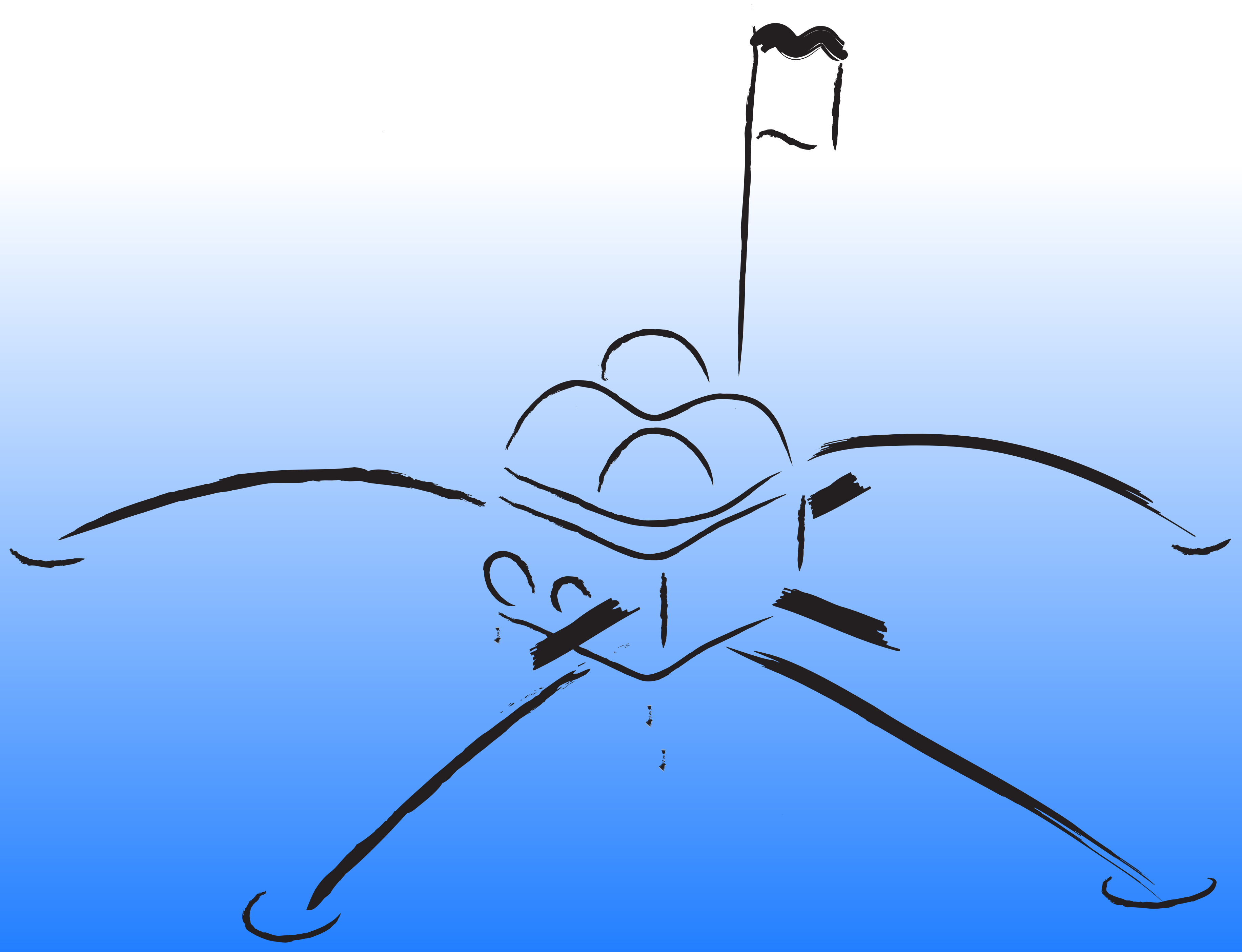
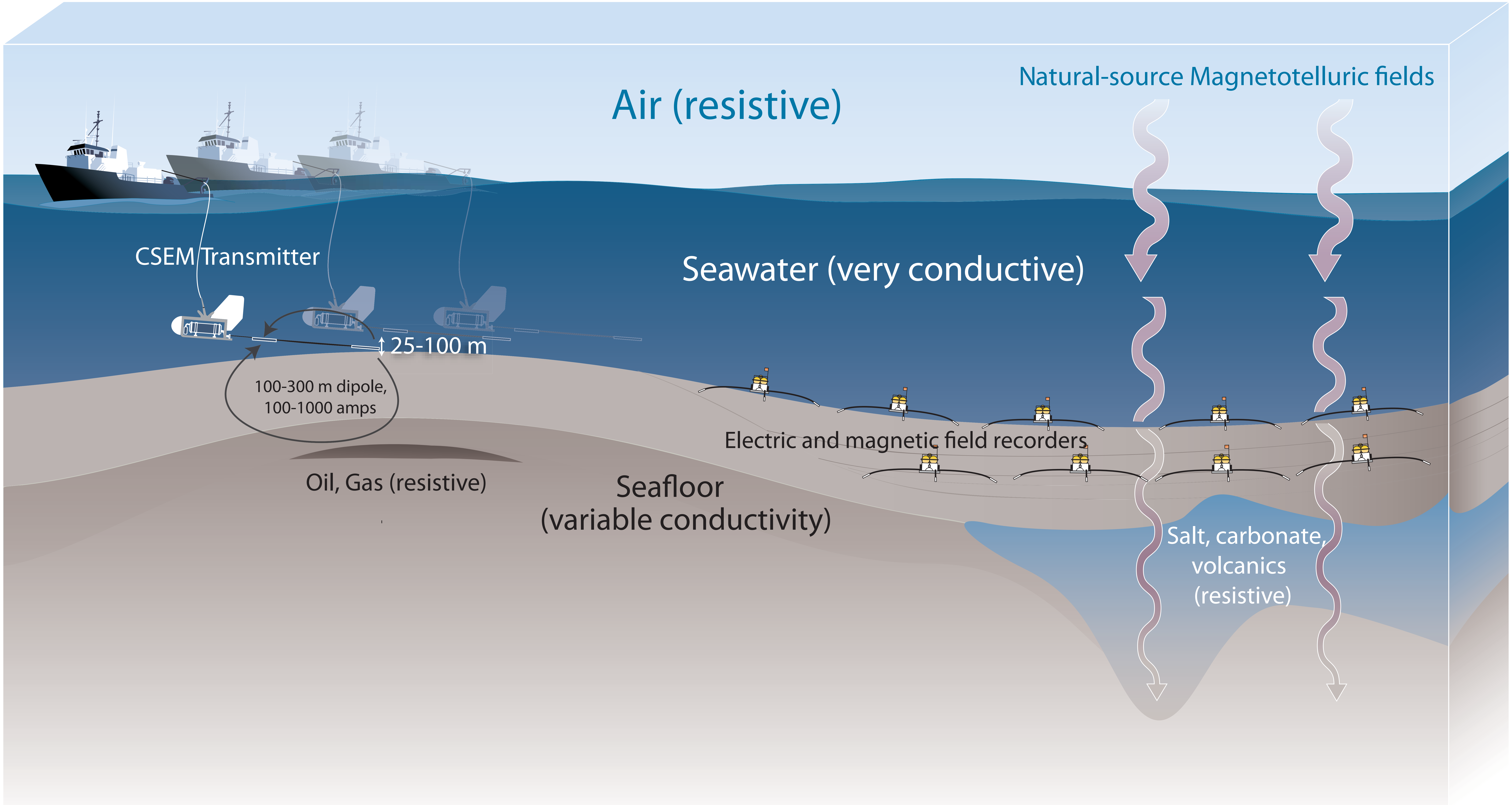
Marine Electromagnetic Methods - Beginnings to Today

Steven Constable
Scripps Institution of Oceanography

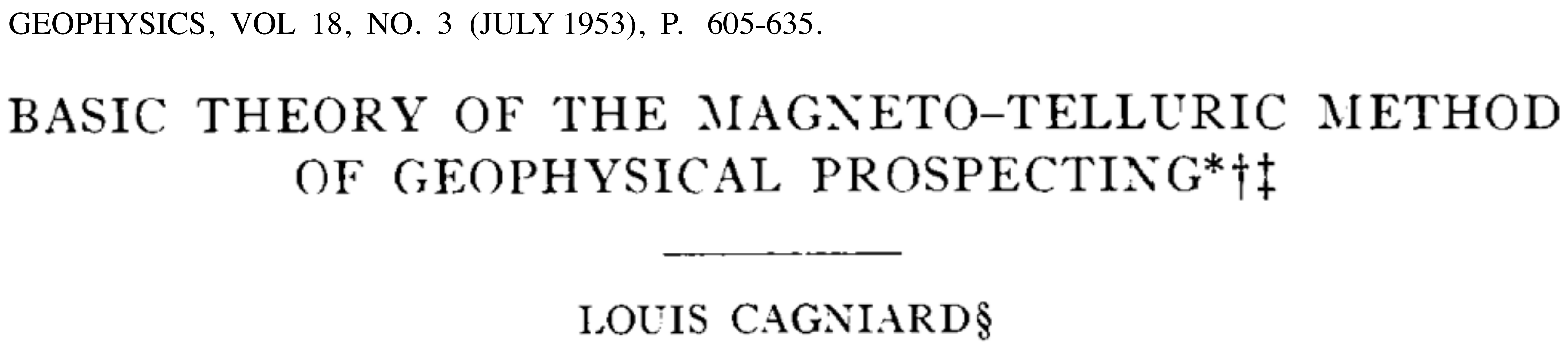


CSEM sounding tends to be sensitive to resistors
Can be used to study crustal geology

MT sounding tends to be sensitive to conductors
Can extend the depth of study to 100’s km



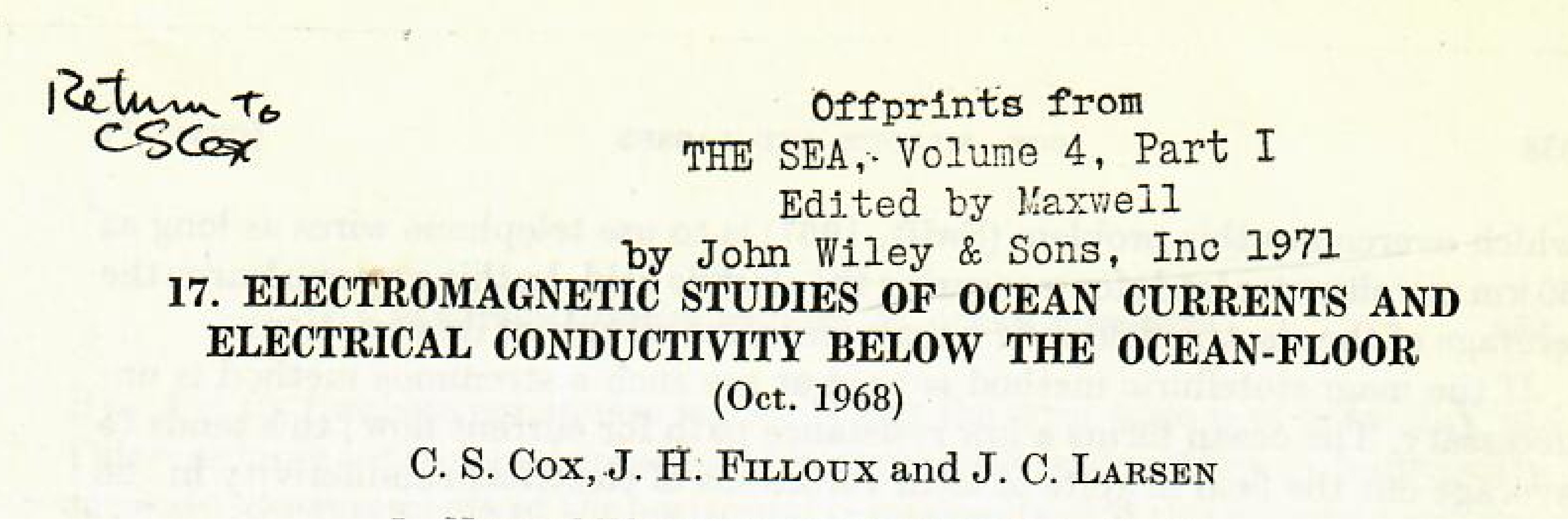
Cagniard proposed adaption to the marine environment in the 1953 paper that first presented the MT method, but the first deepwater measurements were made by Chip Cox, Jean Filloux, and Jimmy Larsen only in 1965.



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

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

LOUIS CAGNIARD§



Return To
CSCox

Offprints from
THE SEA, Volume 4, Part I
Edited by Maxwell
by John Wiley & Sons, Inc 1971

17. ELECTROMAGNETIC STUDIES OF OCEAN CURRENTS AND ELECTRICAL CONDUCTIVITY BELOW THE OCEAN-FLOOR

(Oct. 1968)

C. S. Cox, J. H. Filloux and J. C. Larsen

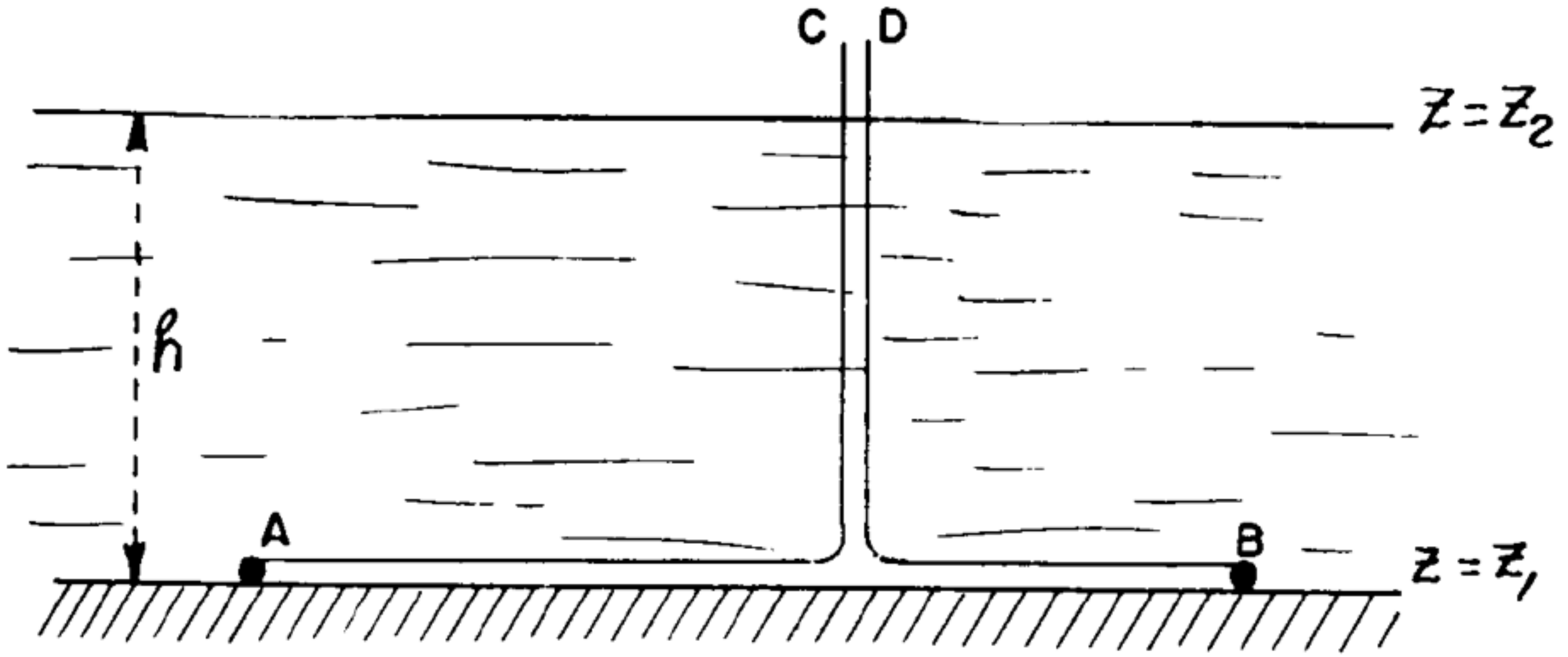
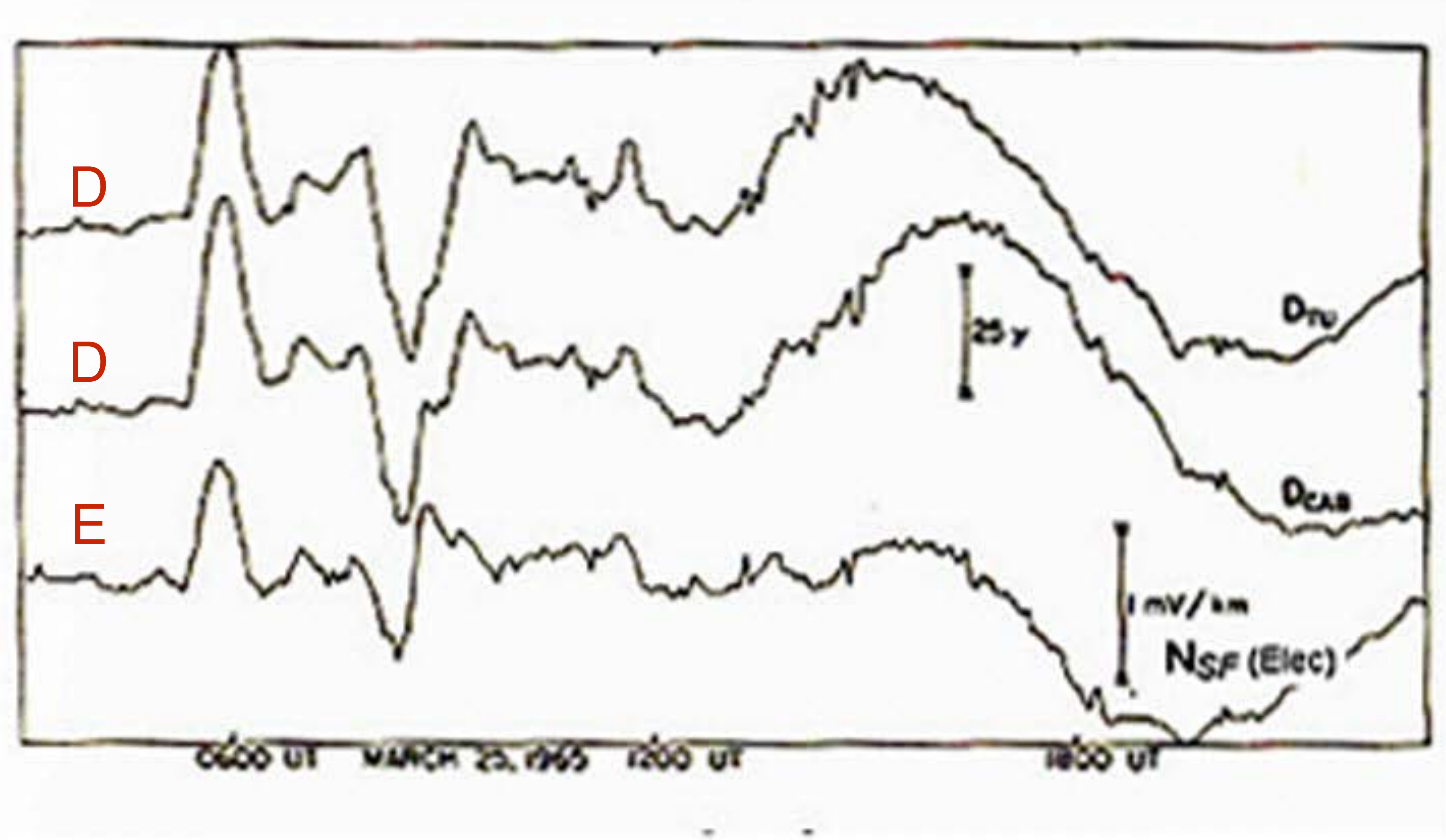
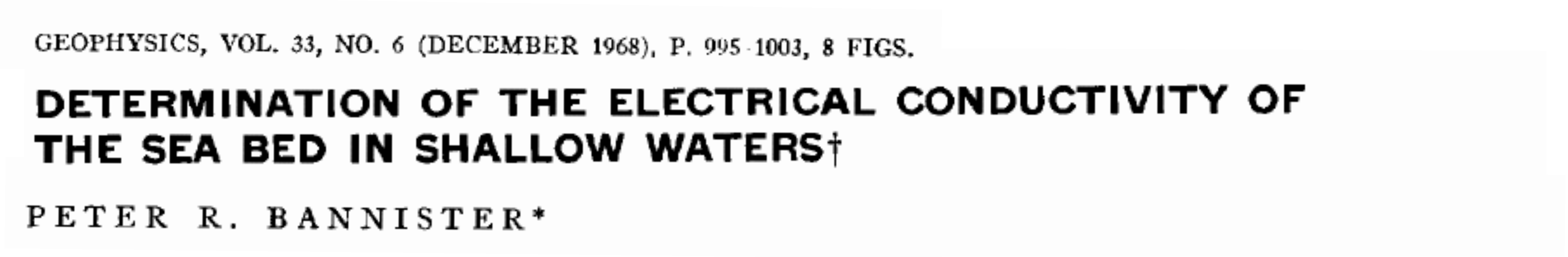


Fig. 13. Configuration of electrodes on water bottom for submarine MT measurements.



The earliest marine EM 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. Chip Cox made the first deep water measurements in 1979.



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*

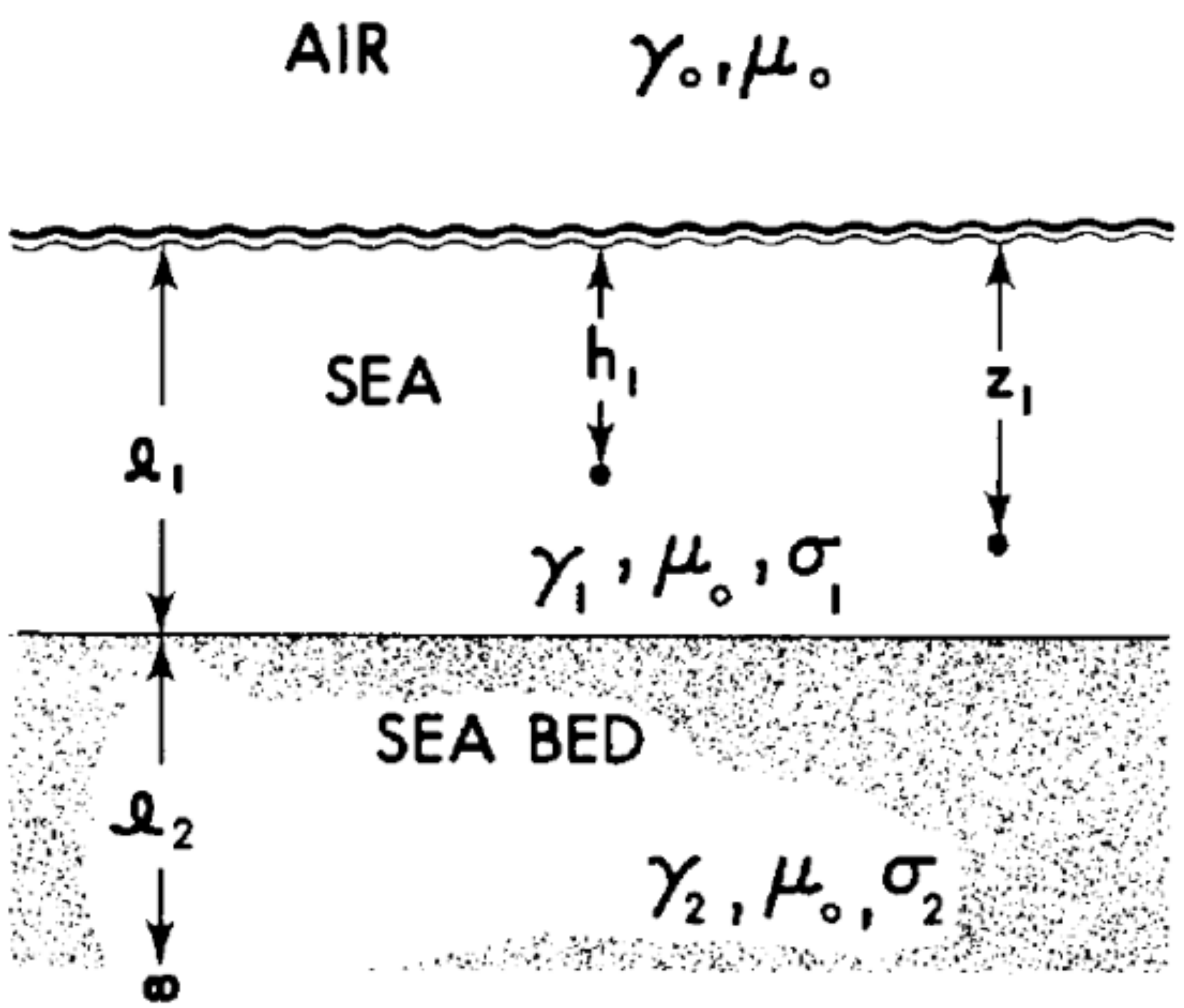
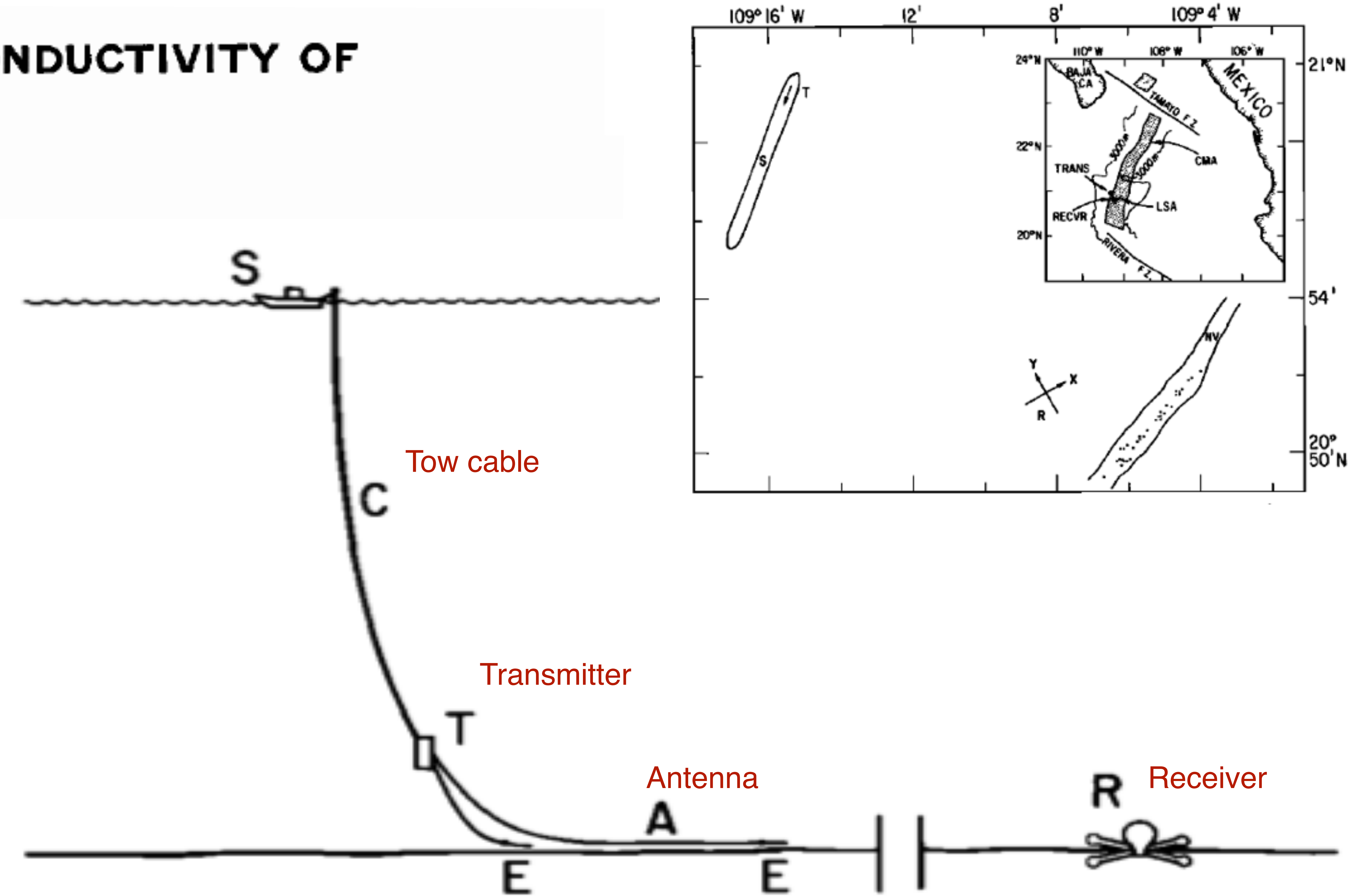


FIG. 1. Two-layer stratified earth.

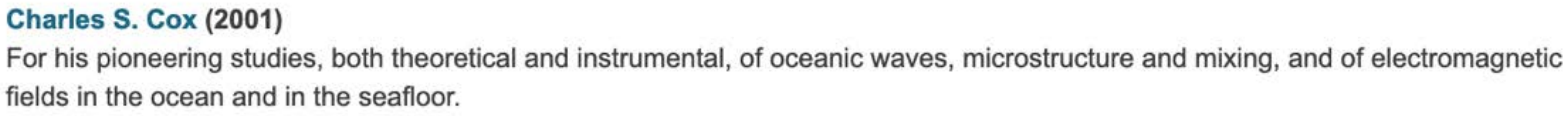


Young and Cox, 1981

Chip was an oceanographer who was famous for his work on ocean microstructure. So why was he interested in marine EM methods?

