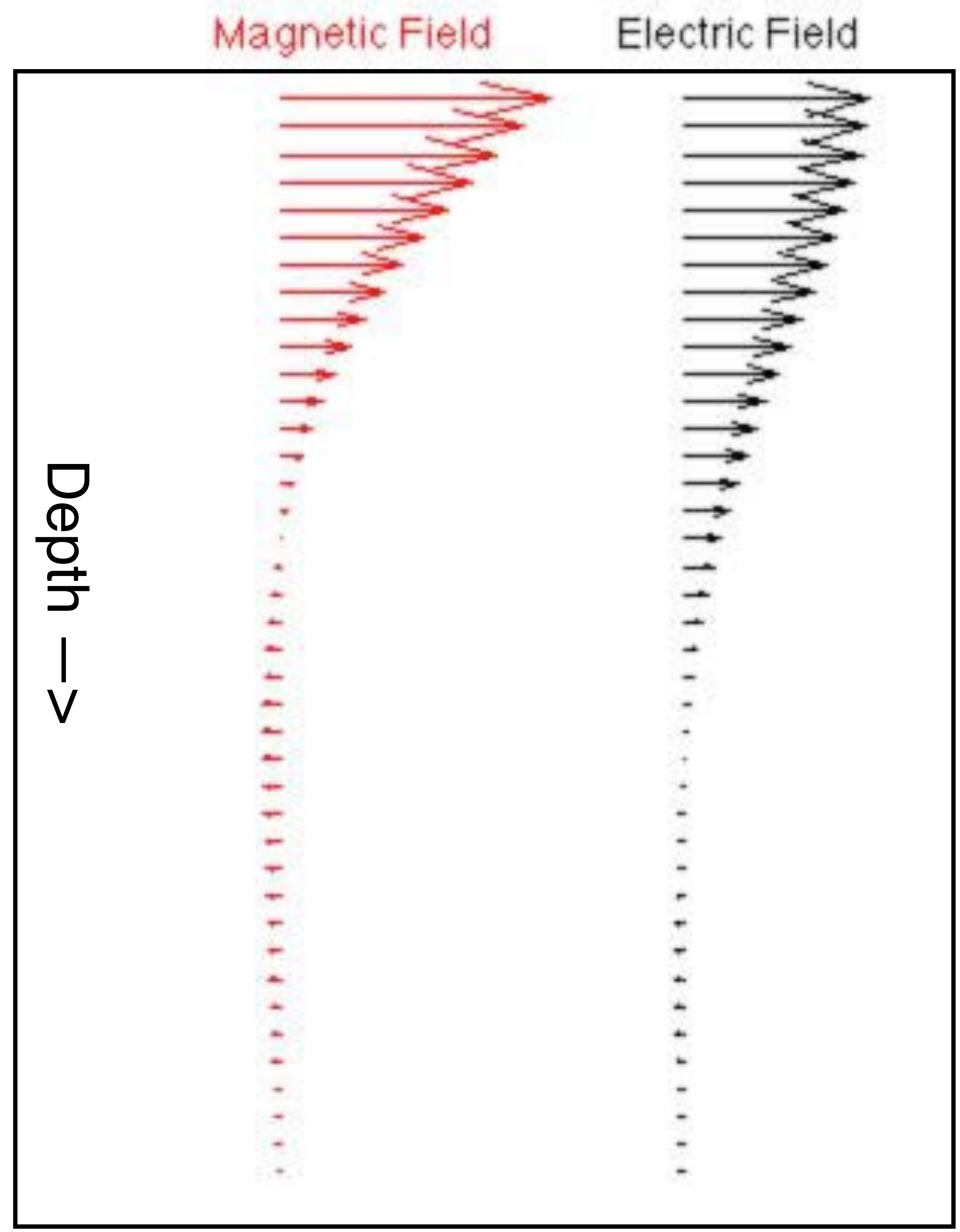
This absorption is exponential:

$$E(z) = E_o e^{-z/z_s}$$

The rate of absorption is given by the skin depth, which depends on rock resistivity and period:

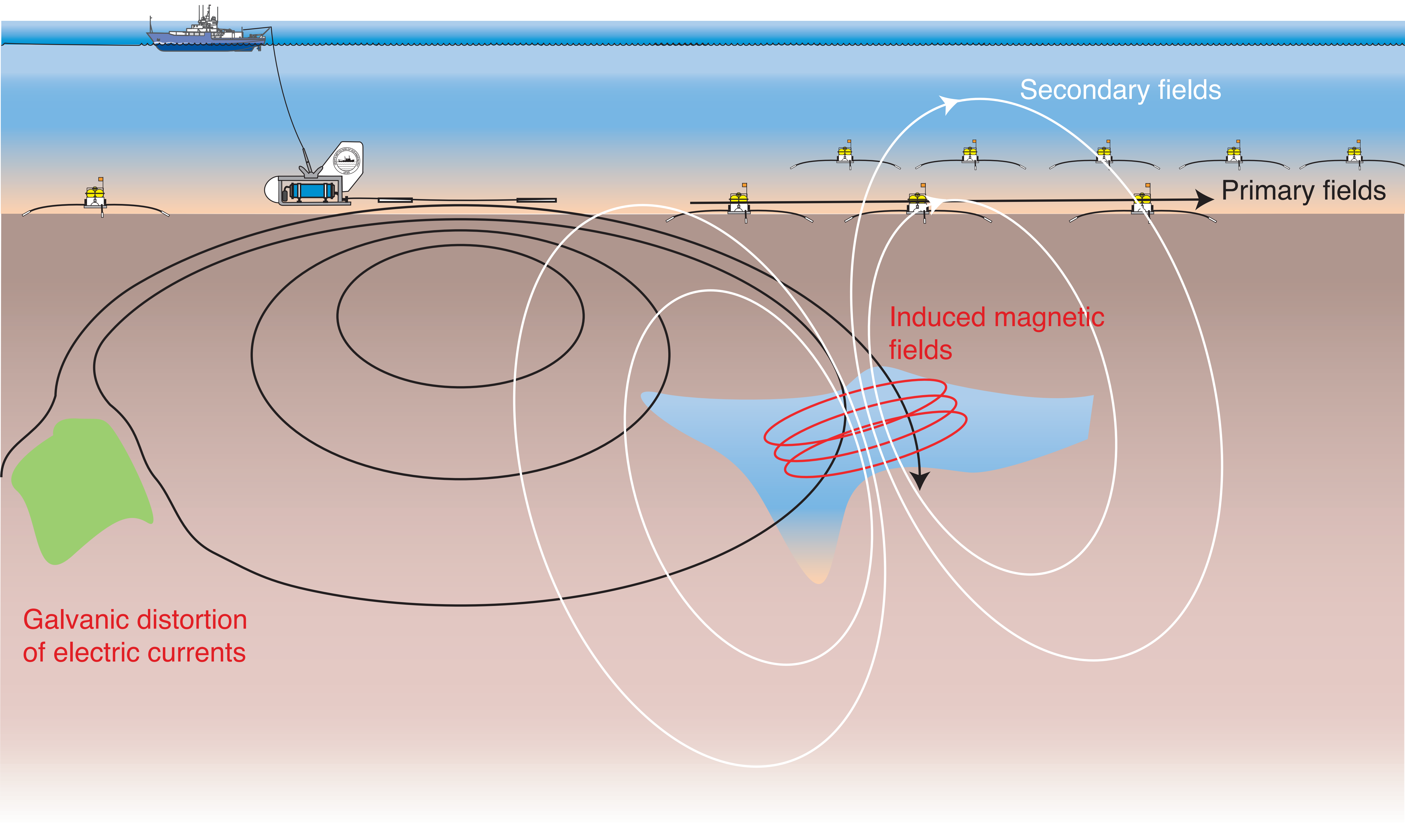
High resistivity, long periods = large skin depths, greater penetration.

Low resistivity, short periods = small skin depths, greater attenuation.

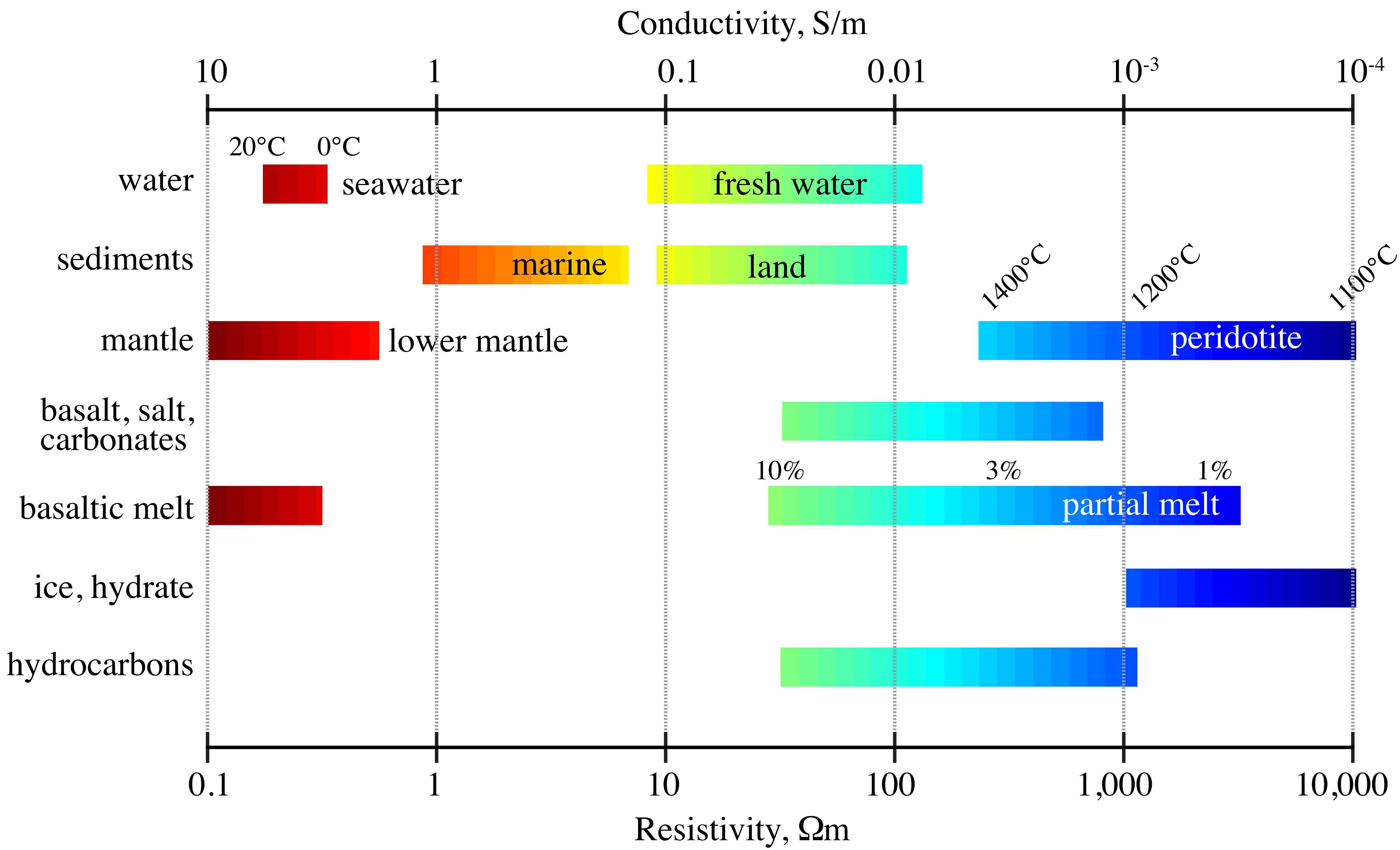


Half-space

Secondary fields are different in amplitude, phase, and direction than the primary magnetic and electric fields. Electric fields can also be distorted galvanically, as in DC resistivity methods.



MT and CSEM are methods to measure electrical conductivity. Conductivity varies over 5 orders of magnitude in common Earth materials, and provides the ideal mechanism for studying fluids, water, and geology, including hydrocarbons.



The Past

Interestingly, Cagniard proposed adaption to the marine environment in the 1953 paper that first presented the MT method.

GEOPHYSICS, VOL 18, NO. 3 (JULY 1953), P. 605-635.

BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING*†‡

LOUIS CAGNIARD§

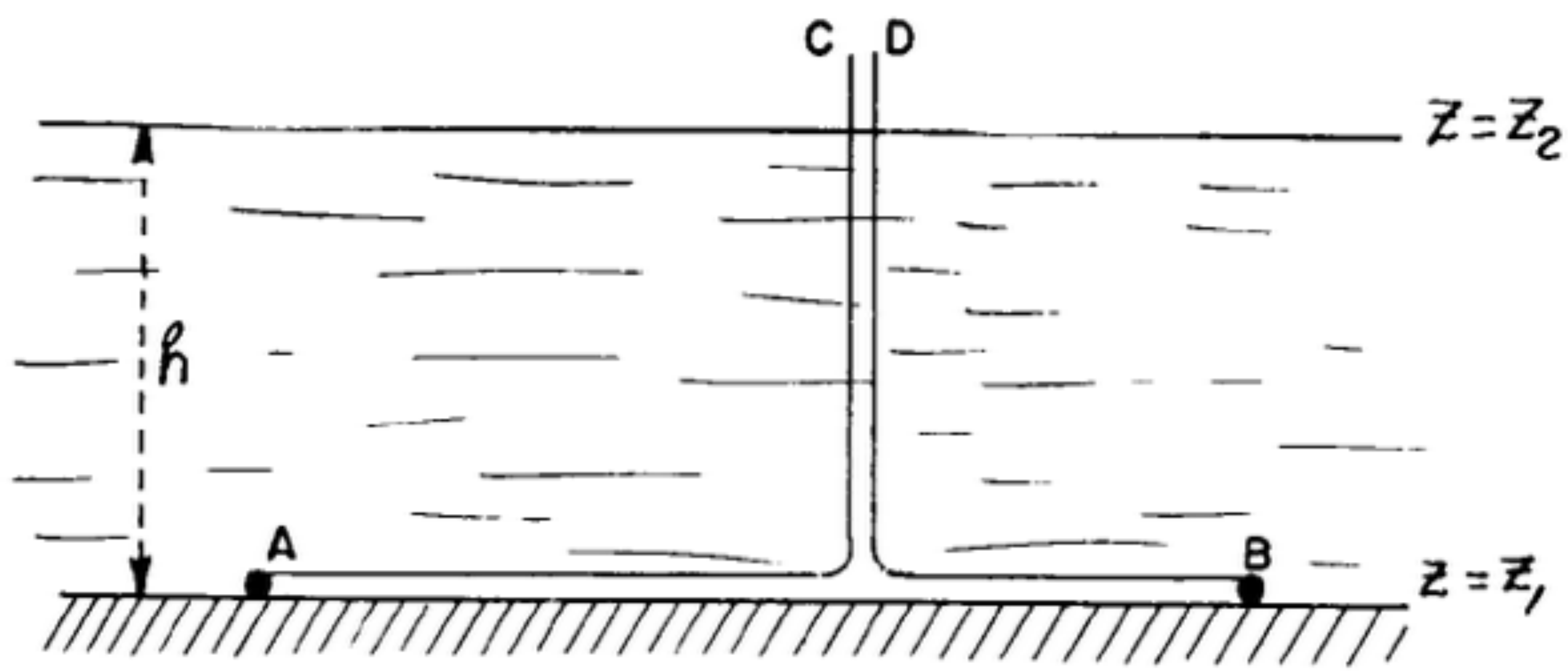
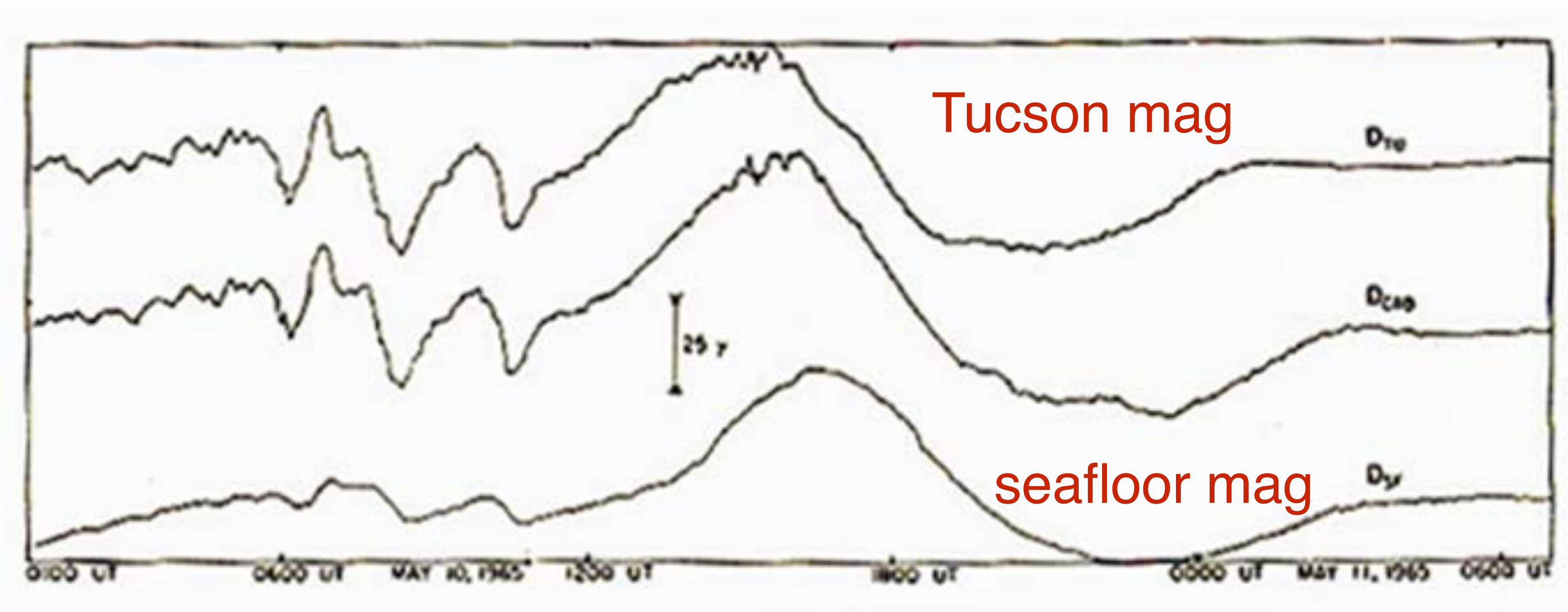
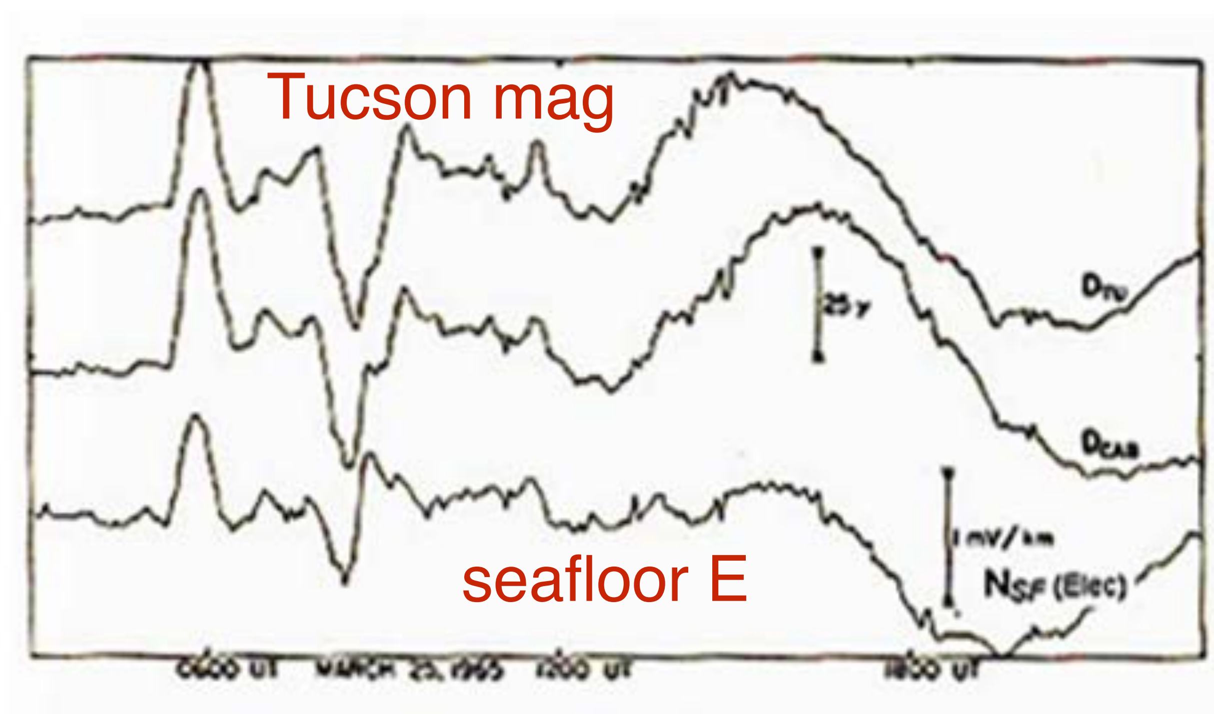
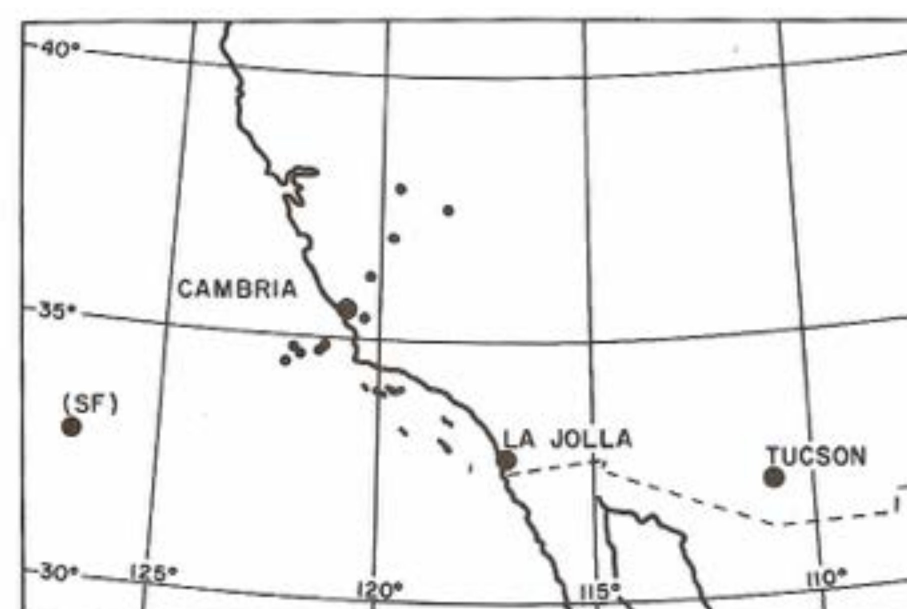


FIG. 13. Configuration of electrodes on water bottom for submarine MT measurements.

Charles (Chip) Cox and Jean Filloux of Scripps Institution of Oceanography made the first marine MT measurements in 1965, in 4300 m water offshore California.







Cox, Filloux, and Larsen, 1968

Theory pre-dates practice, but even so marine CSEM is a young field. The earliest marine CSEM work was carried out by the British and US navies. This 1968 paper out of the US Navy Underwater Sound Lab appears to be the first proposal for marine CSEM as we now know it.

GEOPHYSICS, VOL. 33, NO. 6 (DECEMBER 1968), P. 995-1003, 8 FIGS.