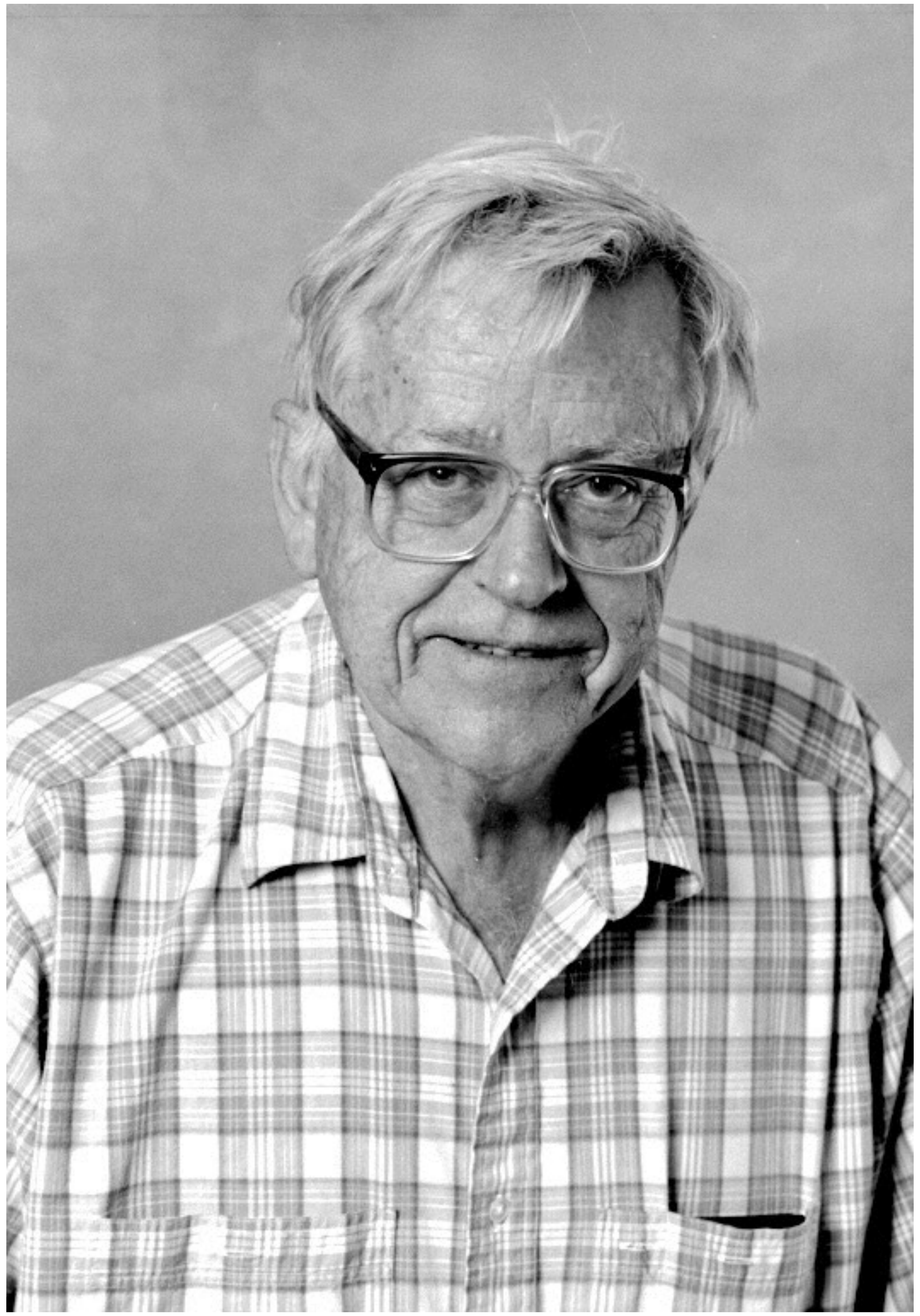
About the Alexander Agassiz Medal

Endowed in 1911 by one of the leading scientists of the Challenger Expedition, Sir John Murray, the Agassiz Medal has been awarded to some of the most outstanding oceanographers in all fields since 1913. Murray established the award to honor his friend, **Alexander Agassiz**, who served as president of the National Academy of Sciences from 1901 to 1907. The Alexander Agassiz Medal is awarded for an original contribution in the science of oceanography. The medal is presented every five years and carries with it a prize of $20,000.



Charles S. Cox (2001)
For his pioneering studies, both theoretical and instrumental, of oceanic waves, microstructure and mixing, and of electromagnetic fields in the ocean and in the seafloor.

Charles (Chip) Cox



He was impressed by Gunther Wertheim's 1953 work on measuring the Florida Current using a submarine telegraph cable, an idea first proposed by Faraday. Water flowing through Earth's magnetic field creates an electric field: $\mathbf{E} = \mathbf{v} \times \mathbf{B}$

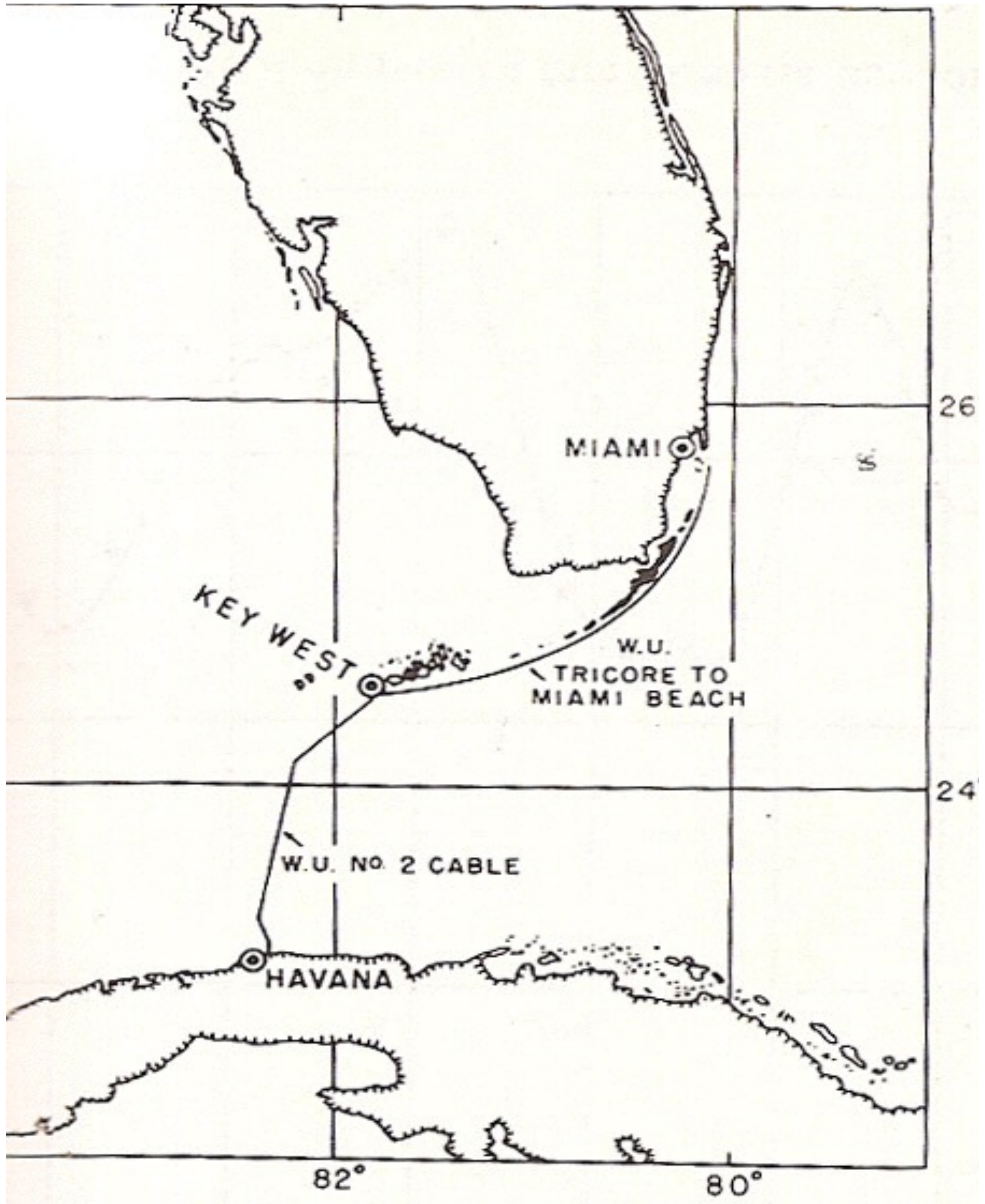


Fig. 1--Cable location

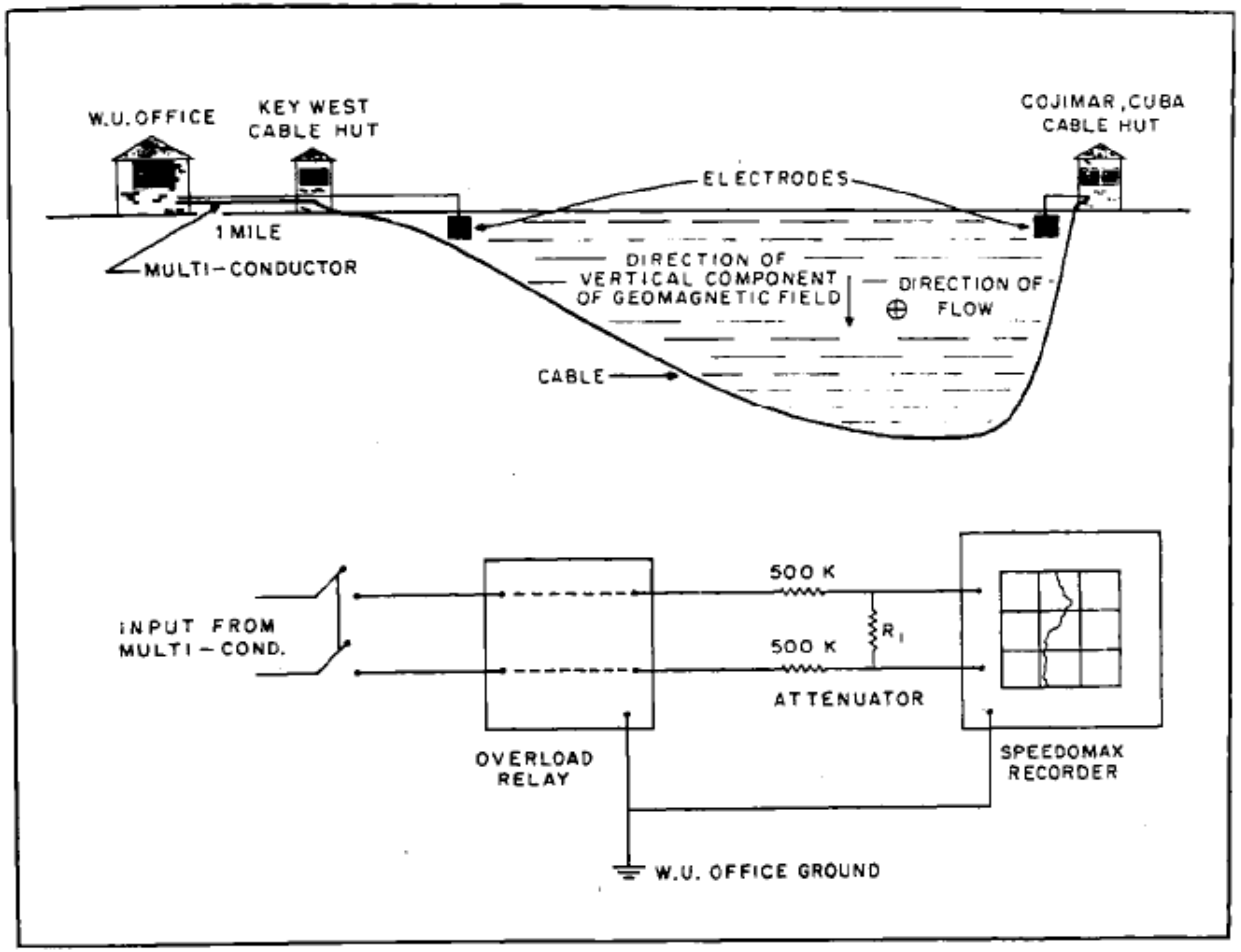


Fig. 9--Recording setup

Wertheim, 1954

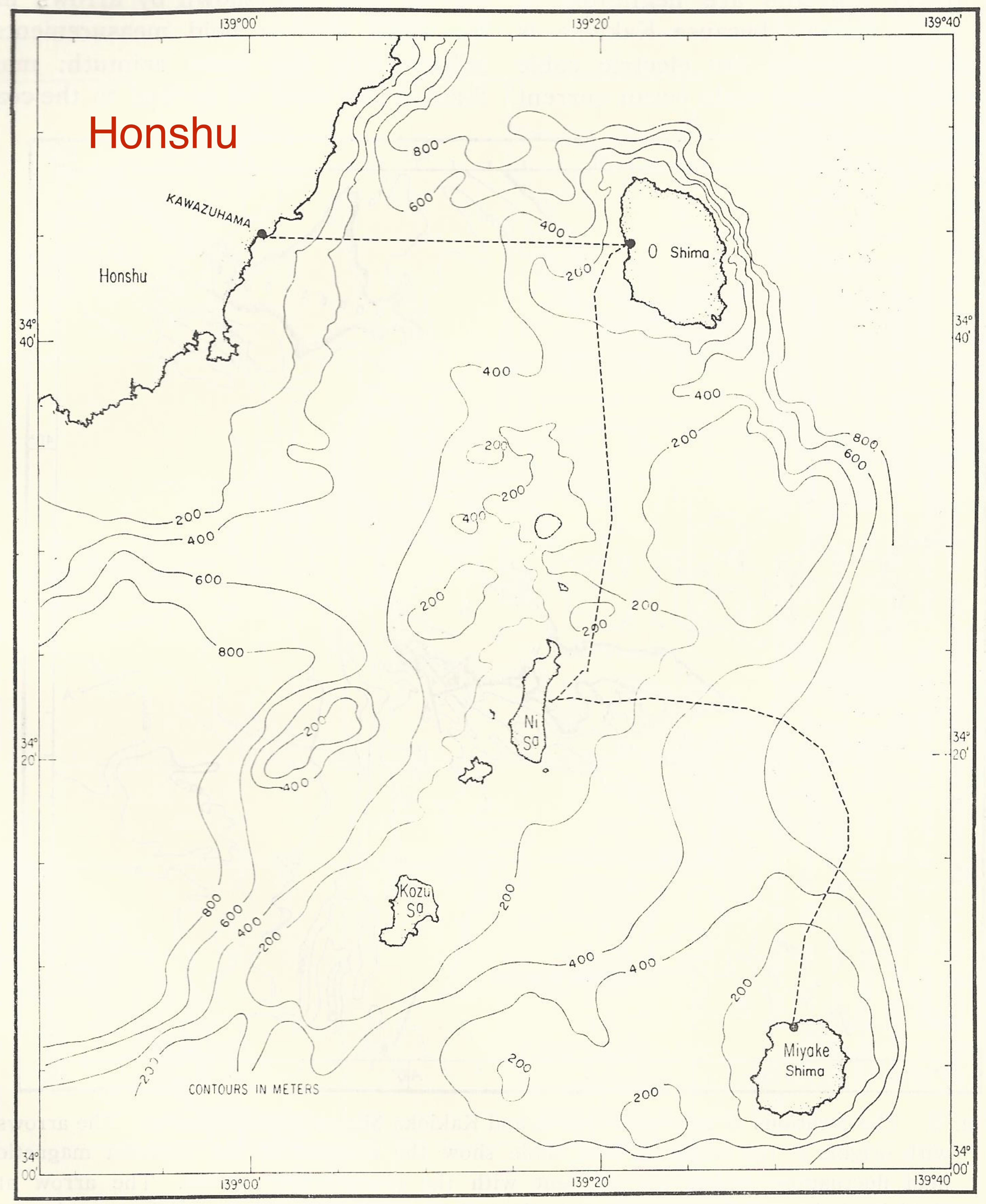


Fig. 4. Paths of submarine telephone cables. One cable runs from Kawazuhama, Honshu to Oshima. The other runs from Oshima to Miyakeshima by way of Nishima.

Cox, Taramoto, & Filloux, 1964

He made some measurements with Toshihiko Teramoto on cables running from the Izu Peninsula (1957), but a hurricane destroyed them. He ran some cables from the Farallon Islands in 1960 but the first winter storm destroyed them too. He realized he needed measurements on the seafloor.

Jan Roletto via NOAA and Wikipedia

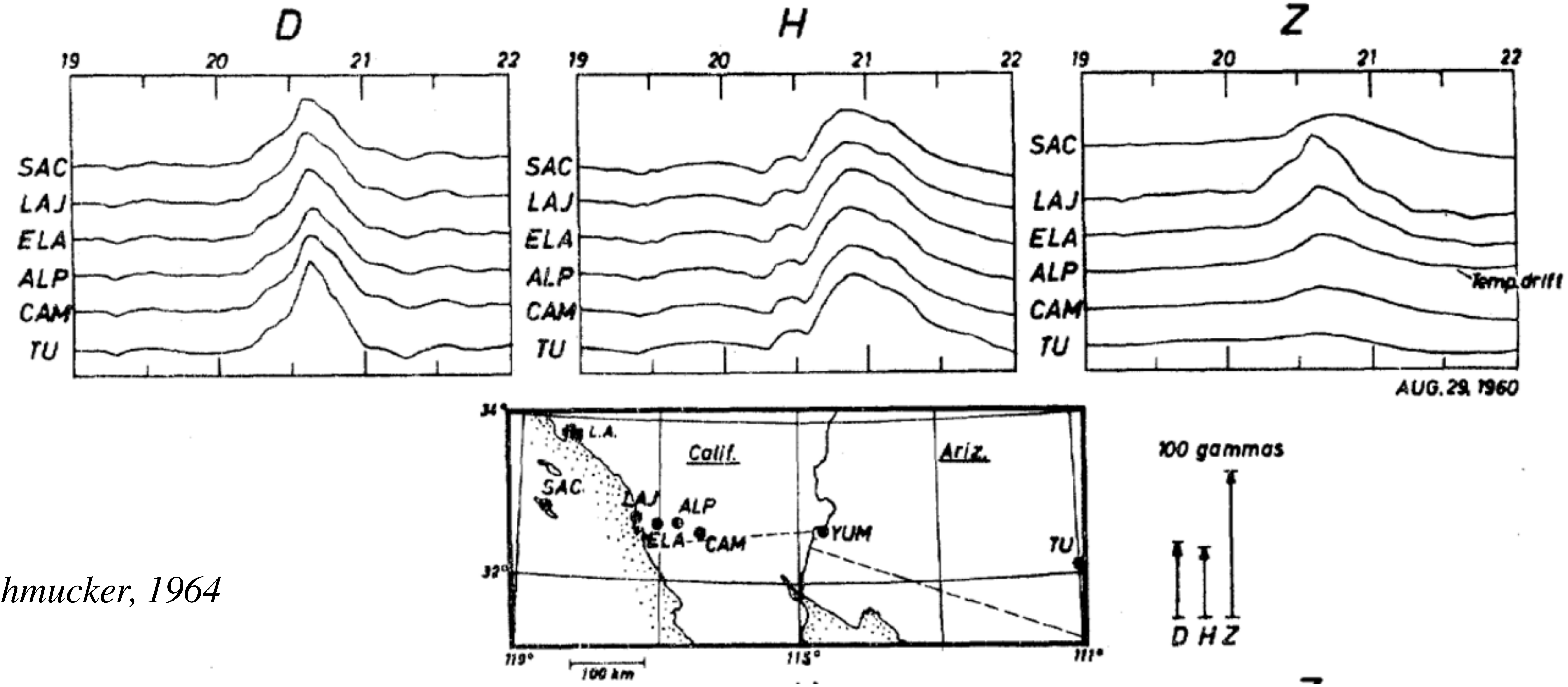
Chip's student, Jean Filloux, was developing seafloor magnetometers. In 1960 Ulrich Schmucker visited Scripps to deploy land magnetometers near the coast. Chip's plan was to deploy a marine extension to Schmucker's array, adding electric field measurements to study ocean currents.

Ulrich Schmucker

Anomalies of Geomagnetic Variations in the Southwestern United States

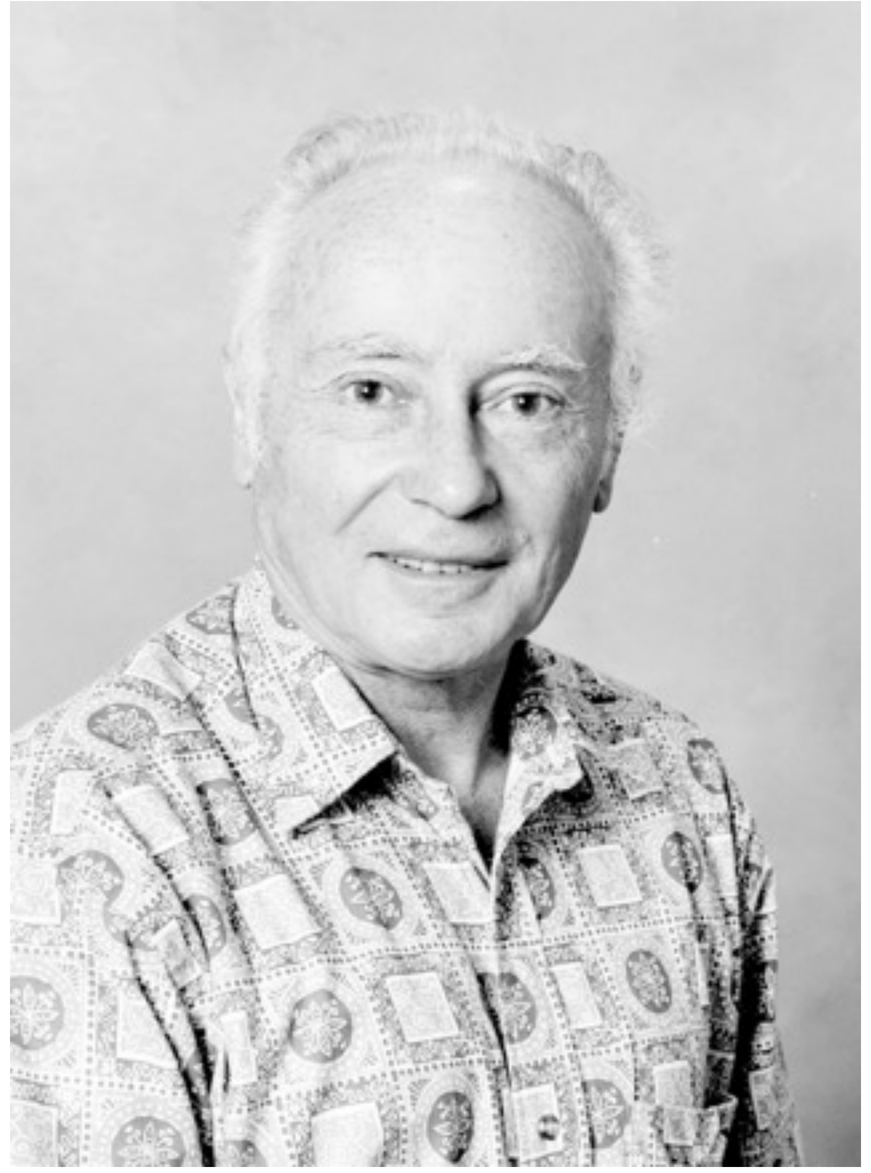
By Ulrich SCHMUCKER

Scripps Institution of Oceanography, University of California, La Jolla, California

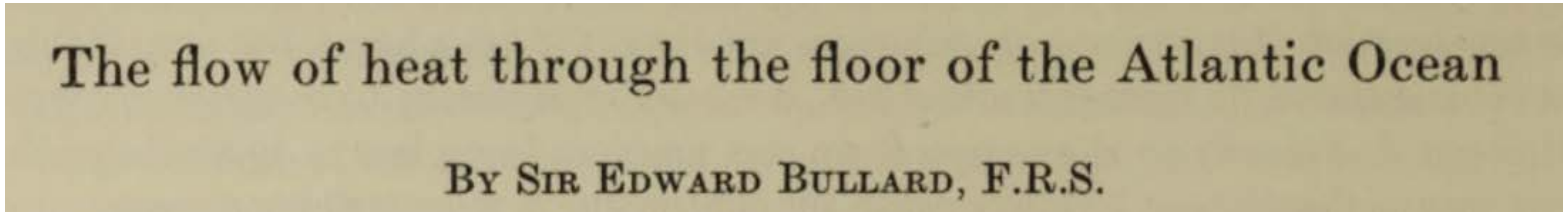


Schmucker, 1964

Jean Filloux

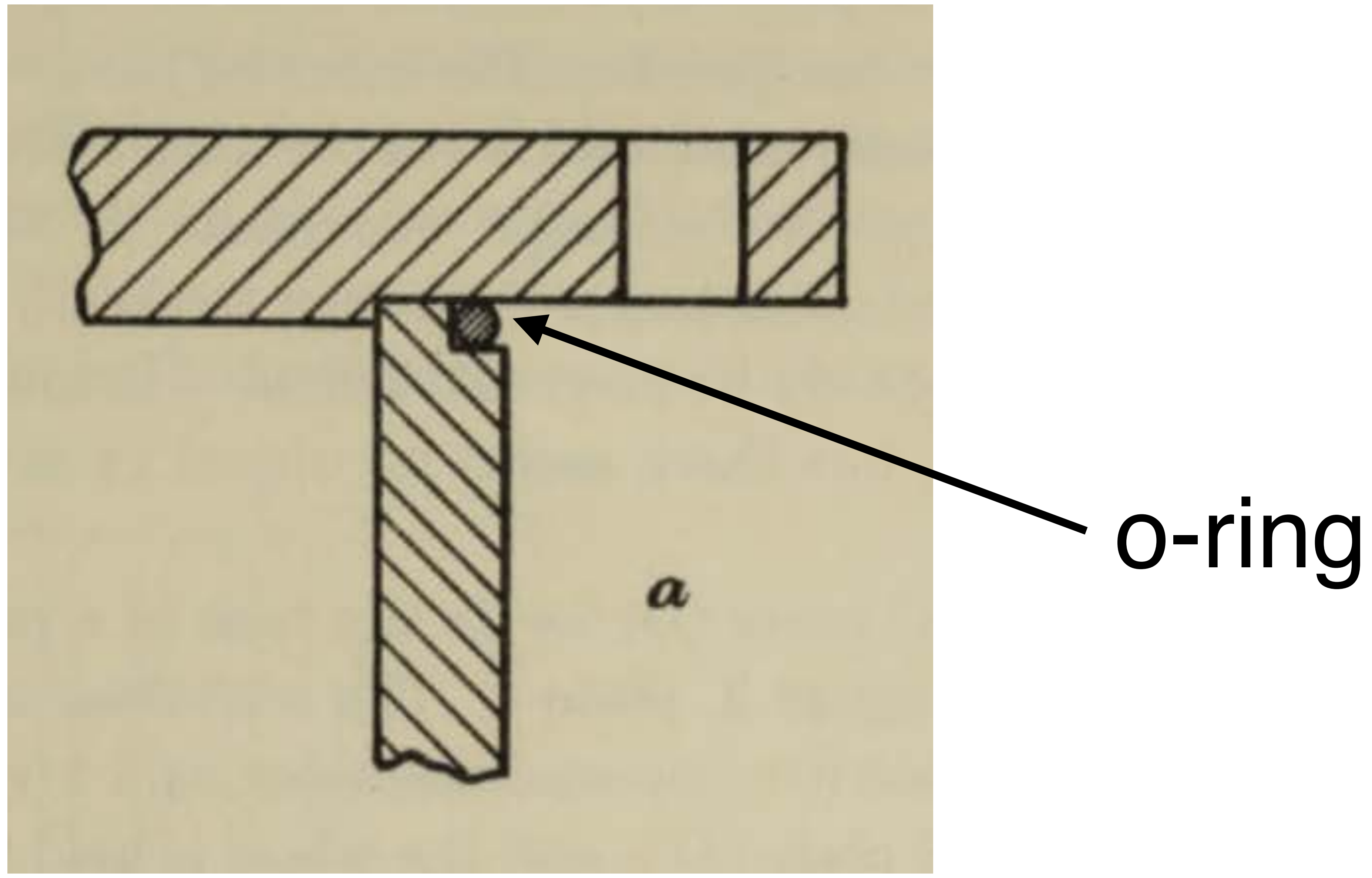


The timing was right - in 1949 Teddy Bullard had introduced ‘o’ rings to oceanography during a visit to Scripps, and this allowed pressure cases to be constructed.

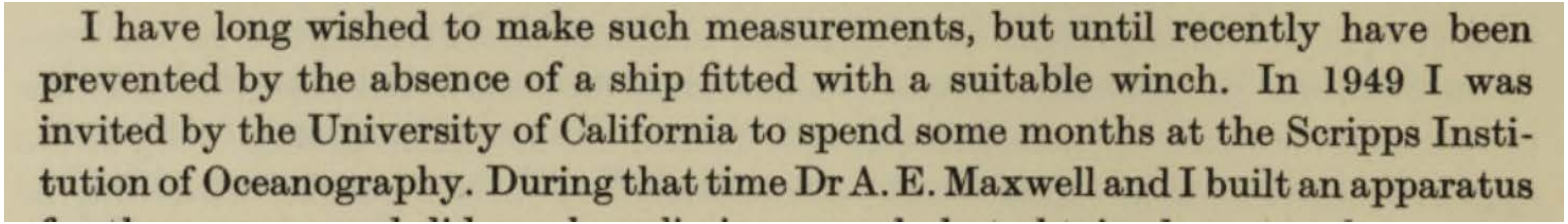


The flow of heat through the floor of the Atlantic Ocean

By Sir Edward Bullard, F.R.S.

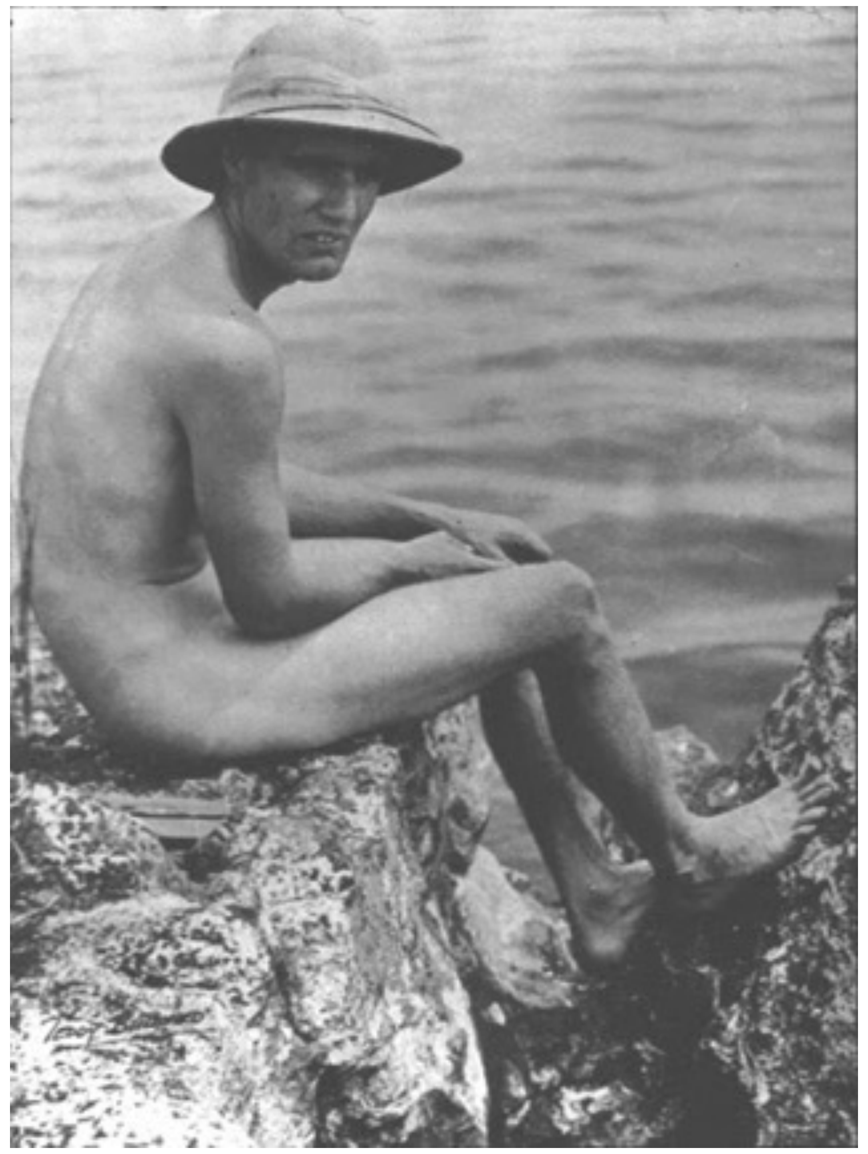


o-ring



I have long wished to make such measurements, but until recently have been prevented by the absence of a ship fitted with a suitable winch. In 1949 I was invited by the University of California to spend some months at the Scripps Institution of Oceanography. During that time Dr A. E. Maxwell and I built an apparatus

Teddy Bullard



The problem was recording data…

The solution: Rustrak recorders triggered by a Bulova tuning-fork watch.

Sample rates of 15 per hour were achieved …

This resulted in the first deepwater MT response being made.

Jimmy Larsen

The Saturday Evening Post

Why you should wear

ACCUTRON†

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ONLY THE ACCUTRON TIMEPIECE is guaranteed 99.9977% accurate on your wrist (not just in a test laboratory).

ONLY THE ACCUTRON TIMEPIECE keeps time by the constant vibrations of a tuning fork activated electronically. It doesn't tick. It hums.

ONLY THE ACCUTRON TIMEPIECE does away with the hairspring and balance wheel, the parts which limit the accuracy of all watches.

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ONLY THE ACCUTRON TIMEPIECE —with just 12 moving parts—is so rugged, so trouble-free you can forget about usual watch maintenance and repair.

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ACCUTRON† by BULOVA

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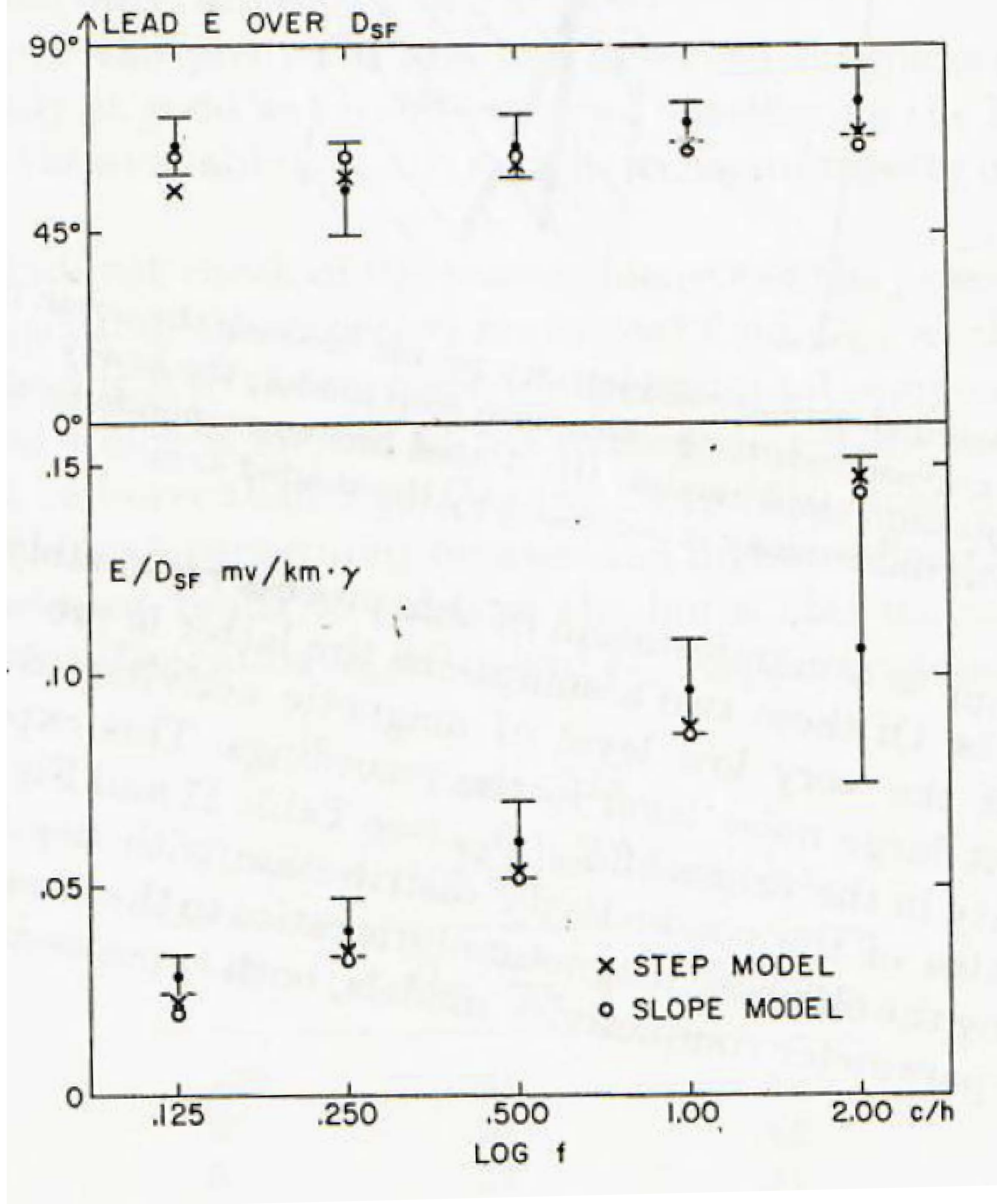
It makes the finest watches—even electric watches—obsolete.

Symbol of accuracy through electronics



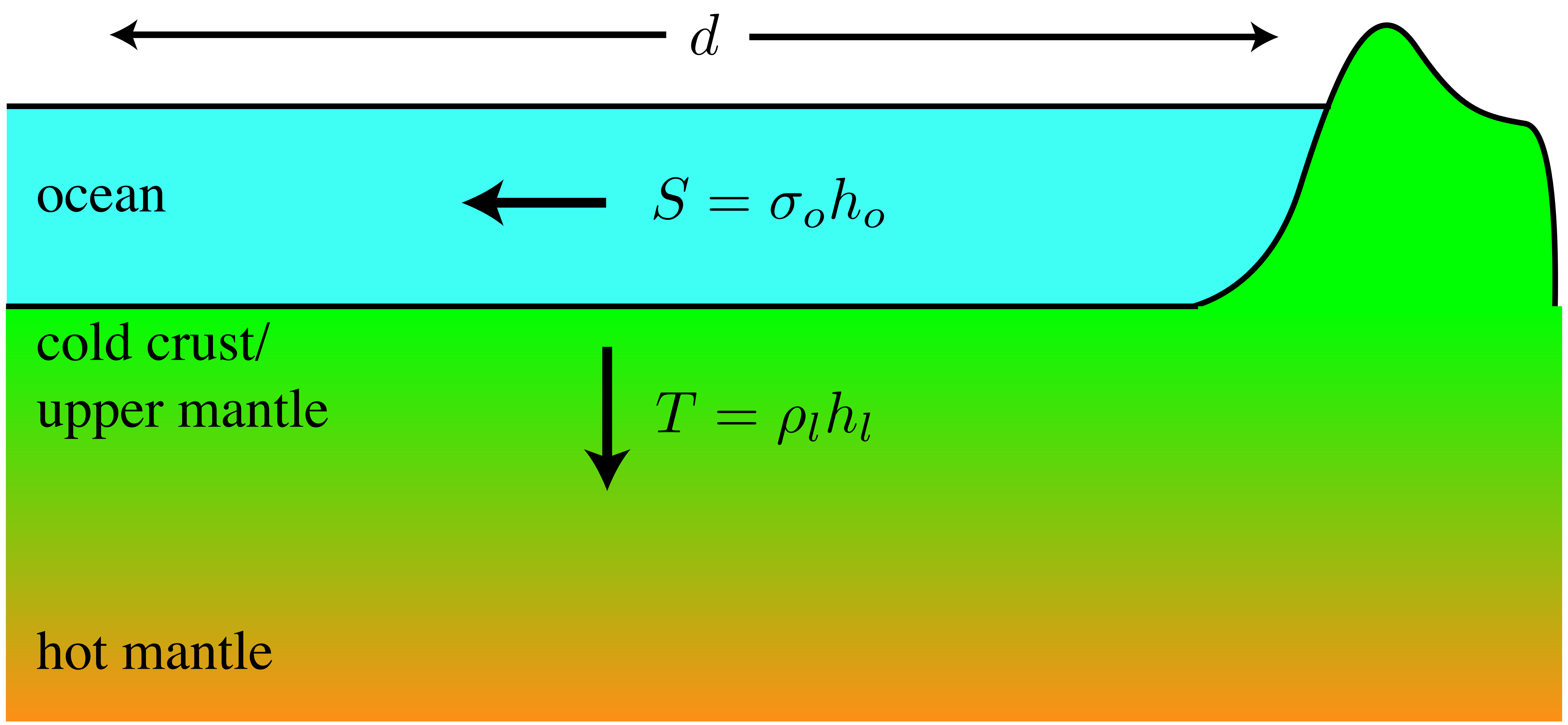
Cox, Filloux, and Larsen, 1971

Chip was by now very interested in the electrical conductivity of the seafloor, since all his oceanographic measurements depended on how much current leaked into the conductive mantle.

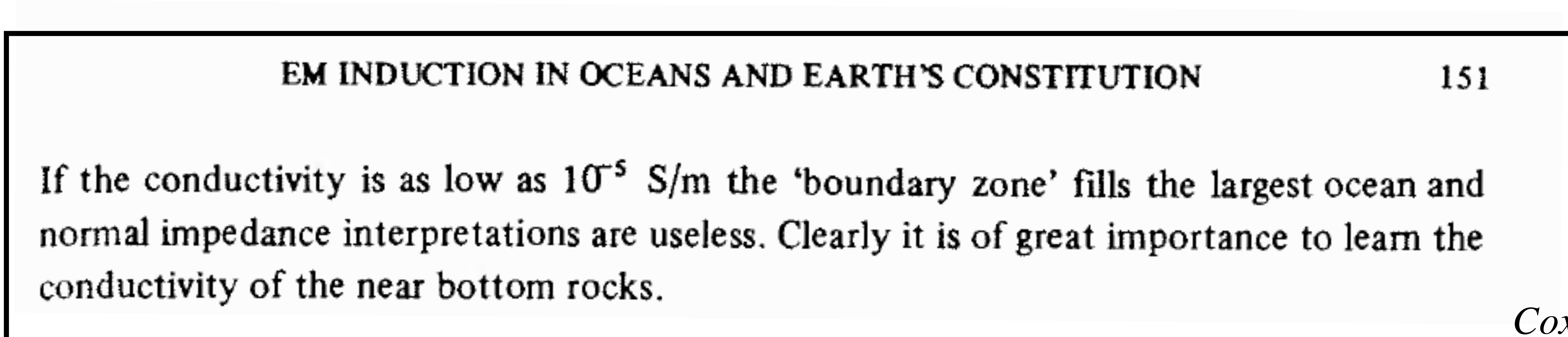
$$S = 4 \text{ km} \times 3 \text{ S/m} = 12,000 \text{ S}$$

$$T = 10^5 \ \Omega\text{m} \times 30 \text{ km} = 3 \times 10^9 \ \Omega\text{m}^2$$

$$d = \sqrt{ST} = 6{,}000 \text{ km}$$



To measure a resistive seafloor, he needed something other than MT methods.

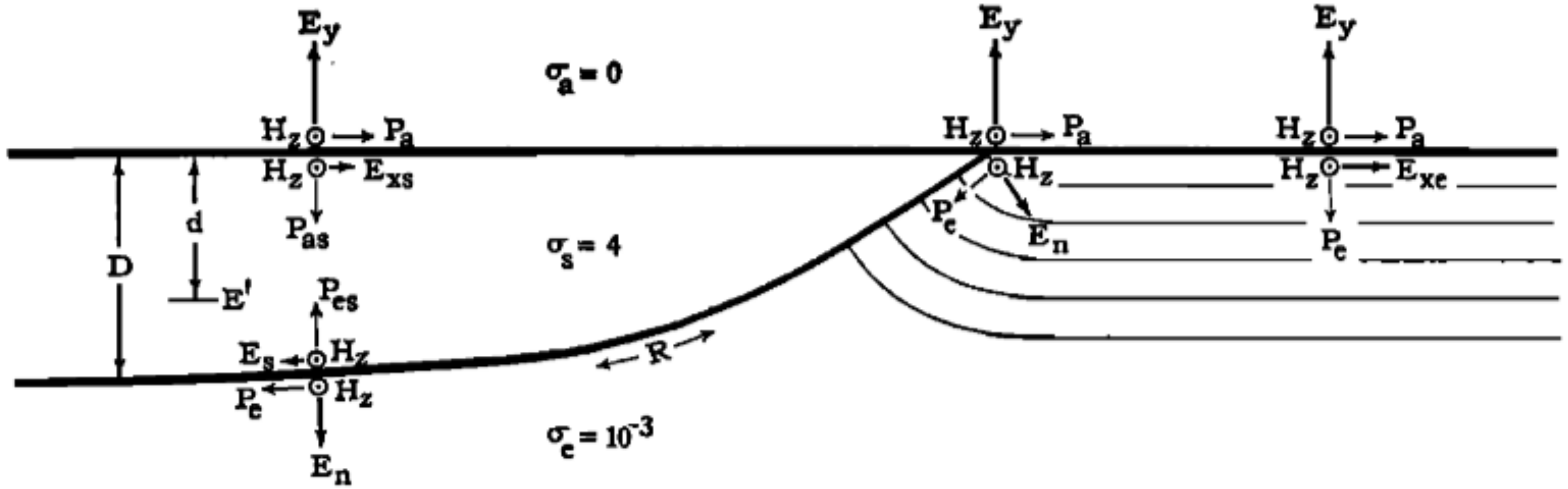


EM INDUCTION IN OCEANS AND EARTH'S CONSTITUTION 151

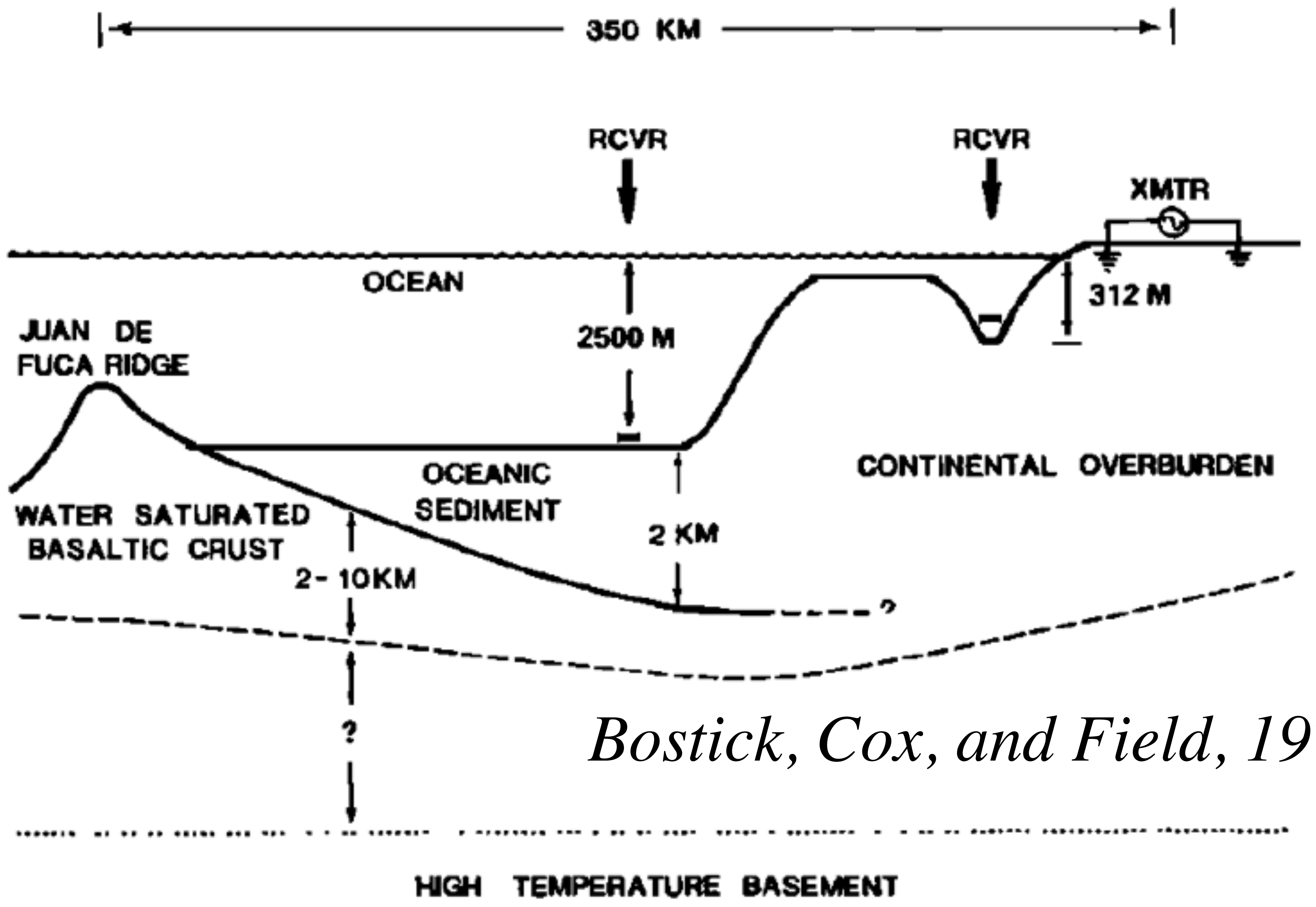
If the conductivity is as low as 10^{-5} S/m the 'boundary zone' fills the largest ocean and normal impedance interpretations are useless. Clearly it is of great importance to learn the conductivity of the near bottom rocks.

Cox, 1980

In 1975 he tried to detect Schumann resonances on the seafloor off a steep part of the continental shelf in Baja California. No luck. He tried again in 1976 using a large transmitter set up by Francis Bostick in Washington state. Again no luck.



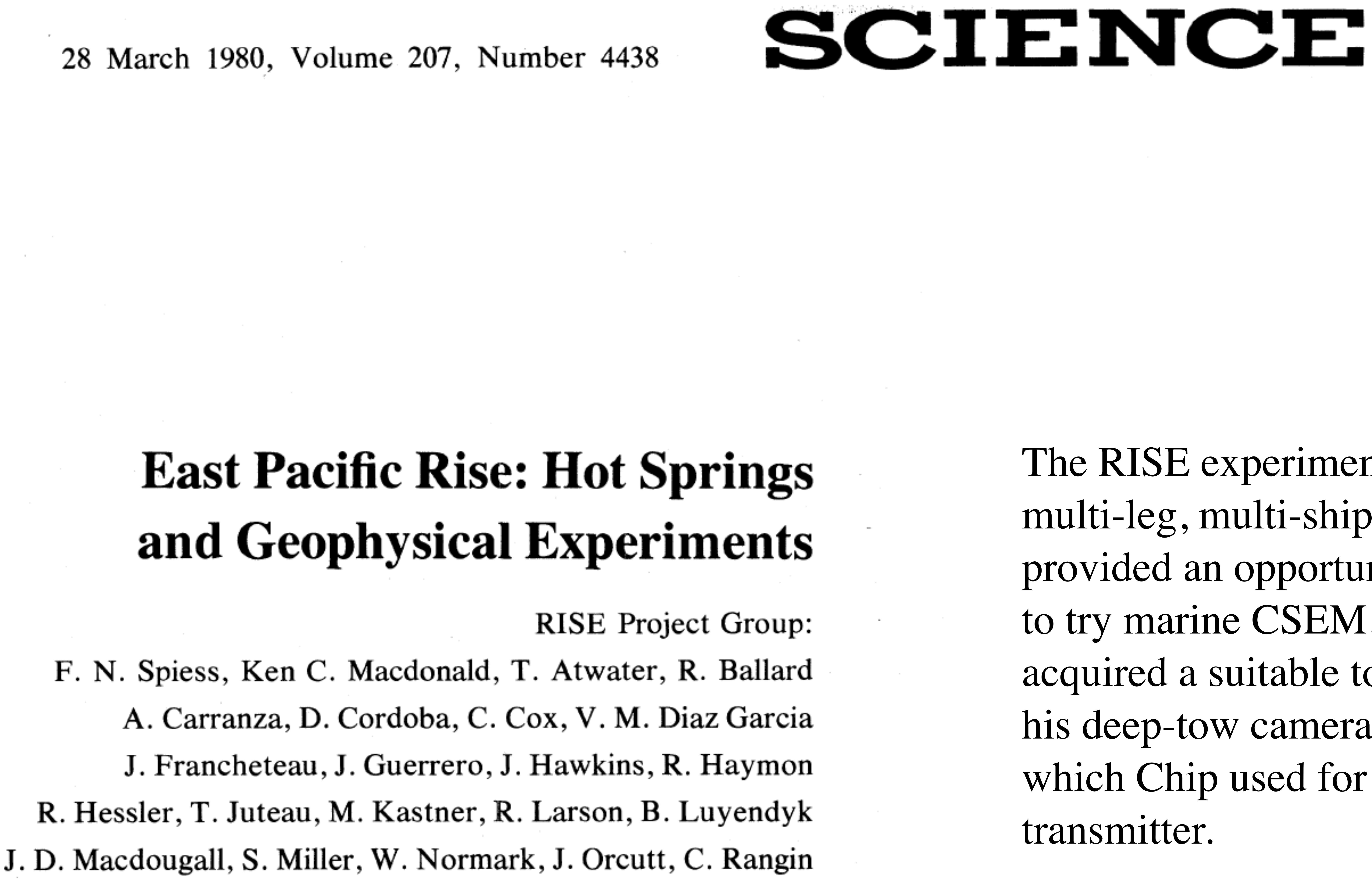
Soderberg, 1969



Bostick, Cox, and Field, 1978.

“It had become clear that an electromagnetic source on the seabed was required to find the conductivity of seabed rocks under deep water.”

Cox, 2011 MARELEC meeting.



28 March 1980, Volume 207, Number 4438

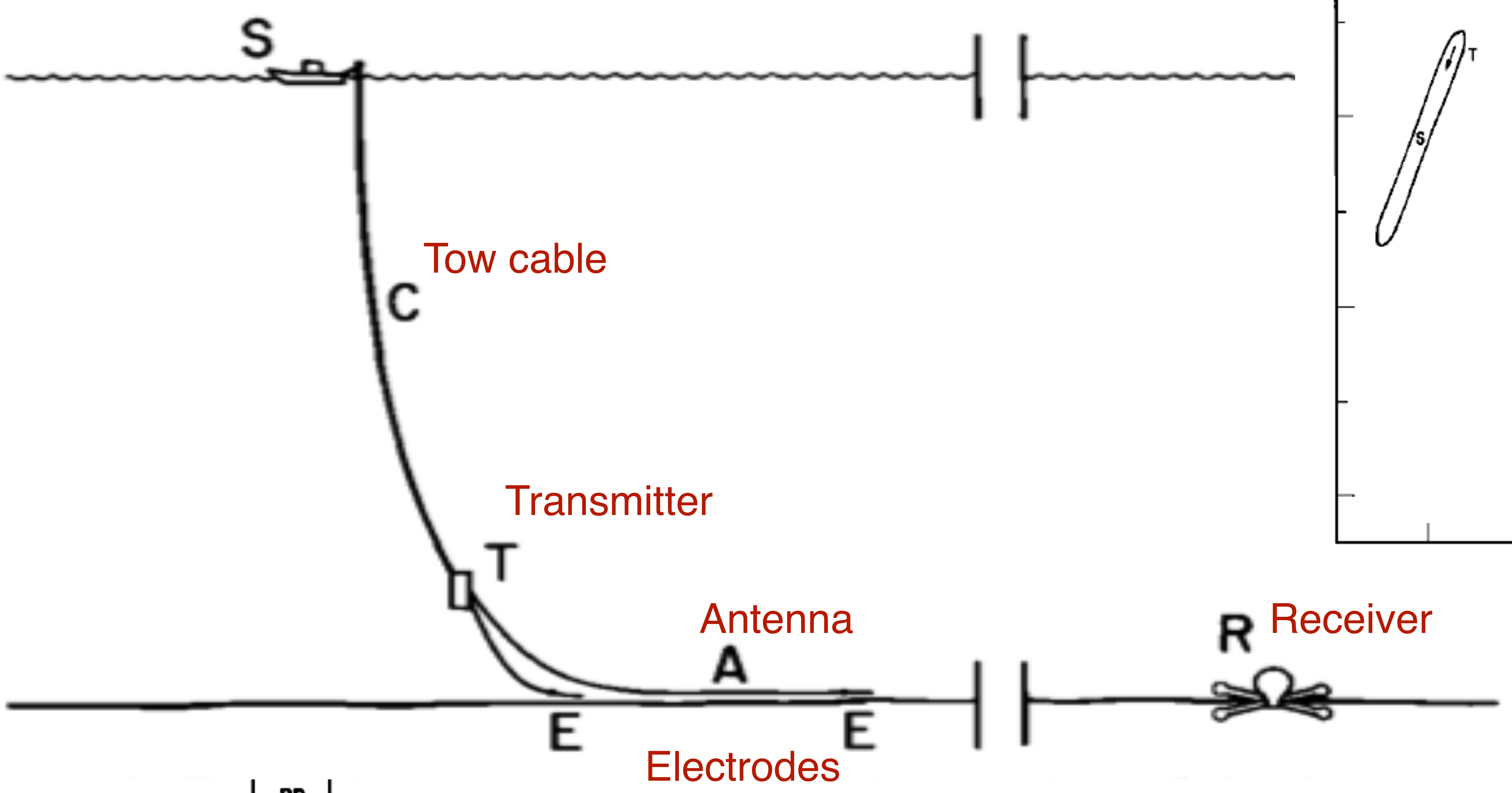
SCIENCE

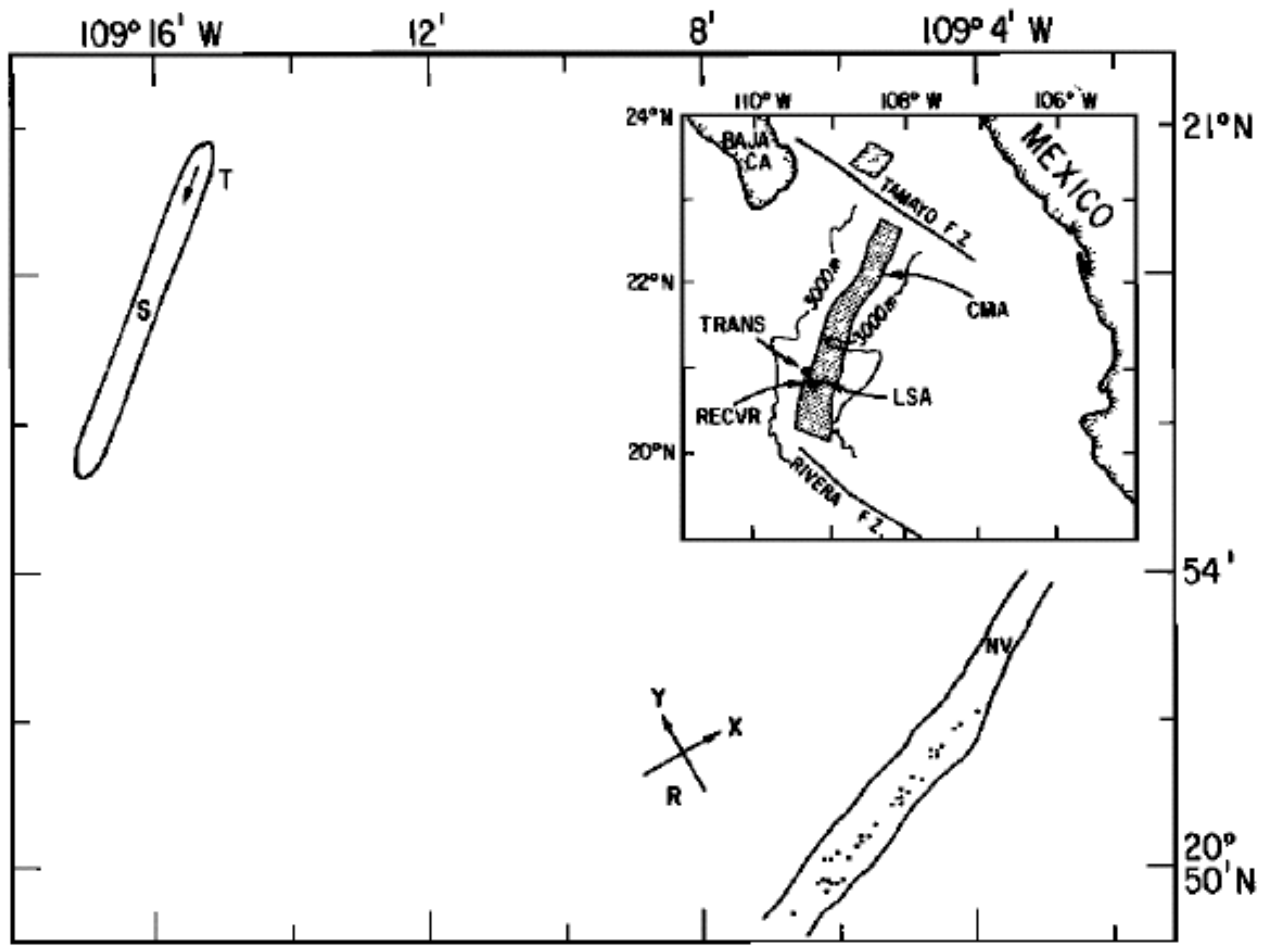
East Pacific Rise: Hot Springs and Geophysical Experiments