DETERMINATION OF THE ELECTRICAL CONDUCTIVITY OF THE SEA BED IN SHALLOW WATERS†

PETER R. BANNISTER*

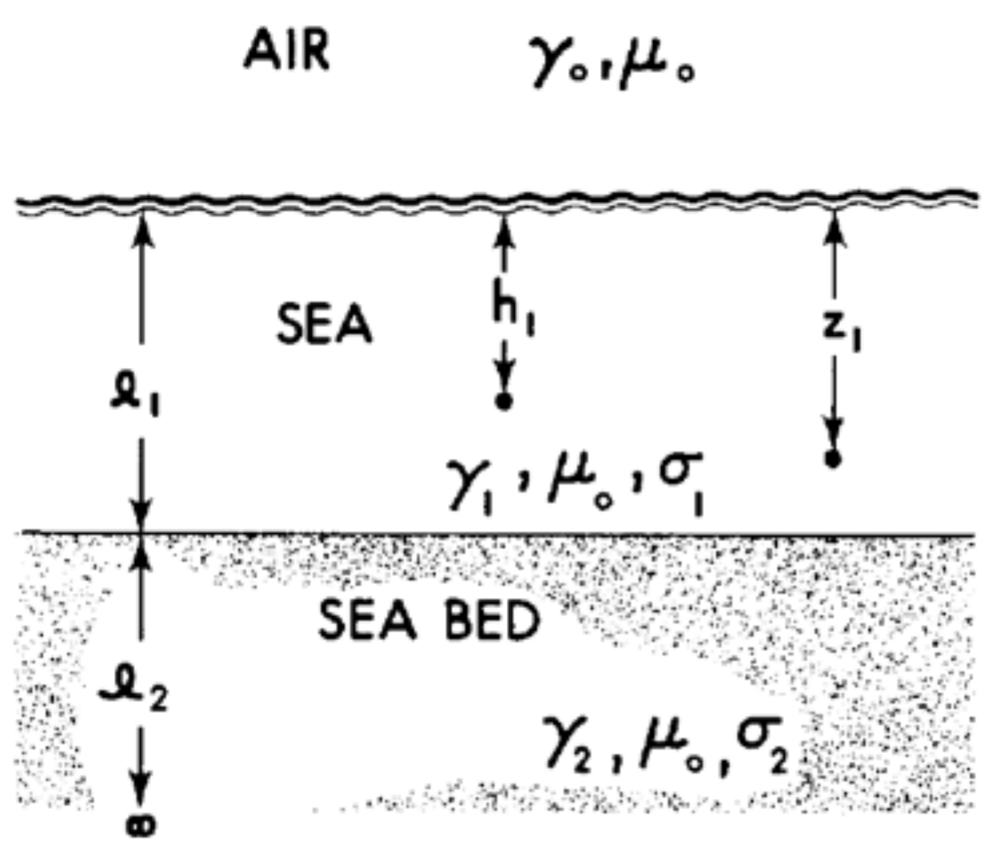
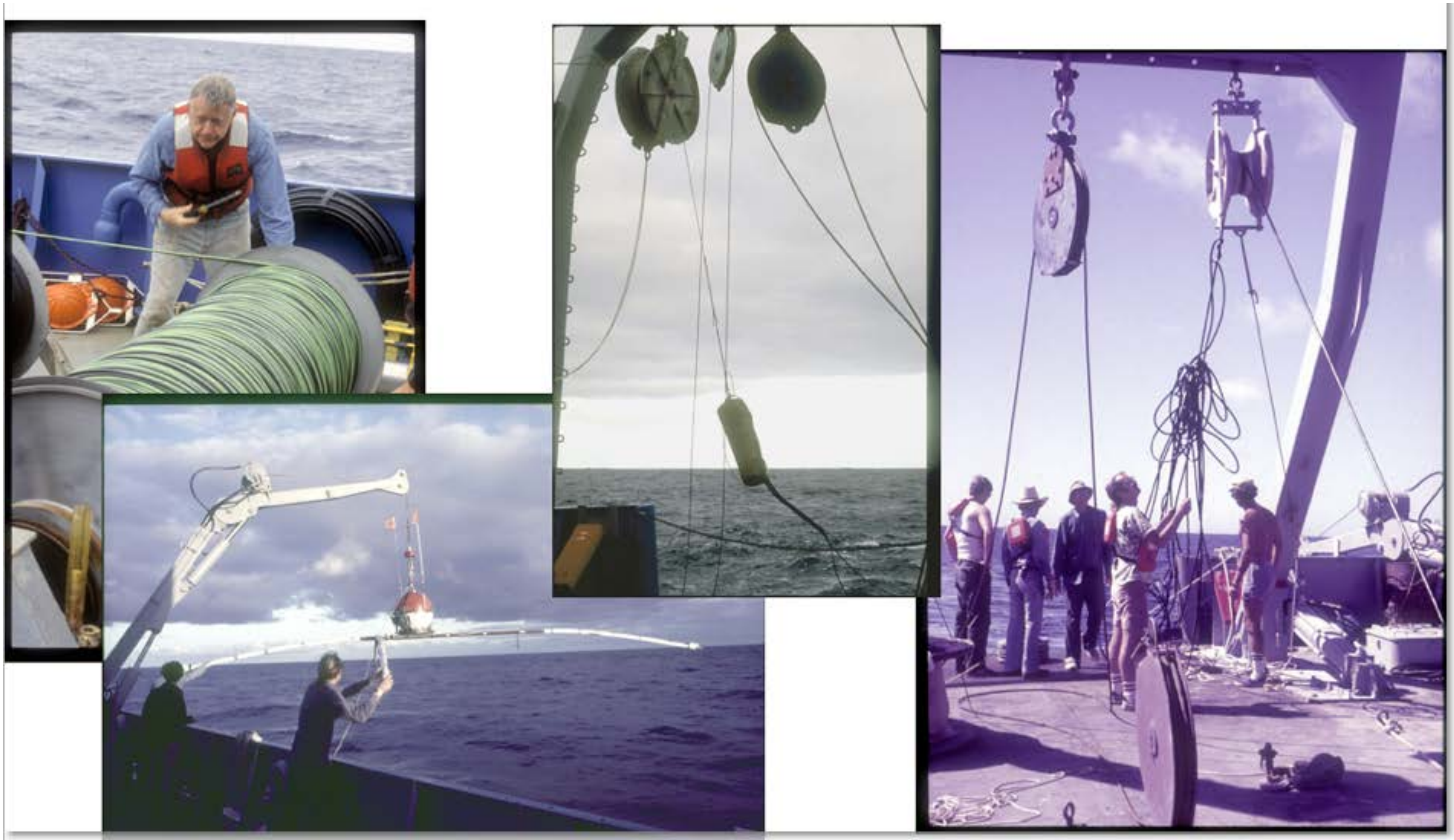
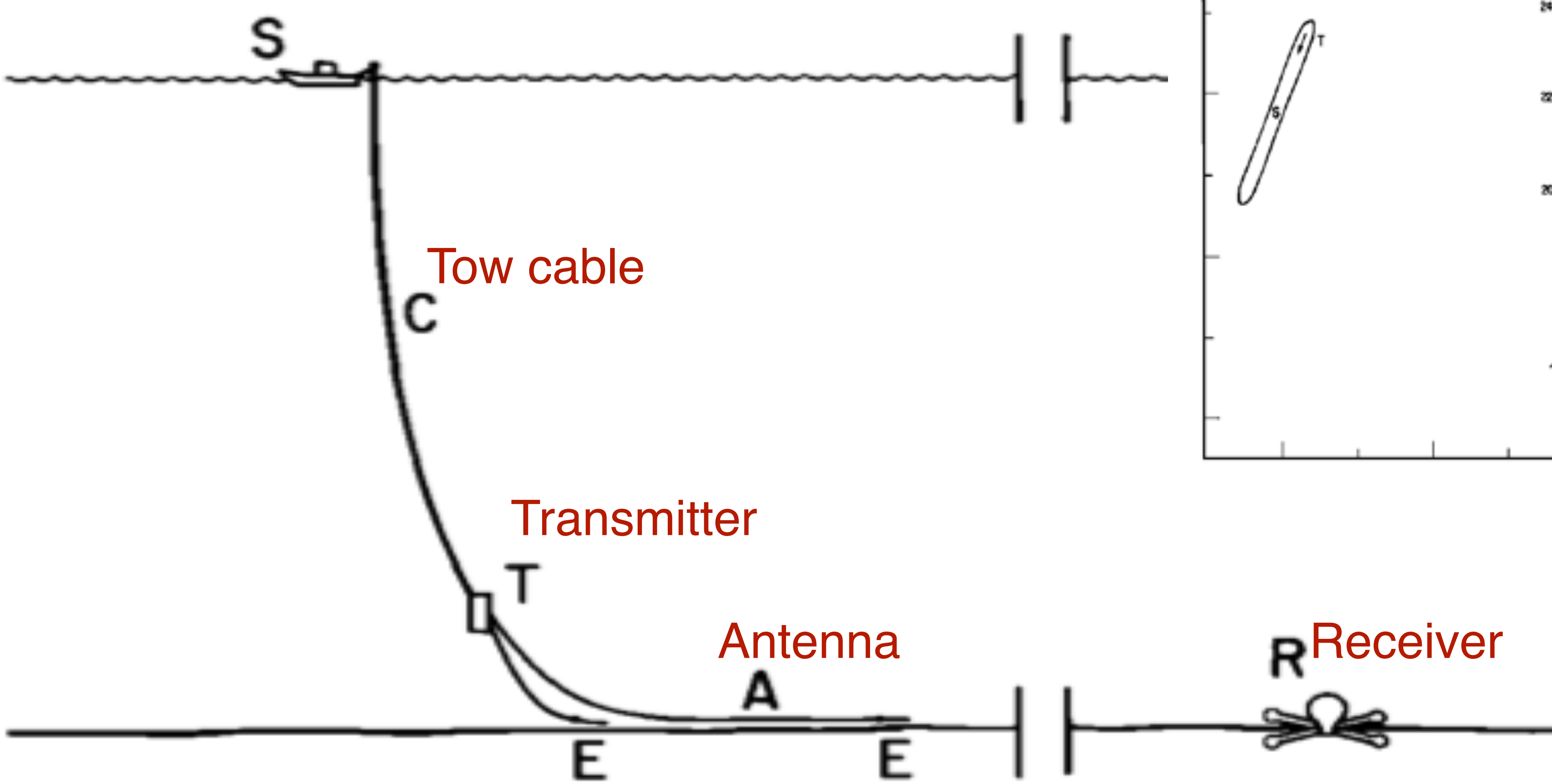


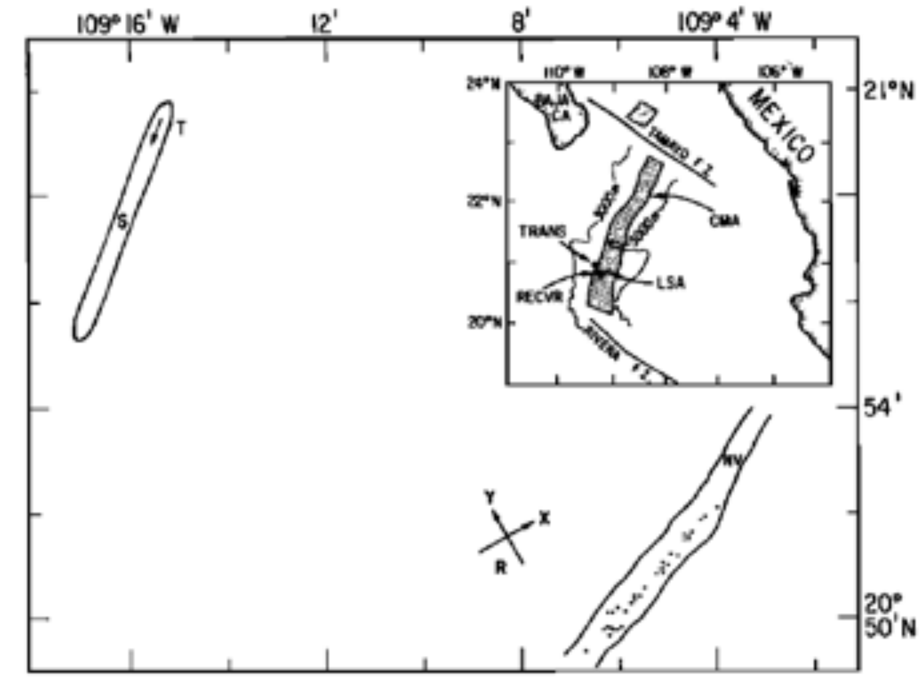
FIG. 1. Two-layer stratified earth.

The same Chip Cox (1922-2015) developed practical deepwater CSEM in the early 1980's, partly under funding by DARPA to improve understanding of seafloor communications, and ONR for submarine noise studies.

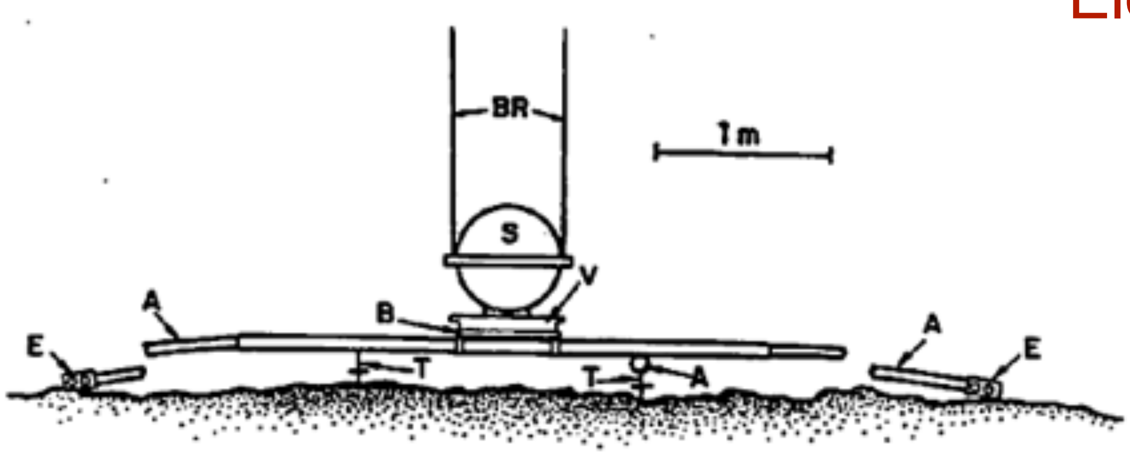


In 1979 Chip carried out an experiment in nearly 3,000m water with transmissions of 80 amps on an 800 m antenna. Frequencies of 0.25 - 2.25 Hz were detected 19 km away. His target was a mid-ocean ridge.





Young and Cox, 1981



Cox et al, 1981

Remarkably, within 2 years, in March 1981, Chip proposed the CSEM method for oil exploration to Exxon:

UCSD 2195

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University of California, San Diego

Office of Contract & Grant Administration, A-010
La Jolla, California 92093
(714) 452-4570

PROPOSAL FOR RESEARCH TO BE CONDUCTED UNDER THE SPONSORSHIP OF

Exxon Production Research Company
N-299B
P. O. Box 2189
Houston, Texas 77001

TITLE OF PROPOSAL: ELECTROMAGNETIC SURVEYING

PROJECT PERIOD: From: 7/1/81 Through: 9/30/81

AMOUNT REQUESTED: $15,807.00

AGENCY CONTRACT OR GRANT NO.: New

PRINCIPAL INVESTIGATOR:
(NAME, TITLE, ADDRESS & TELEPHONE)

Professor Charles S. Cox
Mail Code A-030
Scripps Inst. of Oceanography
La Jolla, CA 92093
(714) 452 3235

In the proposal, Chip explicitly described the direct detection of a hydrocarbon reservoir.

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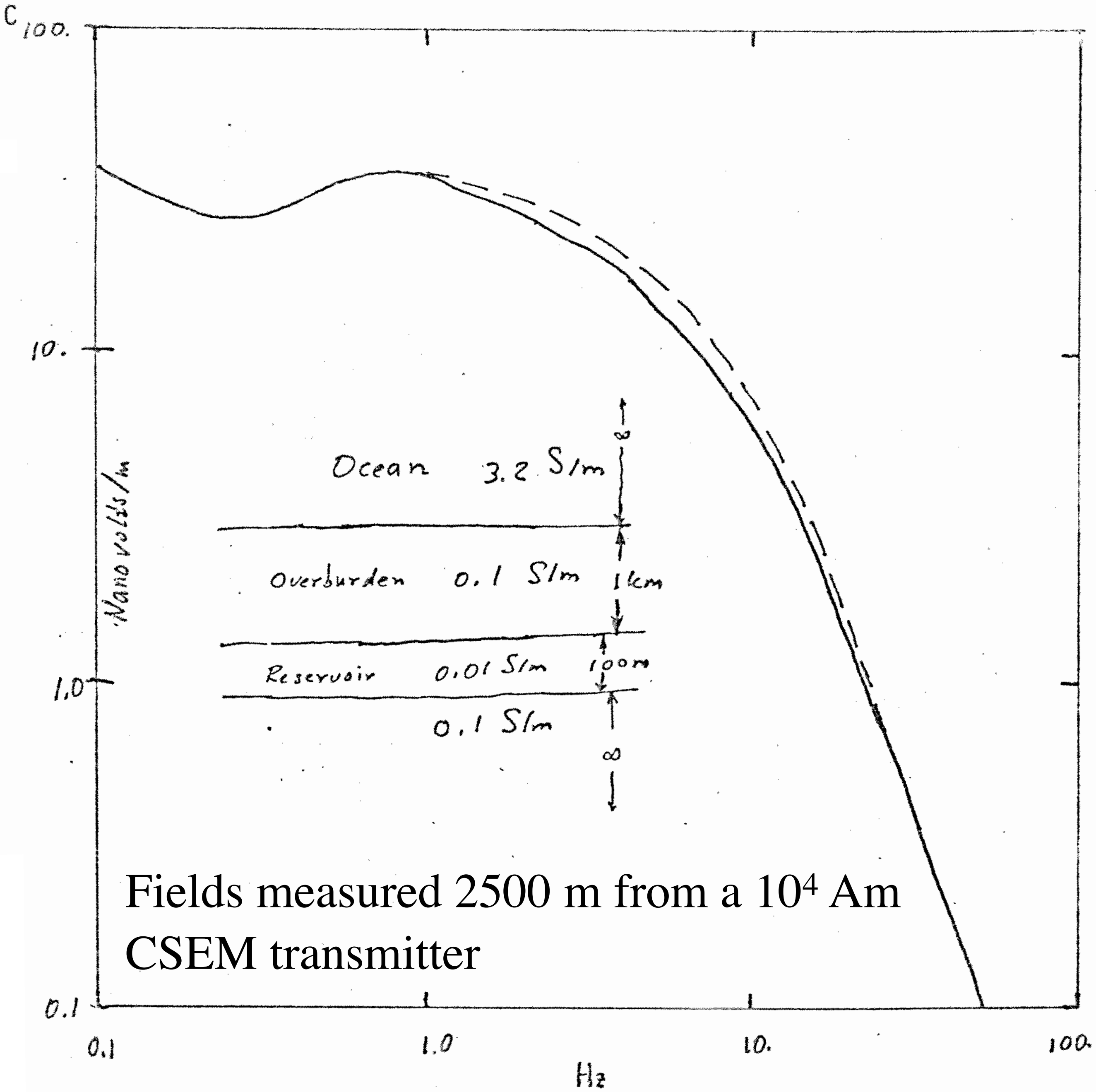

Fields measured 2500 m from a 10^4 Am CSEM transmitter

I checked Chip's calculations and they are basically correct. However, the proposal was declined - Chip was too far ahead of the times.

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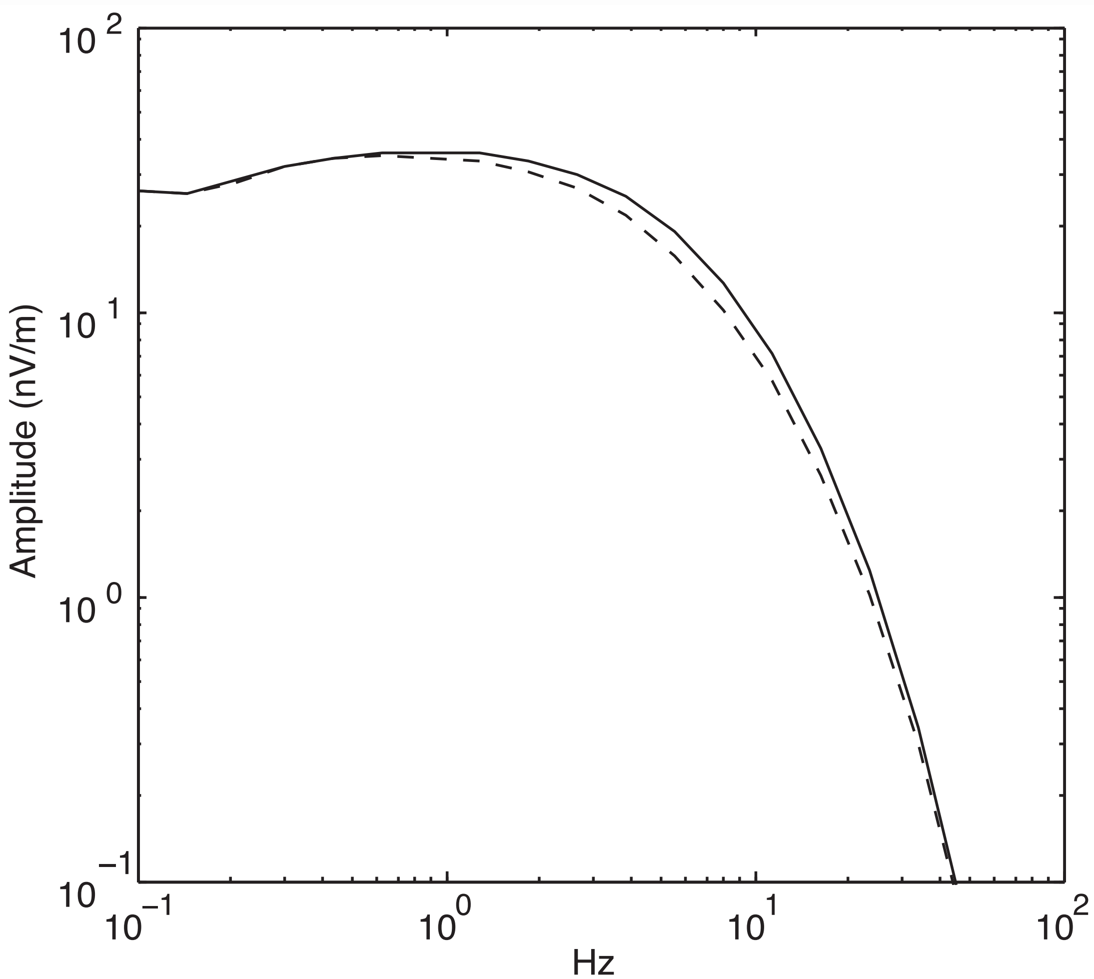
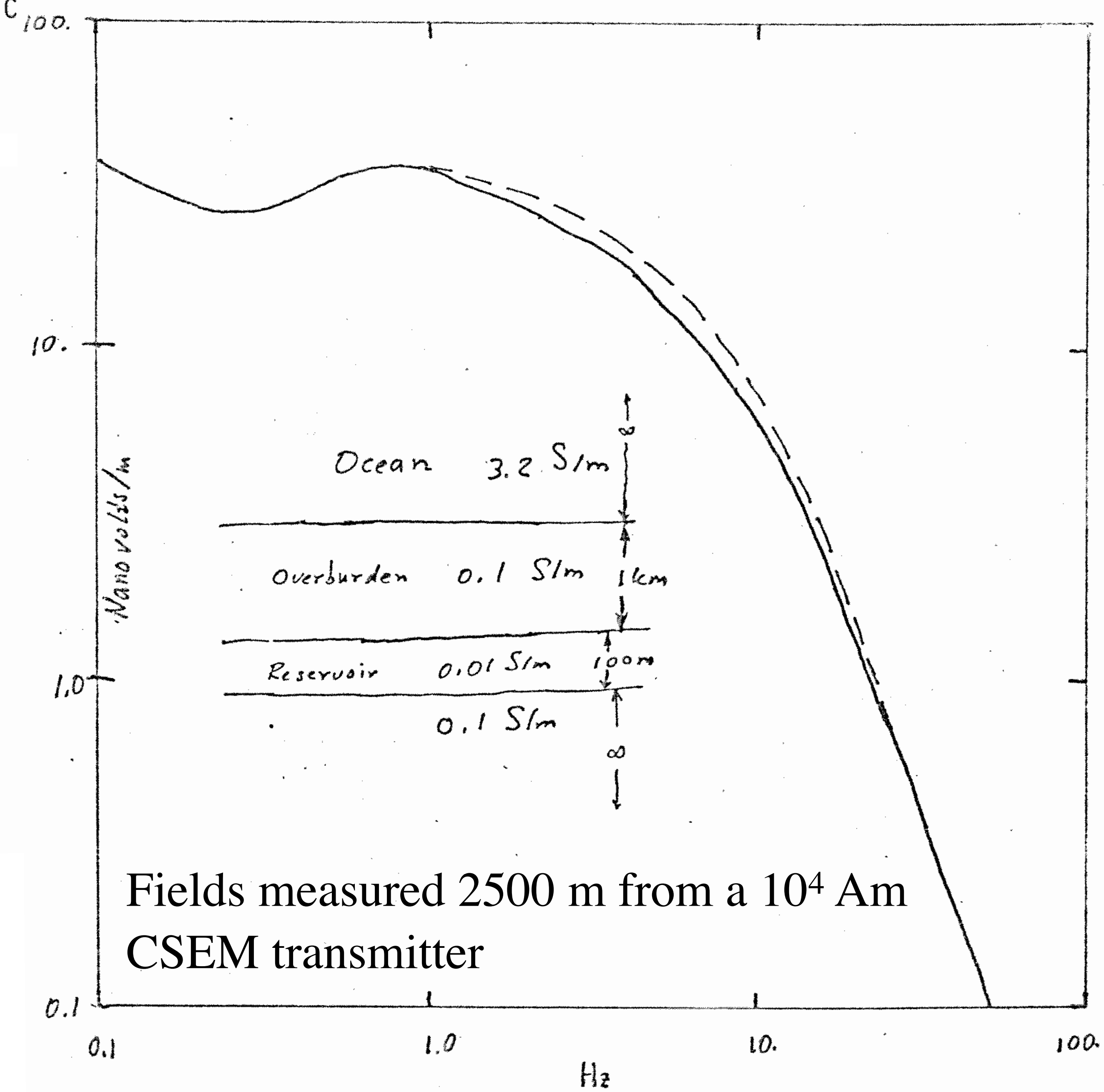




Fields measured 2500 m from a 10^4 Am CSEM transmitter

Meanwhile, in the late 1980's Martin Sinha of Cambridge (later Southampton) developed a UK CSEM capability based on Scripps', but with an "flown" transmitter capable of working over mid-ocean ridges.

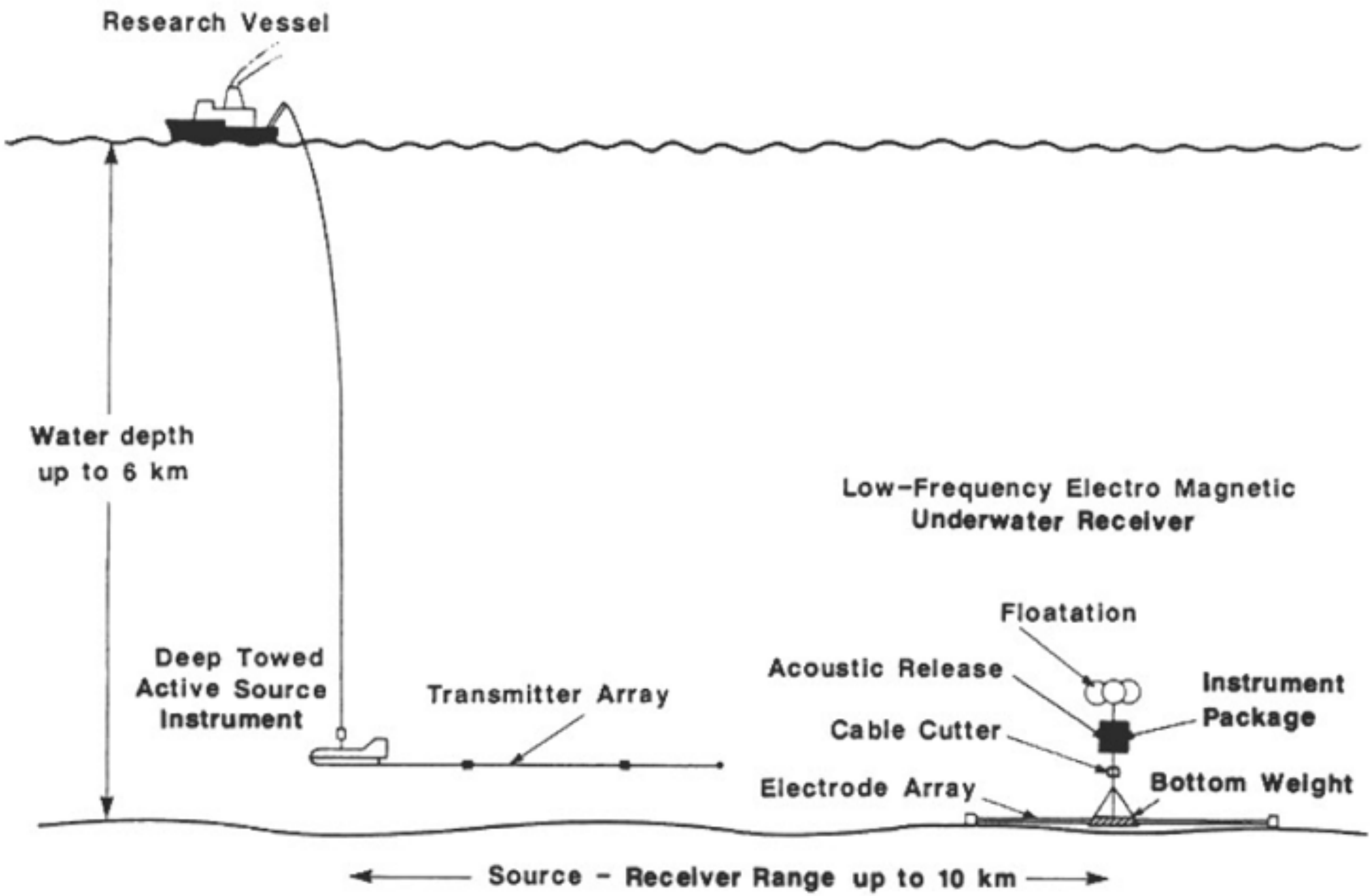
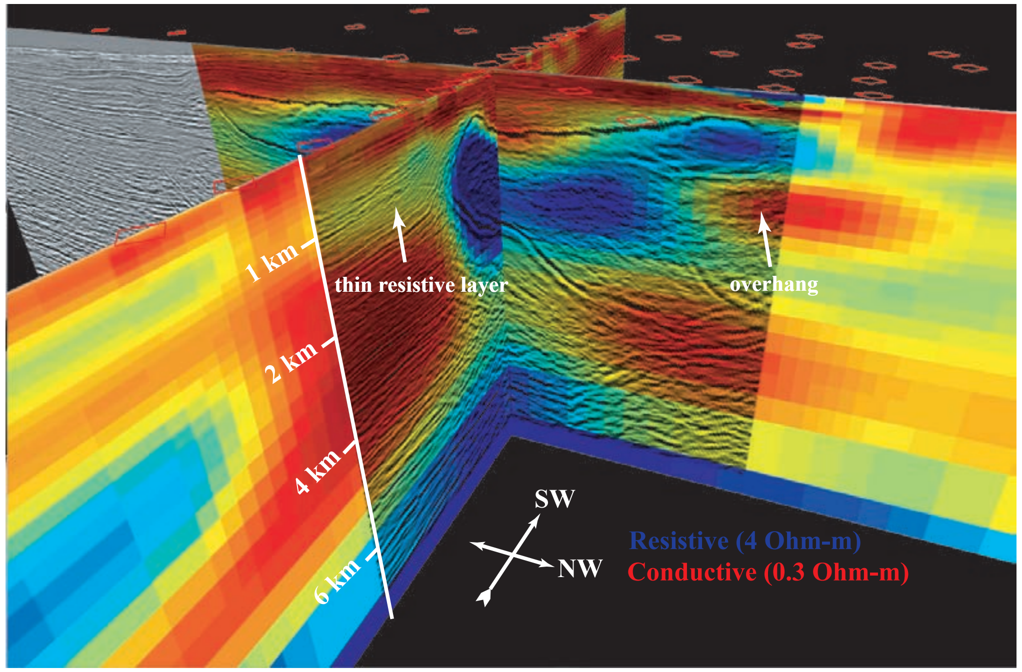


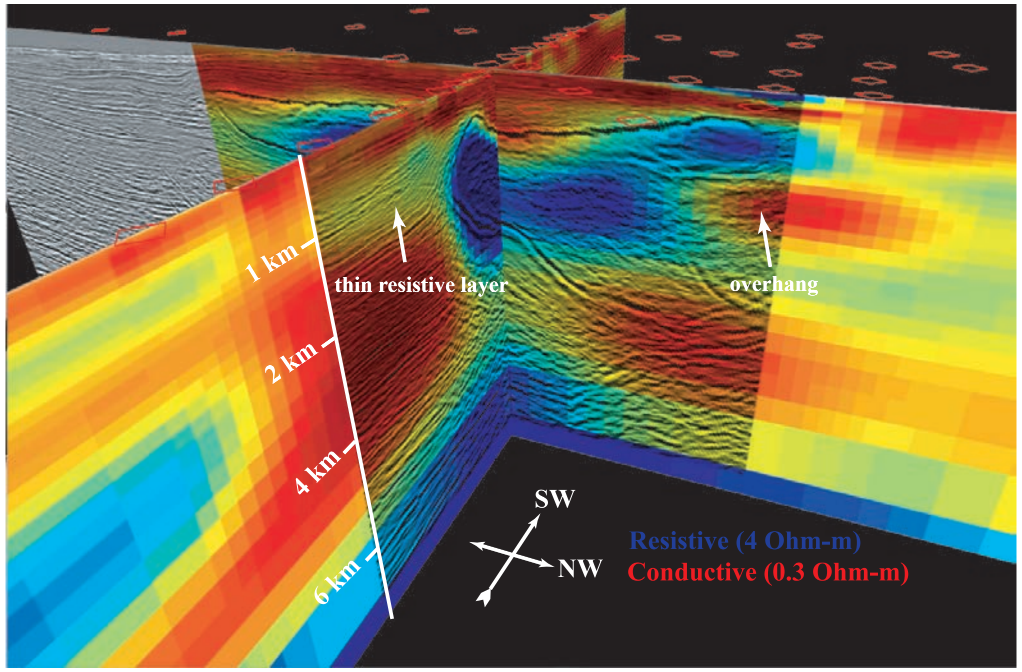
Fig. 1. Schematic arrangement of an active source electromagnetic sounding experiment, showing the deep-towed active source instrument, the surface research vessel and a low-frequency electromagnetic underwater recorder (not to scale).

(From Sinha et al, 1990)



Current industry funding for marine EM started in 1995 in order to develop MT imaging of salt in the Gulf of Mexico. Clearly, the price of oil was not a factor (adjusted for inflation, 1998 was the lowest price in history).

What drove interest in such an expensive, non-seismic method?



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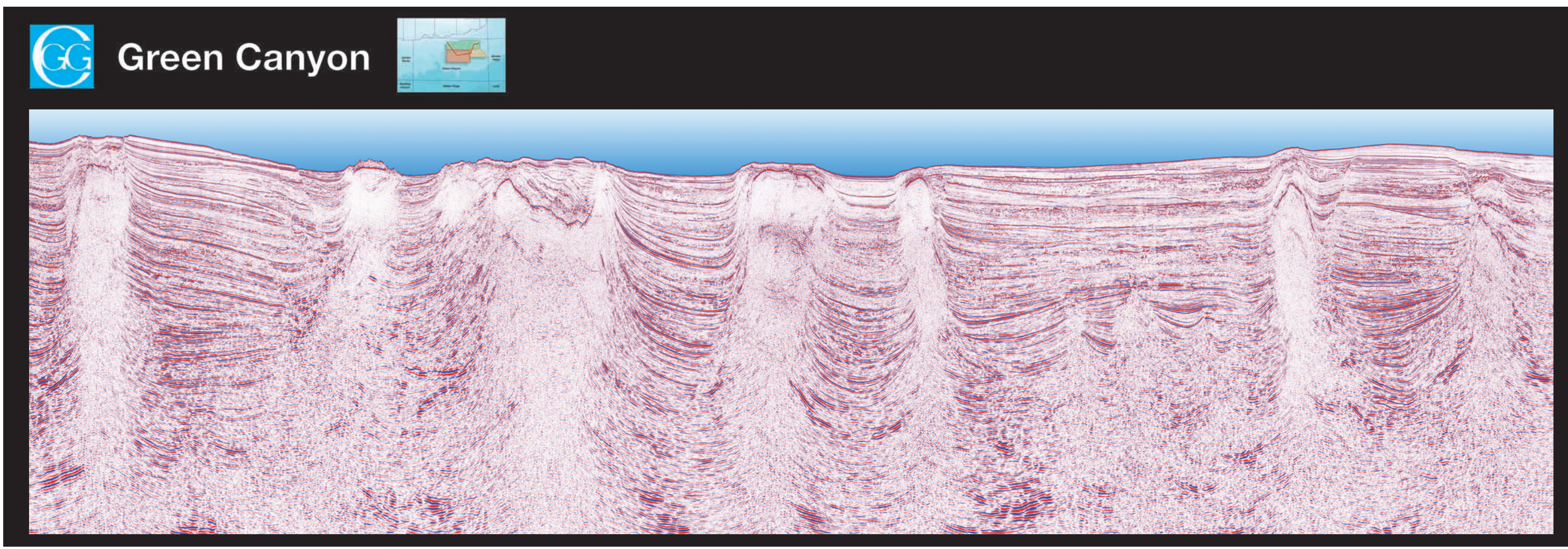
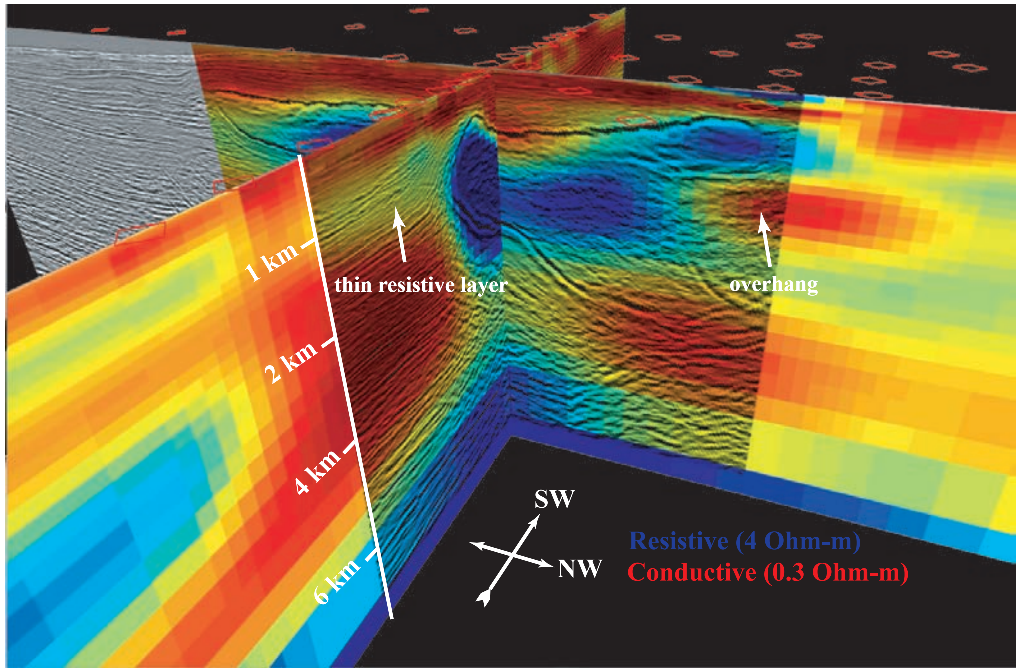
What drove interest in such an expensive, non-seismic method?

First, the seismic method was having great difficultly imaging beneath salt…





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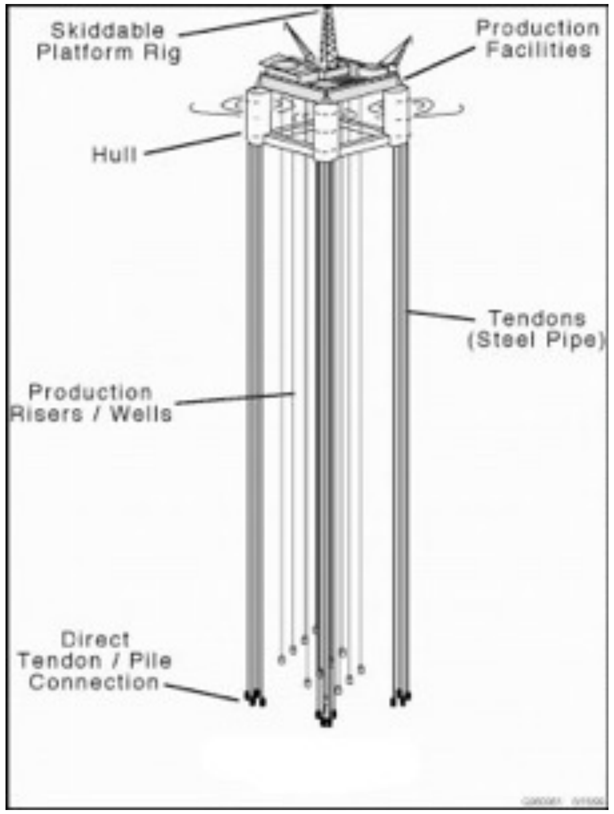
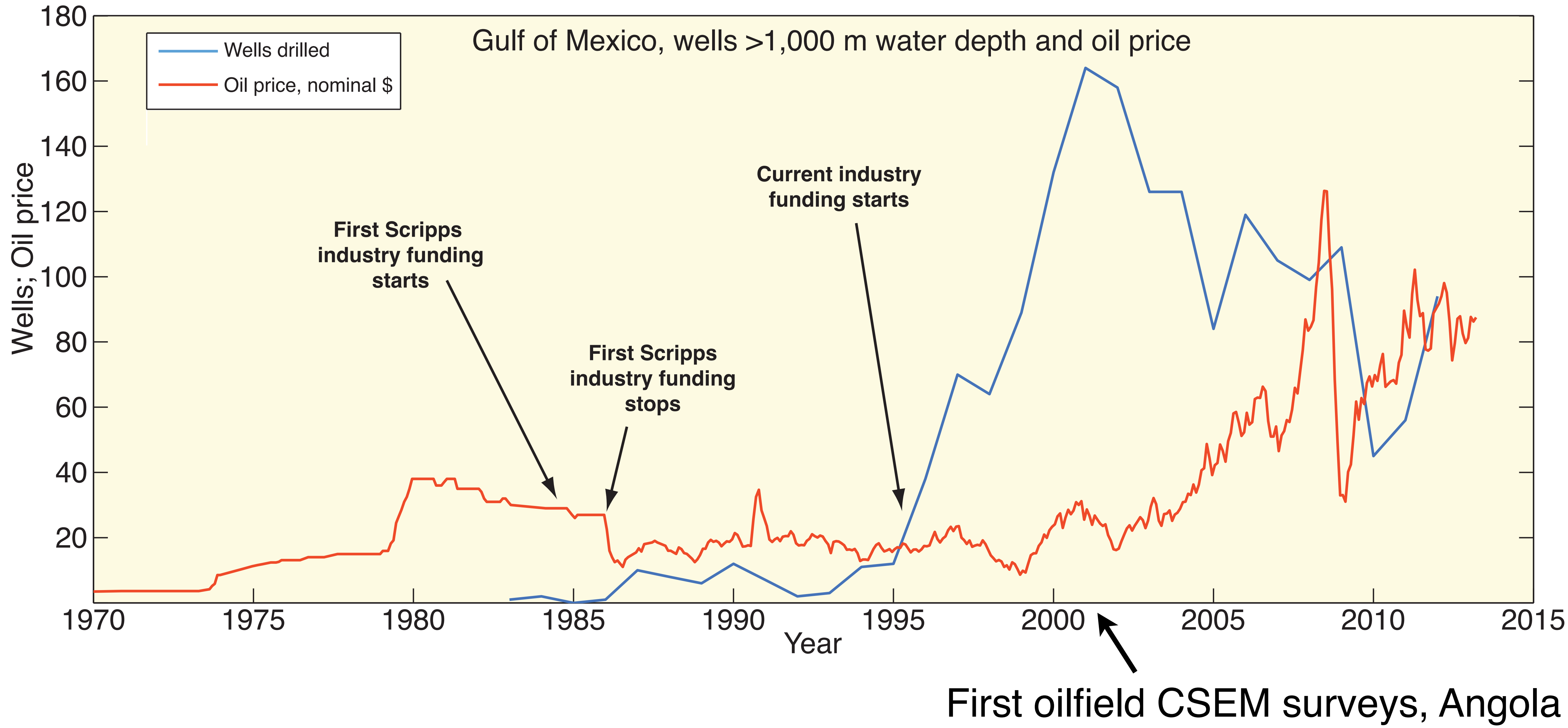


But probably the biggest factor was the development of the tension leg platform, which enabled production of oil and gas from deepwater prospects…

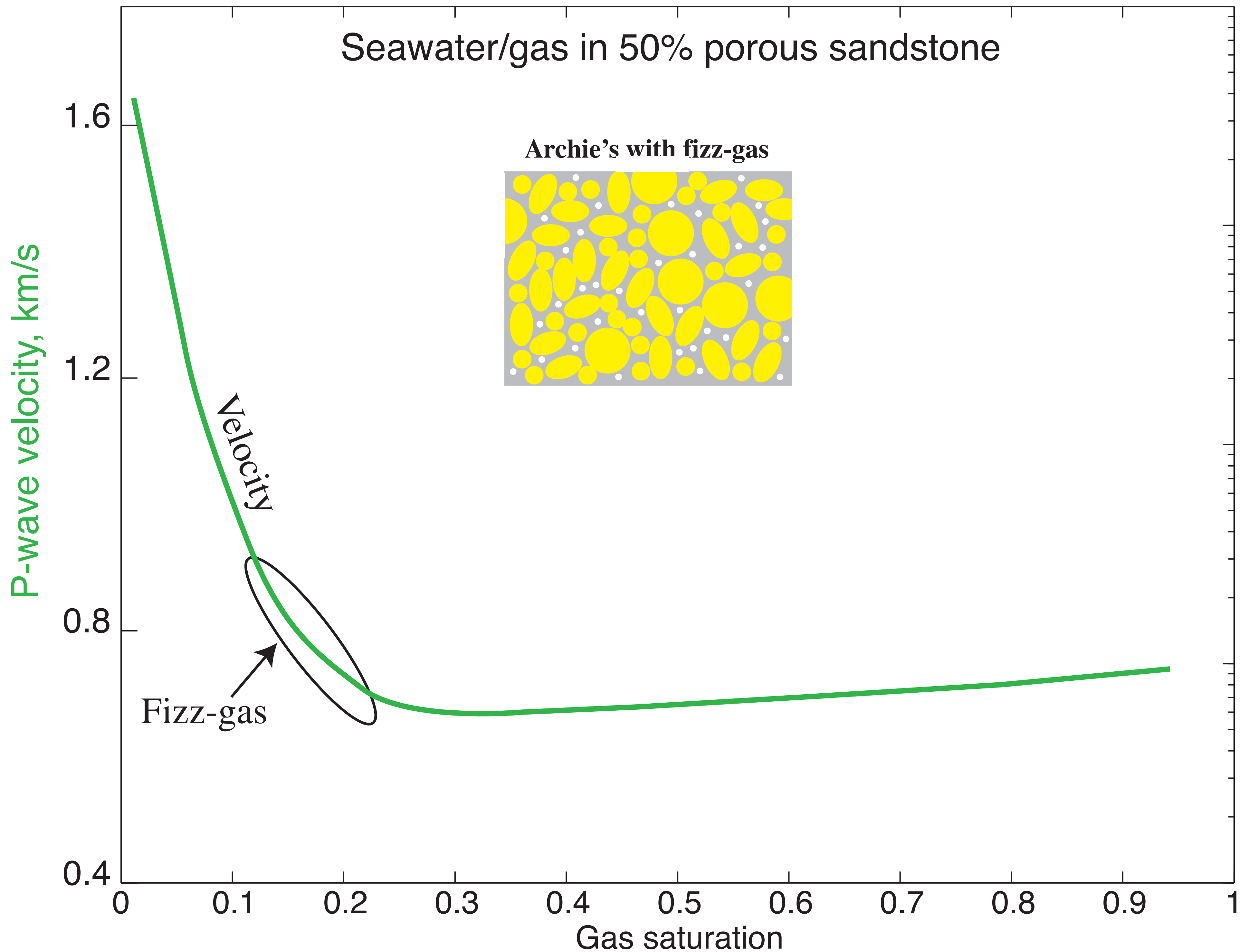
… but deepwater drilling is very expensive.



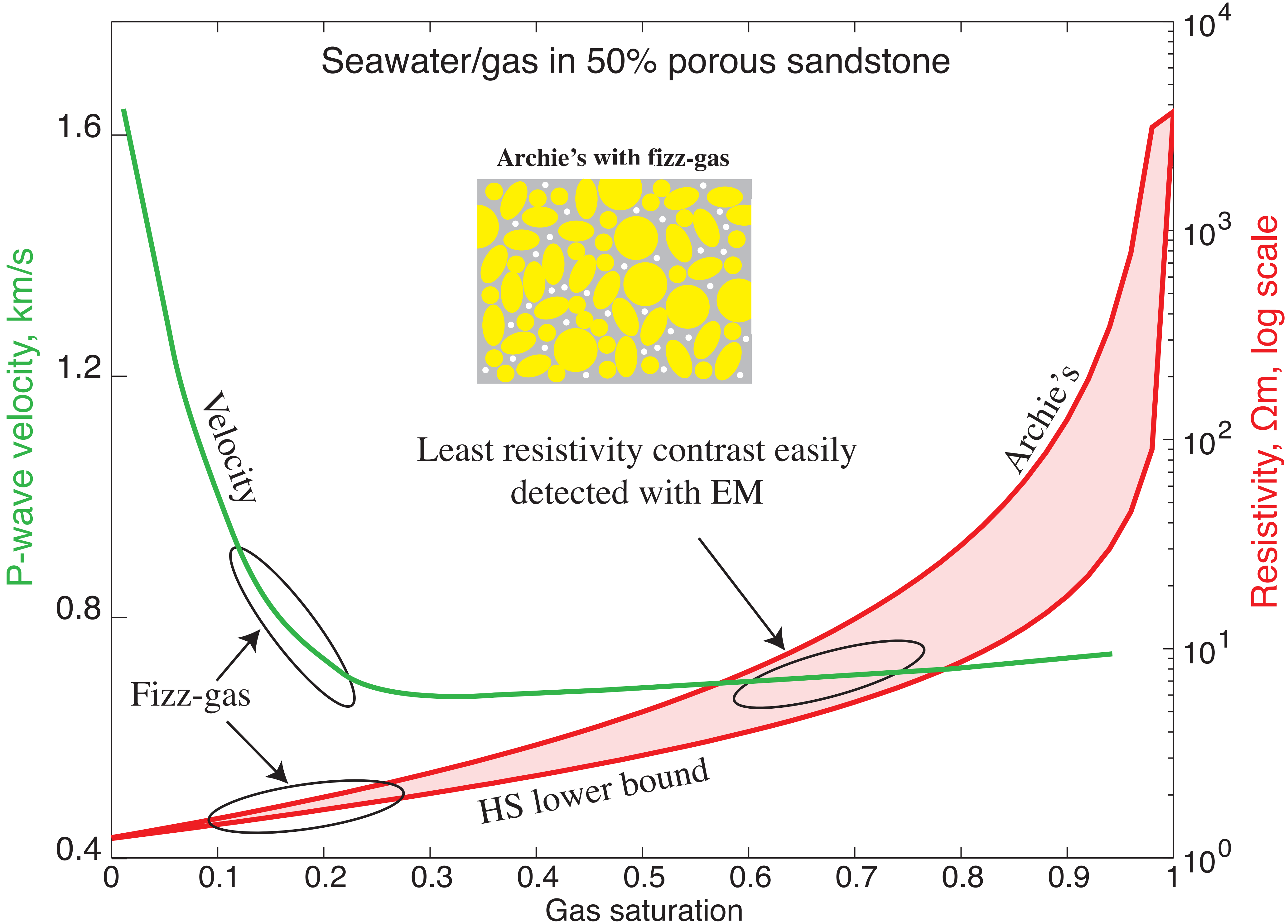
Commercial marine MT was offered starting in 1996. The first oilfield CSEM tests were done in late 2000 - early 2002, by Statoil and ExxonMobil. They both used Scripps receivers and the Southampton transmitter.