RISE Project Group:
F. N. Spiess, Ken C. Macdonald, T. Atwater, R. Ballard
A. Carranza, D. Cordoba, C. Cox, V. M. Diaz Garcia
J. Francheteau, J. Guerrero, J. Hawkins, R. Haymon
R. Hessler, T. Juteau, M. Kastner, R. Larson, B. Luyendyk
J. D. Macdougall, S. Miller, W. Normark, J. Orcutt, C. Rangin

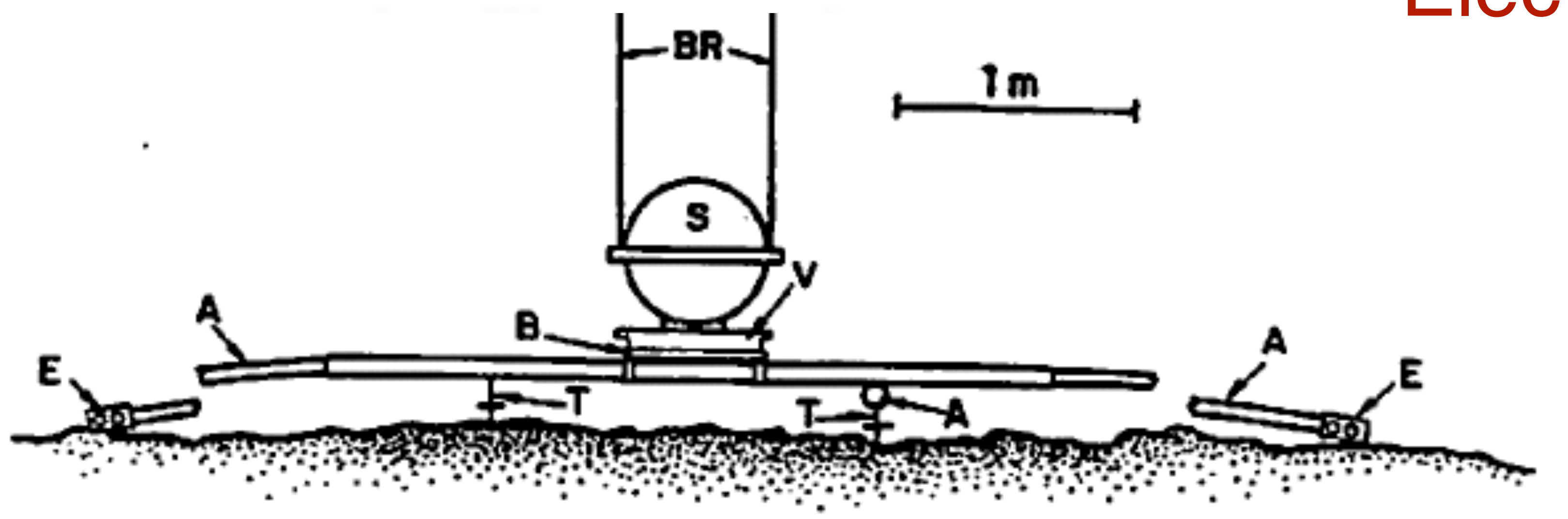
The RISE experiment, a 1979 multi-leg, multi-ship operation, provided an opportunity for Chip to try marine CSEM. Fred Spiess acquired a suitable tow cable for his deep-tow camera operations, which Chip used for his EM transmitter.

Chip carried out a CSEM 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.



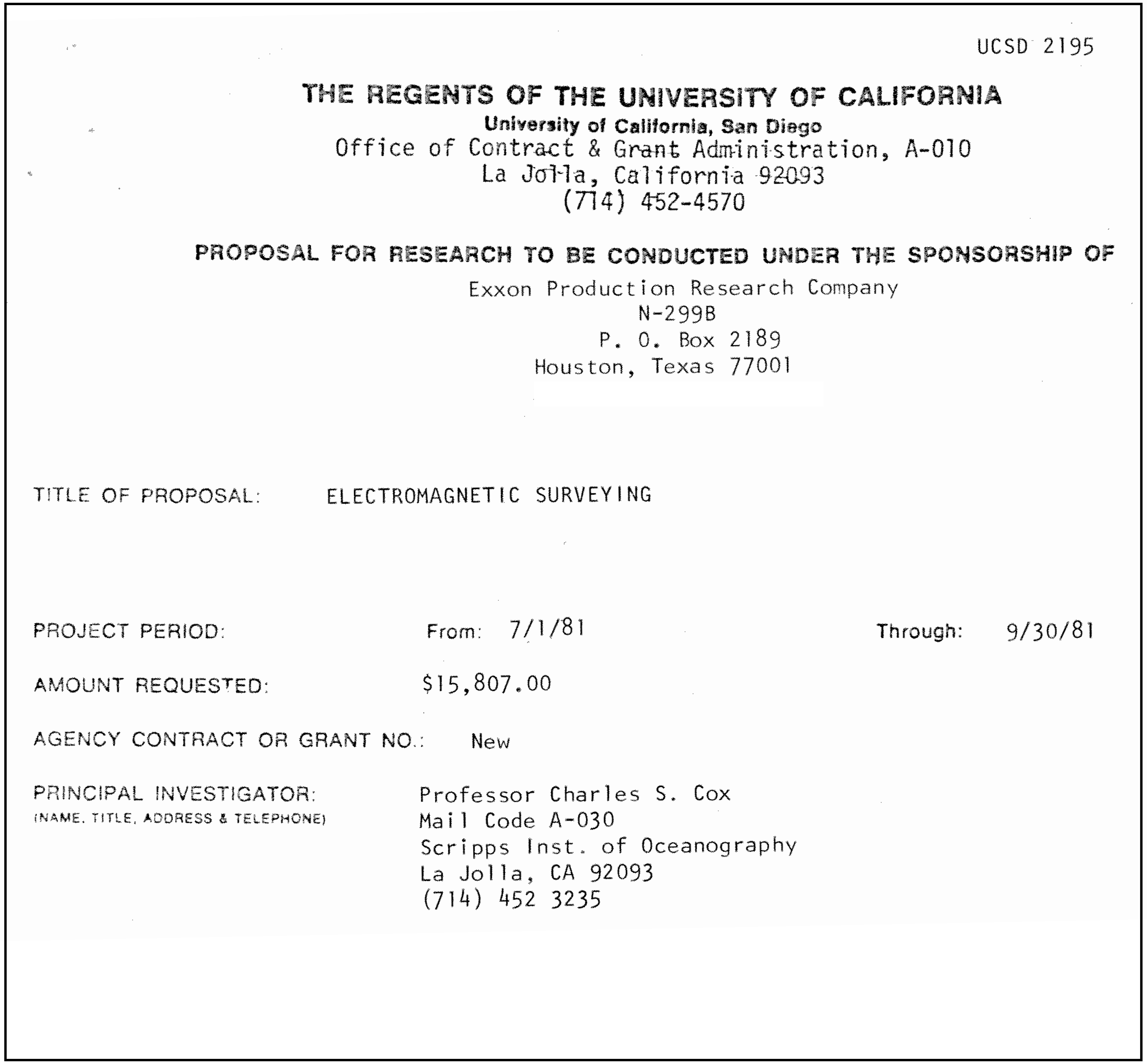


Young and Cox, 1981



Cox et al, 1981

Remarkably, within 2 years, in March 1981, Chip proposed CSEM for direct hydrocarbon detection to Exxon. His model was essentially identical to what I later called the "canonical model" for oil exploration.



UCSD 2195

THE REGENTS OF THE UNIVERSITY OF CALIFORNIA
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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

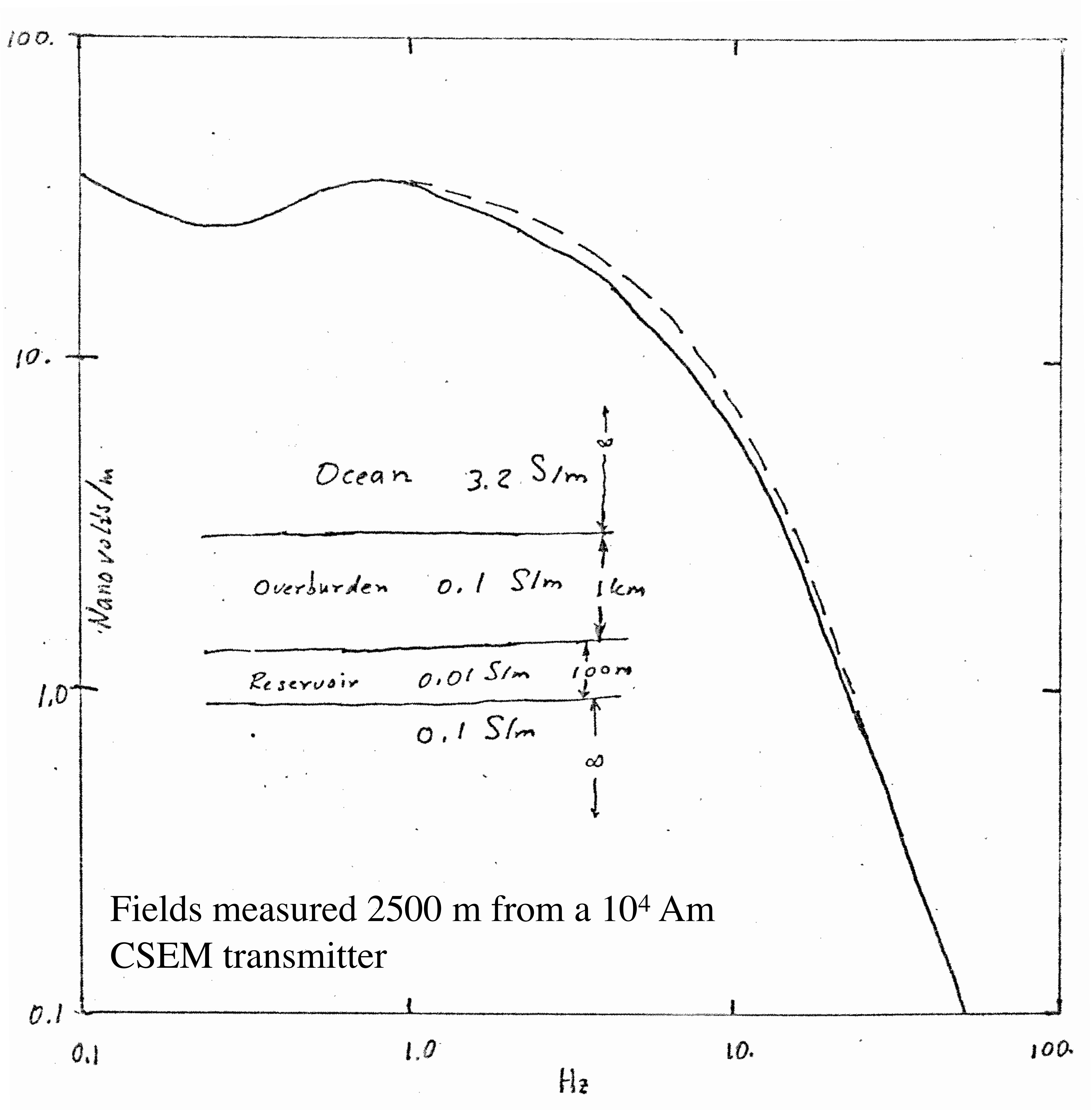
TITLE OF PROPOSAL: ELECTROMAGNETIC SURVEYING

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

AMOUNT REQUESTED: $15,807.00

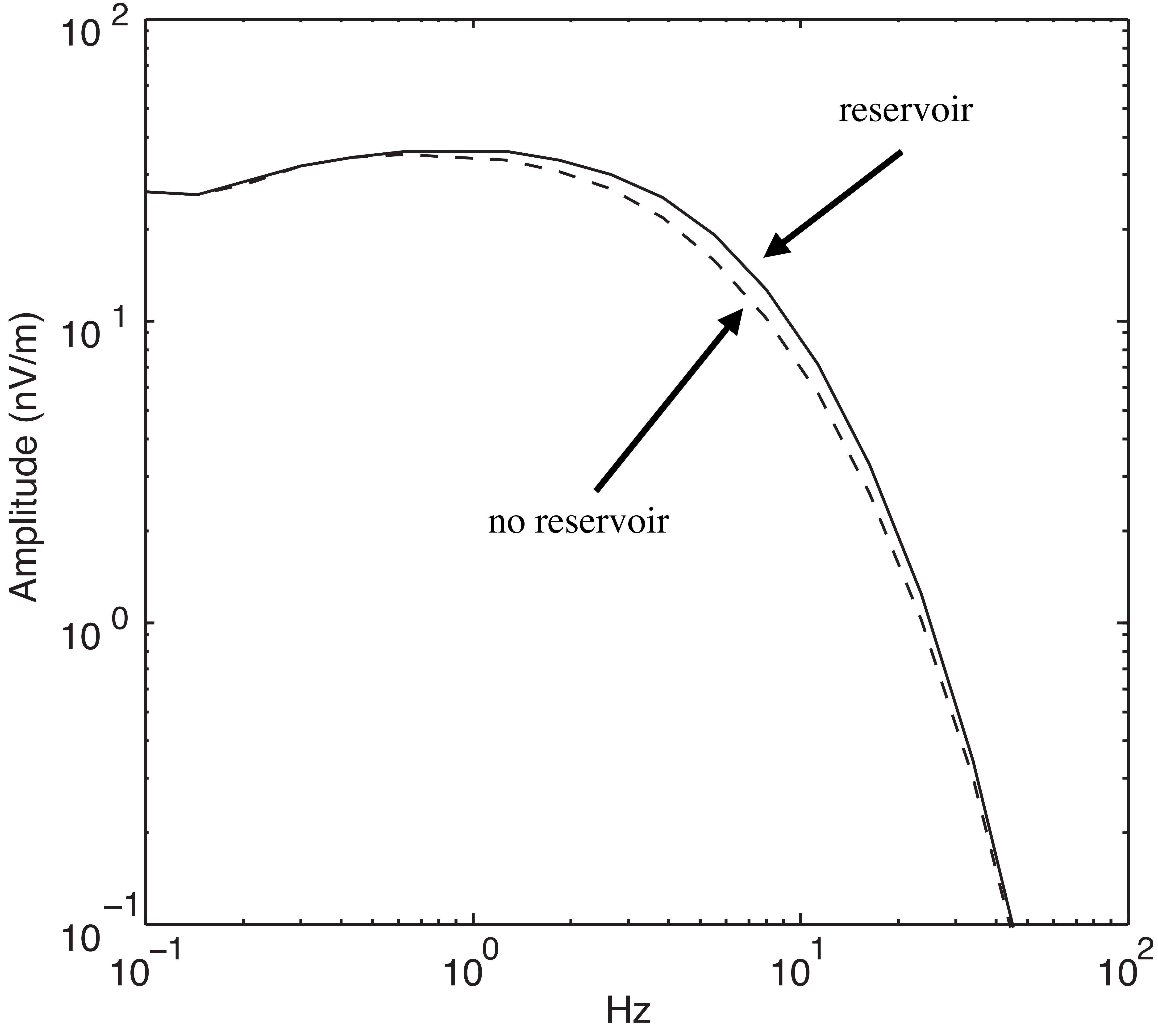
AGENCY CONTRACT OR GRANT NO.: New

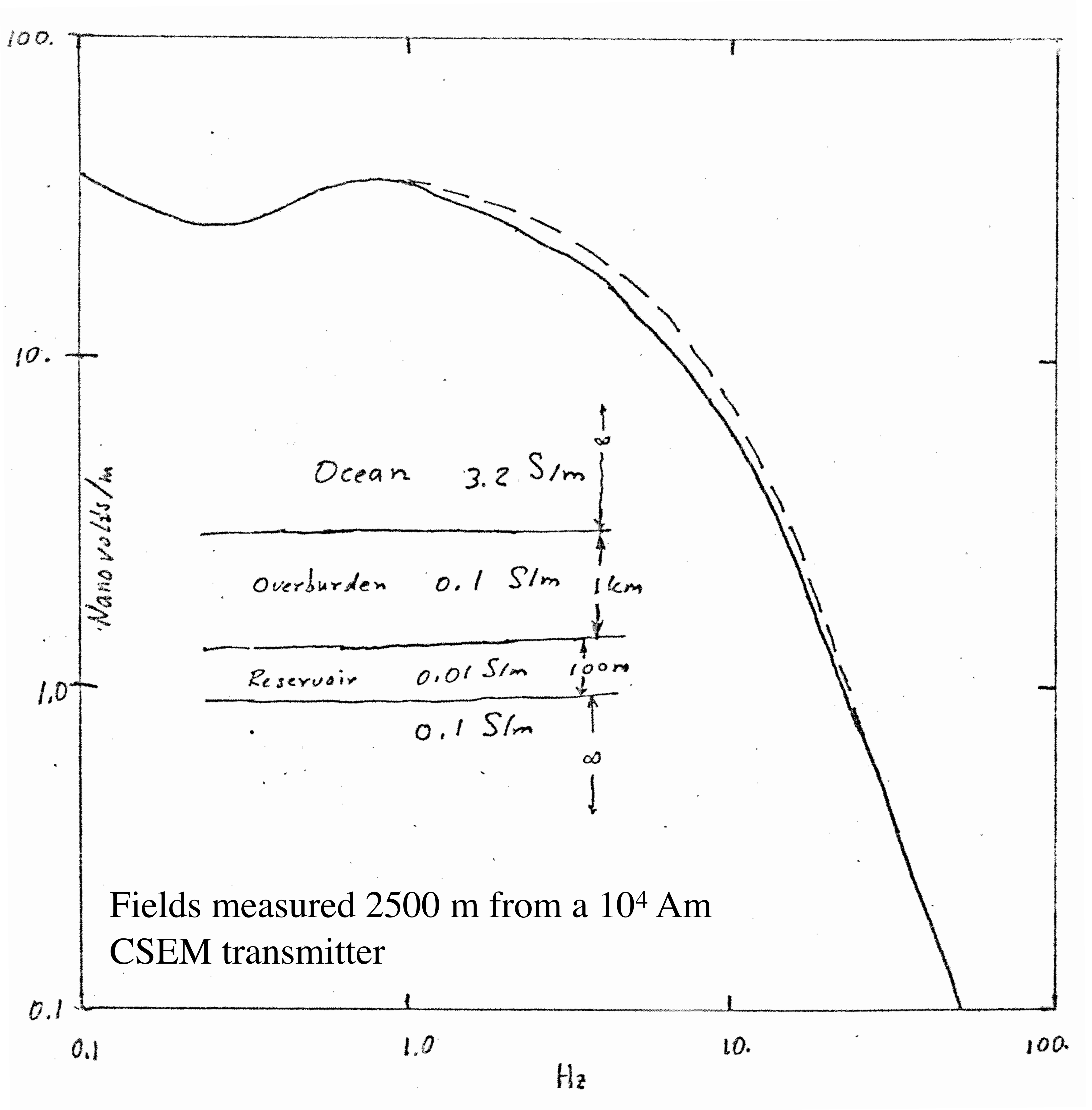
PRINCIPAL INVESTIGATOR: (NAME, TITLE, ADDRESS & TELEPHONE)
Professor Charles S. Cox
Mail Code A-030
Scripps Inst. of Oceanography
La Jolla, CA 92093
(714) 452 3235



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

His model response was hand-drawn, but correct. The proposal was declined - Chip was too far ahead of the times.





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

Chip hired me on as a postdoc in 1983 and thus started my training in the art of marine EM.

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. We worked together on many projects. Nigel Edwards was also developing a marine version of magnetometric resistivity.

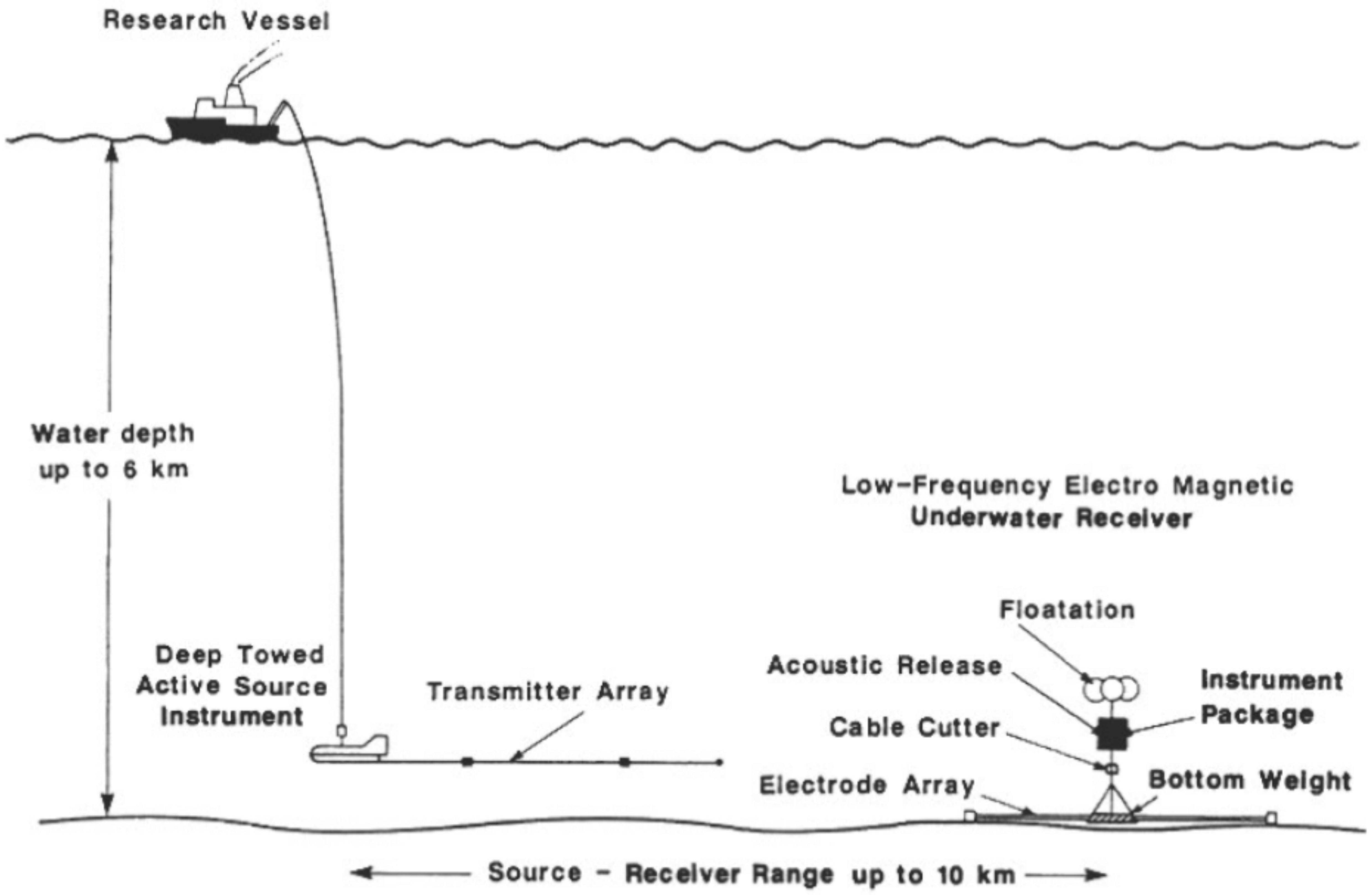
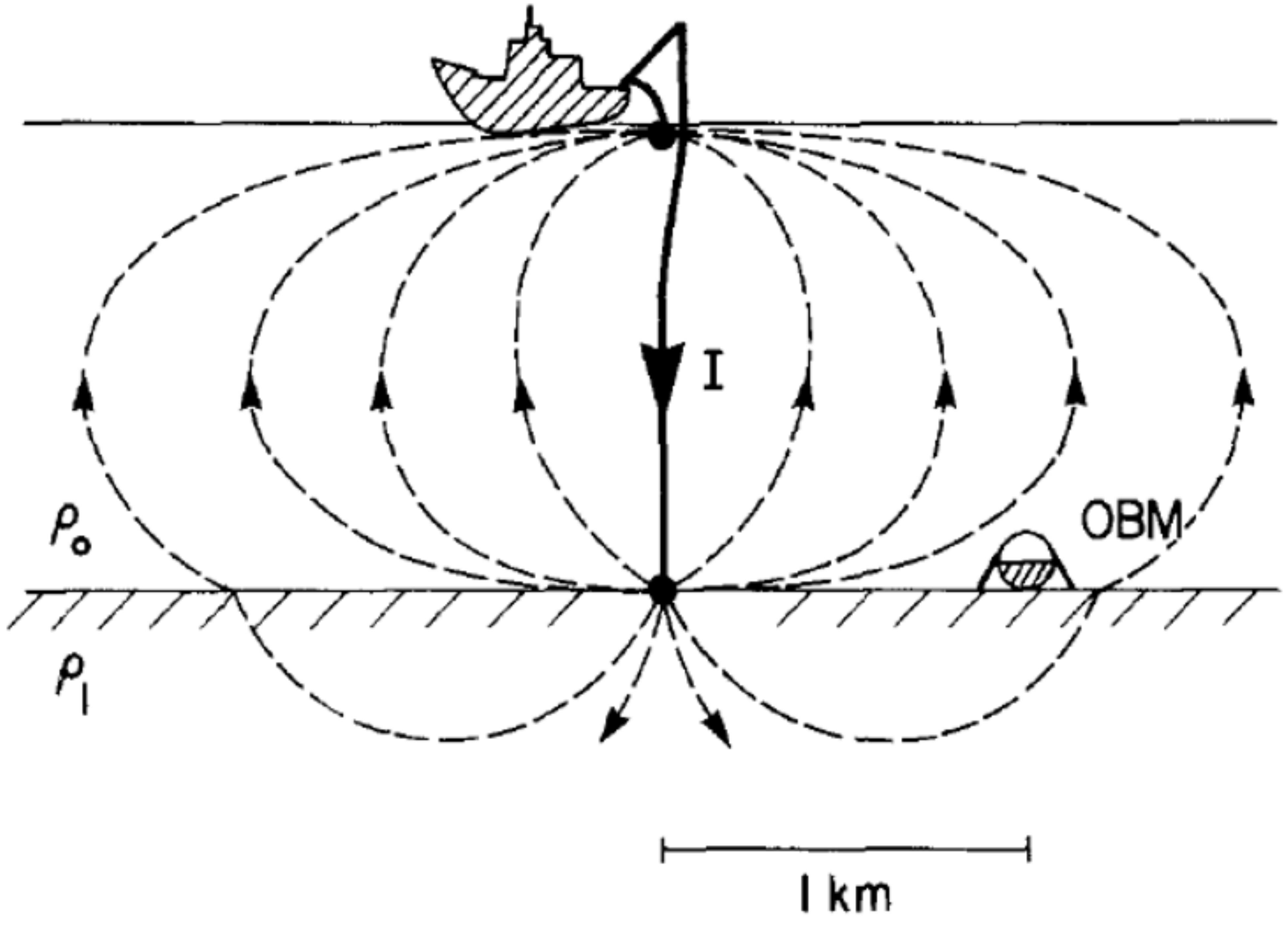


Fig. 1. Schematic arrangement of an active source electromagnetic sounding experiment, showing the deep-towed active source instrument, the surface research vessel and a low-frequency electromagnetic underwater recorder (not to scale).

Sinha et al, 1990

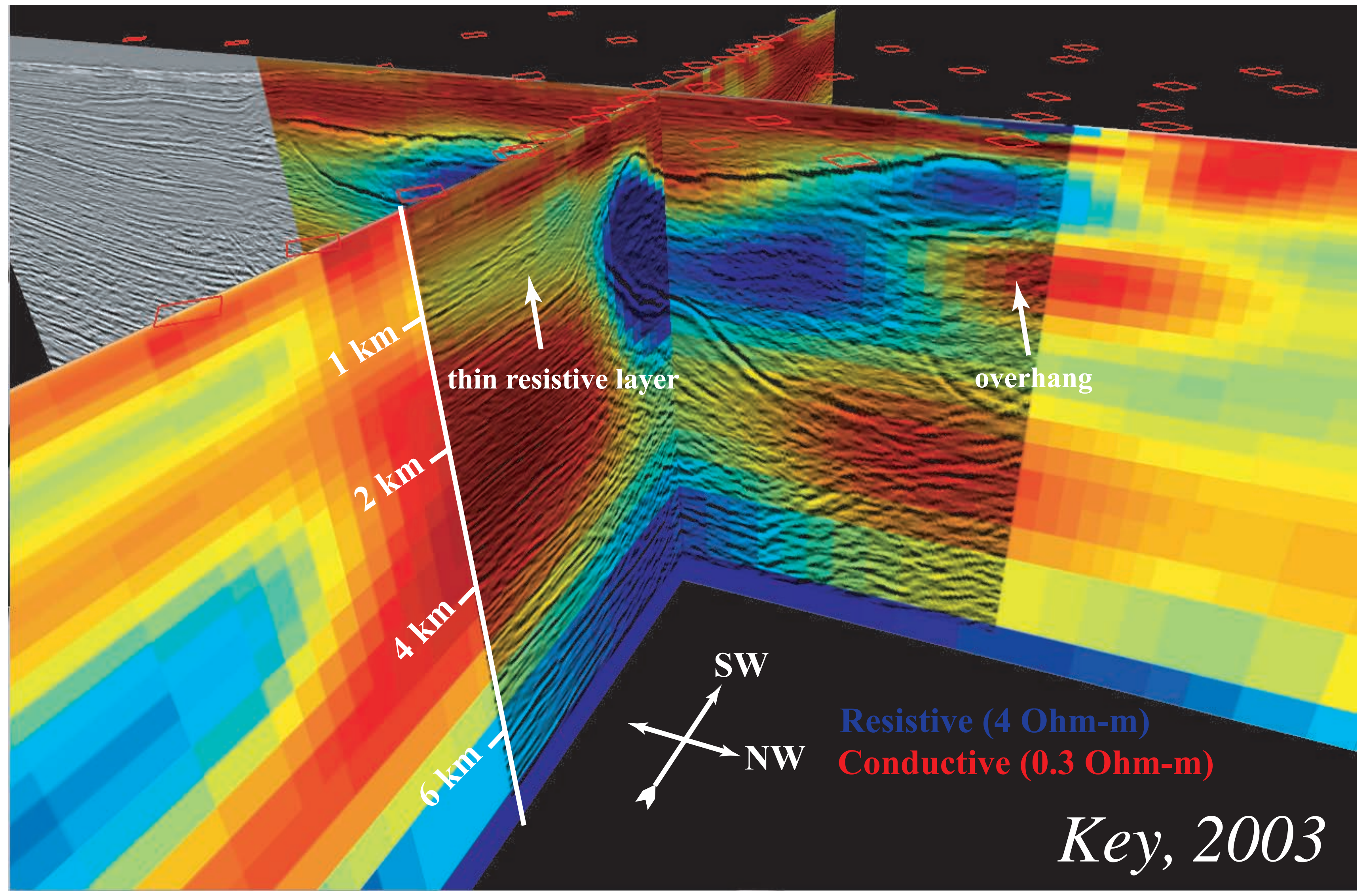


Edwards et al, 1987

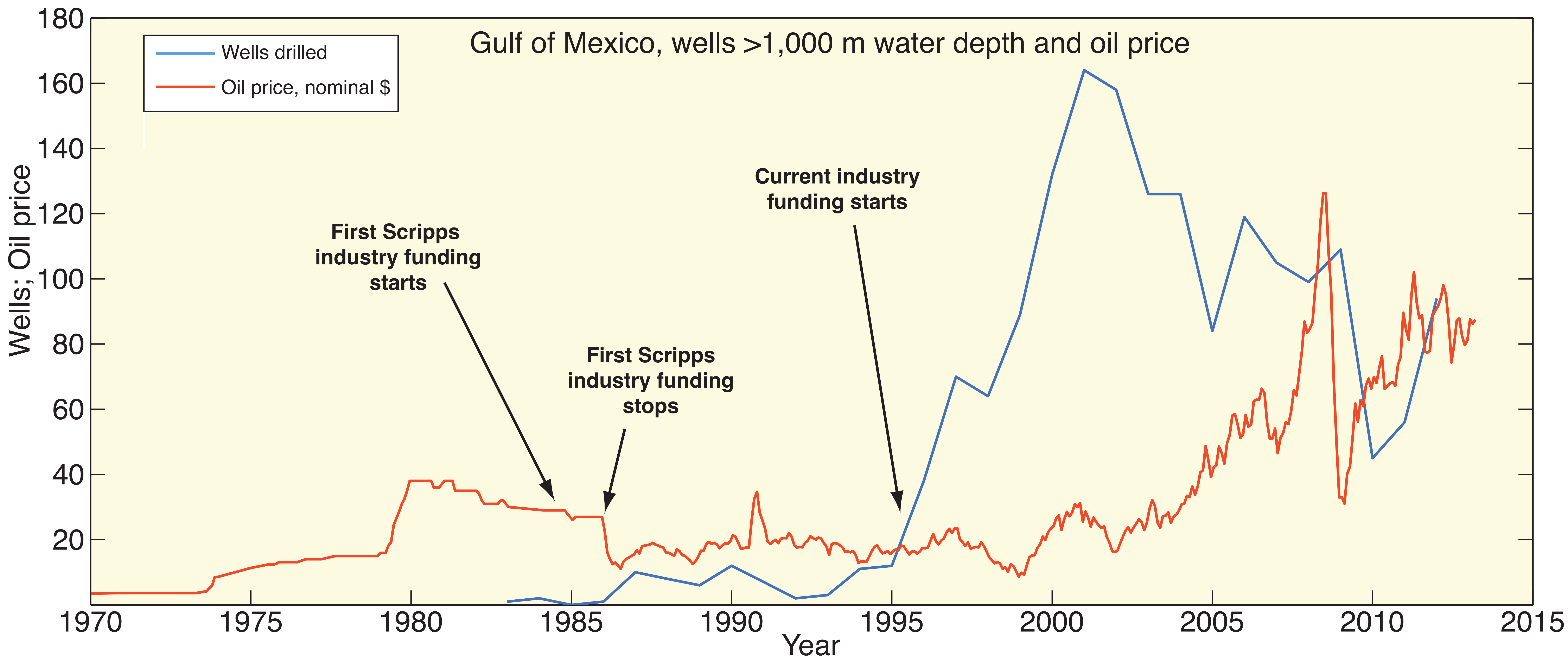
Early funding (~1984) of Scripps by industry was tied to oil prices.

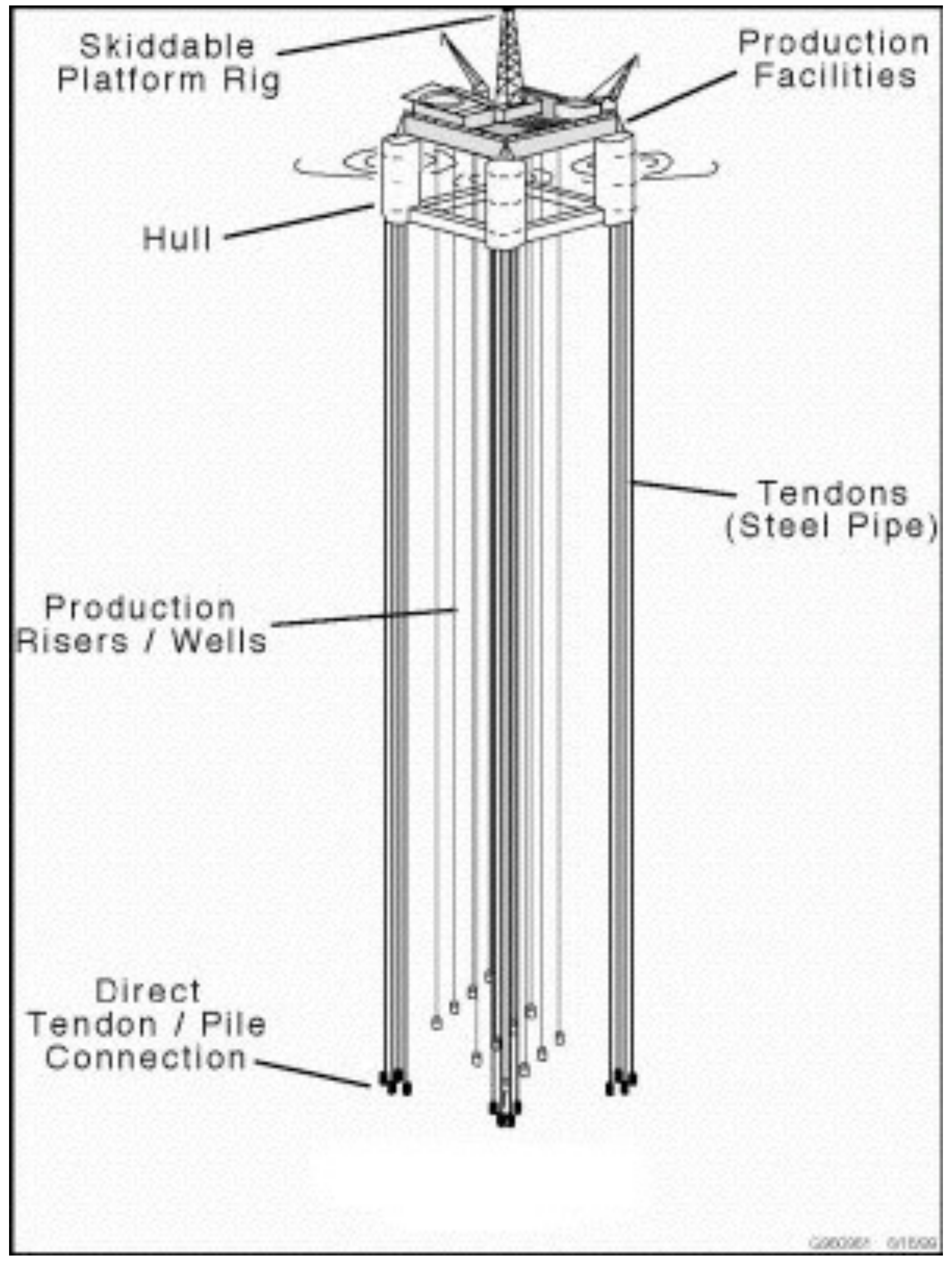
In 1995 Scripps, UC Berkeley, and AOA Geophysics obtained industry funding to develop marine MT for exploration.

This time funding was driven by the high cost of deepwater wells and the difficulty in using the seismic method in salt, carbonate, and volcanic environments.



Key, 2003

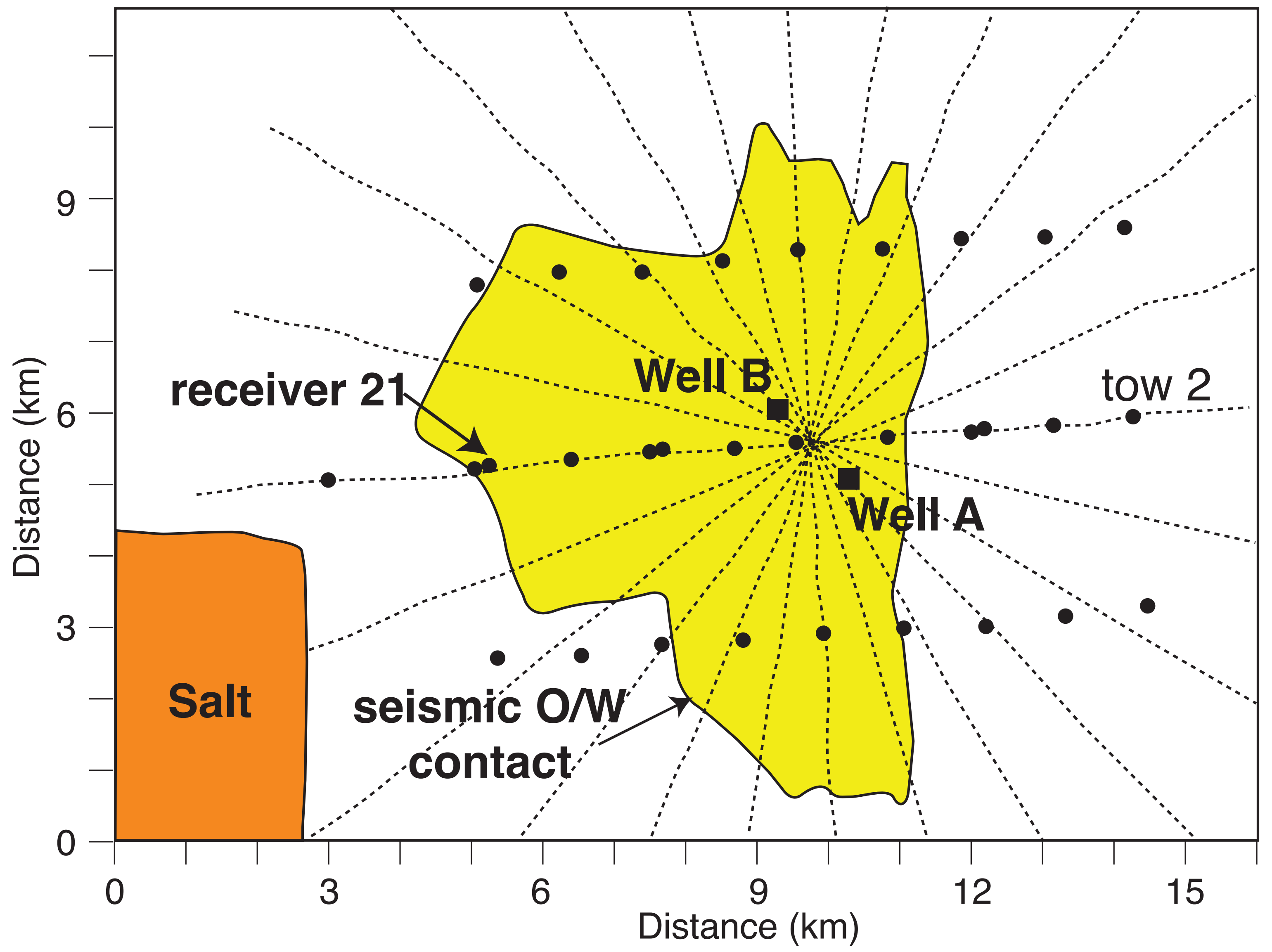


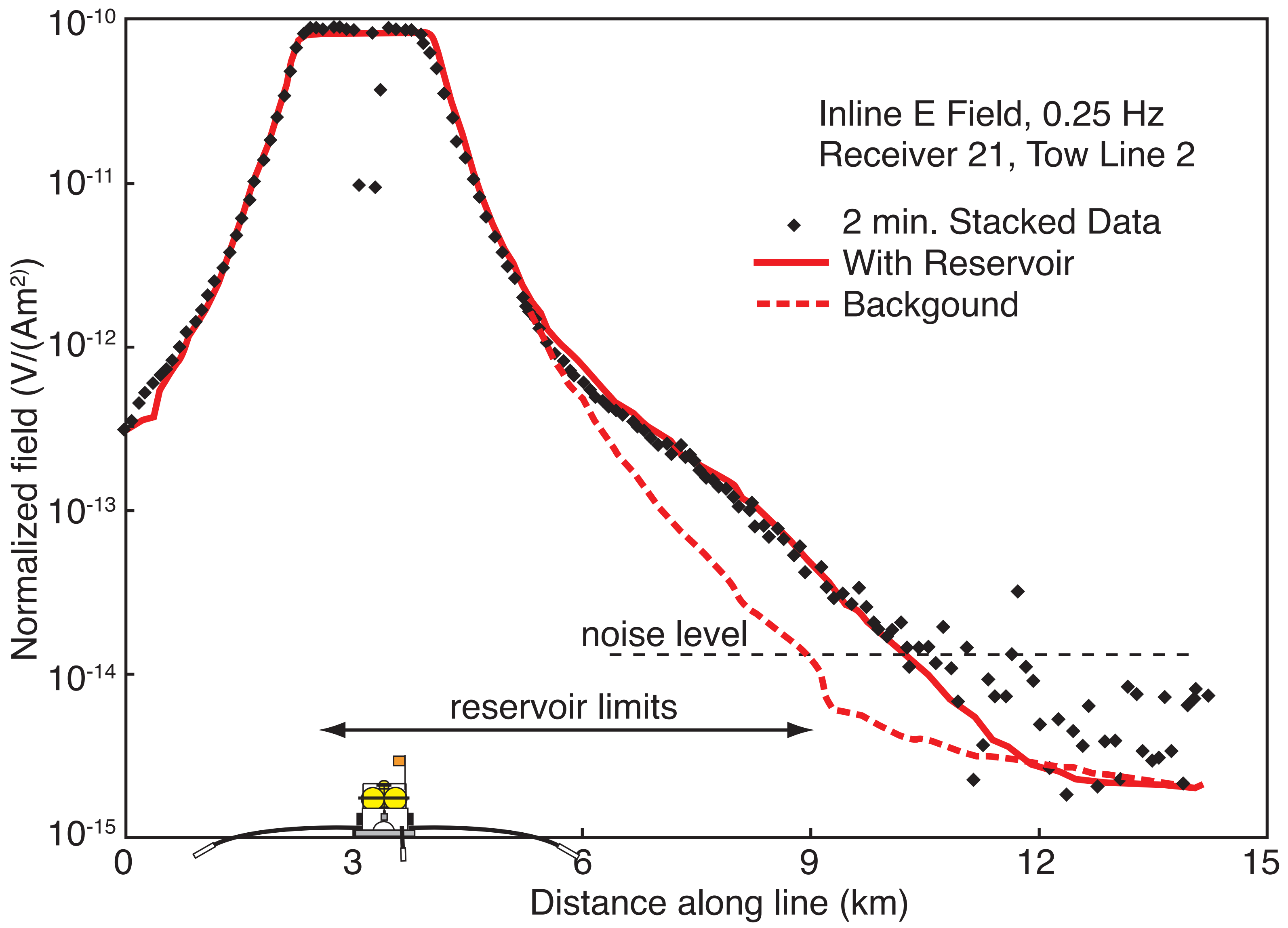


The first CSEM sounding over an oil reservoir was done at Girassol off Angola in Nov 2000 by Statoil, using Scripps and Southampton equipment. Similar studies were carried out by ExxonMobil in Jan 2002.

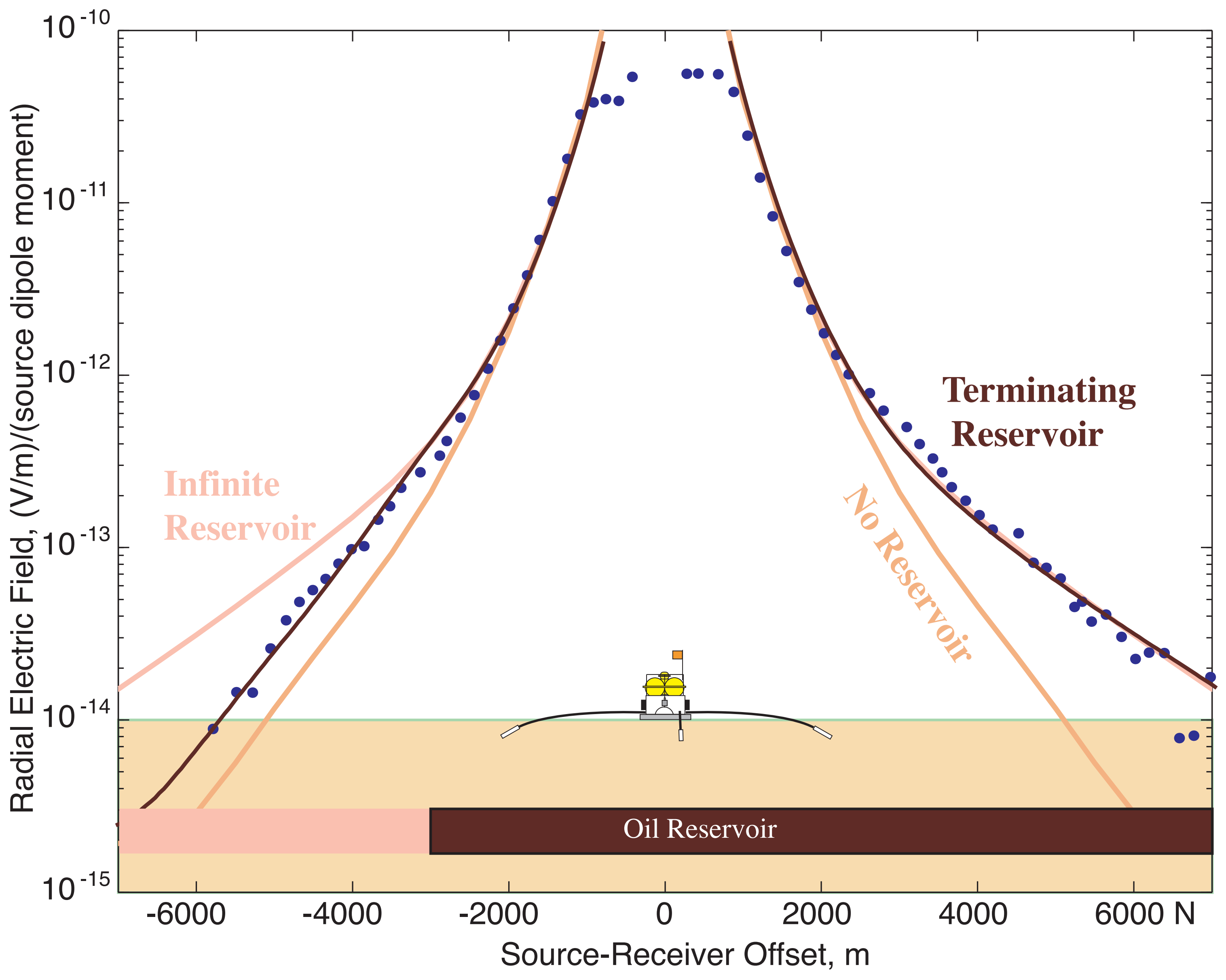
The ExxonMobil studies used 30 new instruments designed and built by Scripps for XoM.

Over a known discovery

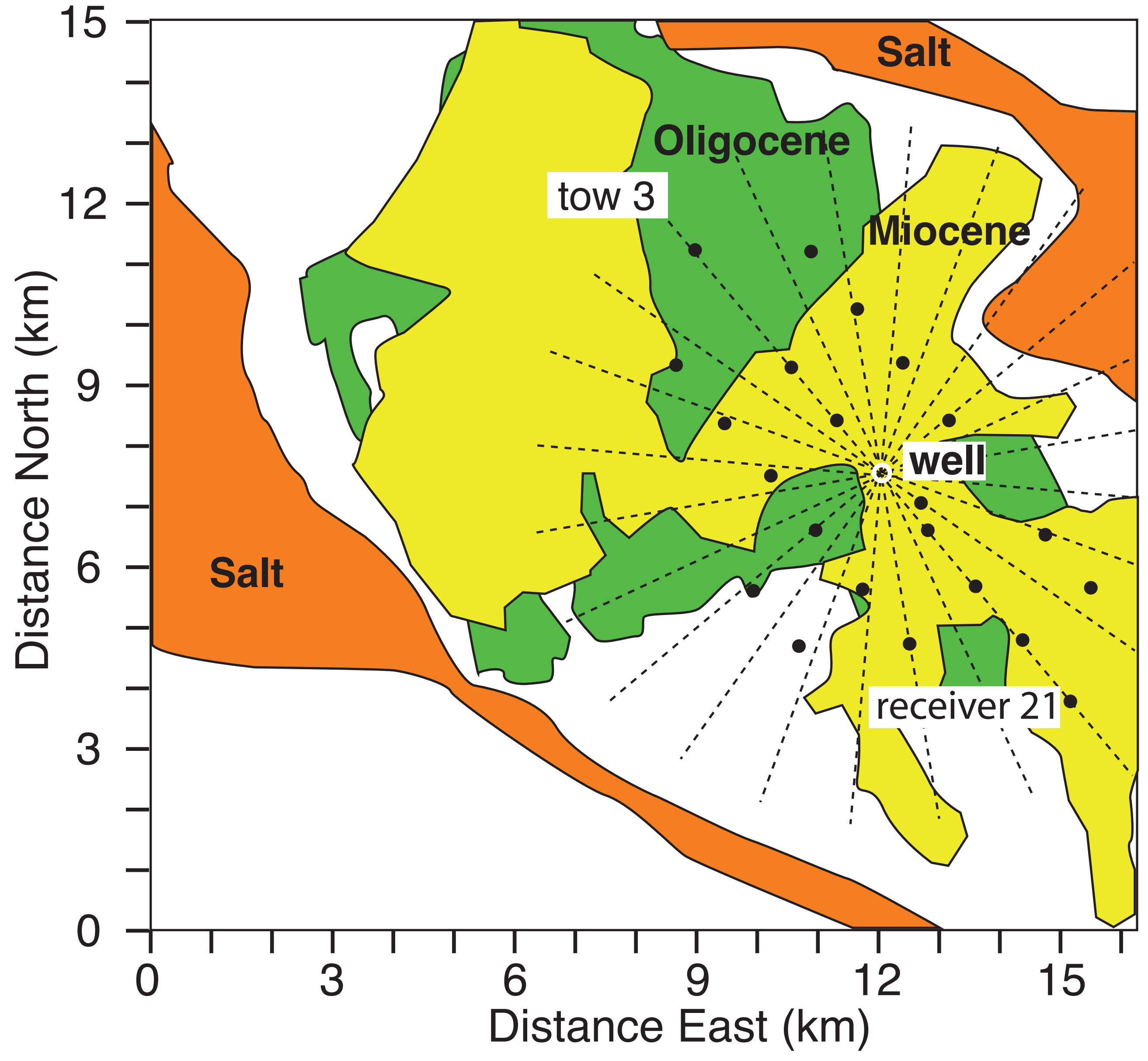


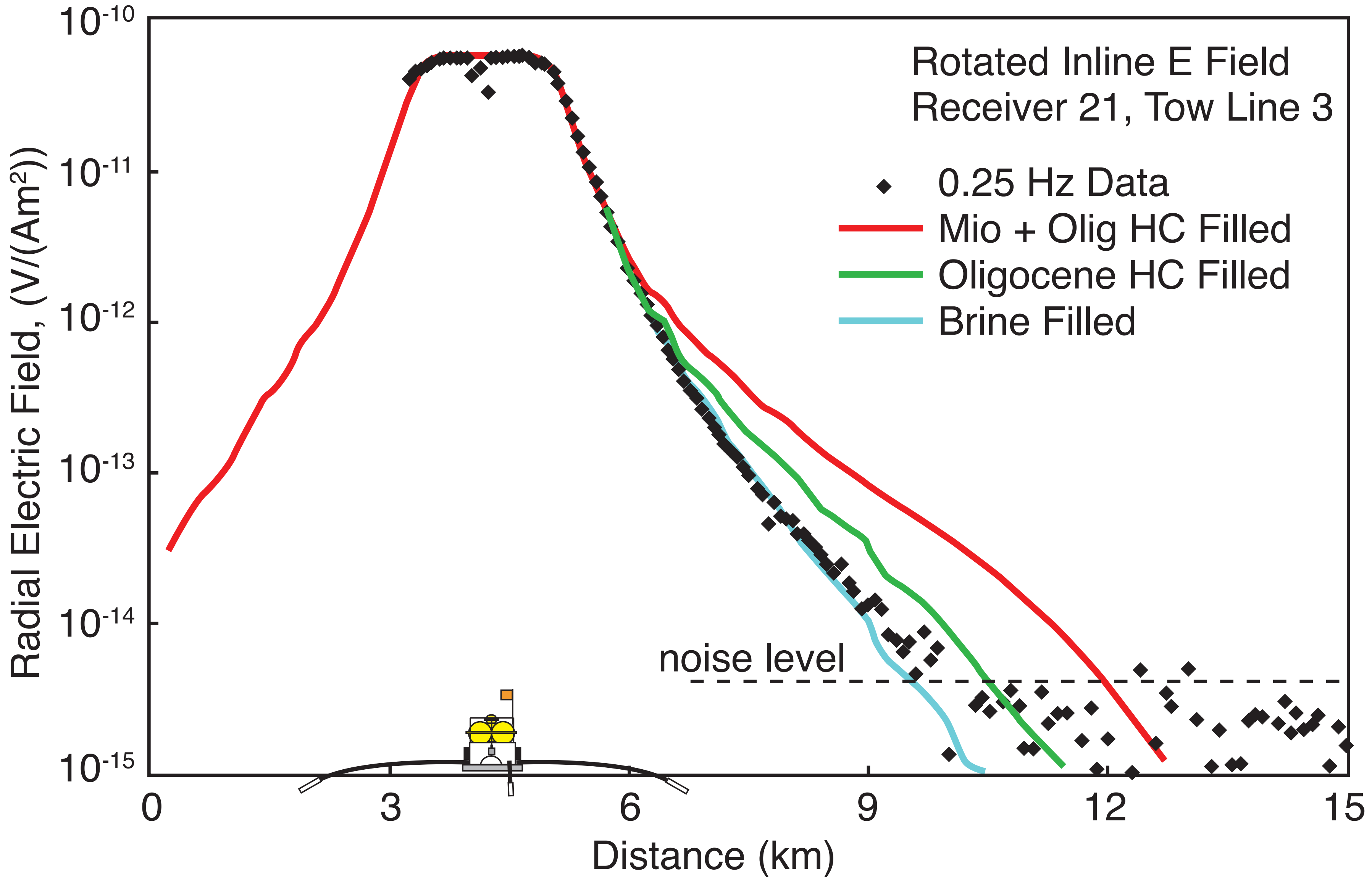


Girassol (known)