Again, the driver was the high cost of drilling combined with limitations in the seismic method.

The seismic method has the problem that small gas saturations produce big velocity changes.

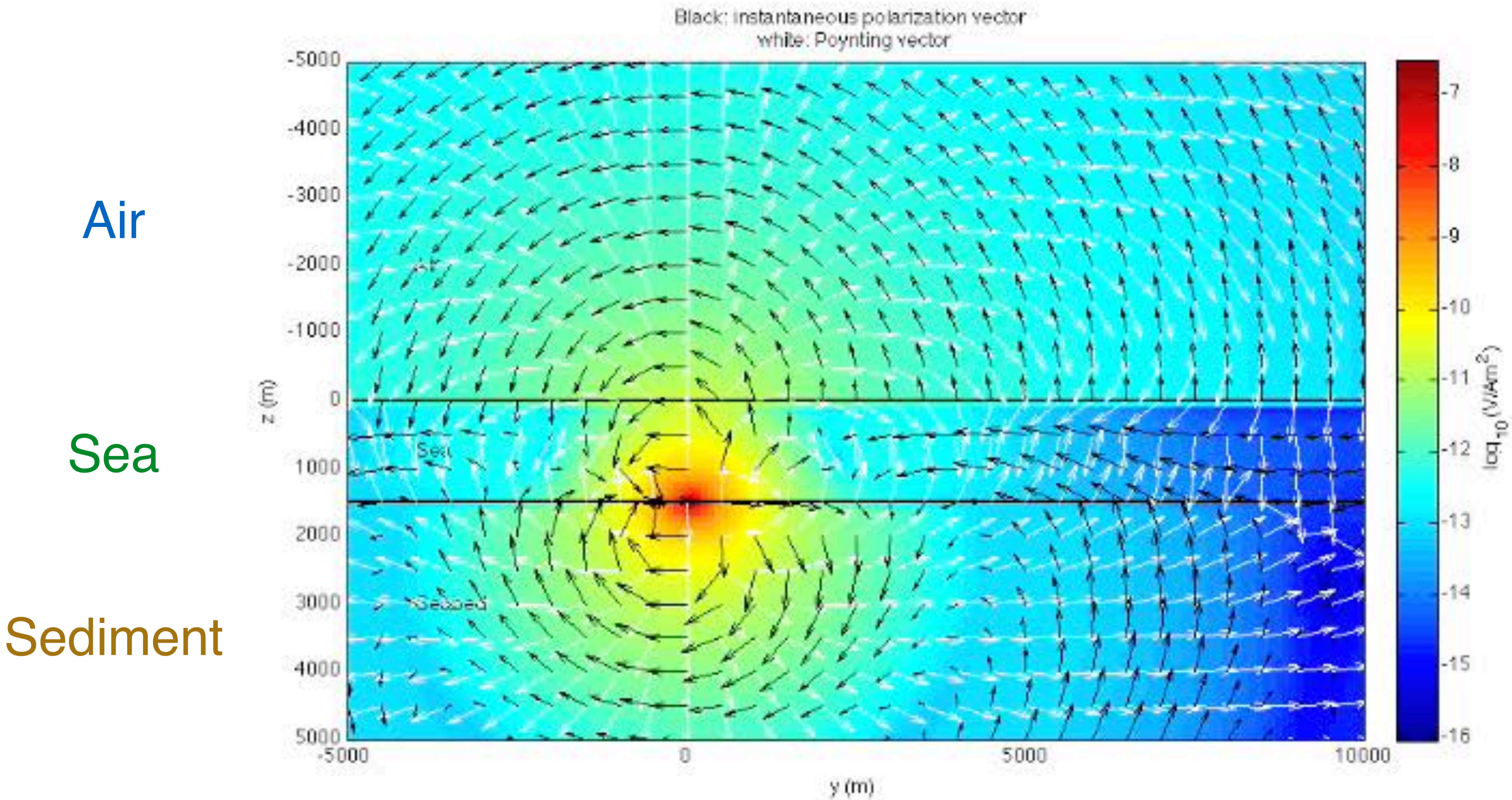


However, electrical resistivity does not change until the gas saturation gets large. This means that marine CSEM can be used to assess targets prior to drilling.



Oil and gas reservoirs are too thin to be sensed with MT - now we need to use a man-made source of energy. Again, EM energy propagates best through the more resistive rocks.

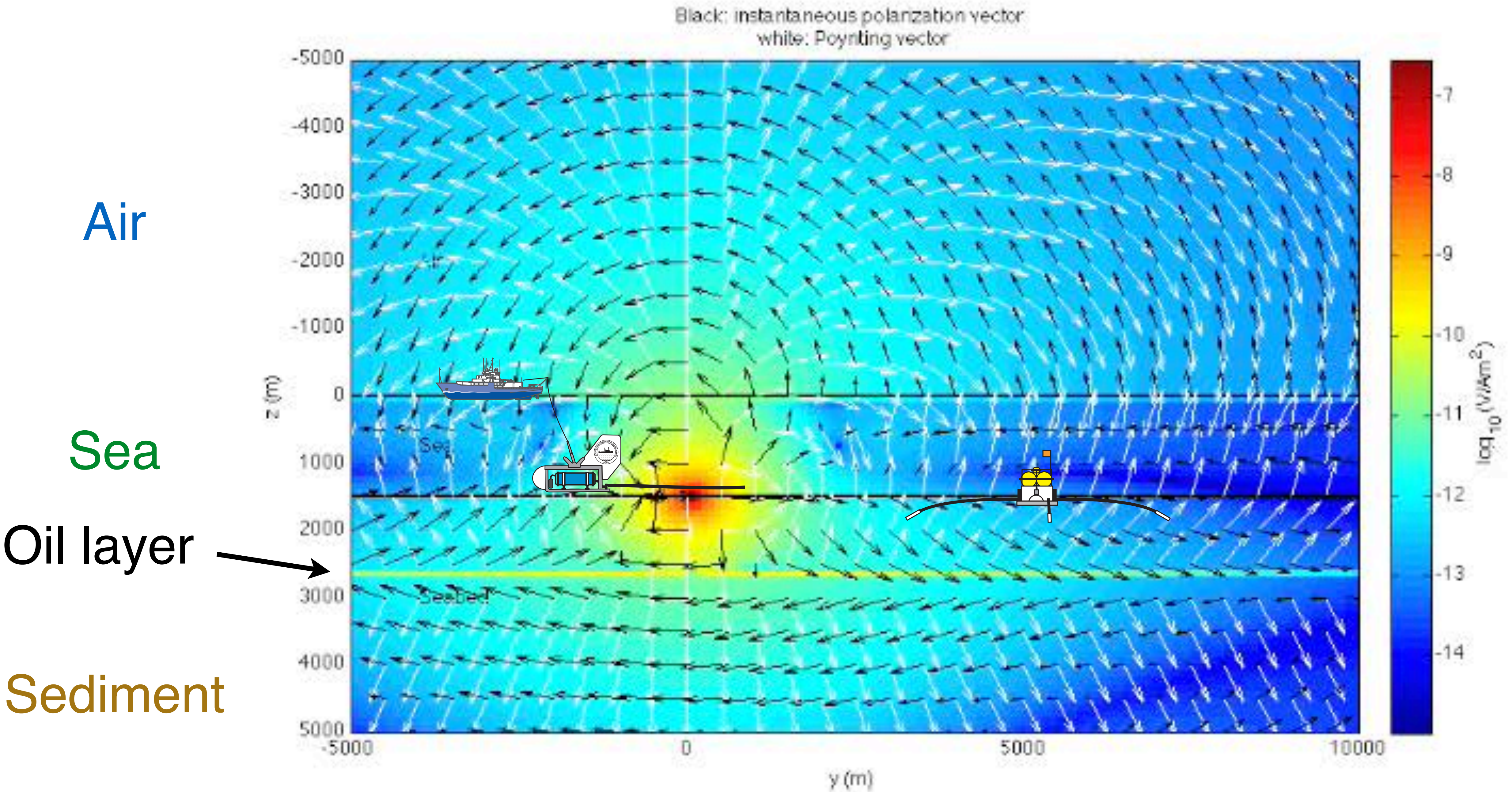
In this movie, the electric fields are absorbed more rapidly in seawater:



movie © Kerry Key, SIO.

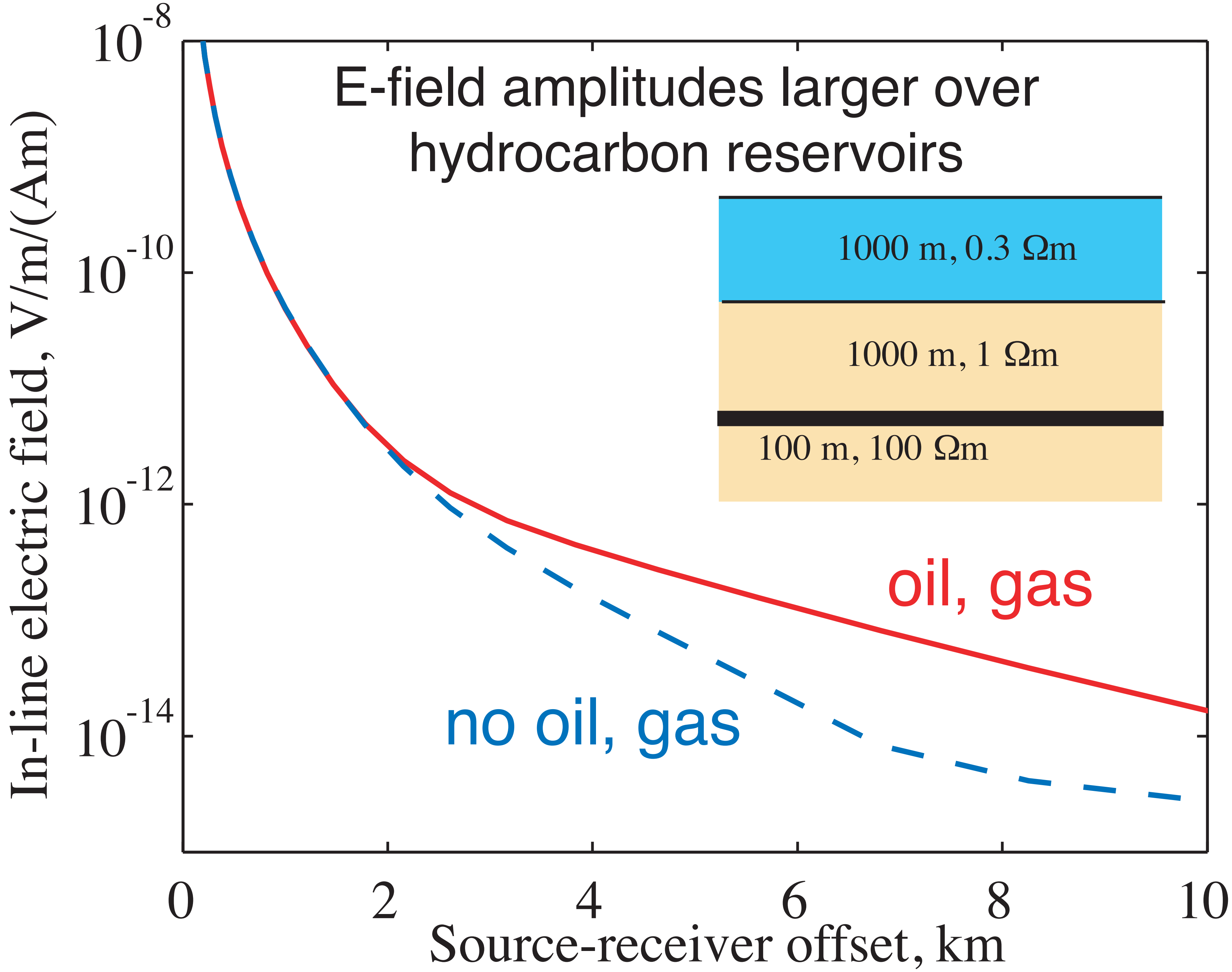
If we add a thin resistive layer to the model (an oil or gas reservoir?), then energy propagates even better through this layer than the surrounding sediments.

Then we add a transmitter and receivers to actually collect these data.

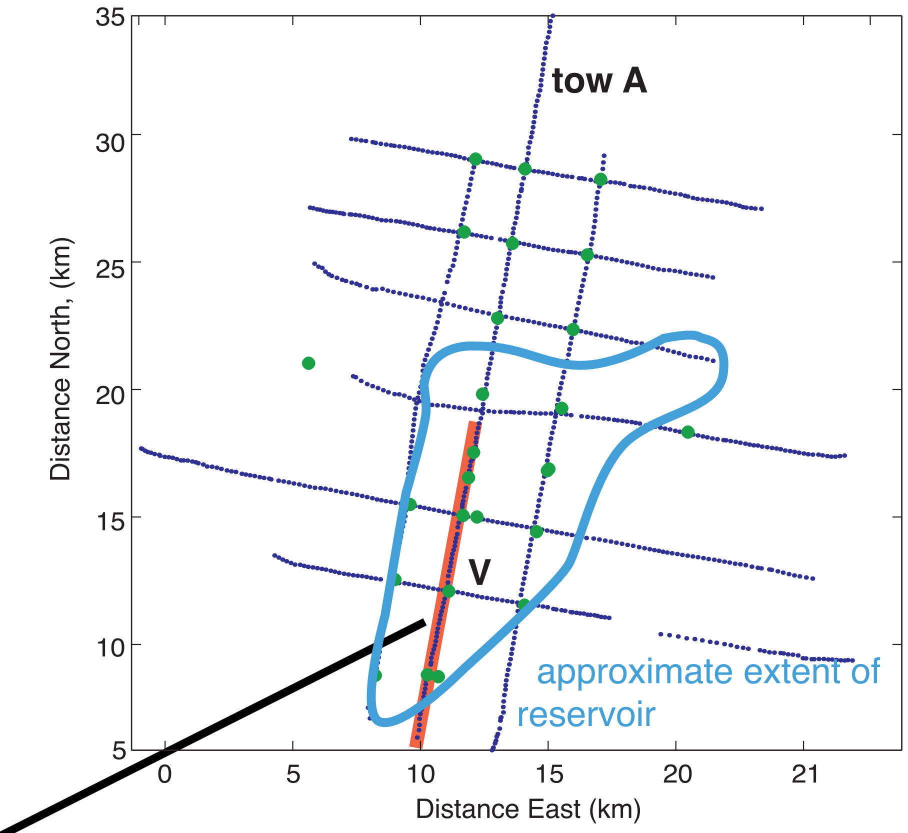


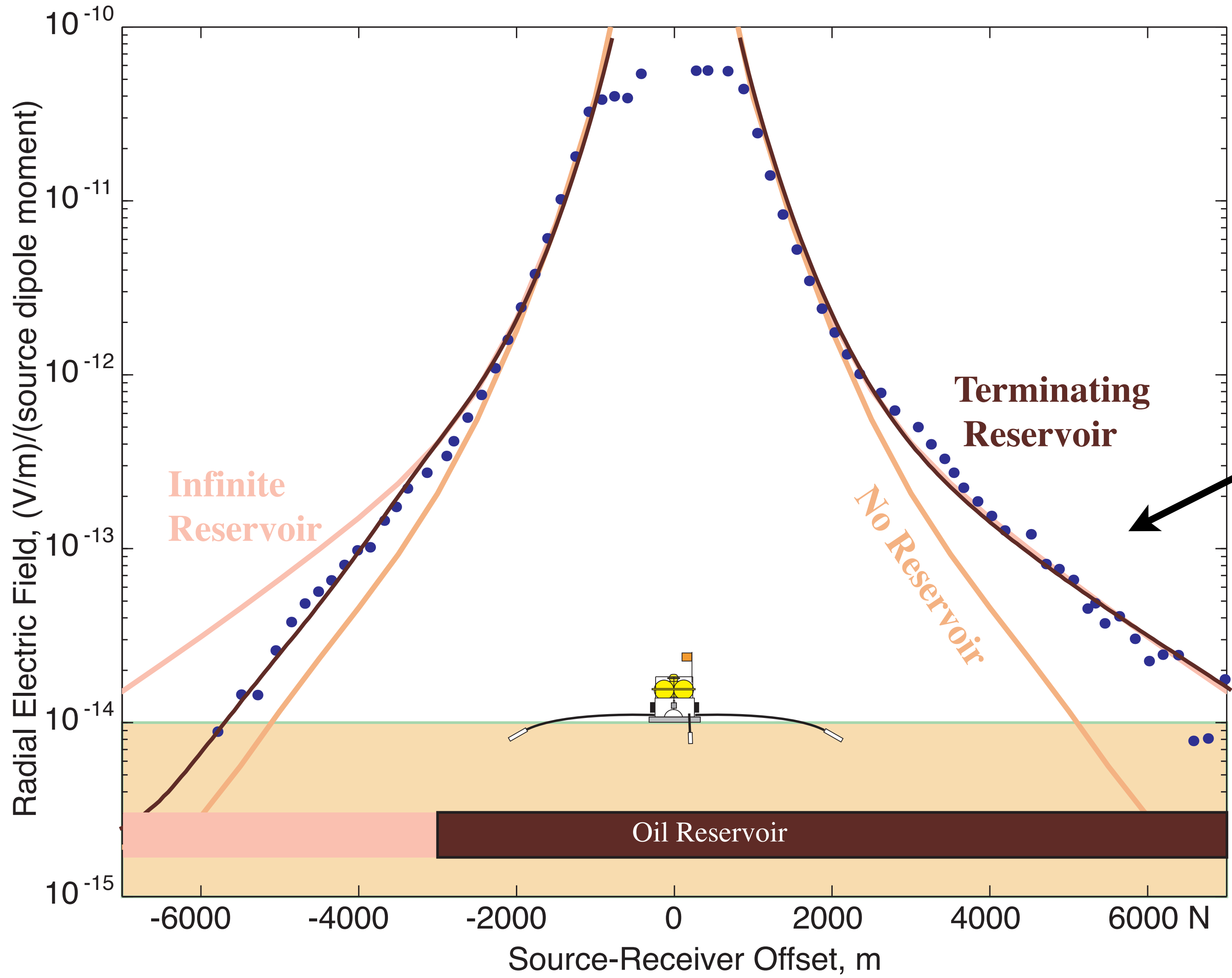
movie © Kerry Key, SIO.

The effect can be up to an order of magnitude for a large oil or gas reservoir. This is what I call the “canonical model”, and is similar to the target chosen by Statoil for the first test of the marine CSEM method, and very similar to the model that Chip used in his proposal.

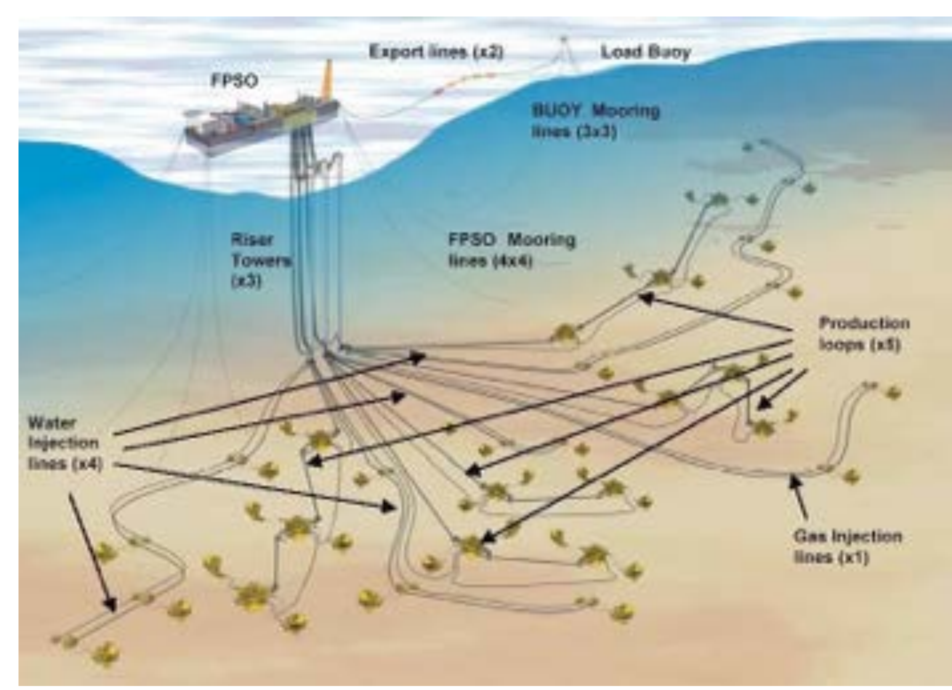


Statoil's tests were made in November 2000 over the Girasoll oil field off Angola:





Constable and Srnka, 2007

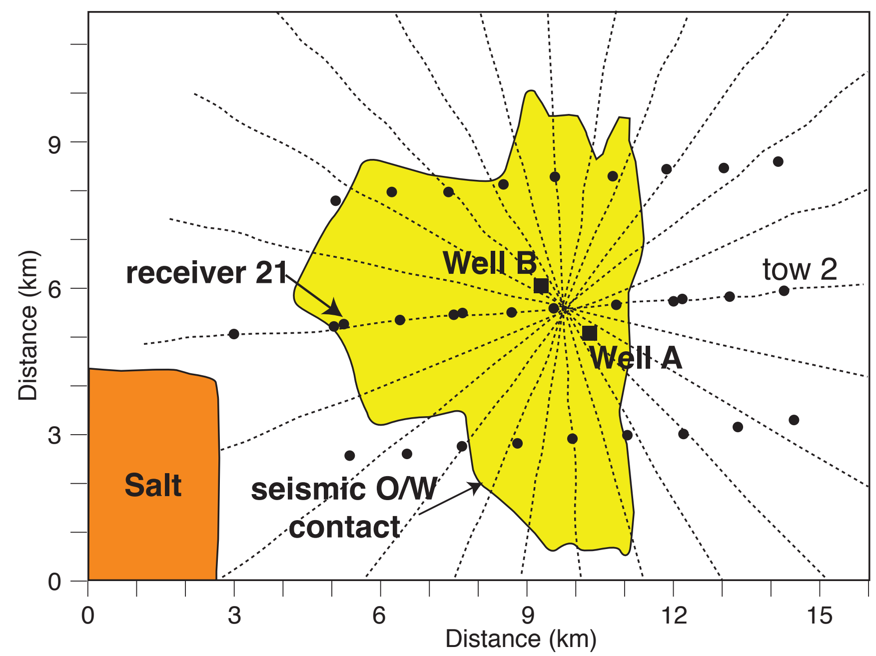


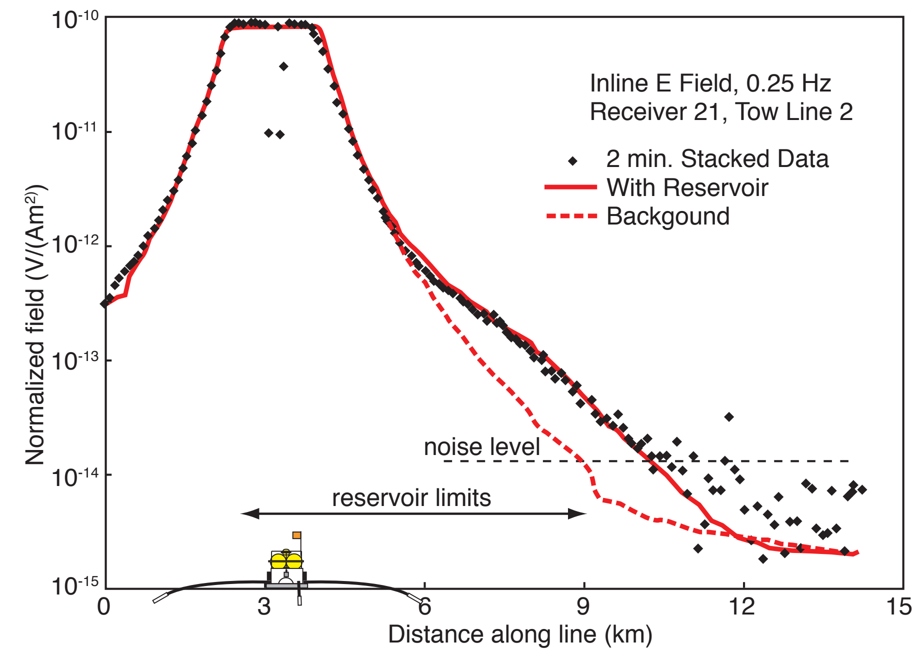
http://www.oilpro.com/

Similar studies were carried out by ExxonMobil in Jan 2002, also off Angola.