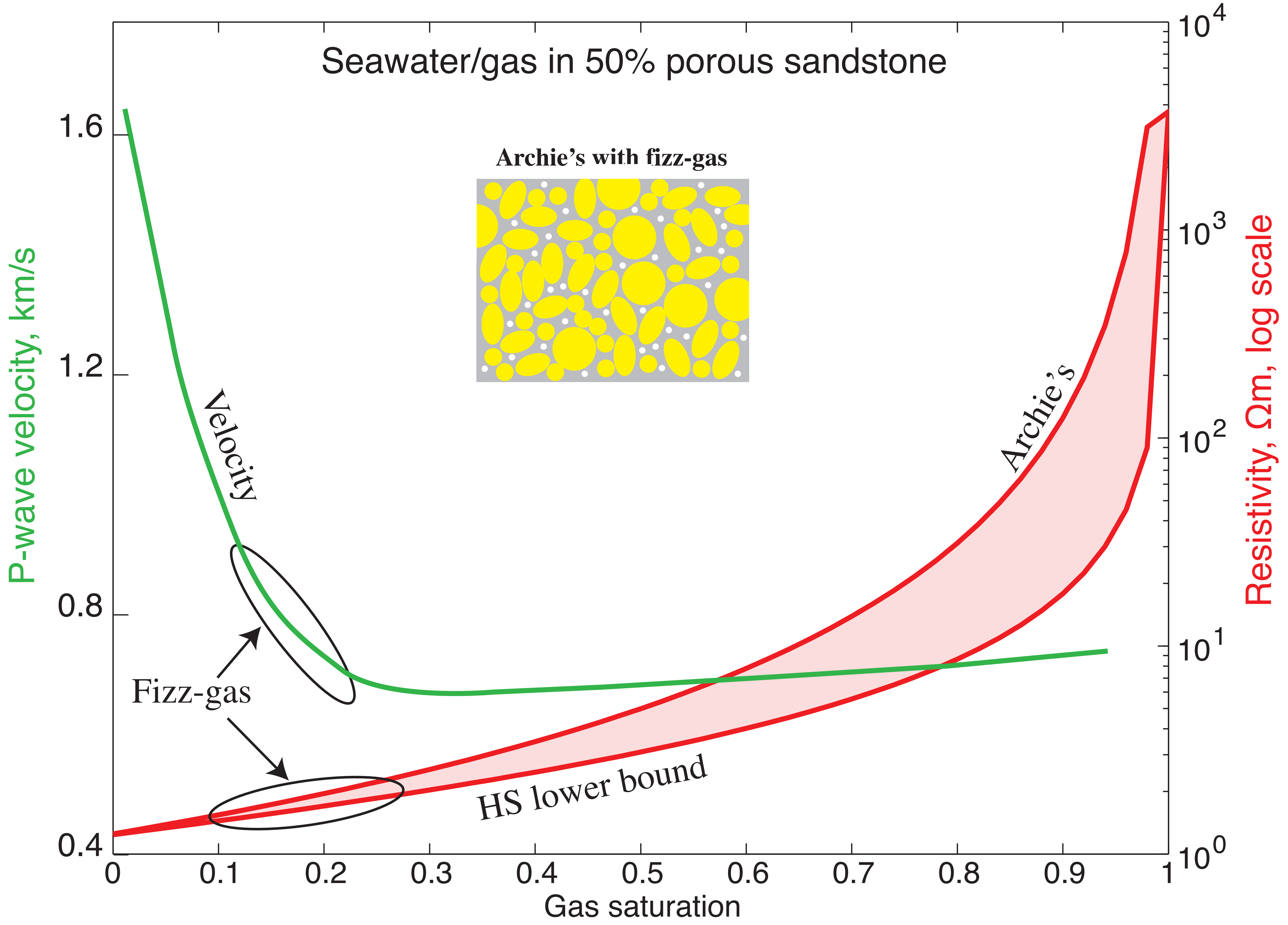
Prior to drilling





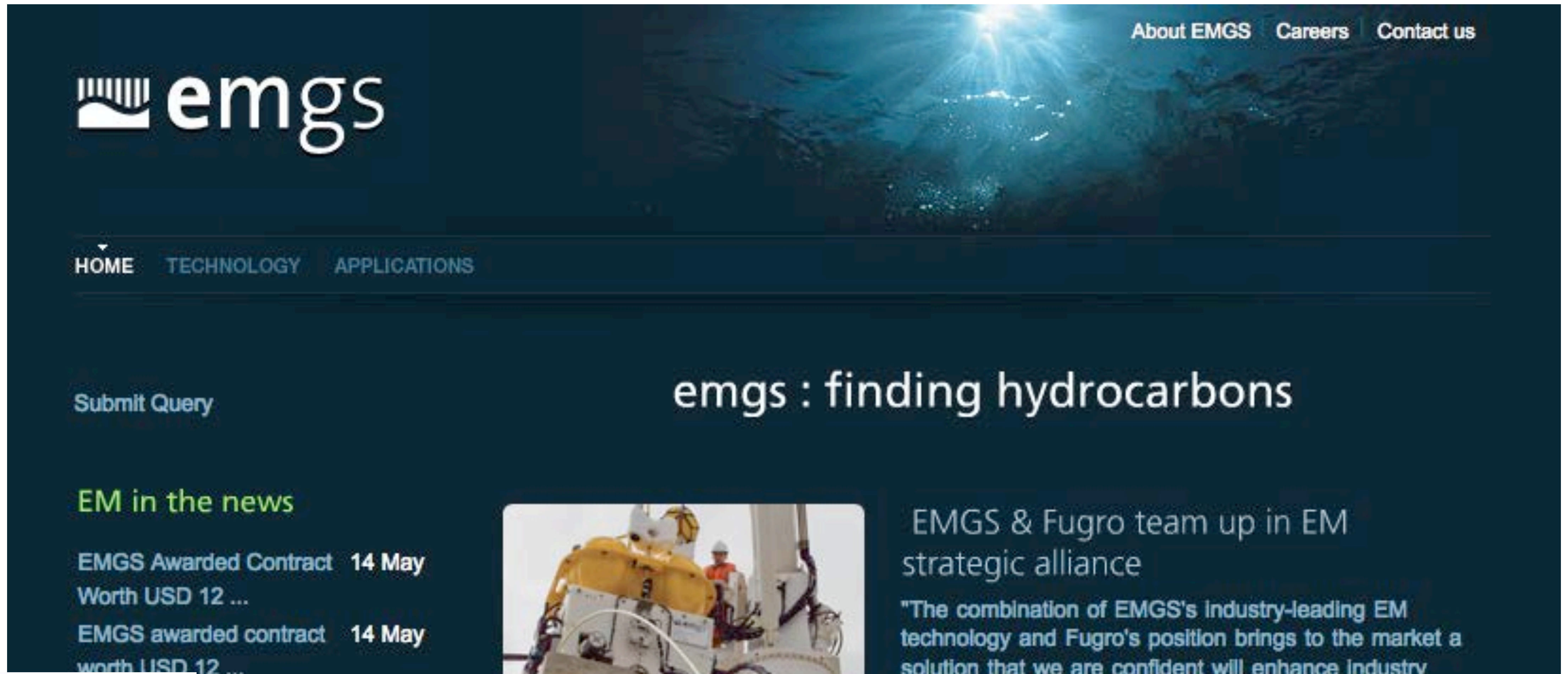
Constable and Srnka, 2007

Why did ExxonMobil think the second target had hydrocarbons? 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.



(modified from Constable, 2010)

By the end of 2002, three companies were offering marine MT and CSEM as a commercial product…



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EMGS & Fugro team up in EM strategic alliance

"The combination of EMGS's industry-leading EM technology and Fugro's position brings to the market a solution that we are confident will enhance industry adoption of our EM technology", says Roar Bekker, acting CEO, EMGS

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OHM welcomes UK High Court decision in Schlumberger –

Taking exploration to the next level:

Controlled Source ElectroMagnetic Imaging (CSEM) provides hydrocarbon explorers with a new remote sensing measurement that significantly de-risks offshore exploration and cost effectively screens prospect portfolios.

OHM combines leading scientists who have been researching into and applying the technique for over 20 years with a team of oil industry professionals drawn largely from the seismic industry. Their combined knowledge and experience has allowed OHM to develop CSEM as an effective decision making tool for explorationists.

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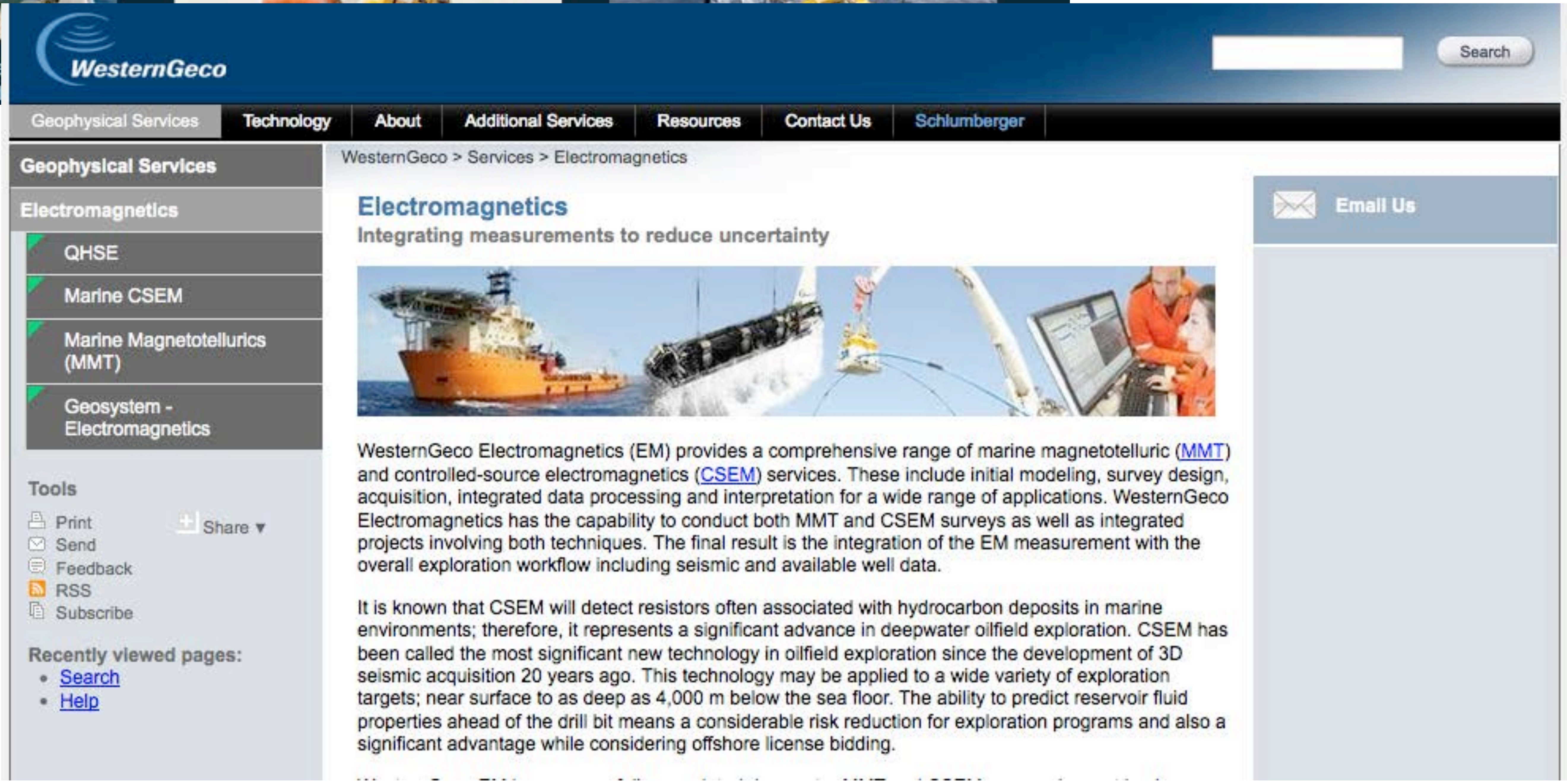
Case Study: Joint Interpretation of Seismic and CSEM Data.



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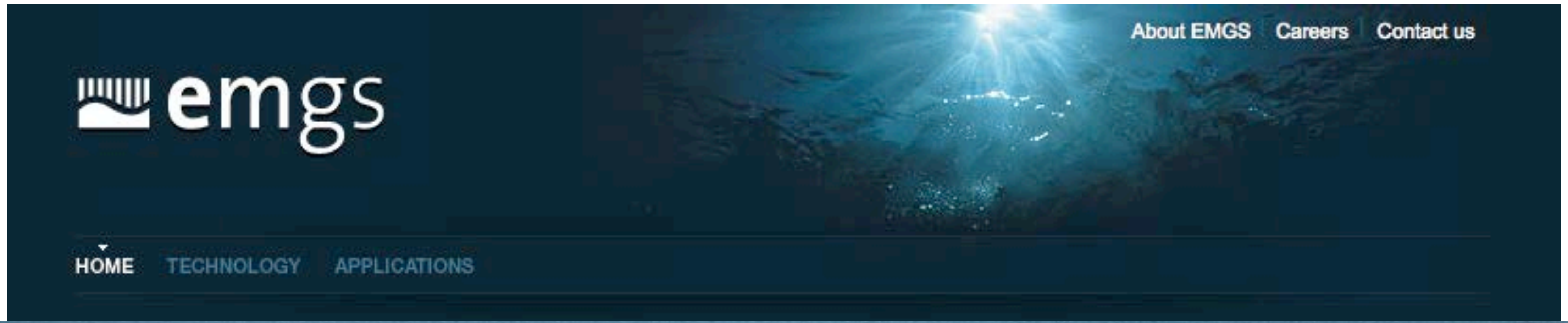
Electromagnetics

Integrating measurements to reduce uncertainty

WesternGeco Electromagnetics (EM) provides a comprehensive range of marine magnetotelluric (MMT) and controlled-source electromagnetics (CSEM) services. These include initial modeling, survey design, acquisition, integrated data processing and interpretation for a wide range of applications. WesternGeco Electromagnetics has the capability to conduct both MMT and CSEM surveys as well as integrated projects involving both techniques. The final result is the integration of the EM measurement with the overall exploration workflow including seismic and available well data.

It is known that CSEM will detect resistors often associated with hydrocarbon deposits in marine environments; therefore, it represents a significant advance in deepwater oilfield exploration. CSEM has been called the most significant new technology in oilfield exploration since the development of 3D seismic acquisition 20 years ago. This technology may be applied to a wide variety of exploration targets; near surface to as deep as 4,000 m below the sea floor. The ability to predict reservoir fluid properties ahead of the drill bit means a considerable risk reduction for exploration programs and also a significant advantage while considering offshore license bidding.

commercial marine EM ships were custom-built…



NEWS

May 2009

First commercial use of WISE technology in North Sea CSEM survey.

>more

March 2009

Corporate Update.

>more

February 2009

Corporate Update.

>more

January 2009

OHM welcomes UK High Court decision in Schlumberger –

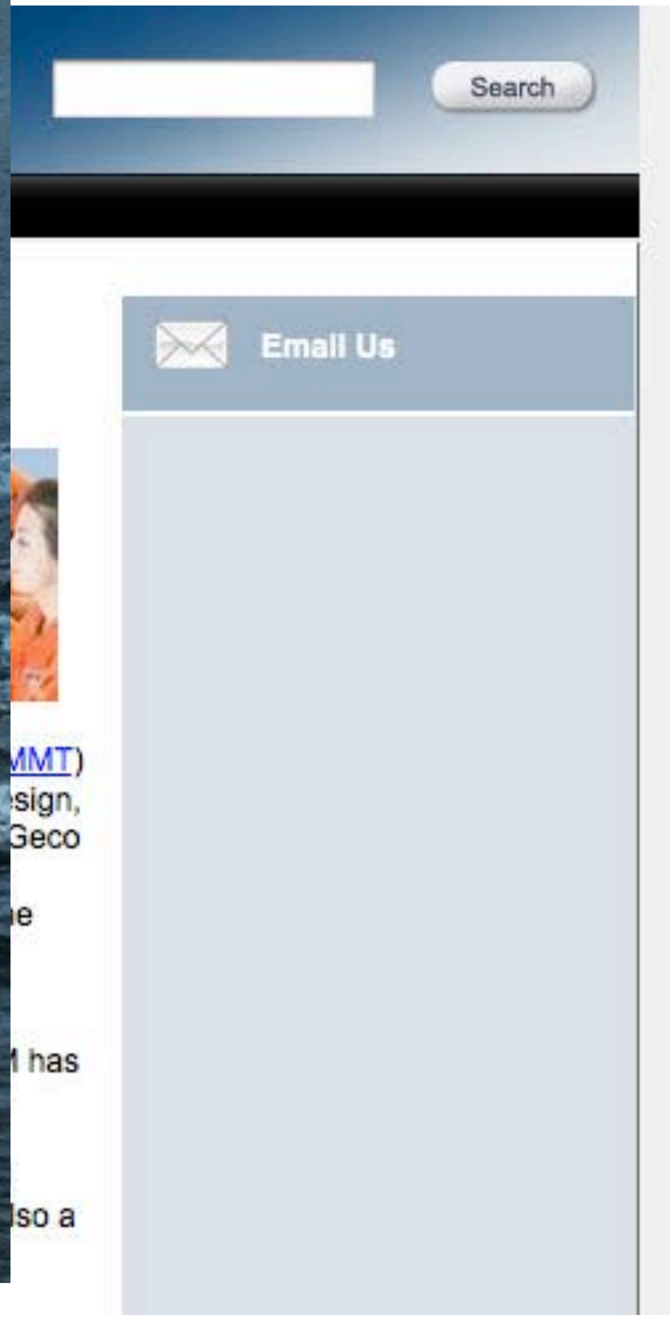
Taking explorat

Controlled Source Ele provides hydrocarbon sensing measurement exploration and cost e portfolios.

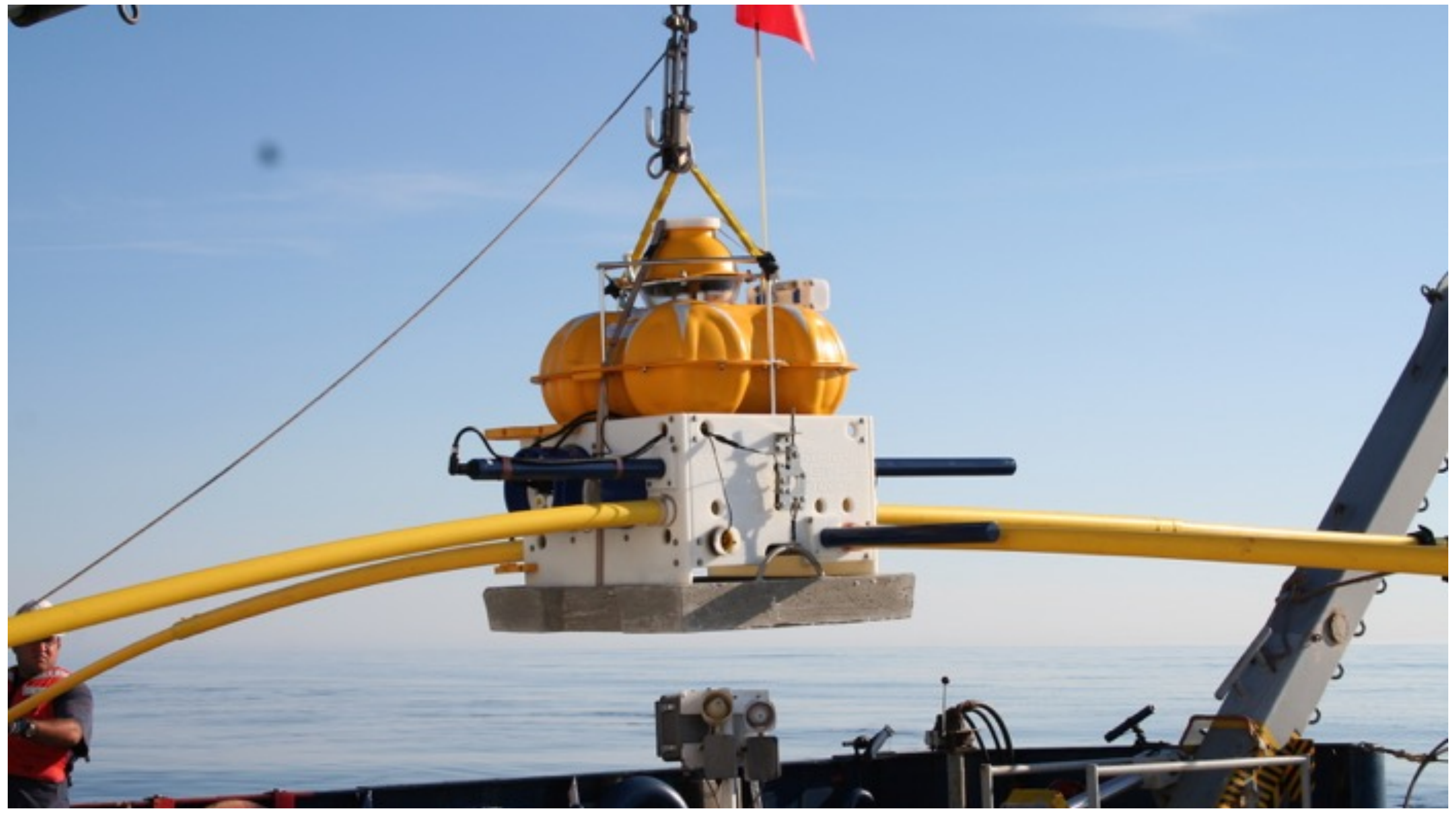
OHM combines leadin researching into and a years with a team of o largely from the seismi knowledge and experi CSEM as an effective d explorationists.

About OHM plc

EMGS website



Working with the oil and gas industry has supported a state-of-the-art instrument fleet of about 50 EM receivers and 2 CSEM transmitters at Scripps. These instruments have been used for numerous academic studies.



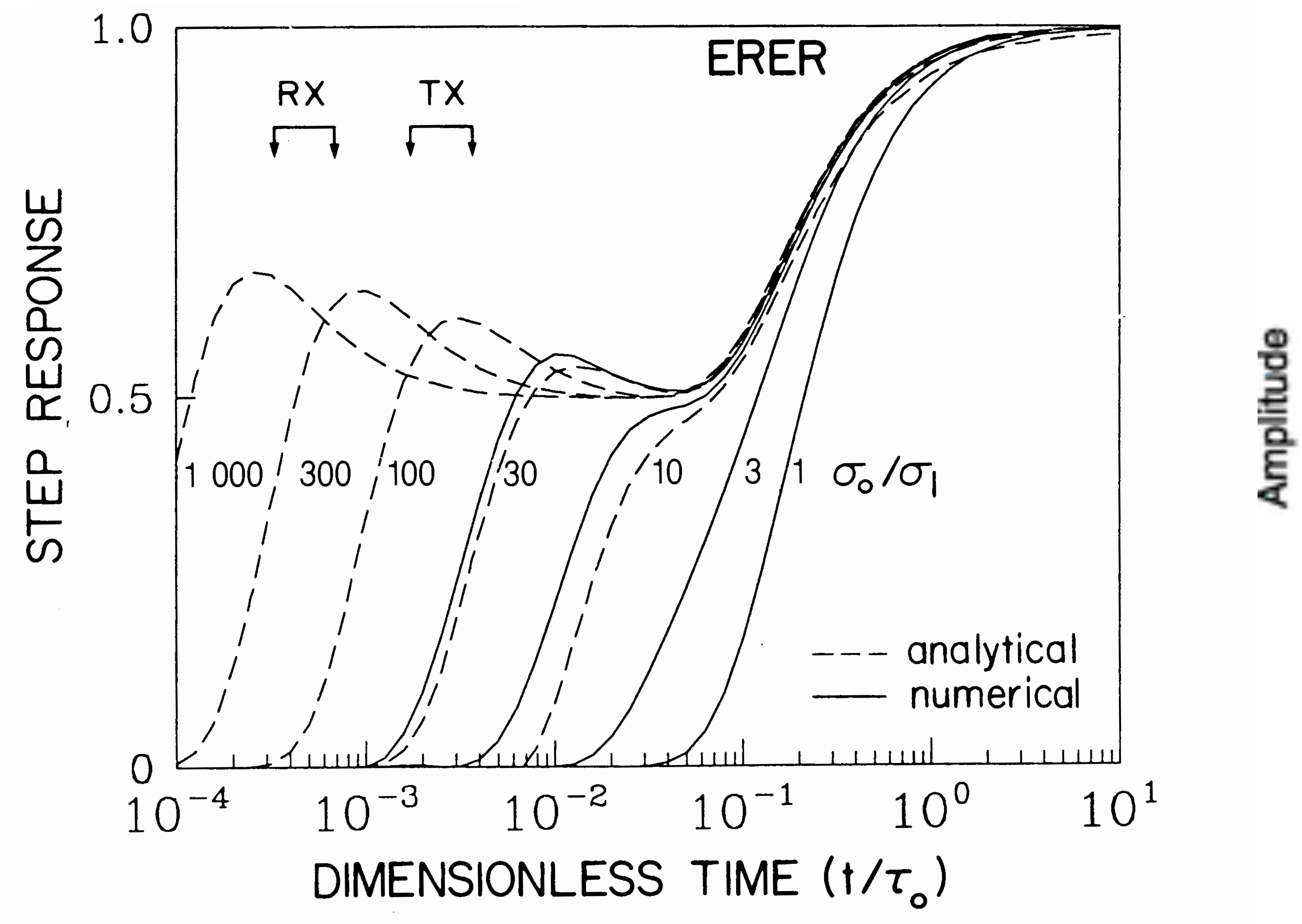
In early 2015 Schlumberger donated its own instrument fleet of 100+ receivers to Scripps.

What’s different about marine EM?

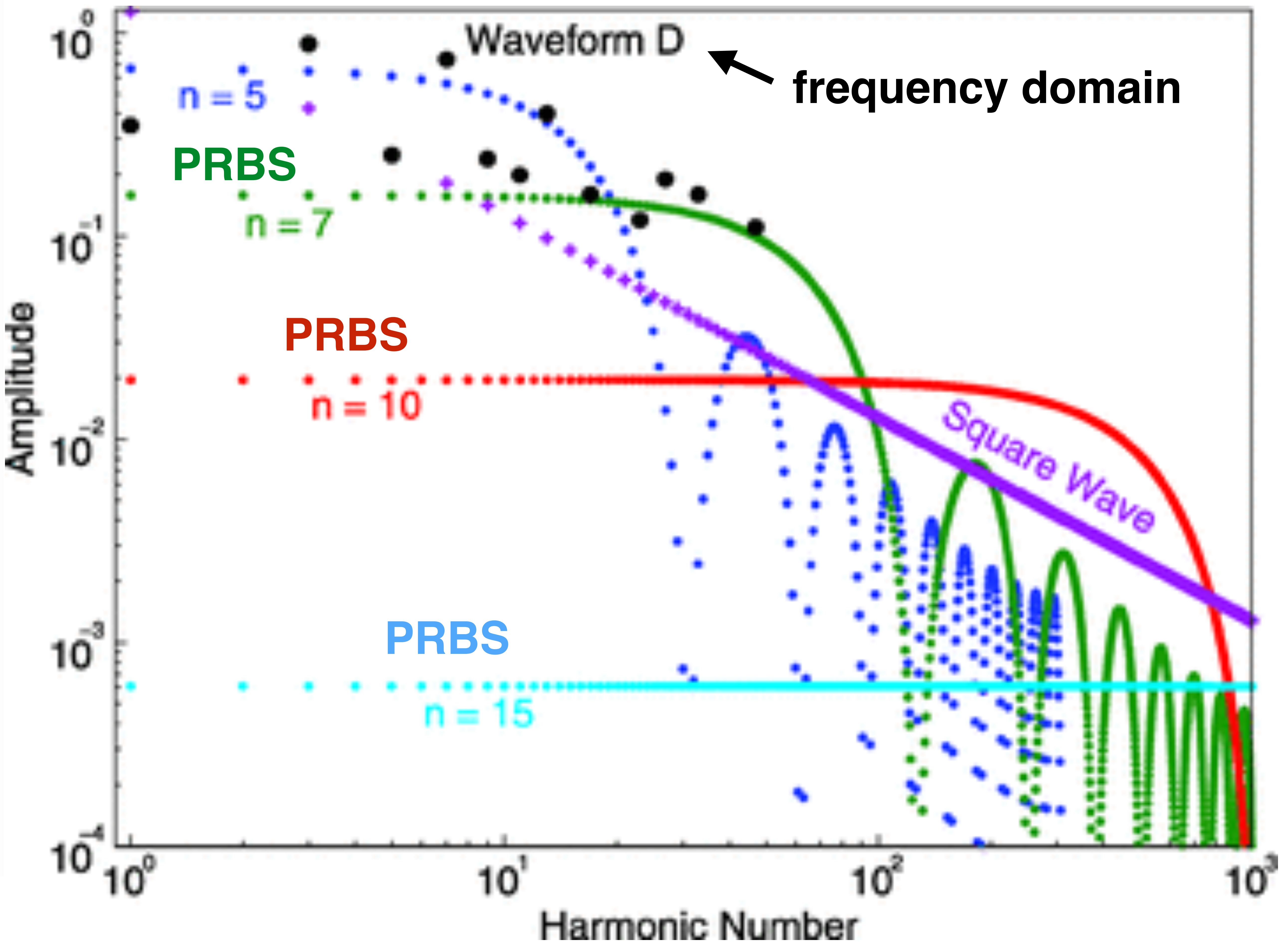
Marine CSEM:

Transmitters, and receivers, can be continuously towed.
Vertical electric fields can be measured.
High conductivity of seawater favors E-field sources and receivers.

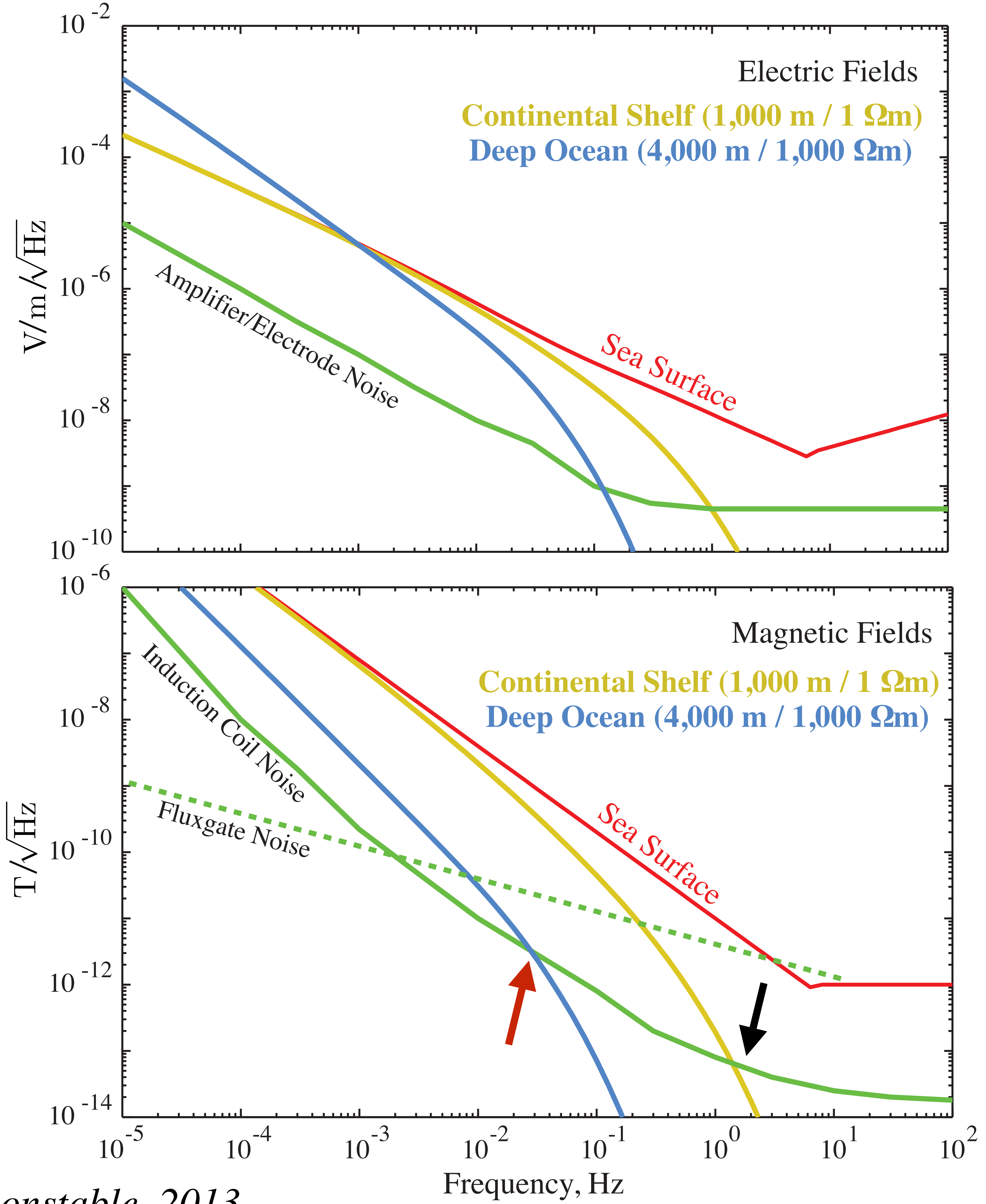
Time domain is less useful than on land. In deep water, seafloor conductivity is manifest in early time and the late time asymptotes to the DC seawater response. In shallow water, the need to have off times of 10's seconds means that stacking times have to be much longer than for frequency domain measurements. Time domain spreads energy across the spectrum, but more than 2-3 frequencies gives little advantage during inversions.



Cheesman et al., 1987



Connell and Key, 2013



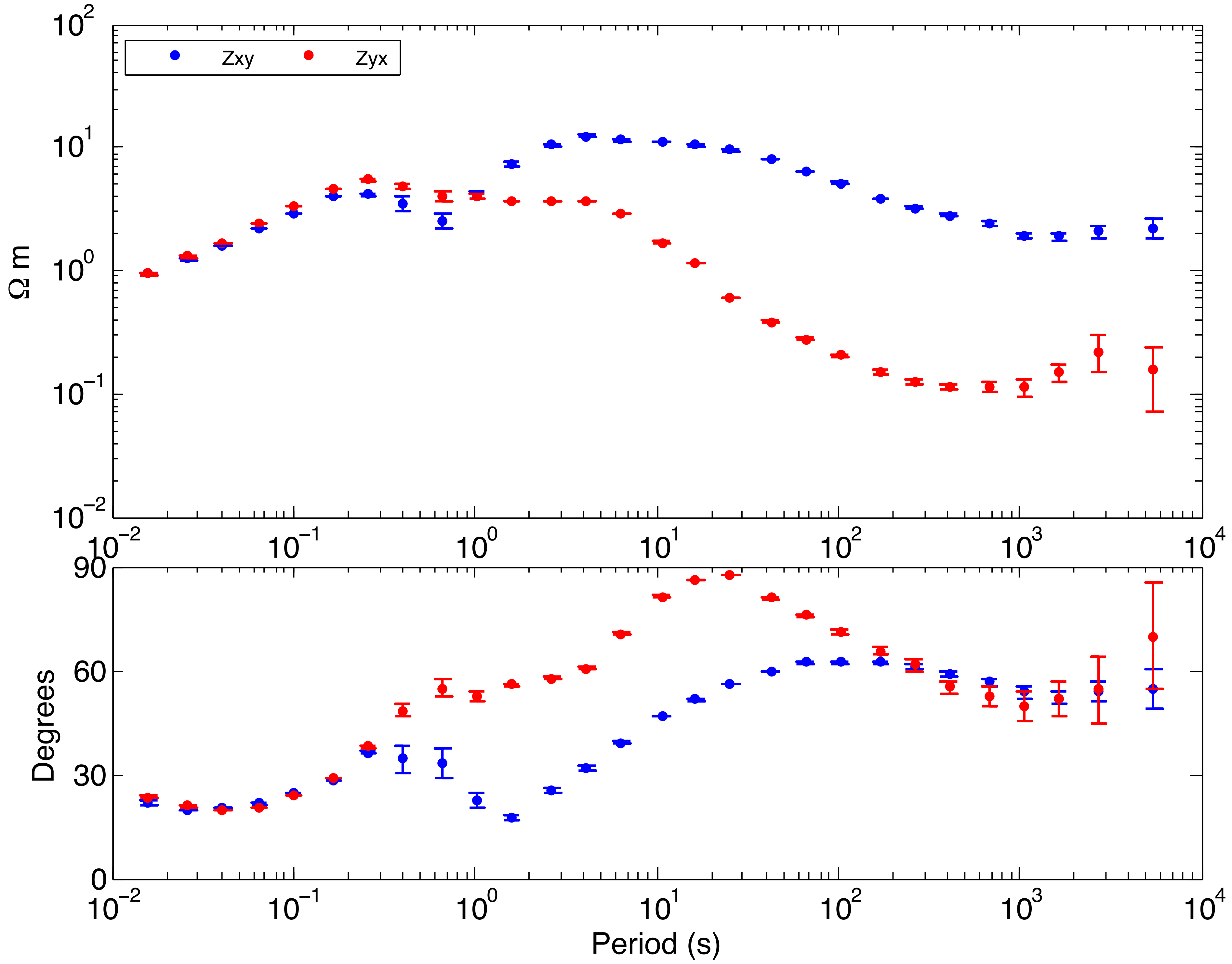
Constable, 2013

Marine MT:

Loss of high frequency signal:

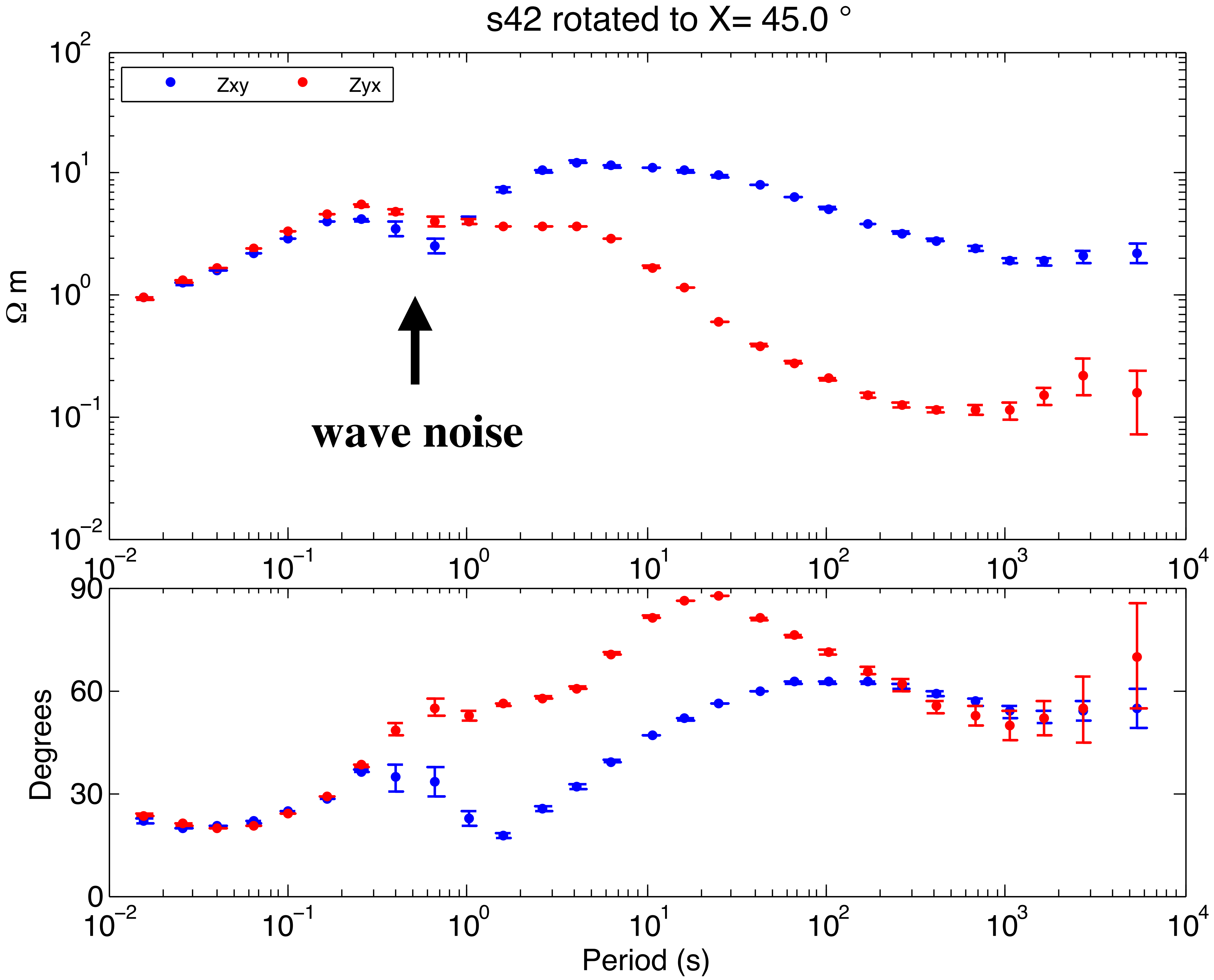
↓ Sensor noise is reached at about 1 s on the continental shelves.

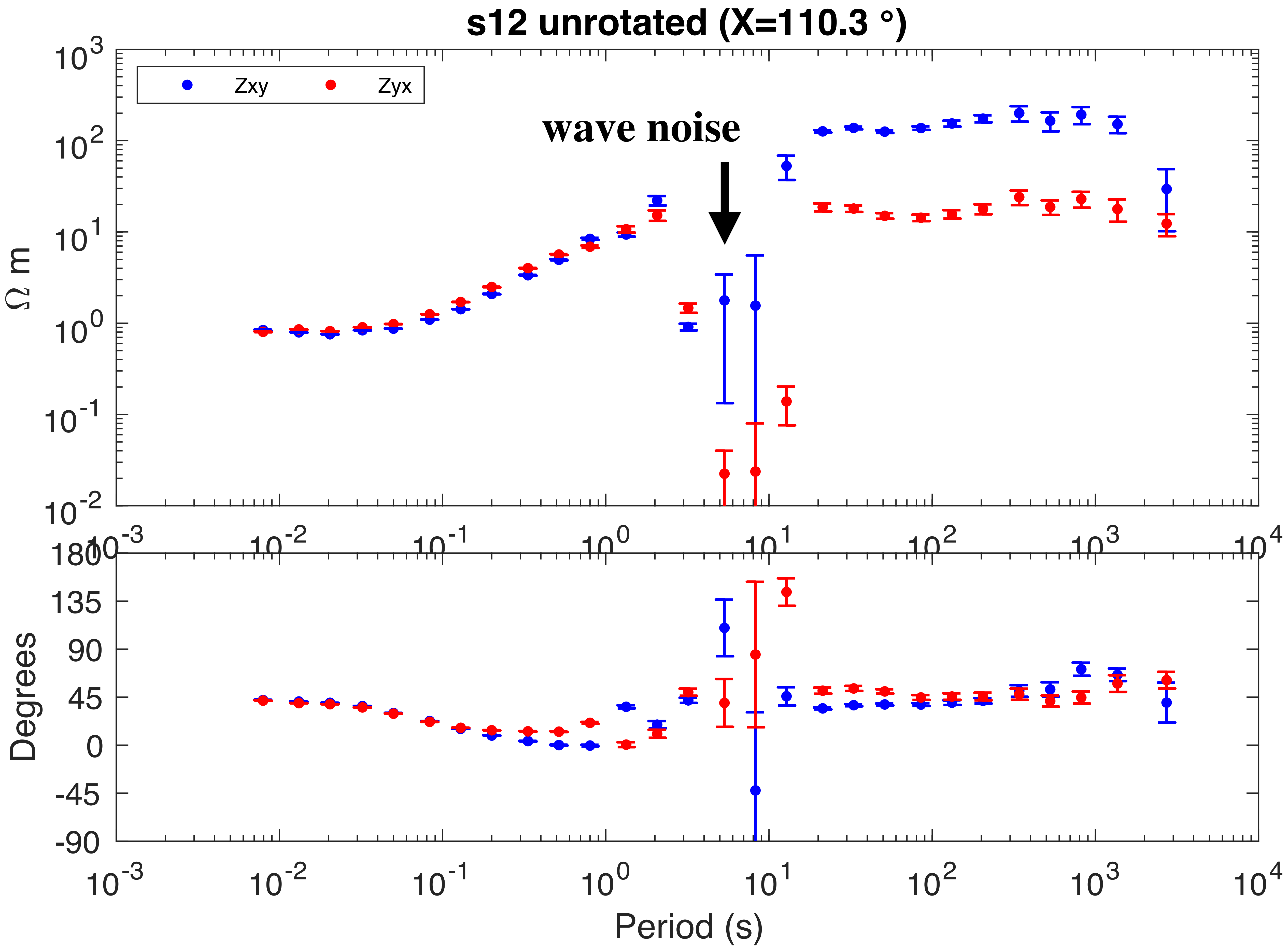
↗ In the deep ocean this noise limit is at 30 s.



MT responses to 100 Hz in shallow water

Wave noise in shallow water (water movement in Earth's magnetic field + motion of magnetometers)

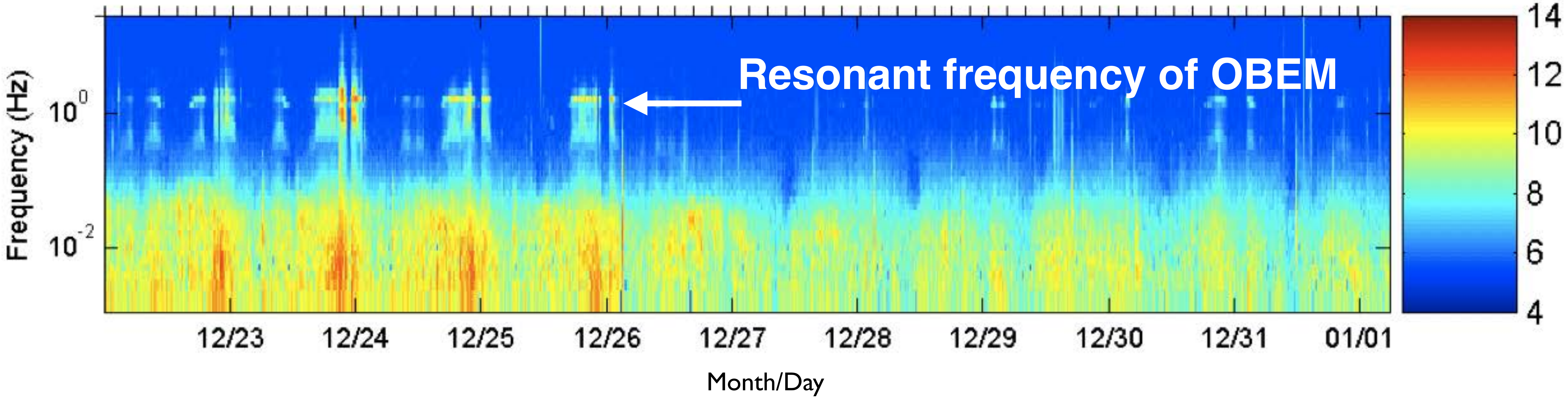




Noise from tidal currents (all water depths) (water movement in Earth's magnetic field + motion of mags)

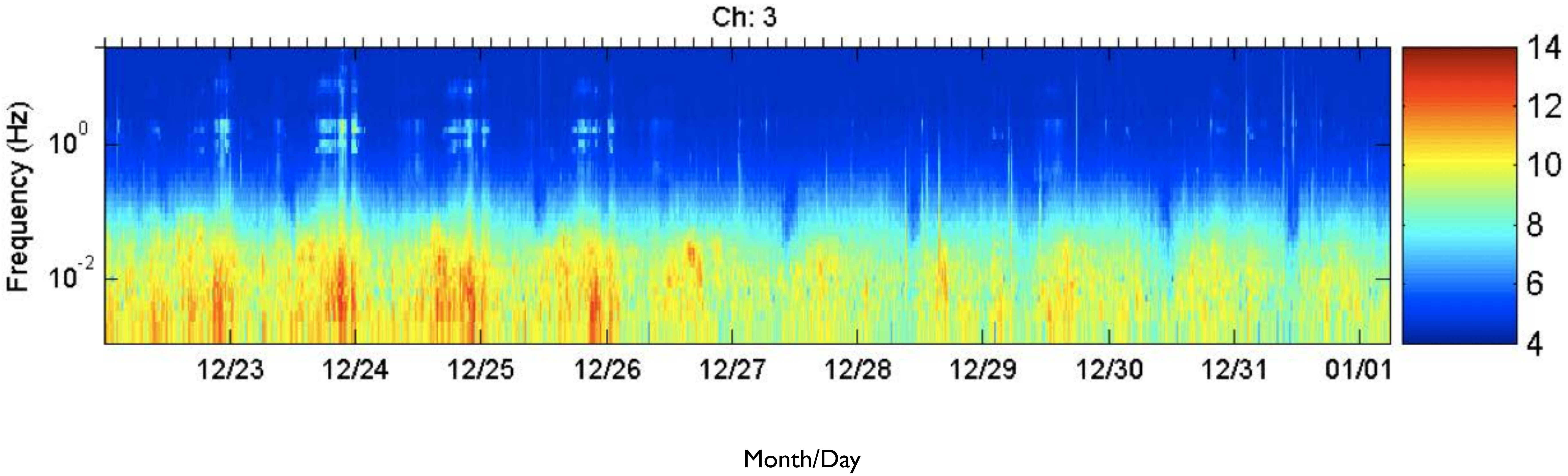
Power Spectrograms

Bx



Resonant frequency of OBEM

Ey



Coast effect: Land-side coast effect is manifest as a strengthening of the vertical magnetic field near the coastlines, observed by Dudley Parkinson. For a 2D coastline this is essentially a TE mode phenomenon.

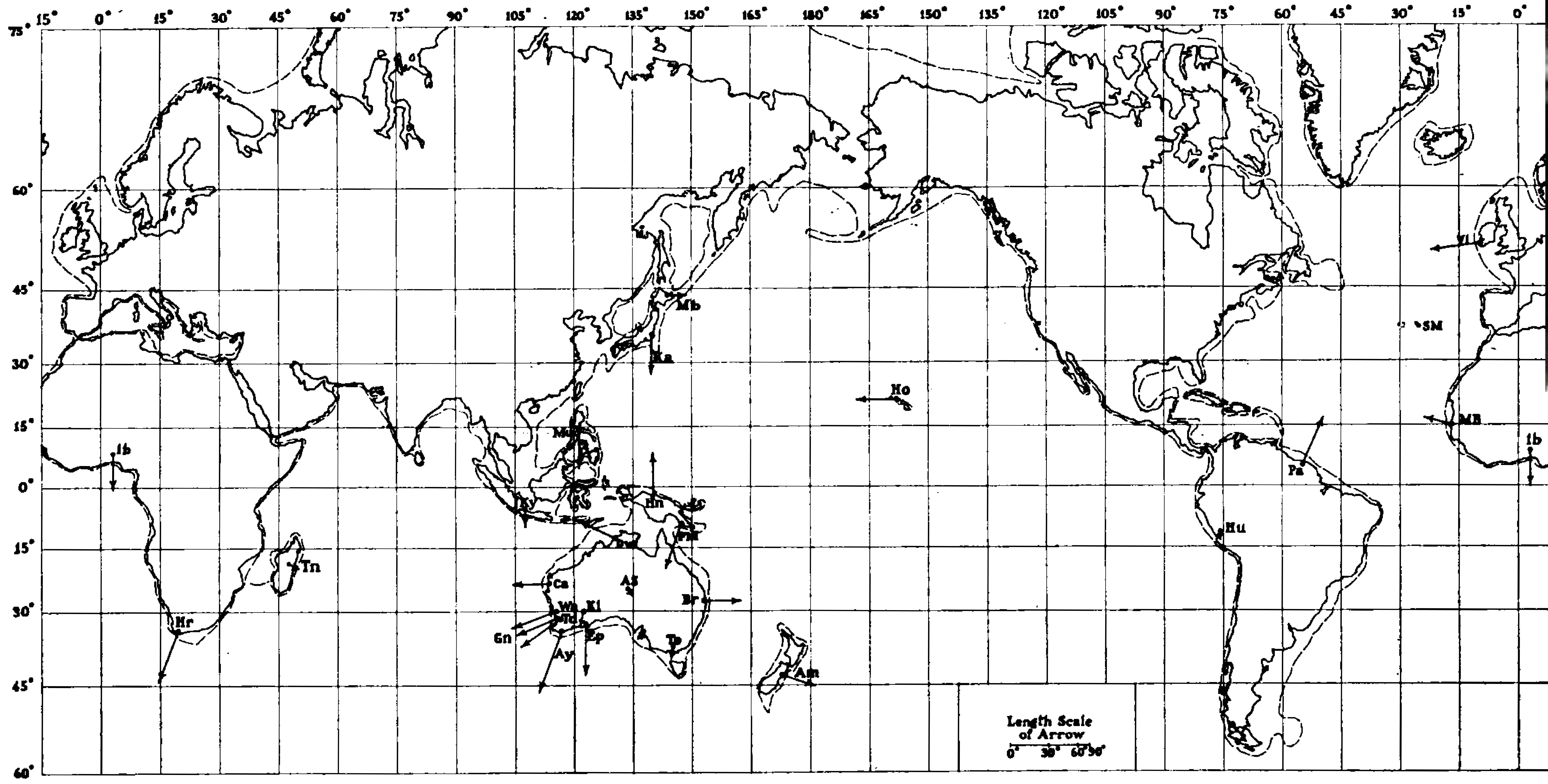
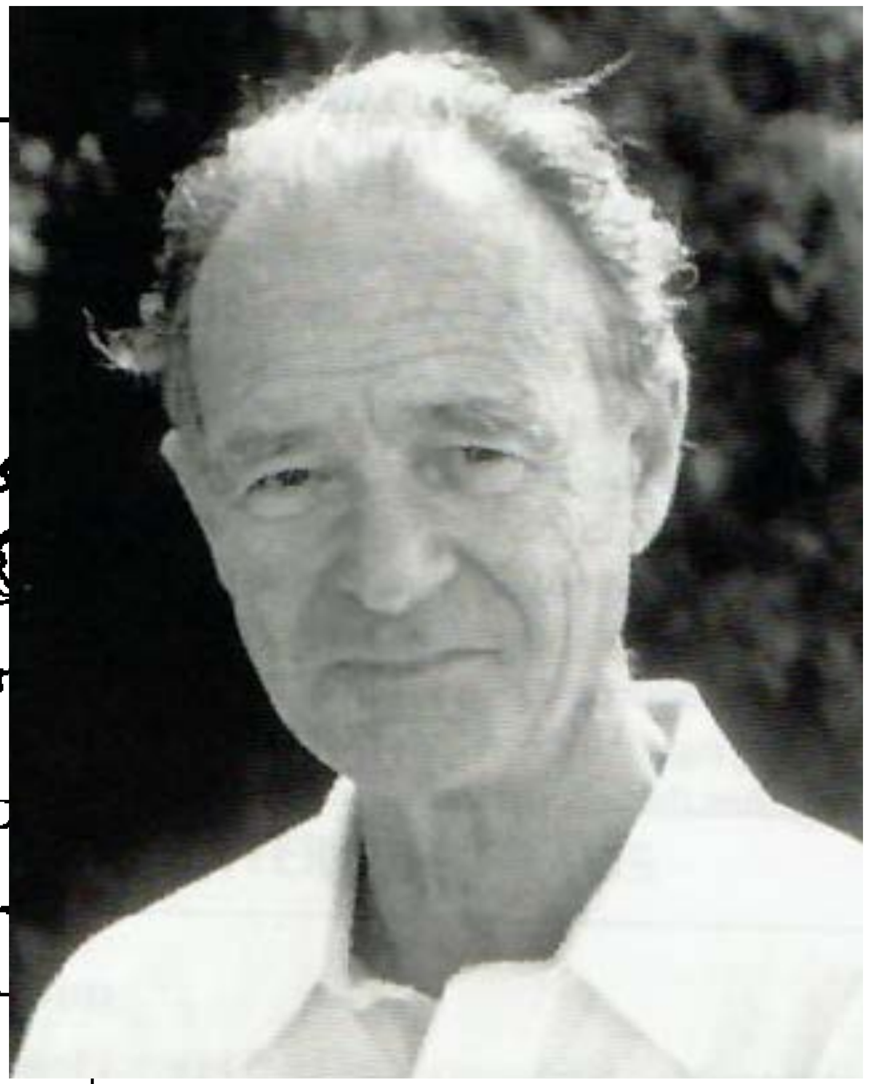
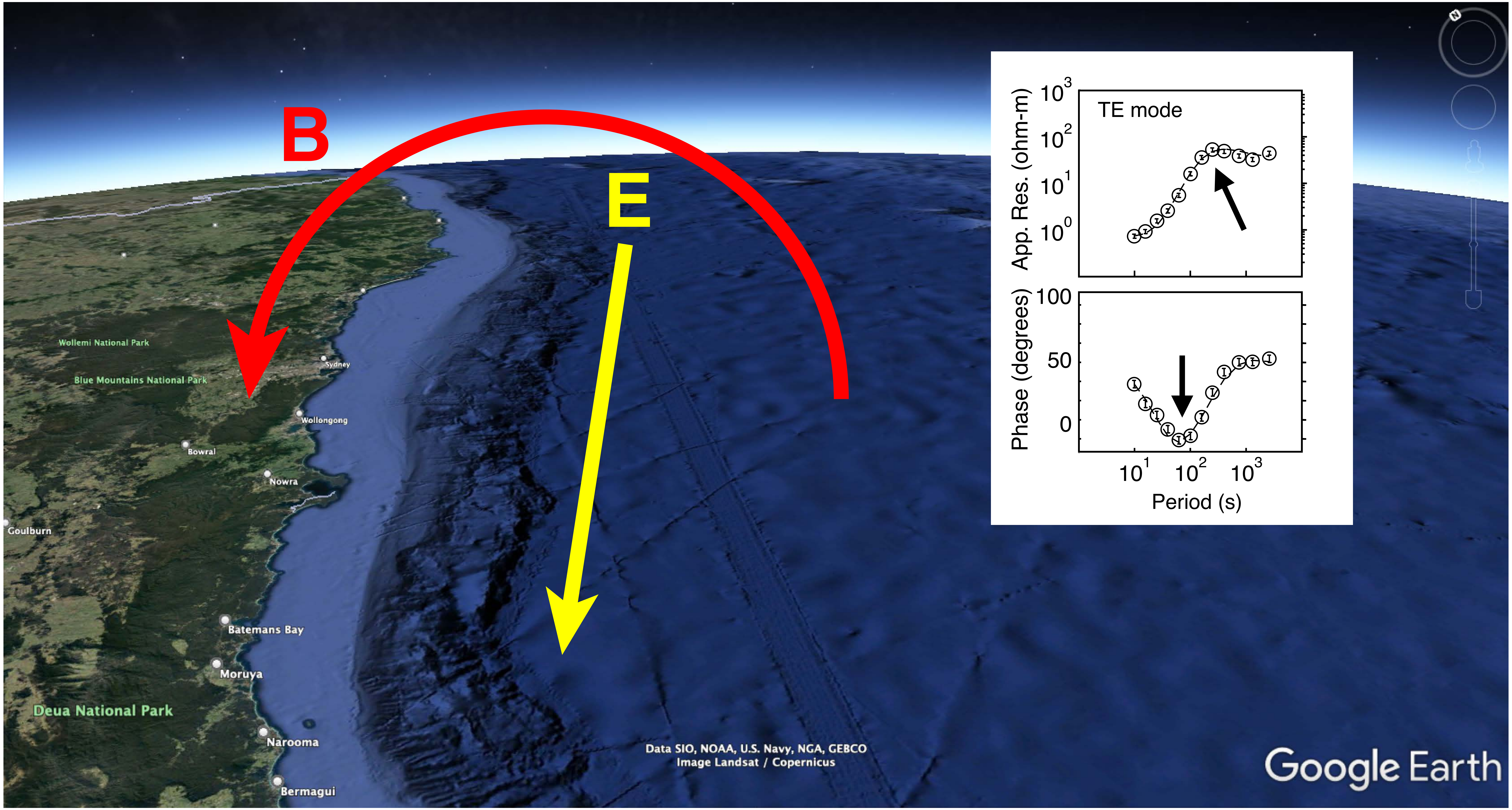


Fig. 2.—Orientations of preferred planes at observatories listed in Table 1. The significance of the arrows is explained in Fig. 3 and the text.