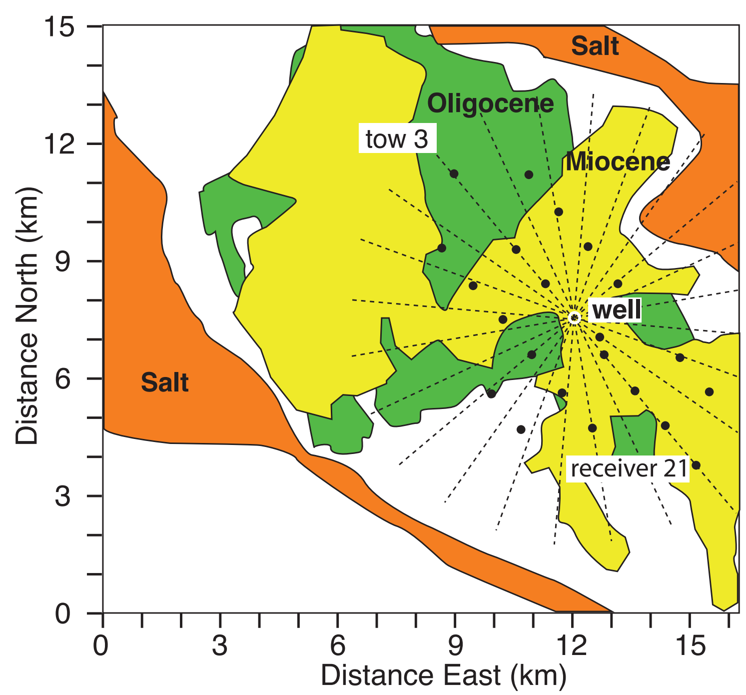
These studies used 30 new instruments designed and built by Scripps for ExxonMobil, operated by AOA Geophysics.

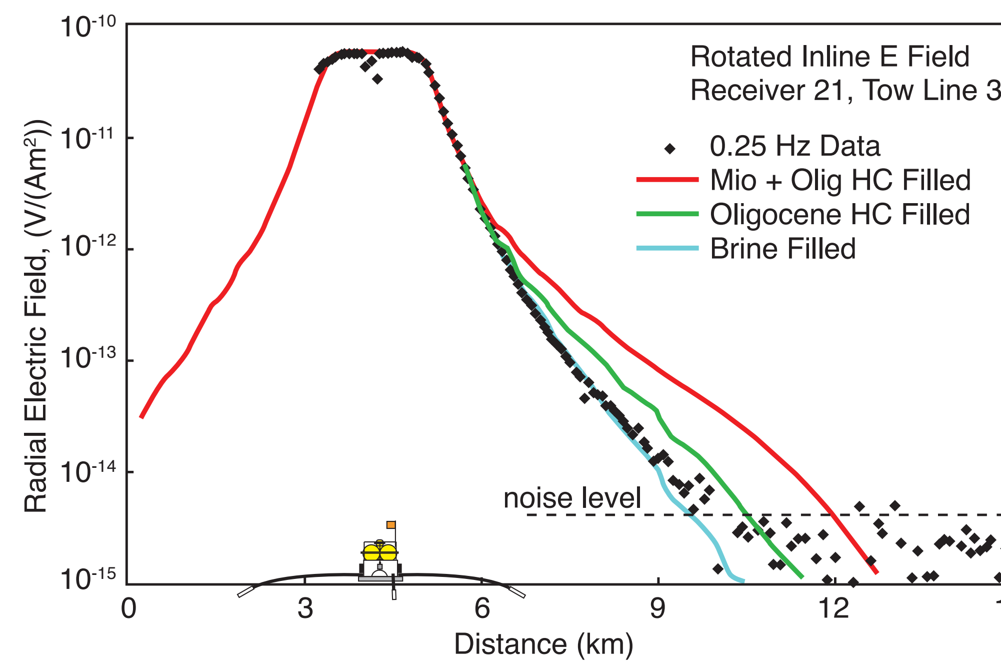
Over a known discovery





Prior to drilling





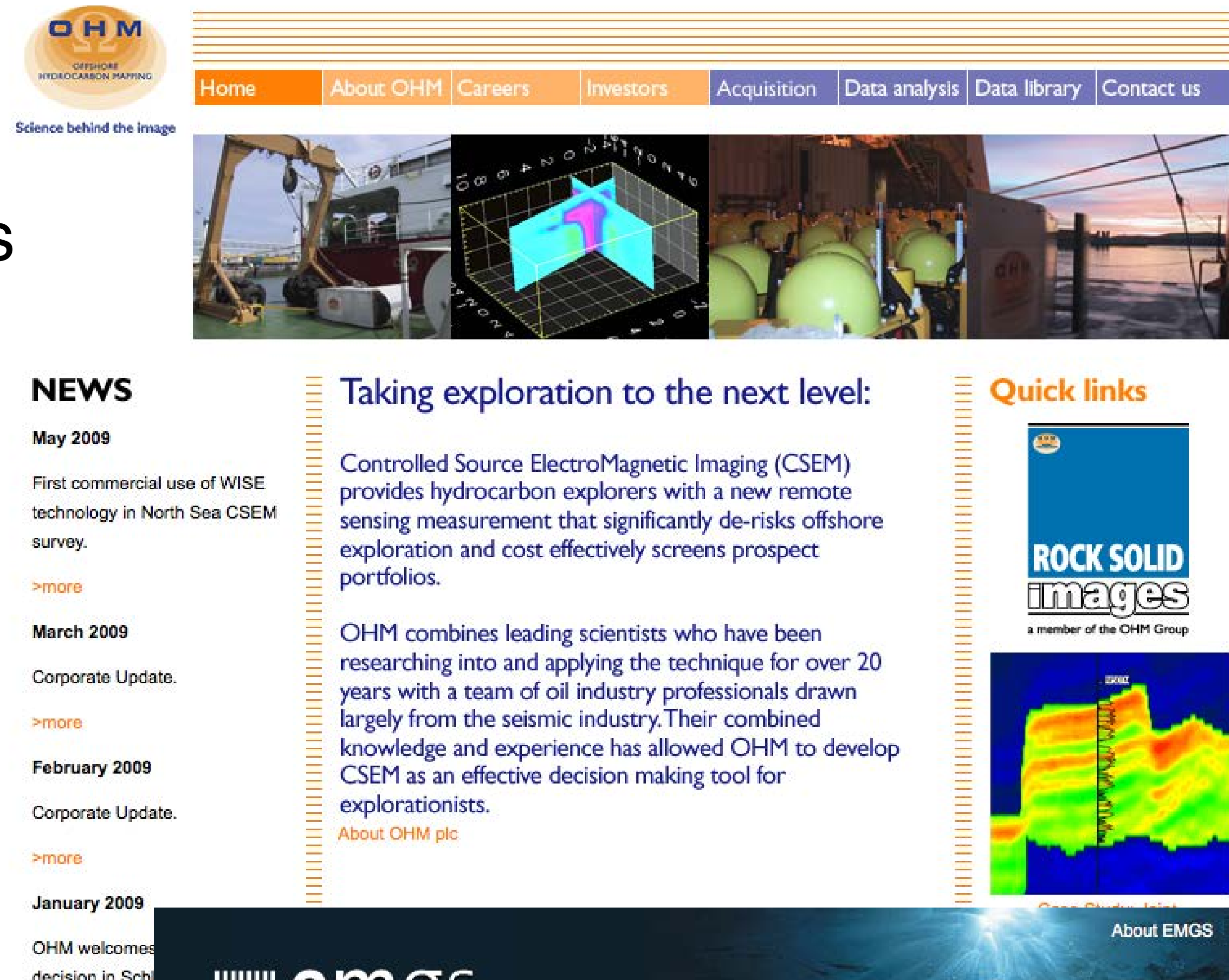
Constable and Srnka, 2007

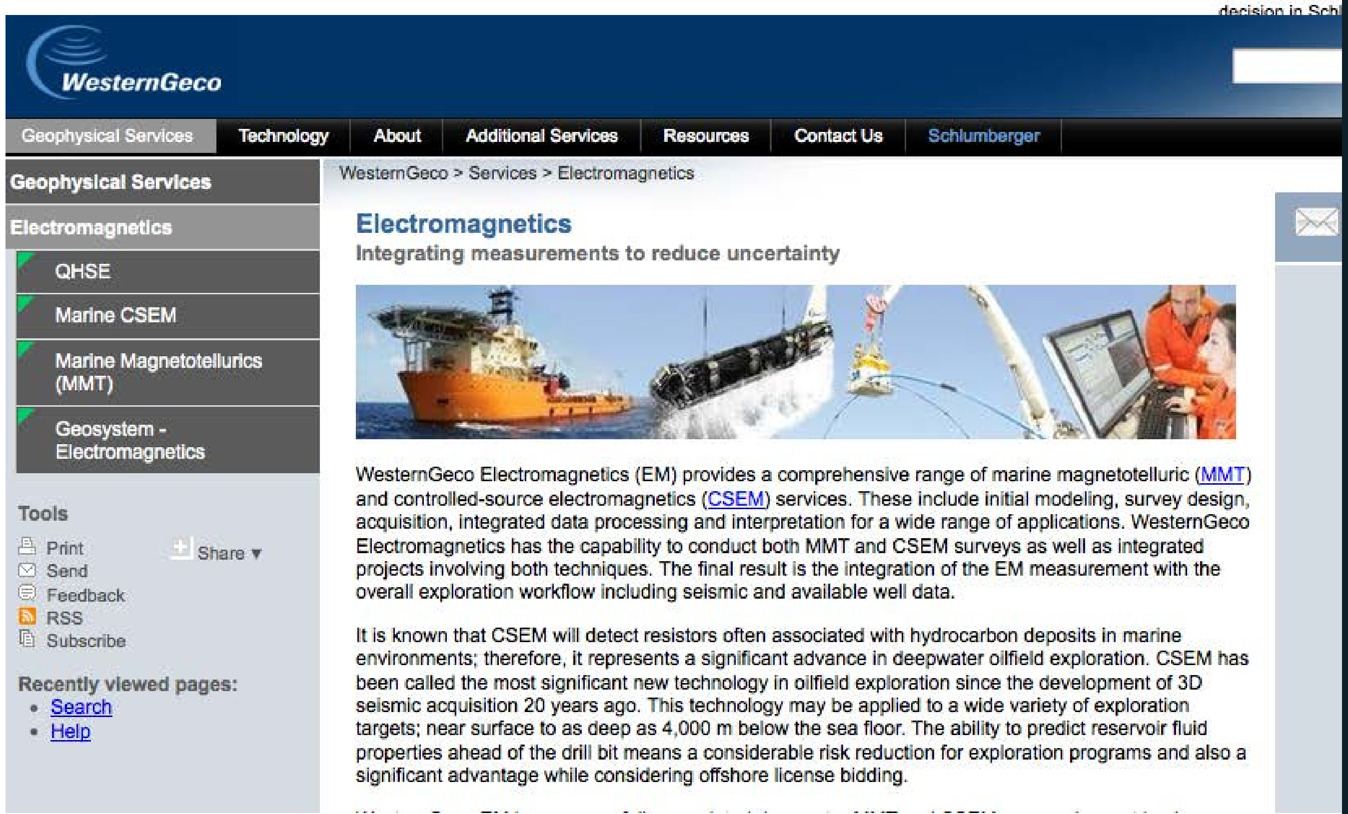
Then things got interesting...

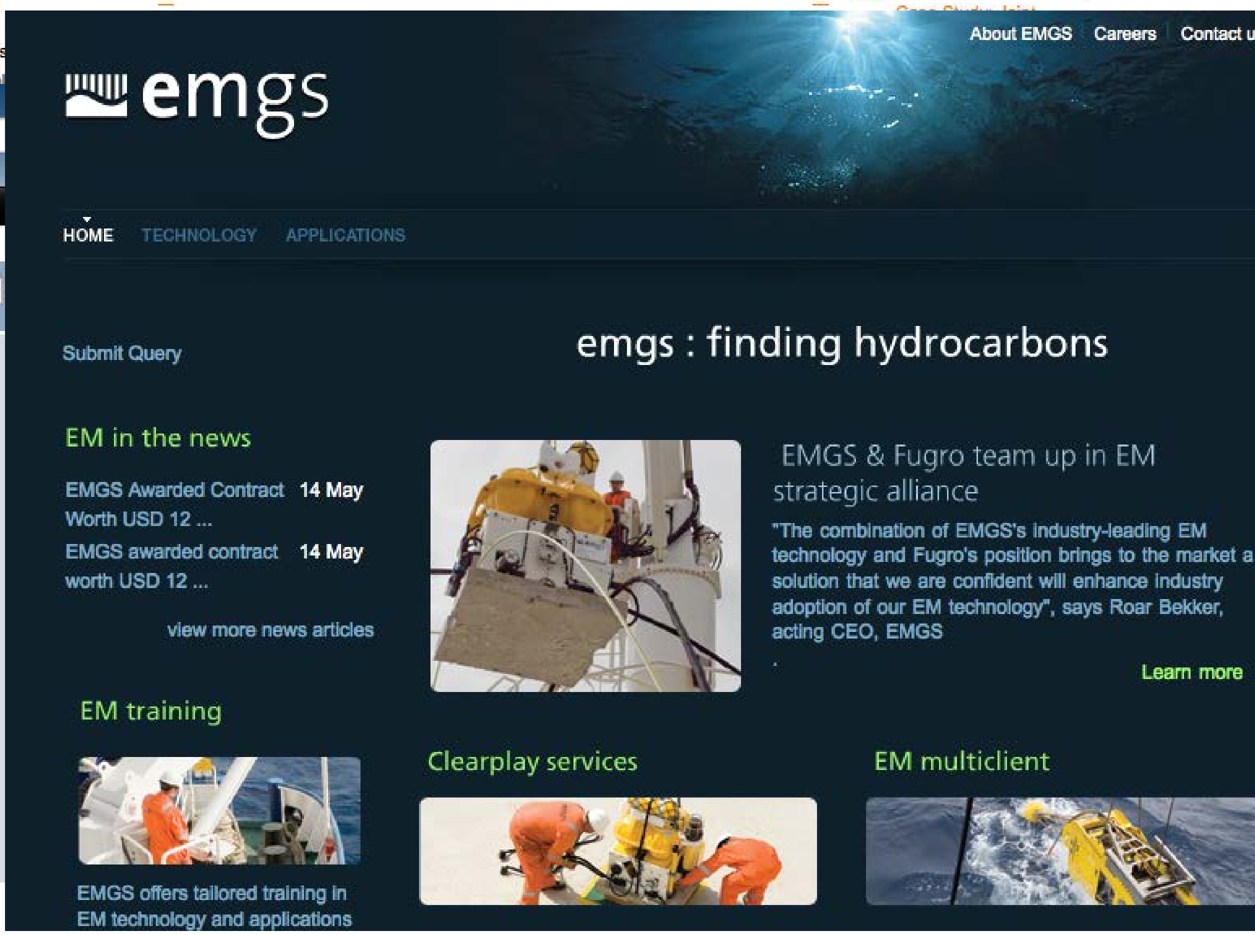
By the end of 2002 three contractors were formed to offer marine MT/CSEM as a commercial product.

Several special-purpose ships have been built since then.

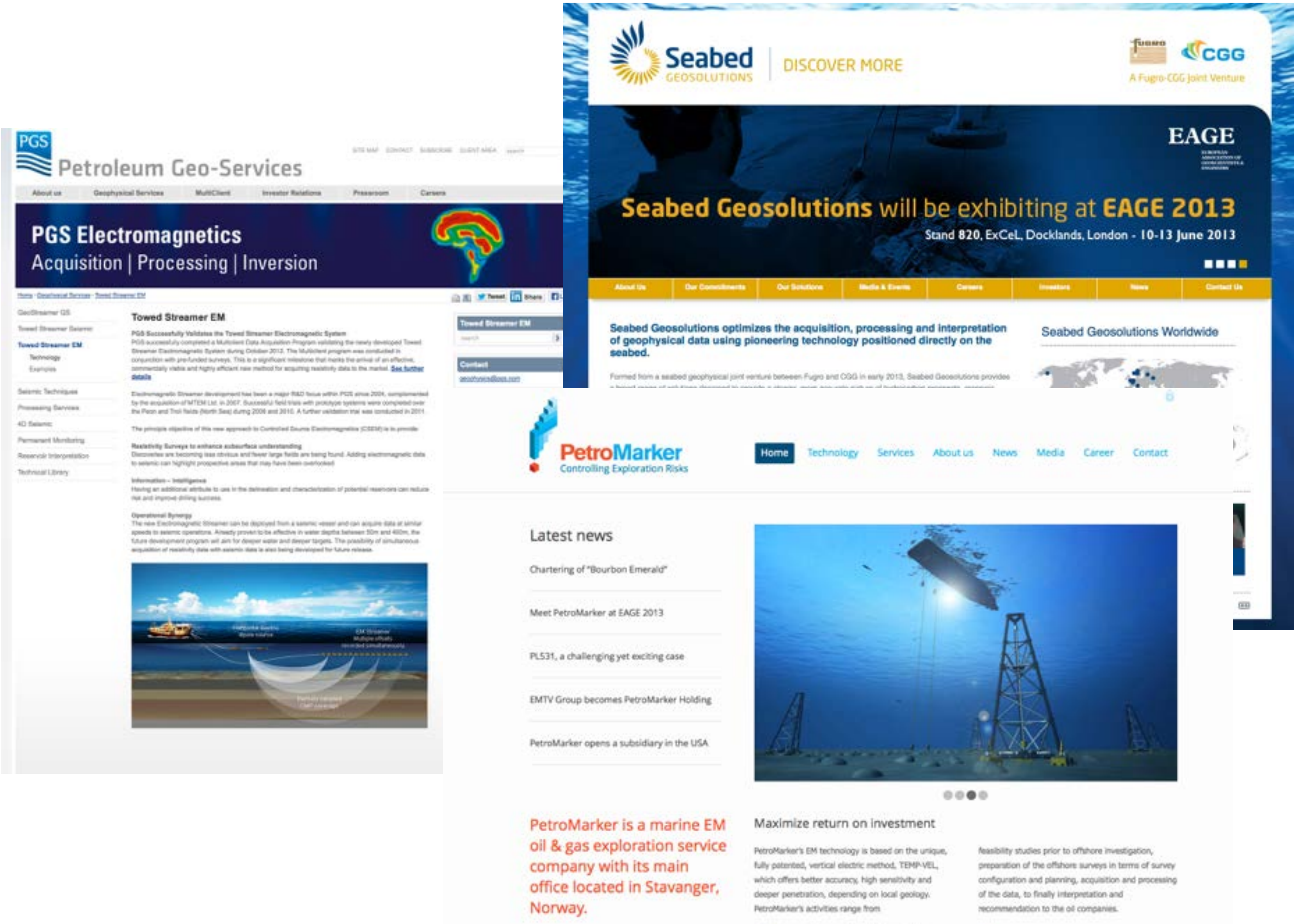
Much based on early academic science and technology.







Since then more companies have joined the party…

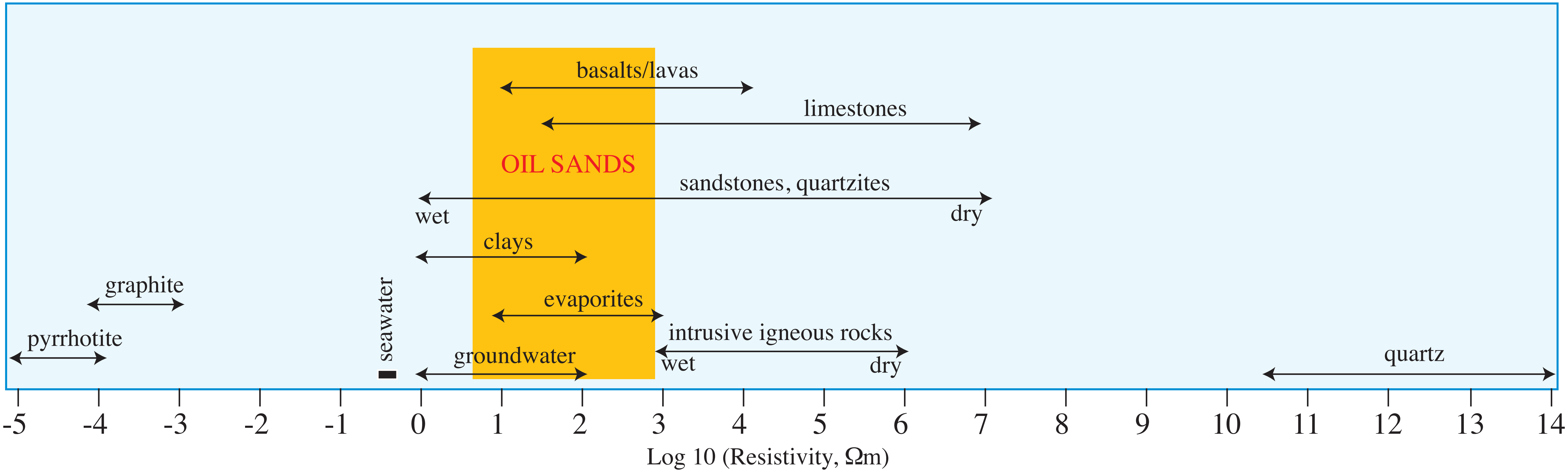


The Present

10 things you should know about marine CSEM that are not likely to change

1. EM does not map oil or gas, or even rock type. We cannot tell the difference between an evaporite, a basalt, or an oil sand based on resistivity alone.

Resistivity of Rocks and Minerals (Data from Telford et al.)



Thus, to manage false positives you need additional data - seismics, geology, magnetics, gravity, … Integration with other data sets is perhaps the only safe way to use marine EM data.

2. The resolution of EM induction is between wave propagation and potential fields:

High frequency (megahertz)

Wave equation: Resolution ~ wavelength

Radar $$\nabla^2 \mathbf{E} = \mu\sigma \frac{\partial \mathbf{E}}{\partial t} + \mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

Seismics $$\nabla^2 u = \epsilon \frac{\partial u}{\partial t} + \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2}$$

Mid frequency (0.001 - 1000 Hz)

Diffusion equation: Resolution ~ size/depth

Inductive EM $$\nabla^2 \mathbf{E} = \mu\sigma \frac{\partial \mathbf{E}}{\partial t}$$

Zero frequency

Laplace equation: Resolution ~ bounds only

DC Resistivity $$\nabla^2 \mathbf{E} = 0$$

Gravity/ Magnetism $$\nabla^2 U = 0$$

σ = electrical conductivity ~ $3 - 10^{-6}$ S/m

μ = magnetic permeability ~ $10^{-4} - 10^{-6}$ H/m

ϵ = electric permittivity ~ $10^{-9} - 10^{-11}$ F/m

3. Frequency is too low for wave propagation in rocks, but does constrain length scale through skin depth z_s:

At a single frequency $\nabla^2 \mathbf{E} = \mu\sigma \frac{\partial \mathbf{E}}{\partial t}$ becomes $\nabla^2 \mathbf{E} = i\omega\mu\sigma\mathbf{E}$

($\omega = 2\pi f$) which for uniform fields has solutions of the form

$$E(z) = E_o e^{-z/z_s + i(\omega t - z/z_s)}$$

where we have defined a skin depth

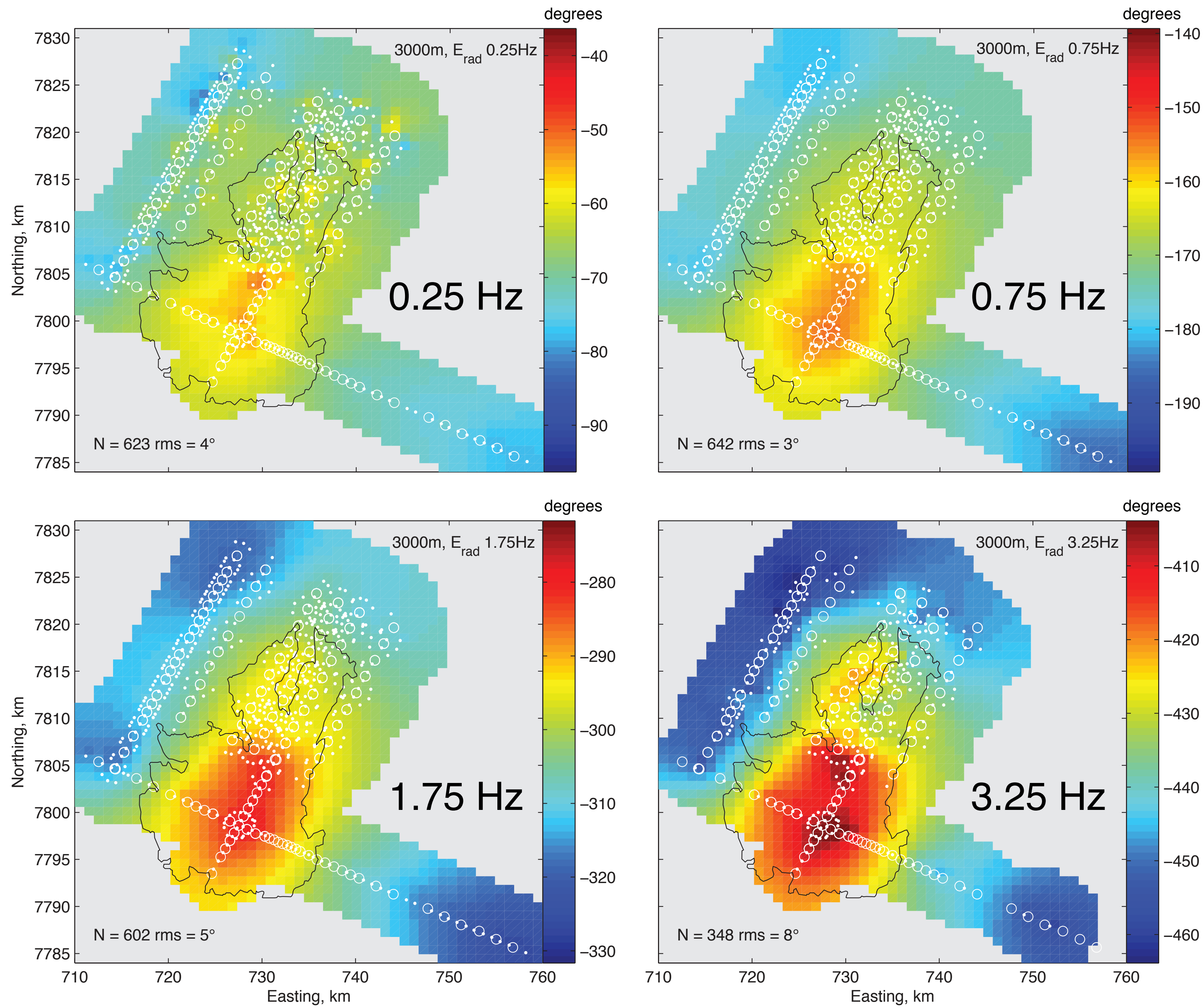
$$z_s = \sqrt{2/\omega\mu\sigma}$$

For every skin depth the fields decay by 1/e (~37%) and phase lags by one radian (~57°).

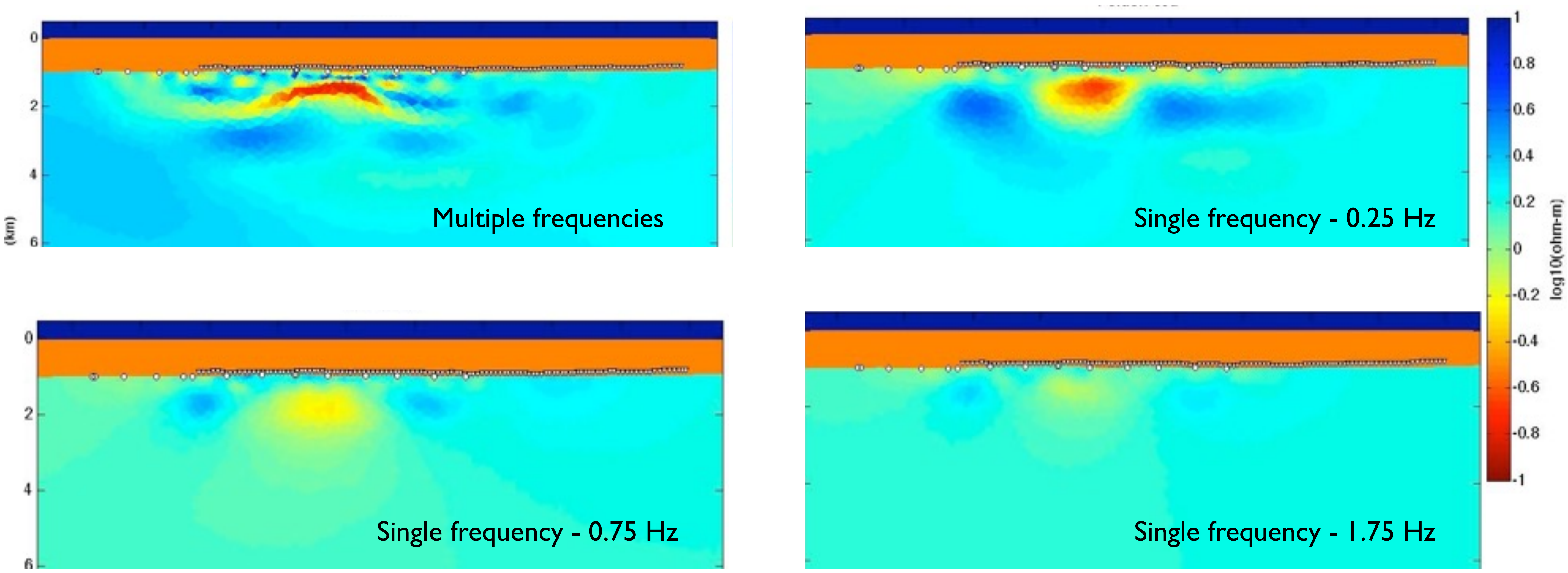
In 1 Ωm sediments:

frequency	skin depth
0.1Hz	1,600 m
0.25 Hz	1,000 m
1.0 Hz	500 m
5.0 Hz	225 m

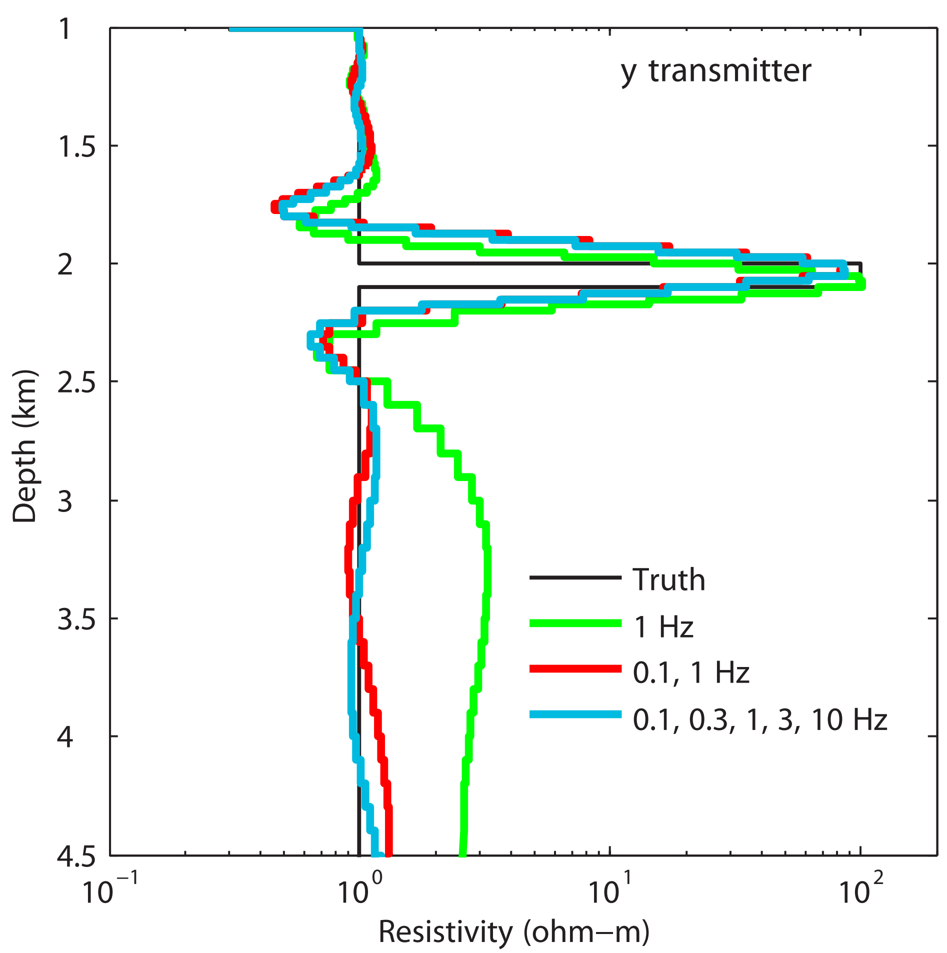
Although you need a low enough frequency to reach your target, sensitivity can increase with frequency (E_{radial}, 3,000 m, phase):



(But your signal size gets smaller.) These are data over the Scarborough gas field offshore NW Australia, collected by Scripps with support from BHP Billiton.



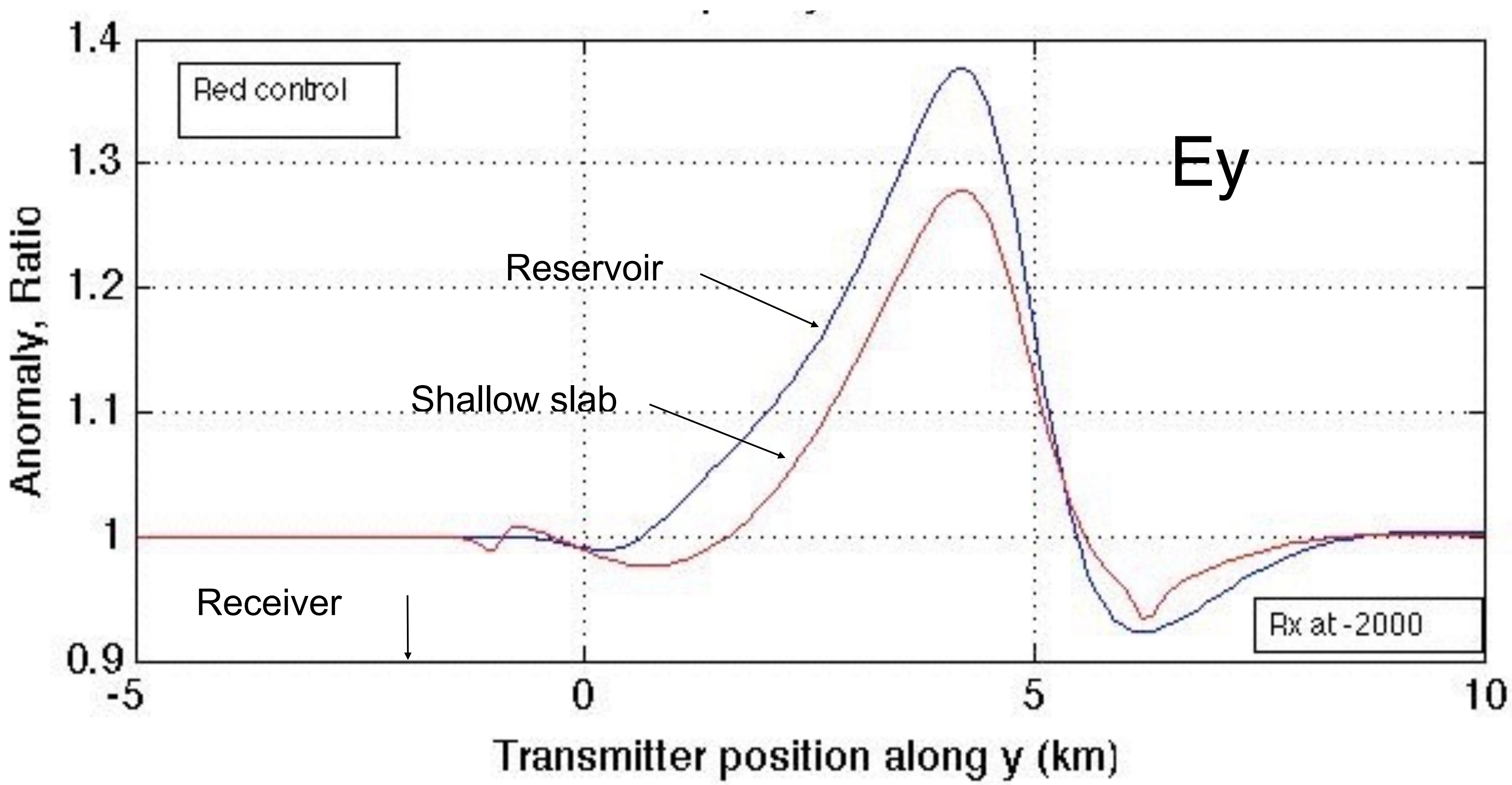
Constable, Orange, and Key, 2015

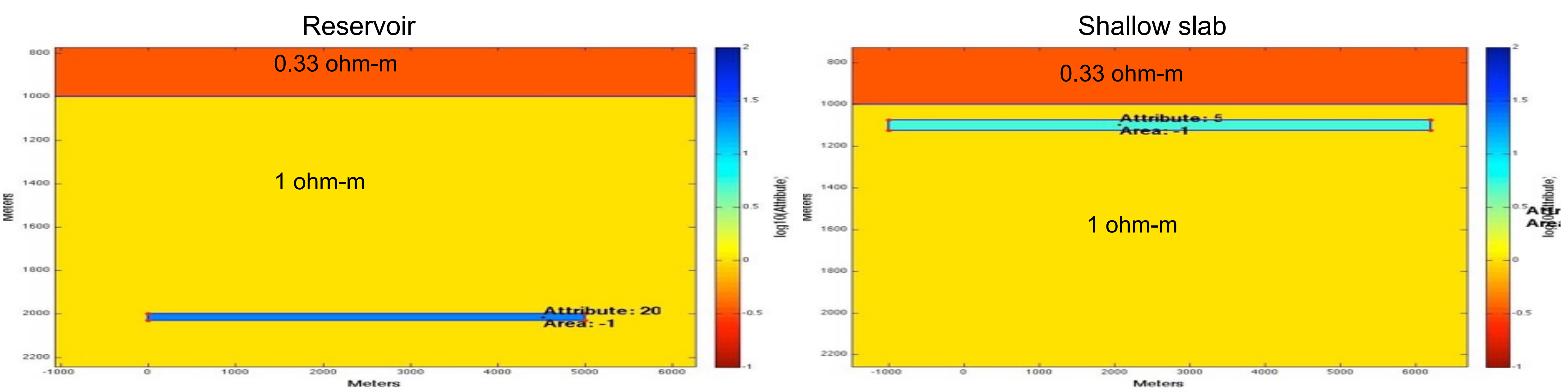


Key, 2009

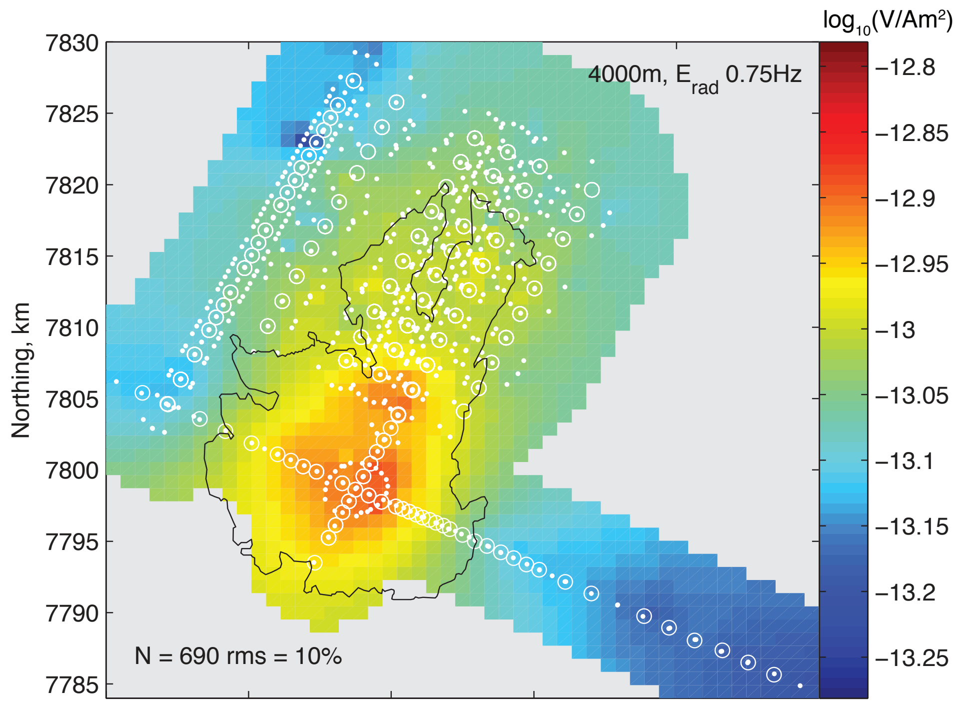
4. Good inversion technology is key to getting the most out of EM data, and inversions of multiple frequencies are **much** better than single frequency inversions.

With a single frequency and no phase data, a shallow resistor (say, hydrate) has an almost identical response to a deep hydrocarbon reservoir. This led to actual drilling errors.

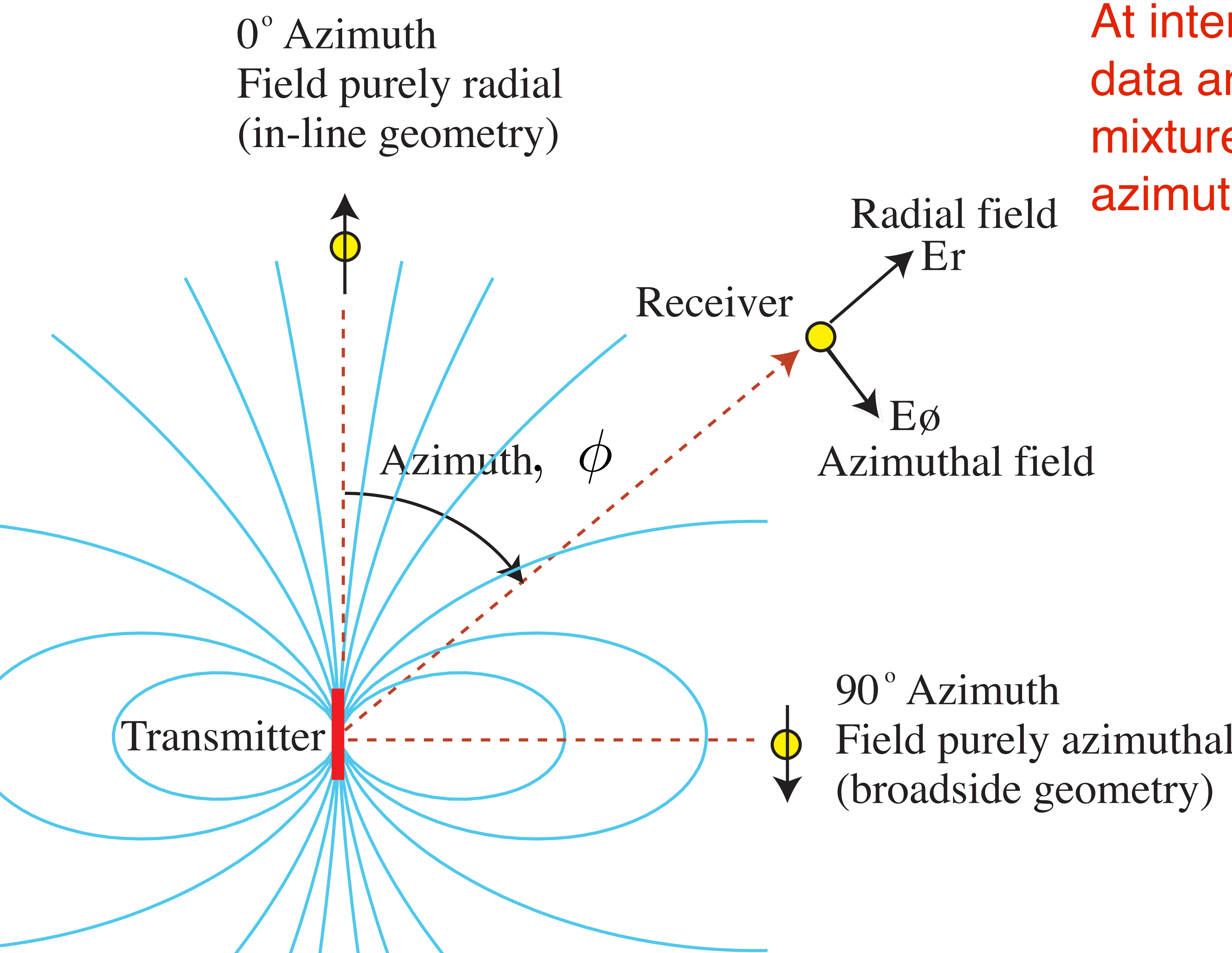




Courtesy Arnold Orange

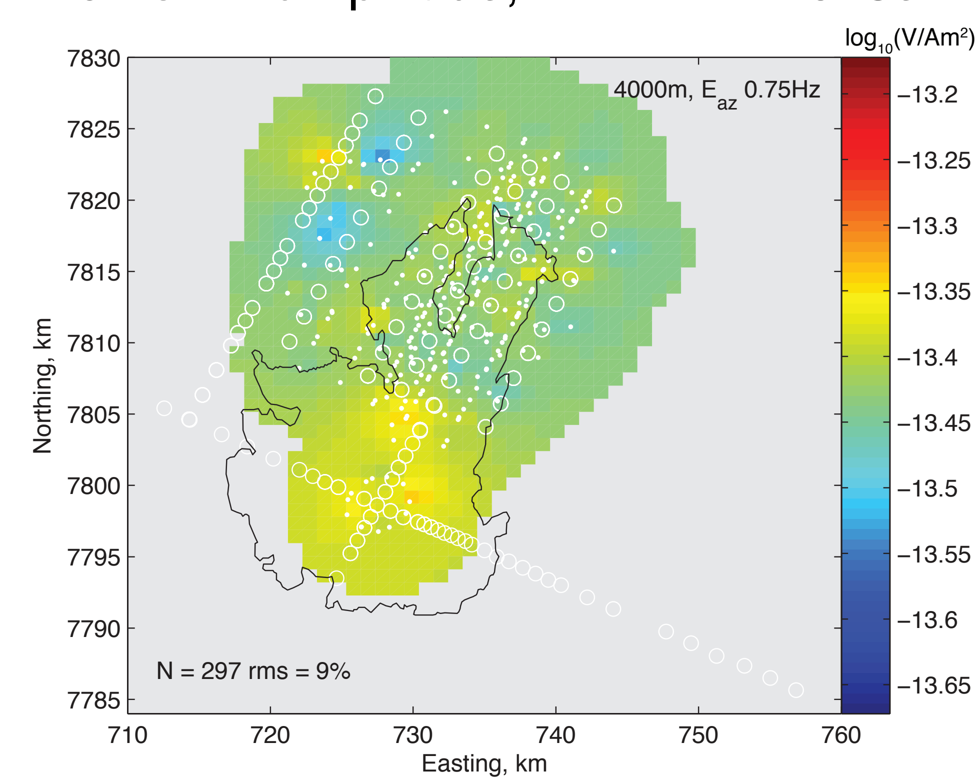


5. Transmitter fields have a dipole geometry. The radial (inline) and azimuthal (broadside) fields behave differently. The greater vertical component of the radial fields creates greater sensitivity to thin, sub-horizontal resistors (reservoirs). You can use this to tell thick from thin resistors. The modes also behave differently to anisotropy.

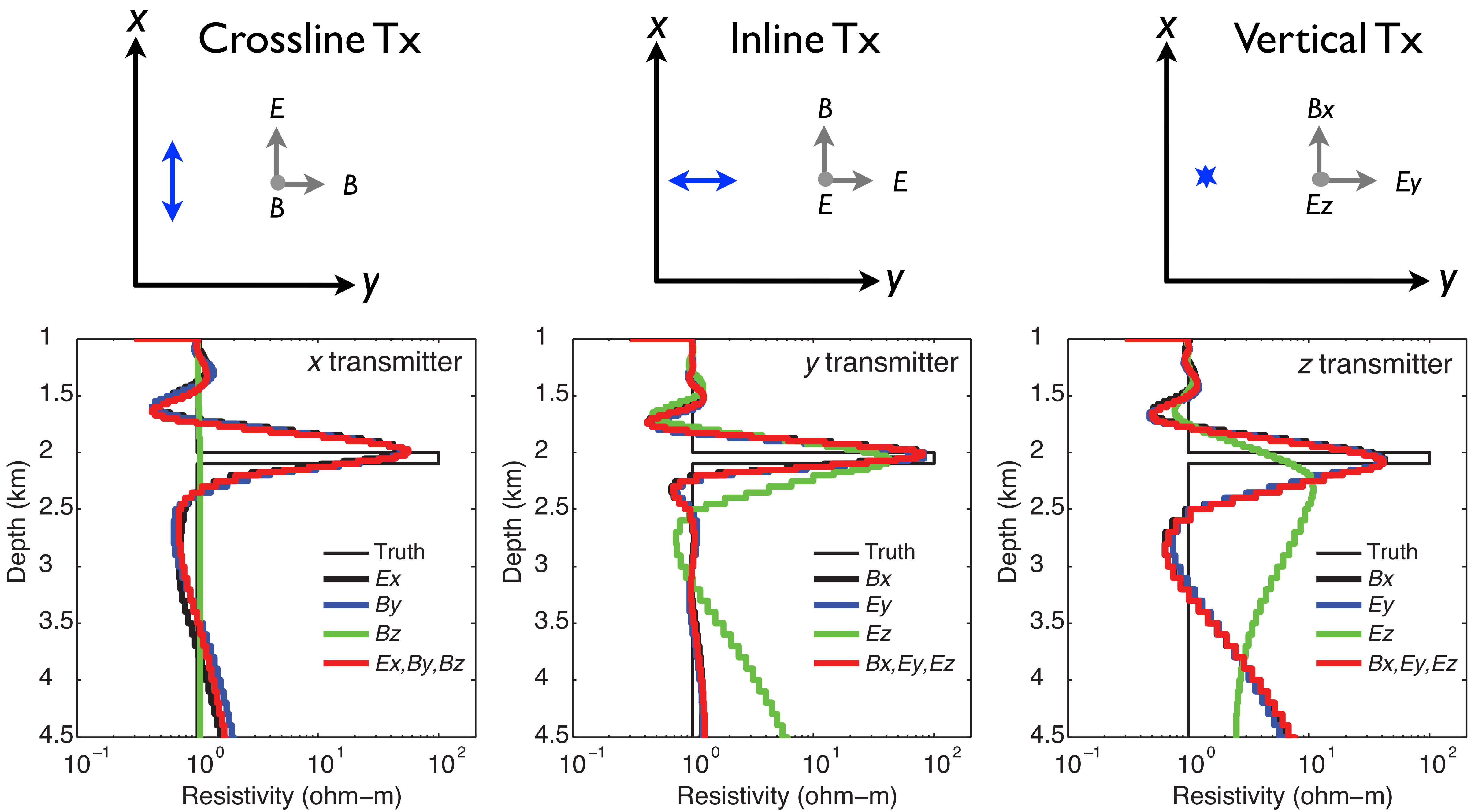


At intermediate azimuths the data are a trigonometric mixture of the radial and azimuthal fields.

0.75 Hz amplitude, 4km Tx-Rx offset



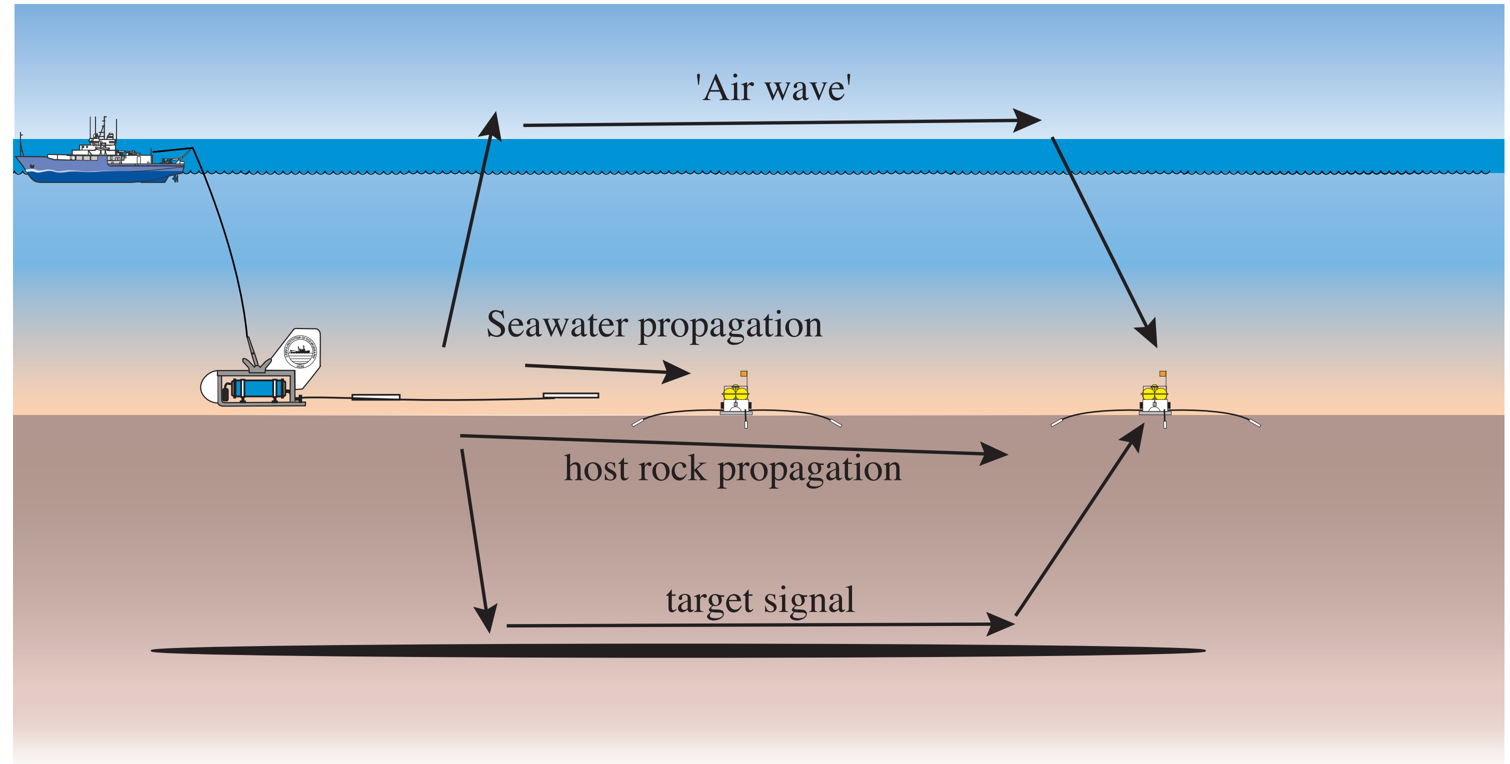
Inverting either inline *Bx* or *Ey* provides best resolution to reservoir targets. Note *Ez*: don't confuse sensitivity with resolution.

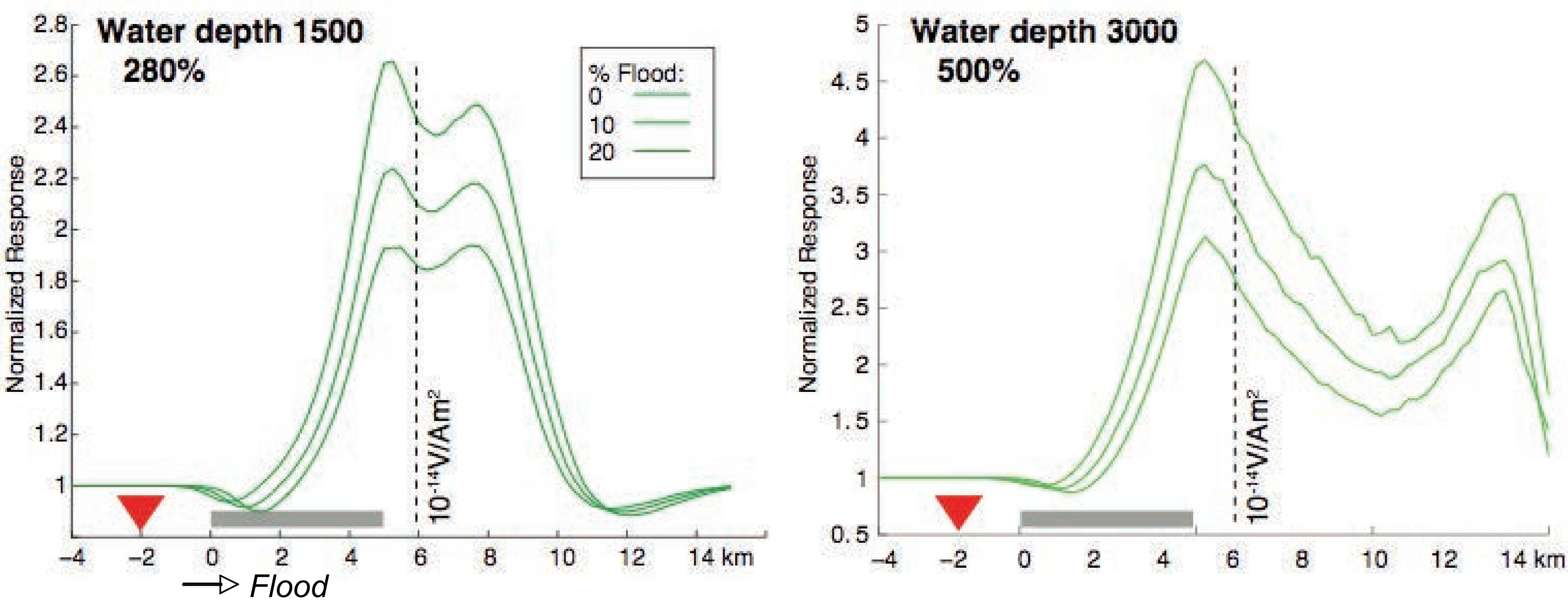


1D Inversions of synthetic 0.1 and 1.0 Hz data with 1% noise added:

Key, 2009

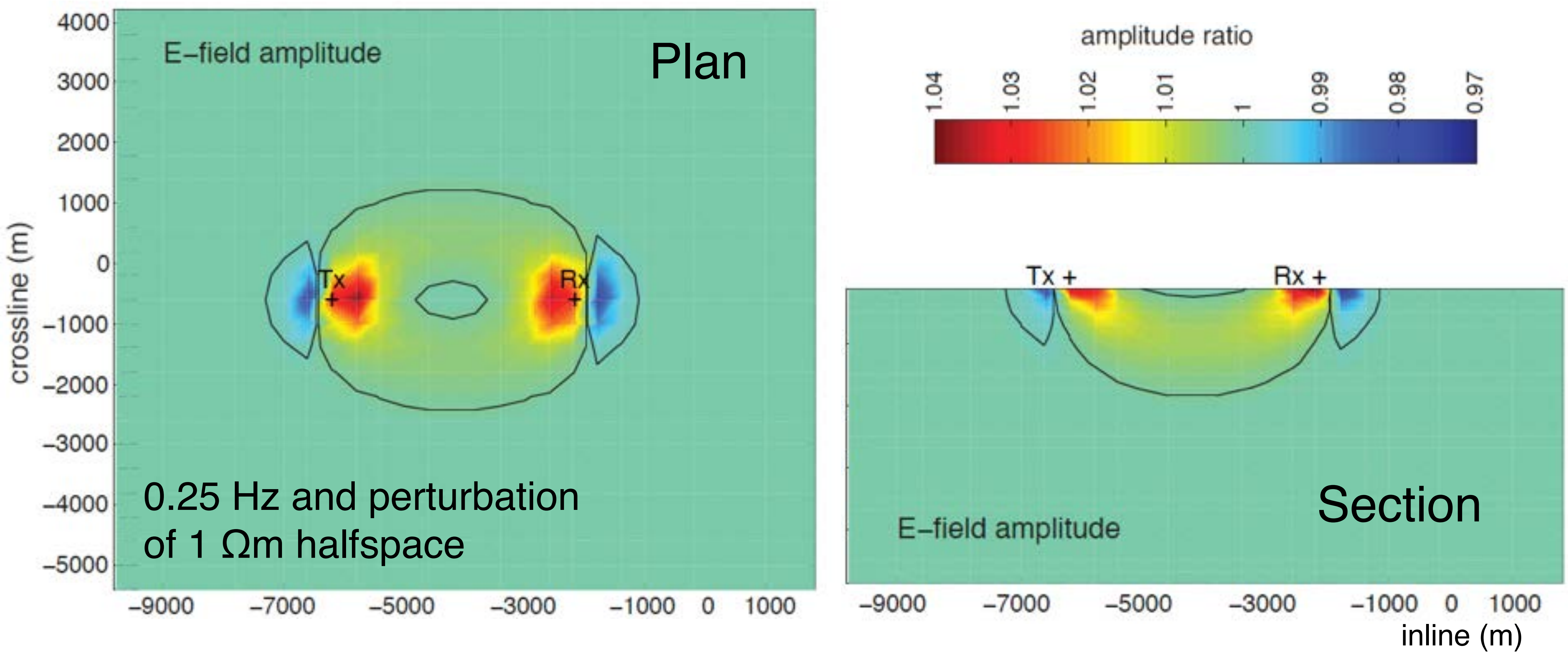
6. CSEM works best in deep water, where the “air wave” is small. But, it works OK in shallow water because the air wave and target response are coupled. Don’t try to remove the air wave.





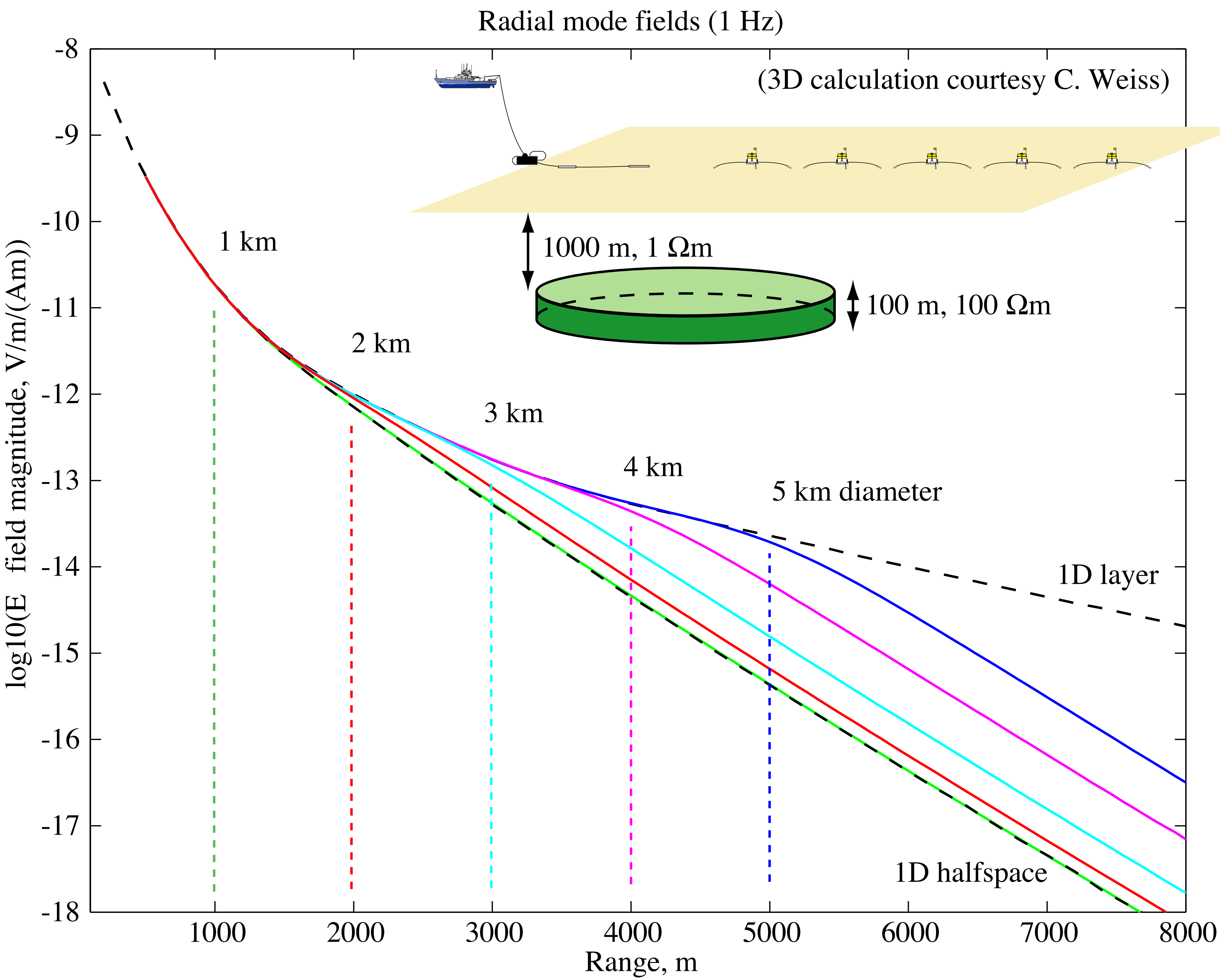
Orange, Key, and Constable, 2009

7. Depth sensitivity in CSEM is largely determined by geometry. Sensitivity is always greatest right below the Tx and Rx. Depth sensitivity is about half Rx-Tx spacing, and so is sensitivity to off-line structure.



Constable, 2010

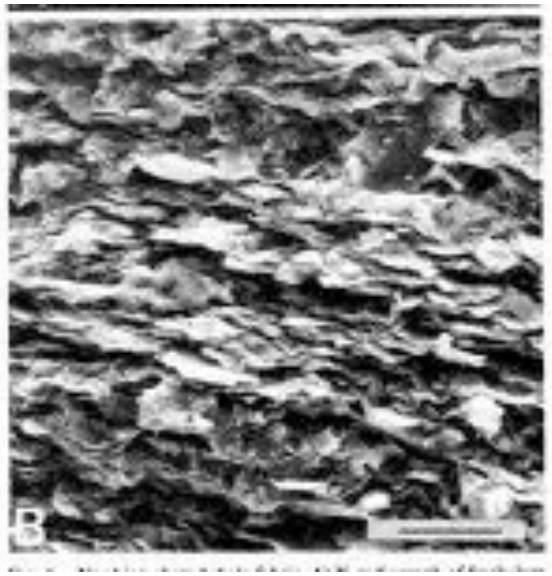
Targets have to be bigger than their depth of burial to be detected (note that this has nothing to do with transmitter power!).



Constable and Weiss, 2006

8. Anisotropy is important. Aligned crystals and inter-bedding can produce anisotropy on microscopic to macroscopic scales.

CSEM cannot tell micro- from macro-anisotropy until the layers get very thick.

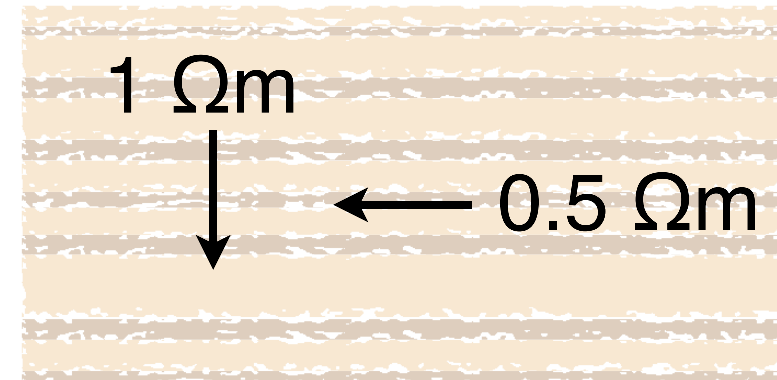


NR O'Brien, J. Sed. Res. 1987

http://www.sleepingdogstudios.com/

To a good approximation (10% or so), the anisotropic response follows the vertical resistivity for the radial mode, and the horizontal resistivity for the azimuthal mode.

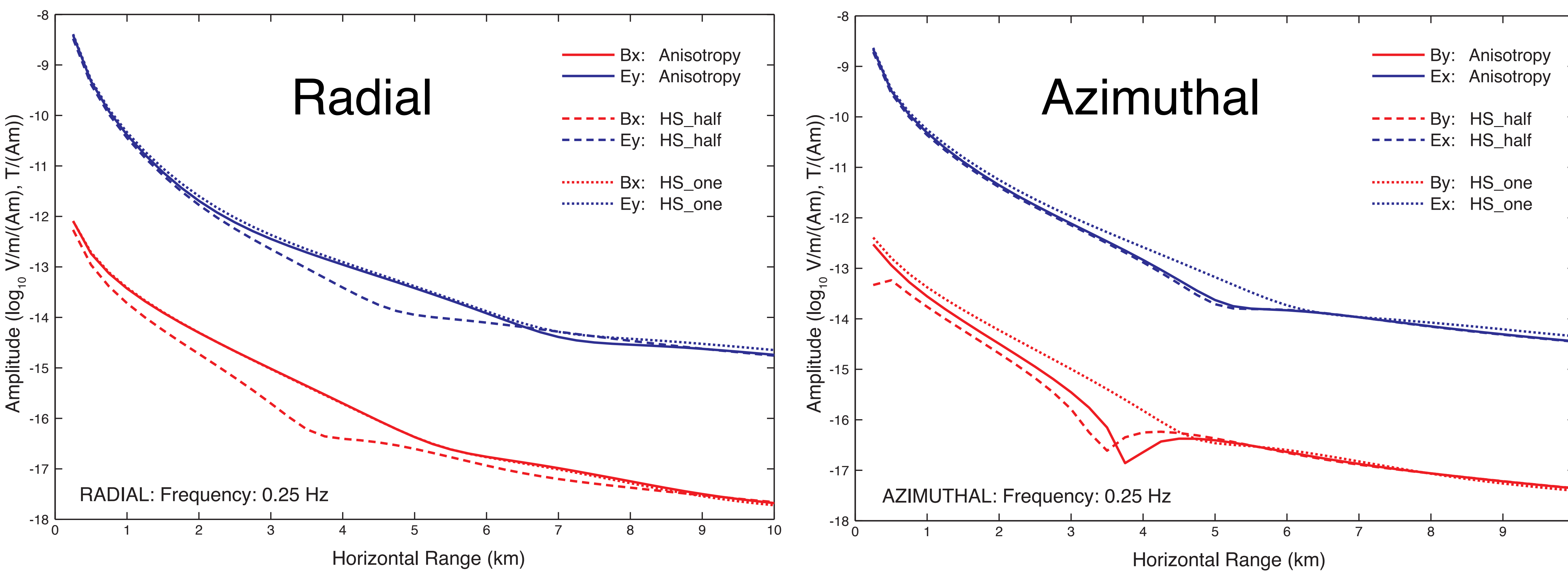
Inverting the modes separately using isotropic models may give reasonable results, but joint inversion of both modes will fail without anisotropy.



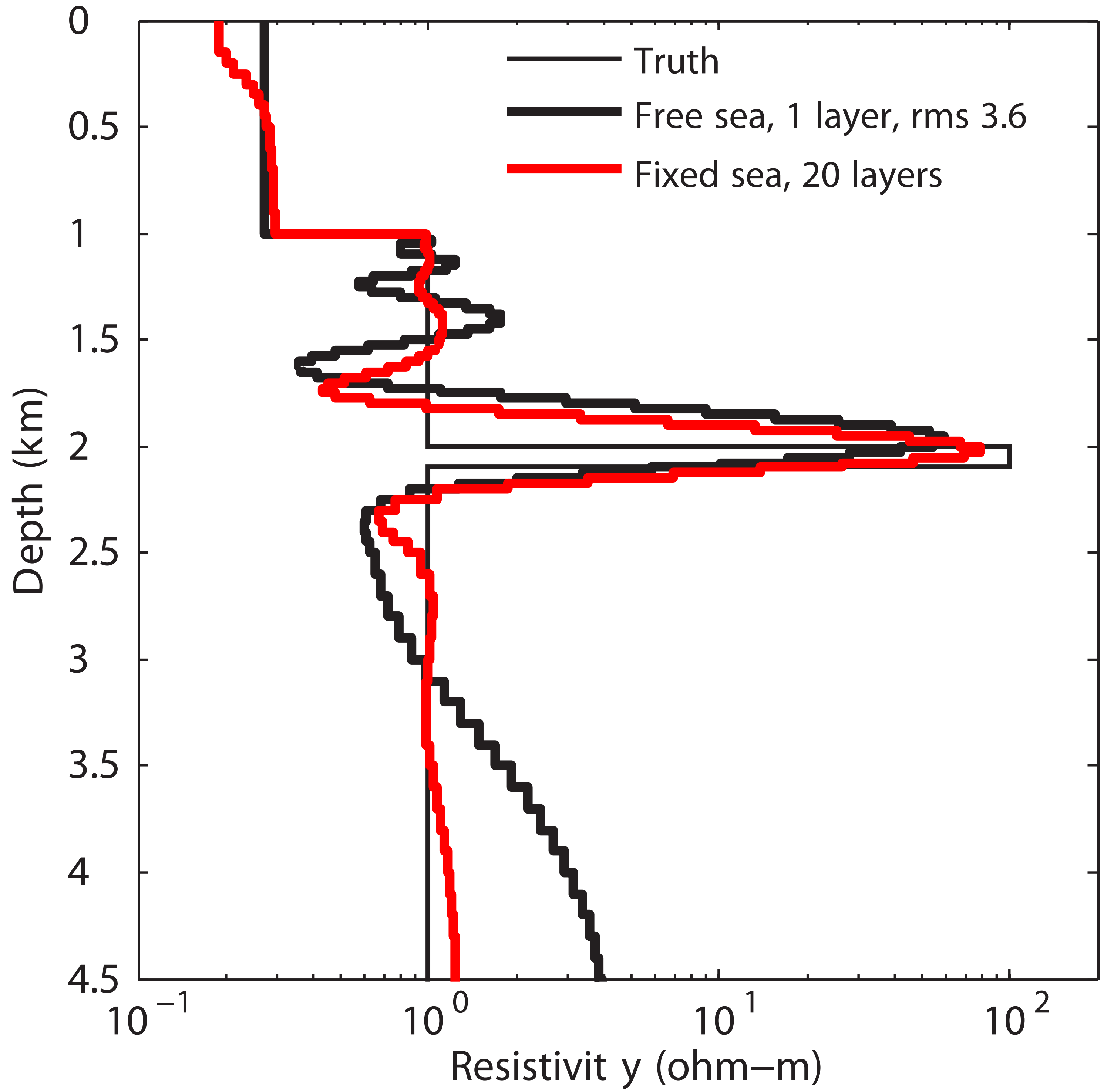
Red - magnetic fields
Blue - electric fields

—— Anisotropic
- - - - Horizontal
· · · · · Vertical

Constable, 2010

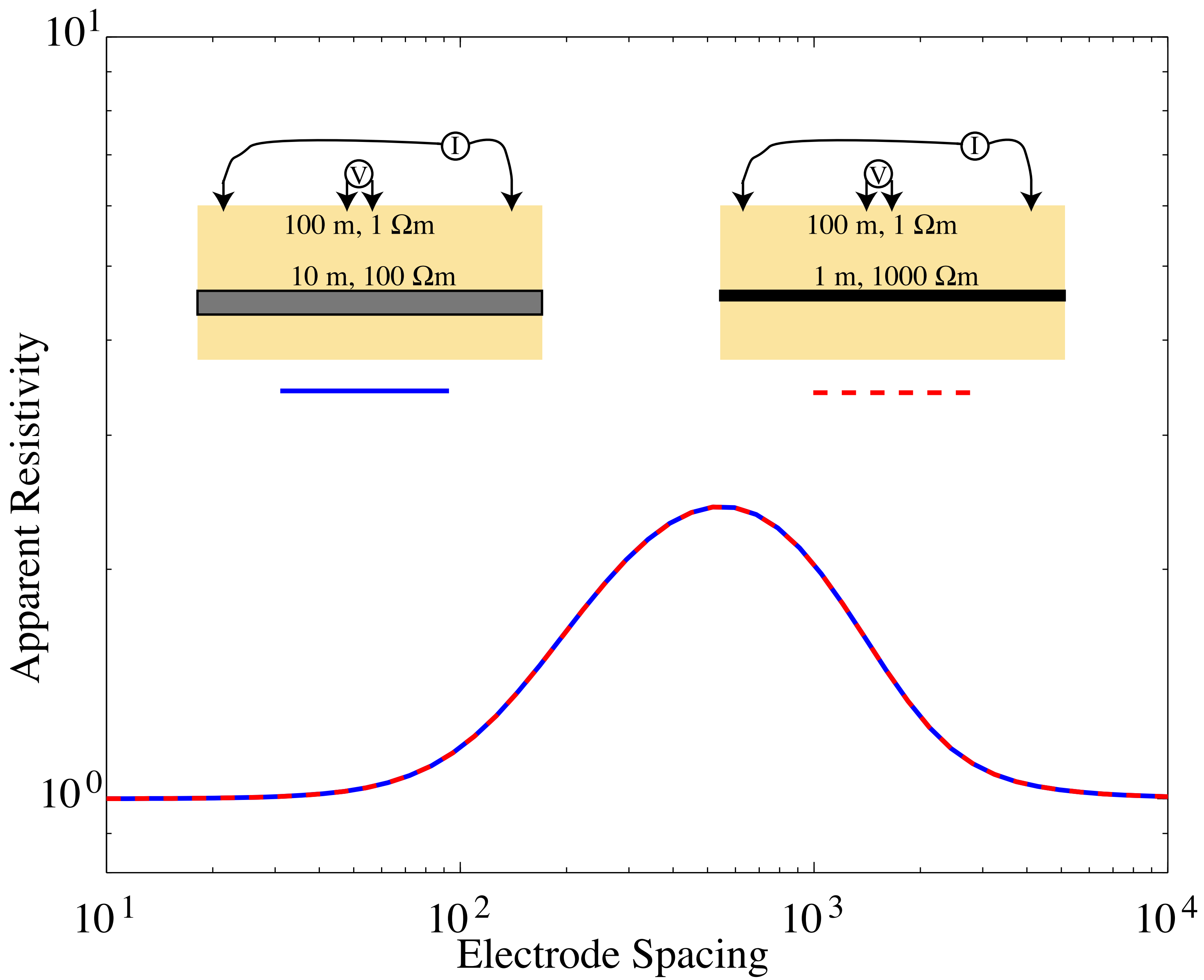


9. Seawater conductivity matters. Getting it wrong can introduce spurious structure into CSEM models (red = correct, black = 1-layer approximation). Expensive mistakes have been made...



Key, 2009

10. Like DC resistivity, CSEM is mainly sensitive to the resistivity-thickness product of thin resistive layers. This is called T-equivalence, where “T” = transverse resistance (i.e. resistivity times thickness).



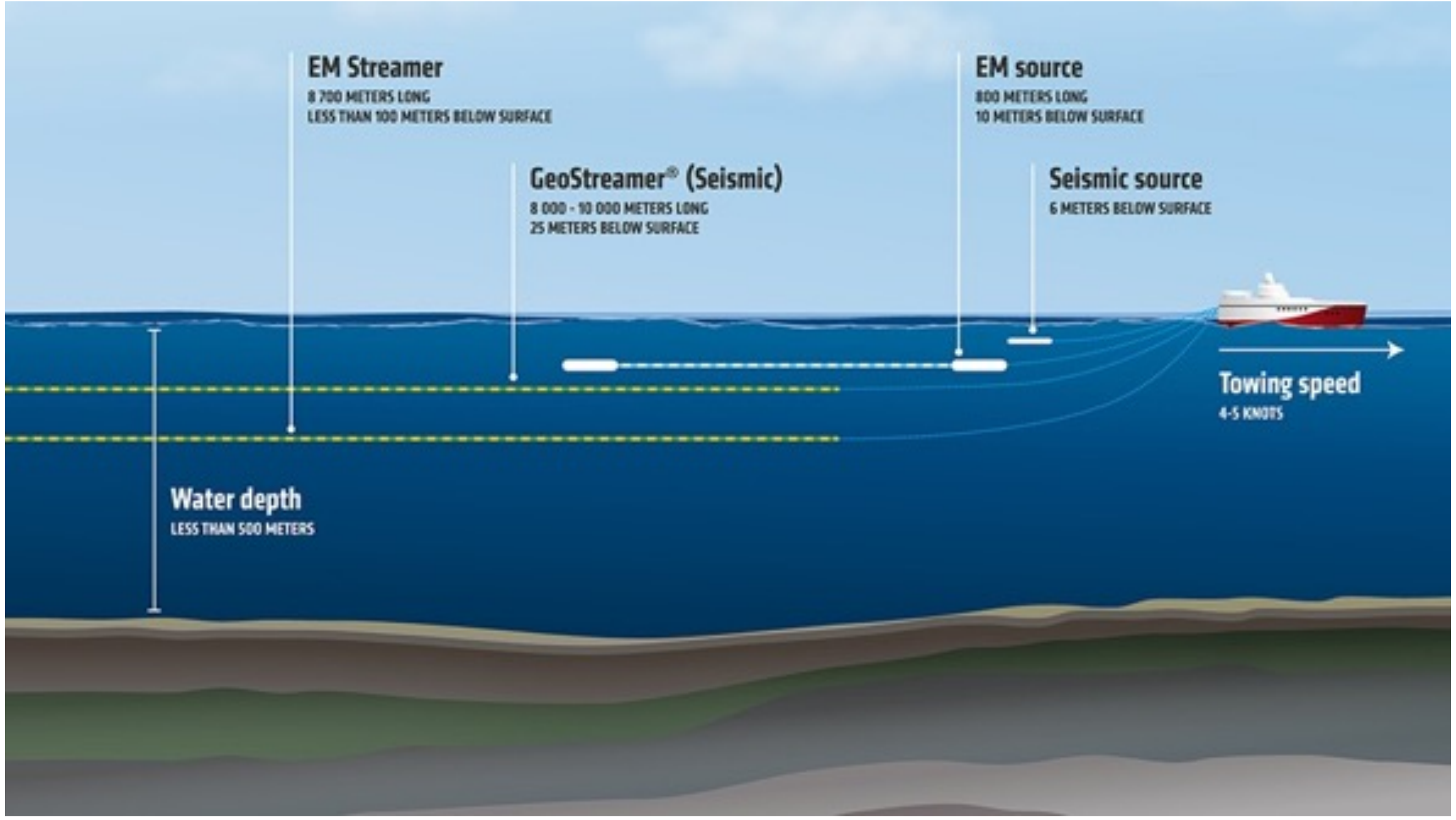
If resistivity is proportional to net pay, this may not be much of a problem.

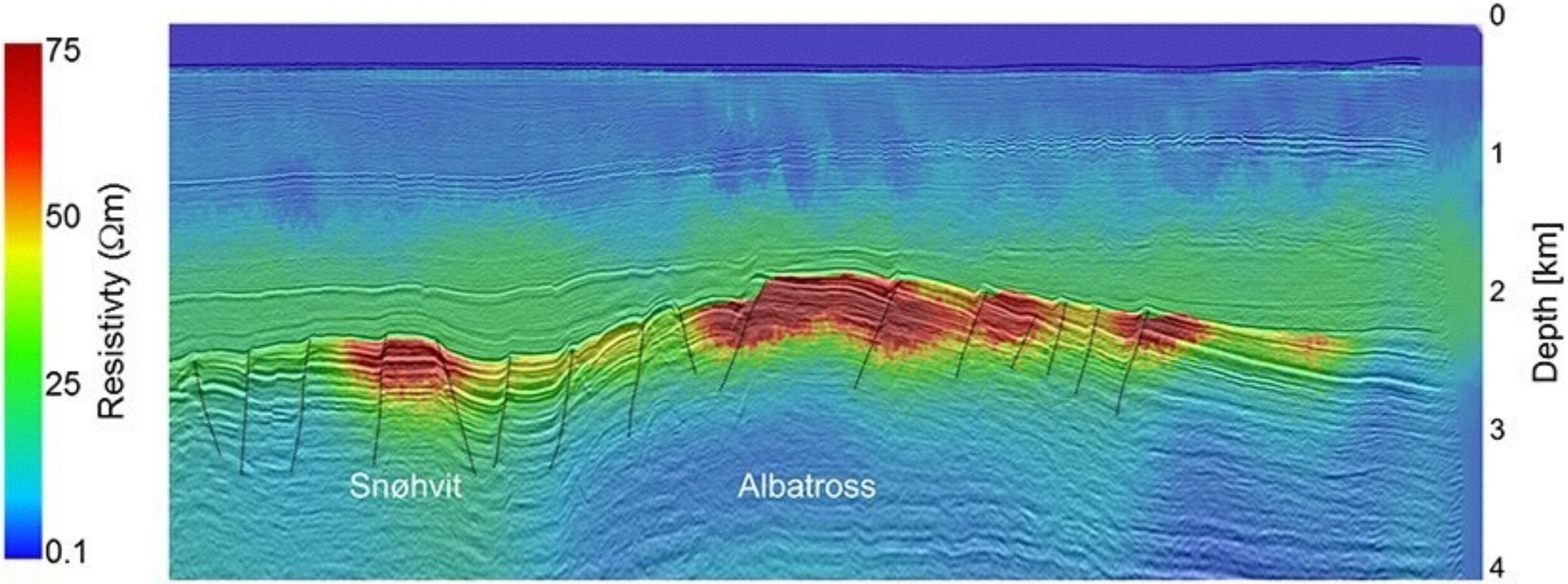
The Future

Marine EM was almost certainly over-sold between 2002 and 2007 or so. WesternGeco pulled out of the marine EM business in 2010 and OHM was absorbed into EMGS in 2012.

The marine EM market was recently worth around $200m/year, or about 5% of the marine seismic market. Marine EM is a capital-intensive business and there is a persistent fear of patent lawsuits, so it is difficult for smaller, innovative companies to enter the market. On the other hand, there probably isn't enough profit for the big companies to care. But there is some progress.

PGS' surface towed streamer system is providing good data in water depths up to 400 m or so, and allows data collection co-incident with 2D seismics.

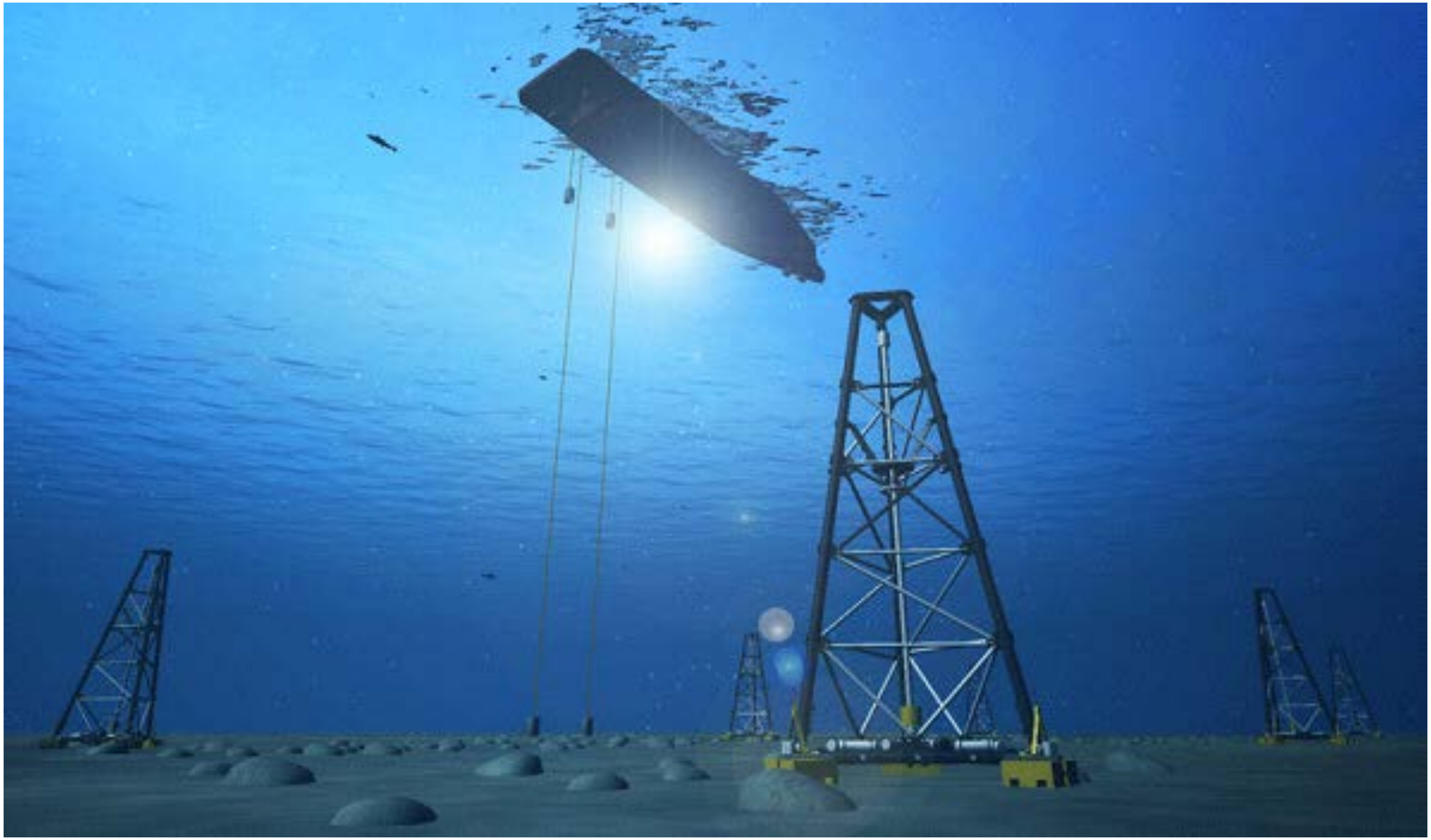




PGS website

PetroMarker

Petromarker has a novel vertical-vertical system which can operate in deep water, but has limited lateral capabilities.



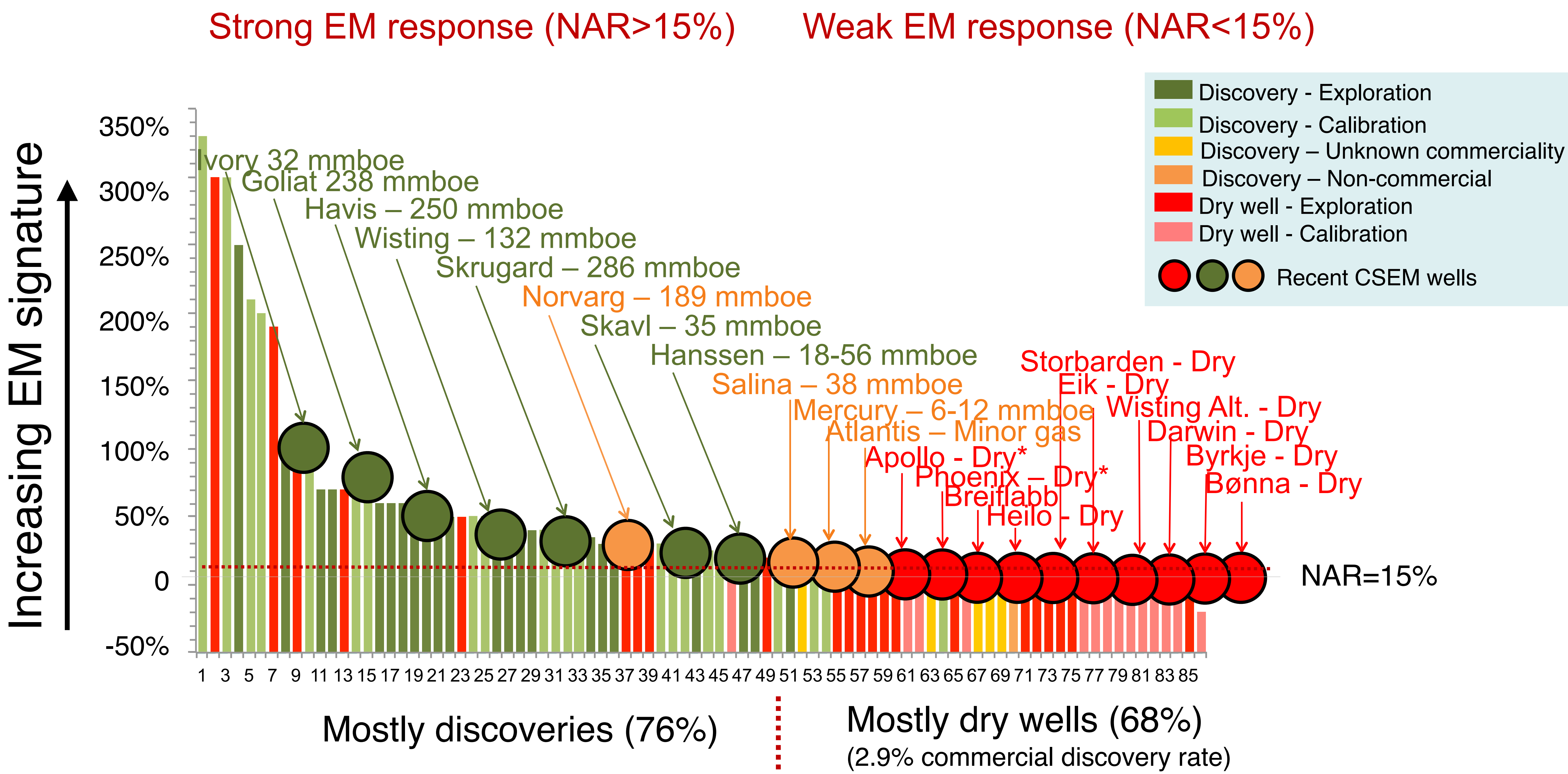
Petromarker website

On the other hand, there is only one contractor offering the standard approach that works so well in deep water.

EMGS website

However, the custom vessel, large (3D) survey model has made CSEM a relatively expensive commodity.

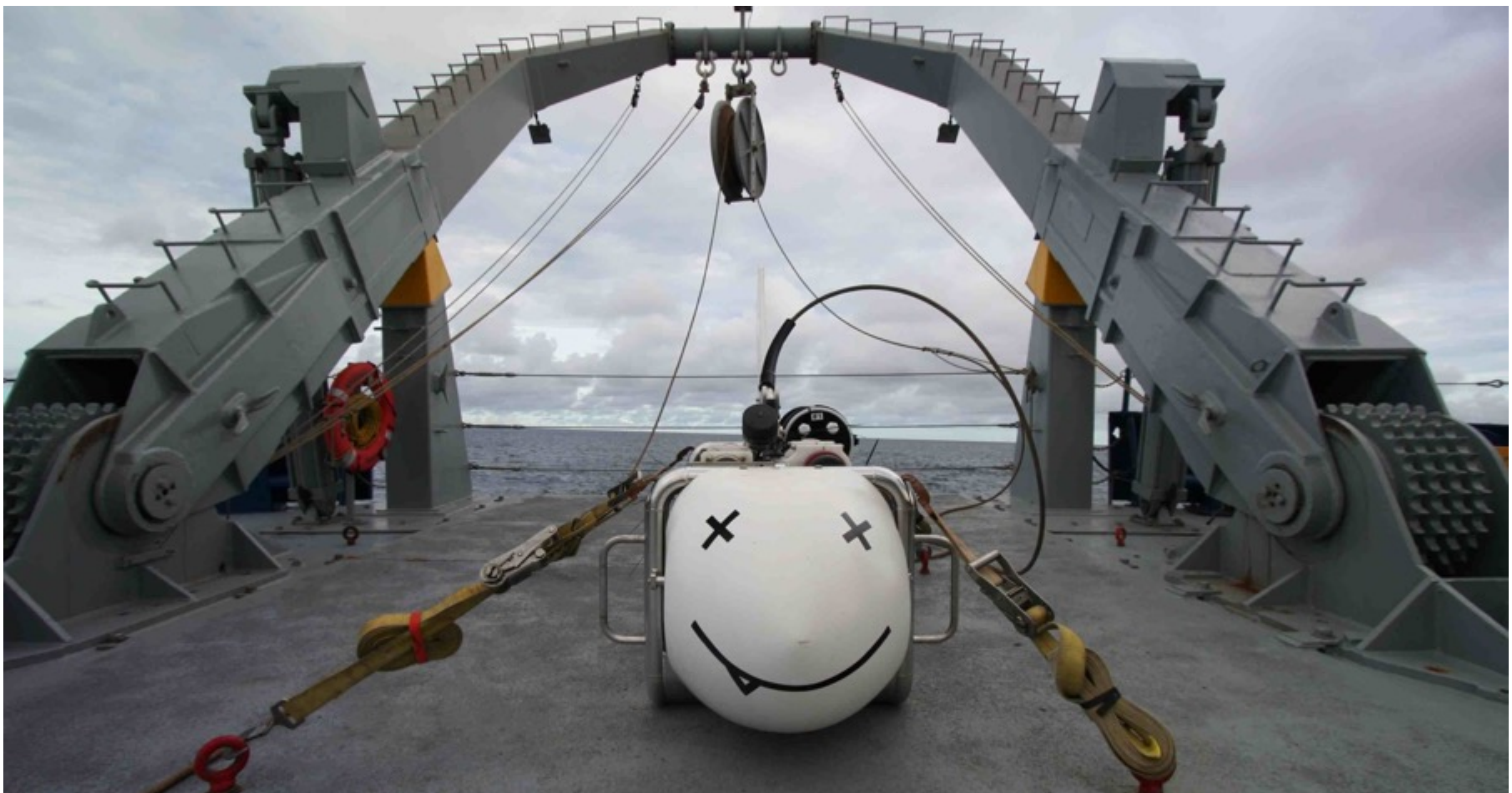
Does it work? Jonny Hesthammer thinks so. False positives have been drilled (mostly lithological resistors), but false negatives are very rare. That is, without a CSEM signature the likelihood of a commercial discovery is very low - but industry just keeps drilling and providing more data for Jonny's plot - without more confidence in the method it is difficult to realize its value.



Hesthammer et al., First Break, 2012; Hesthammer pers. comm. 2015

Much of the CSEM data is collected by the majors (ExxonMobil, Shell, Chevron, etc.) and the large NOCs (Petrobras, Pemex, etc.). These companies keep their success rate statistics fairly confidential. But they are still collecting data… I think the future lies in smaller, portable, ship-of-opportunity systems (like the ones academics must use), expanding the market to smaller client companies. This may take the passing of a few years and a rise in oil prices, but I think we can count on both of these.

Thank you!



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