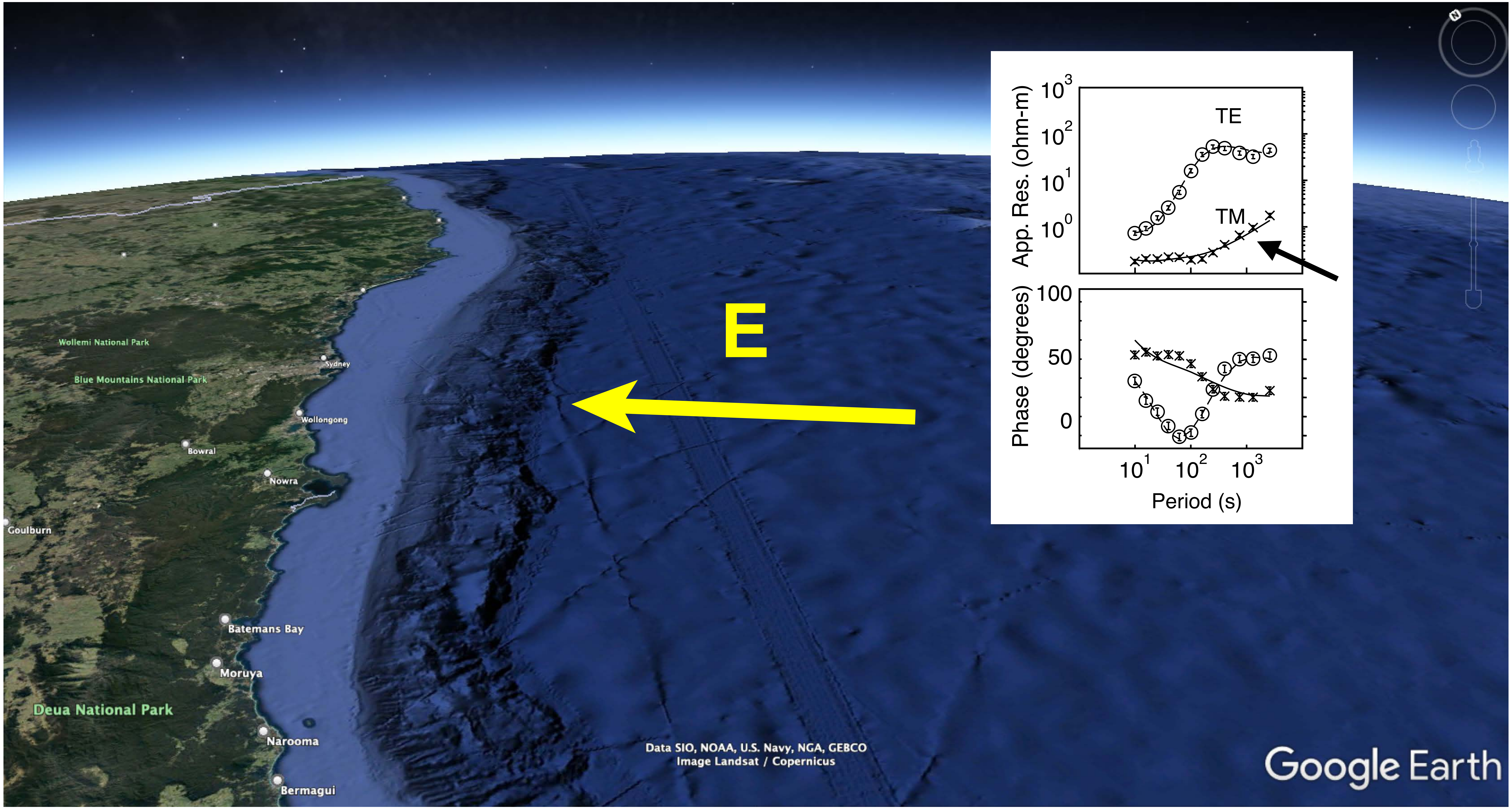
Parkinson, 1962

On the marine side the horizontal magnetic field can actually go to zero, causing cusps in the TE apparent resistivity and negative phases near shore.

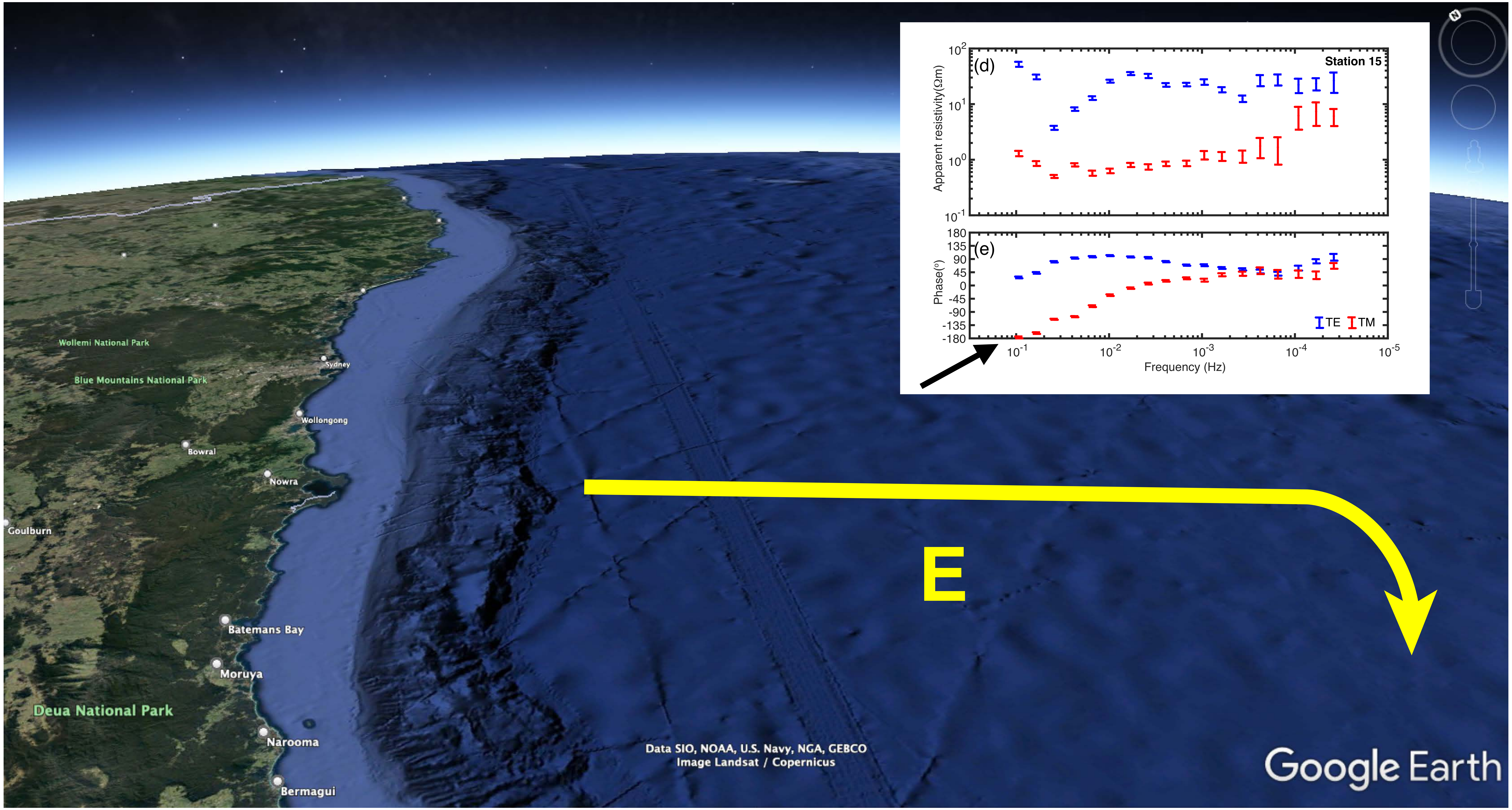


Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus

The classic TM mode coast effect is a galvanic reduction in the electric field, depressing the TM mode resistivities and leaving the phase largely unchanged. This is Cox's boundary zone $d = \sqrt{ST}$



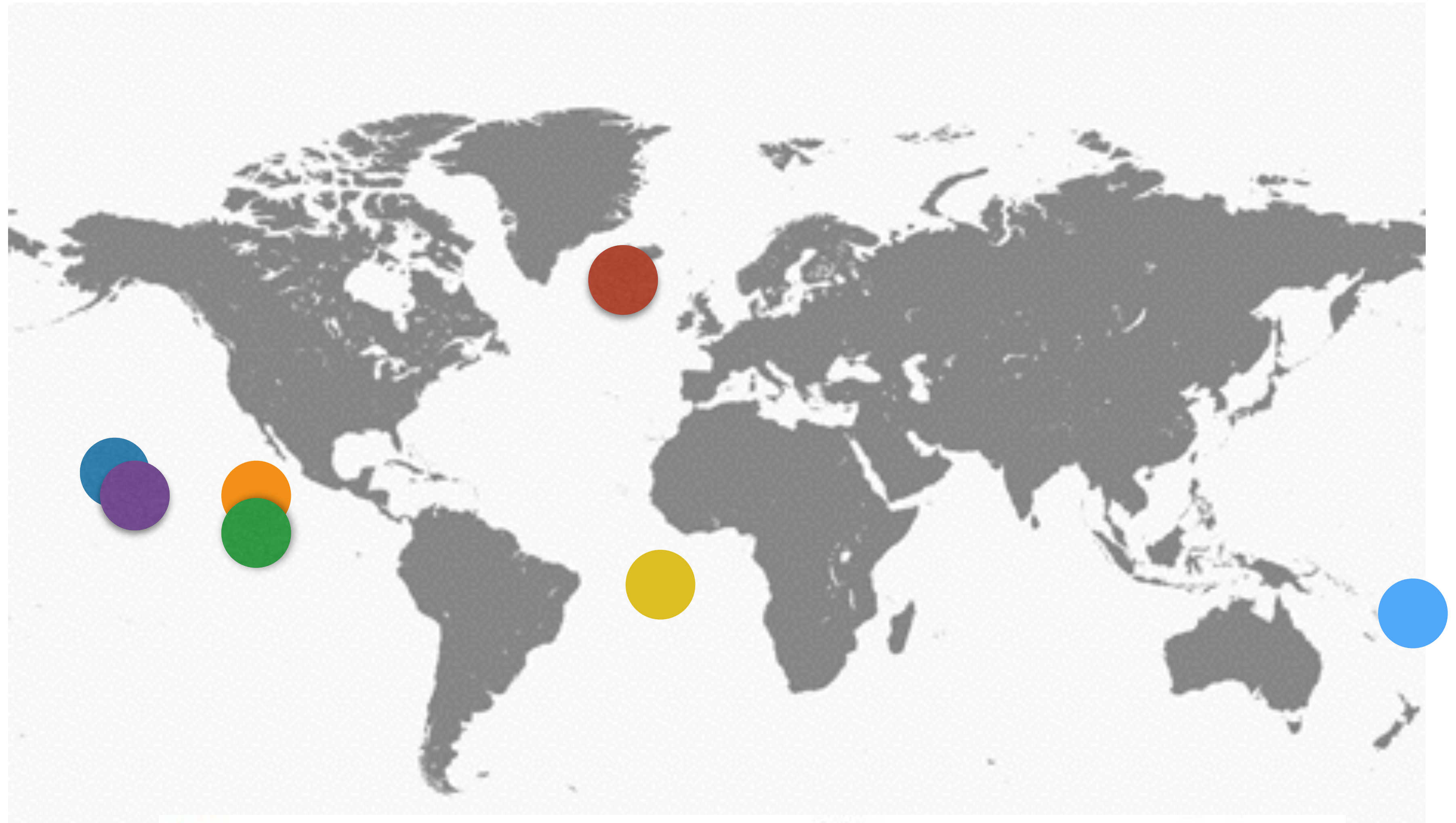
But further offshore the TM mode currents can leak vertically into the conductive upper mantle, generating secondary magnetic fields and negative MT phases at high frequencies.



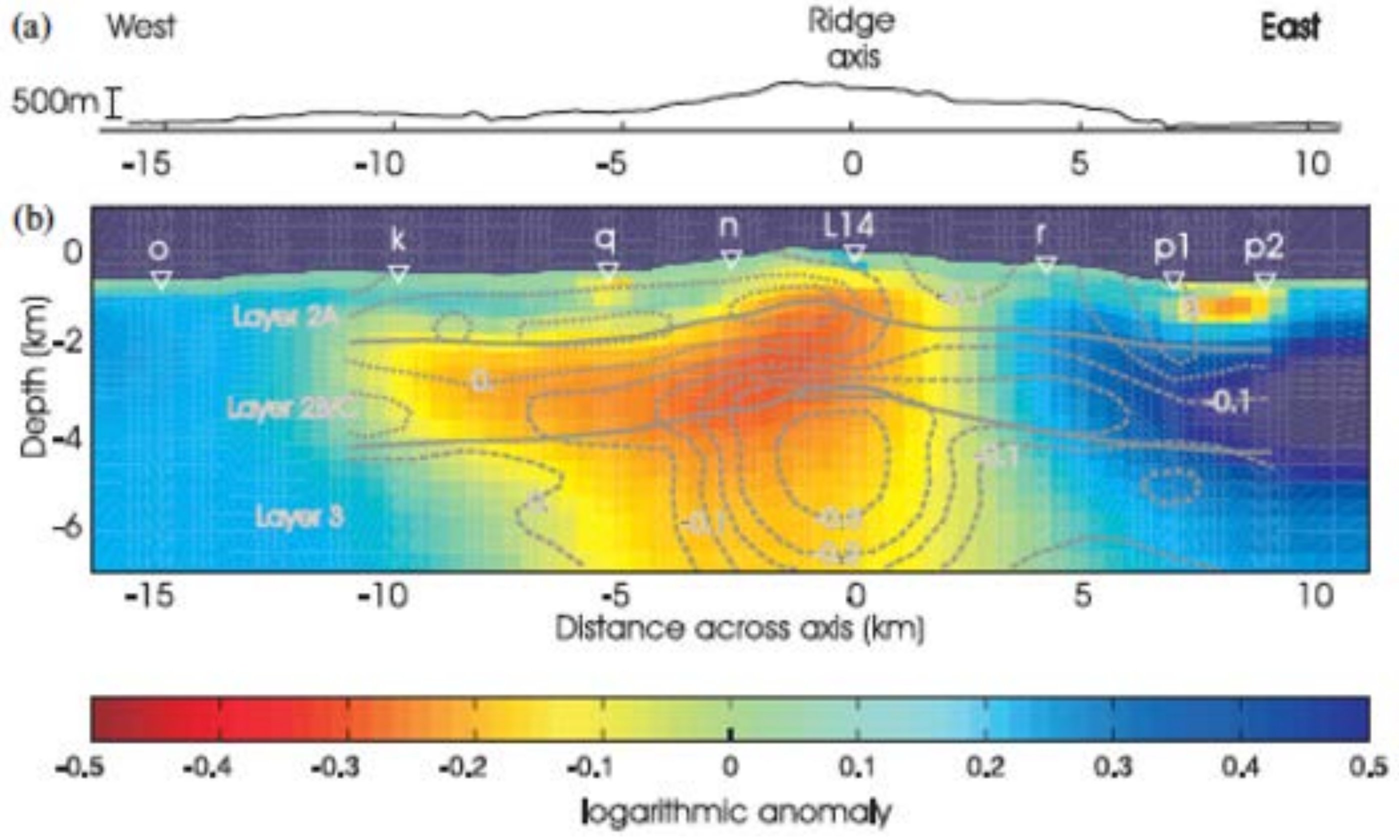
All the things you can do with marine EM:

Hotspots + Ridges:

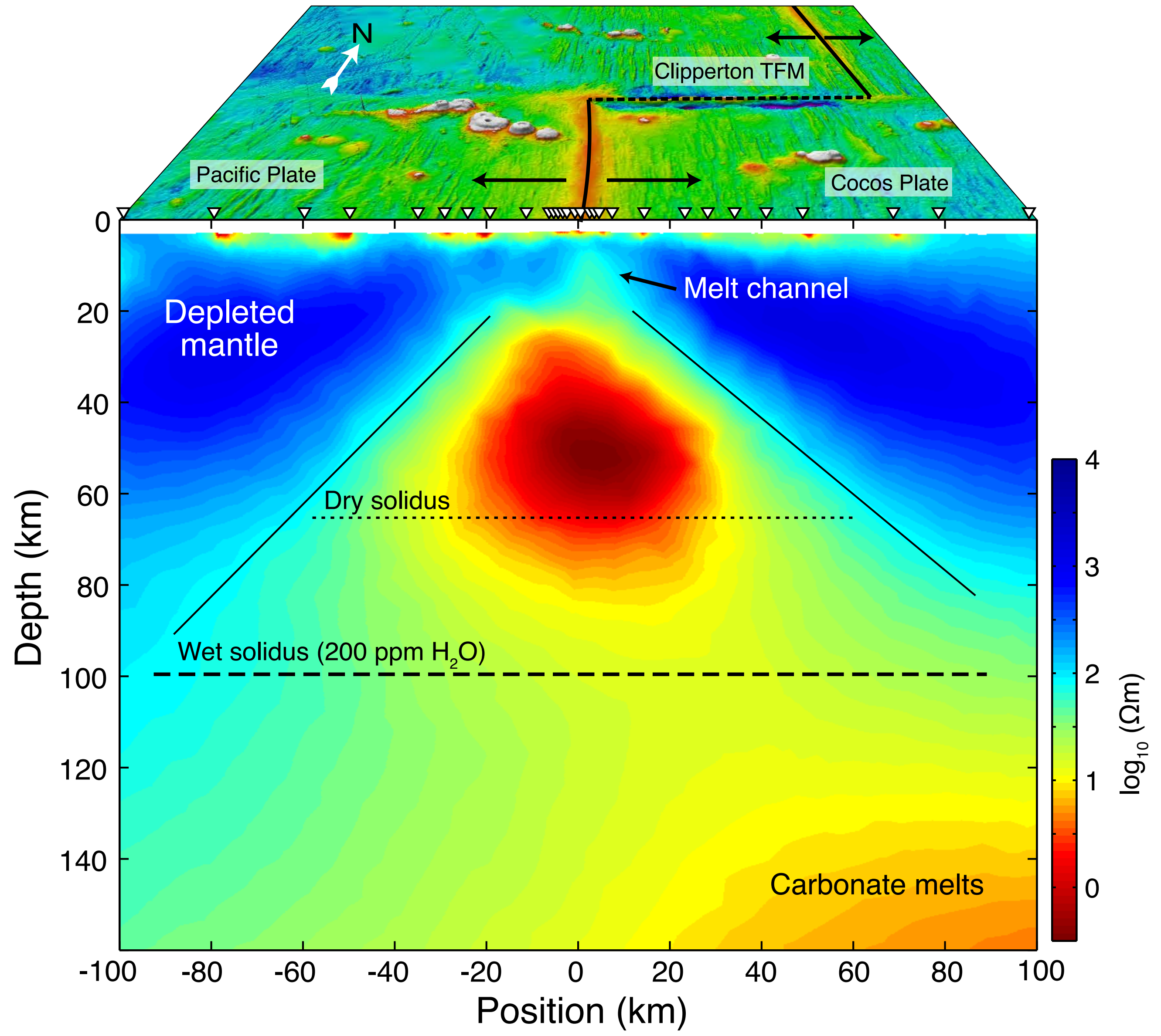
- ● 1989: CSEM at East Pacific Rise 13 N
- ● 1993: MT + CSEM Reykjanes Ridge (RAMESSES)
- ● 1995: Lau Basin CSEM
- ● 1997: MT off Hawaii (SWELL)
- ● 2000/2004: MT + CSEM East Pacific Rise at 9 N
- ● 2006: CSEM Loihi Seamount
- ● 2016: MT Mid-Atlantic Ridge (CalLAB/PiLAB)



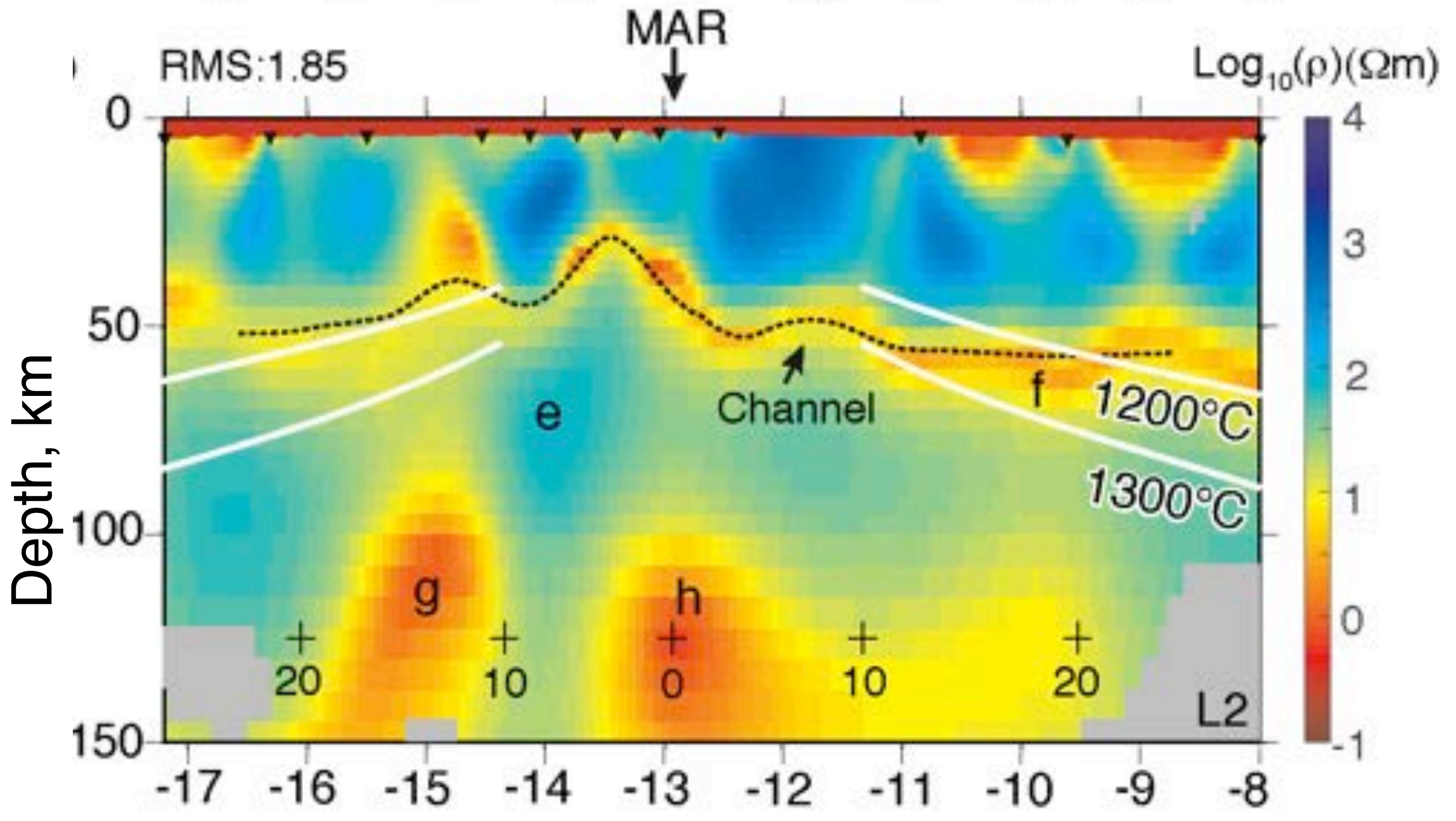
MacGregor et al., 2001

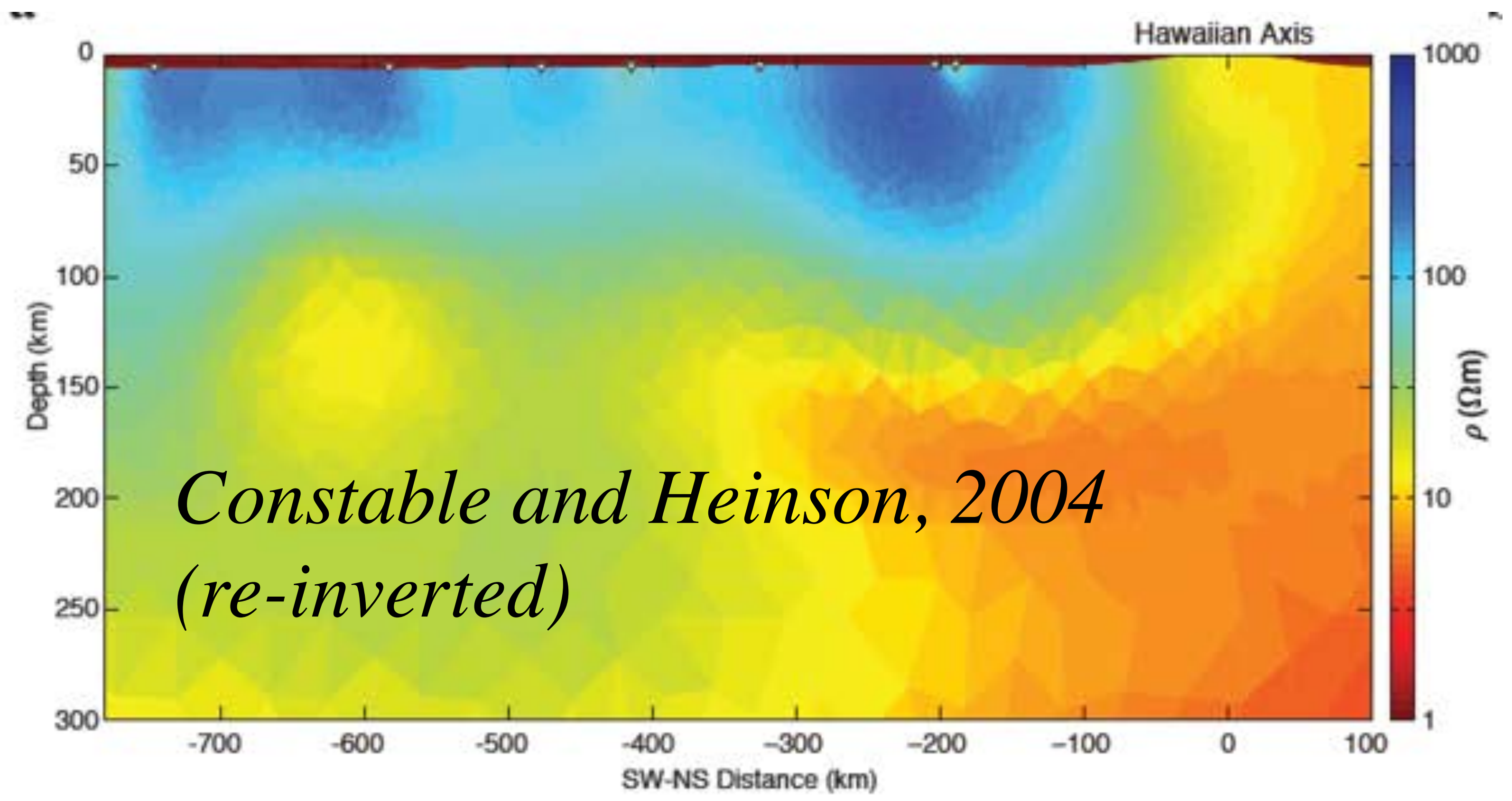


Key et al., 2013



Wang et al., 2020

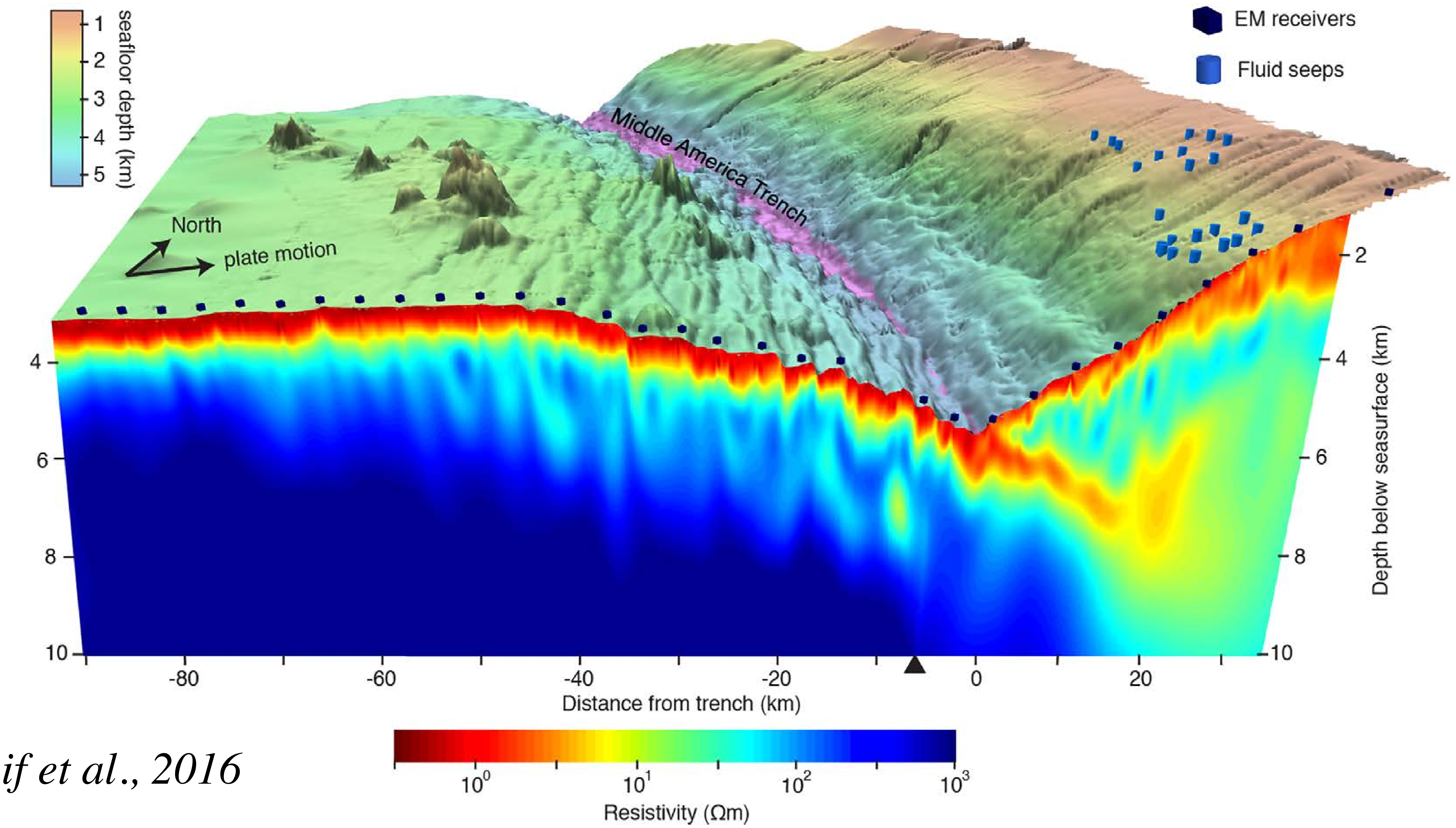




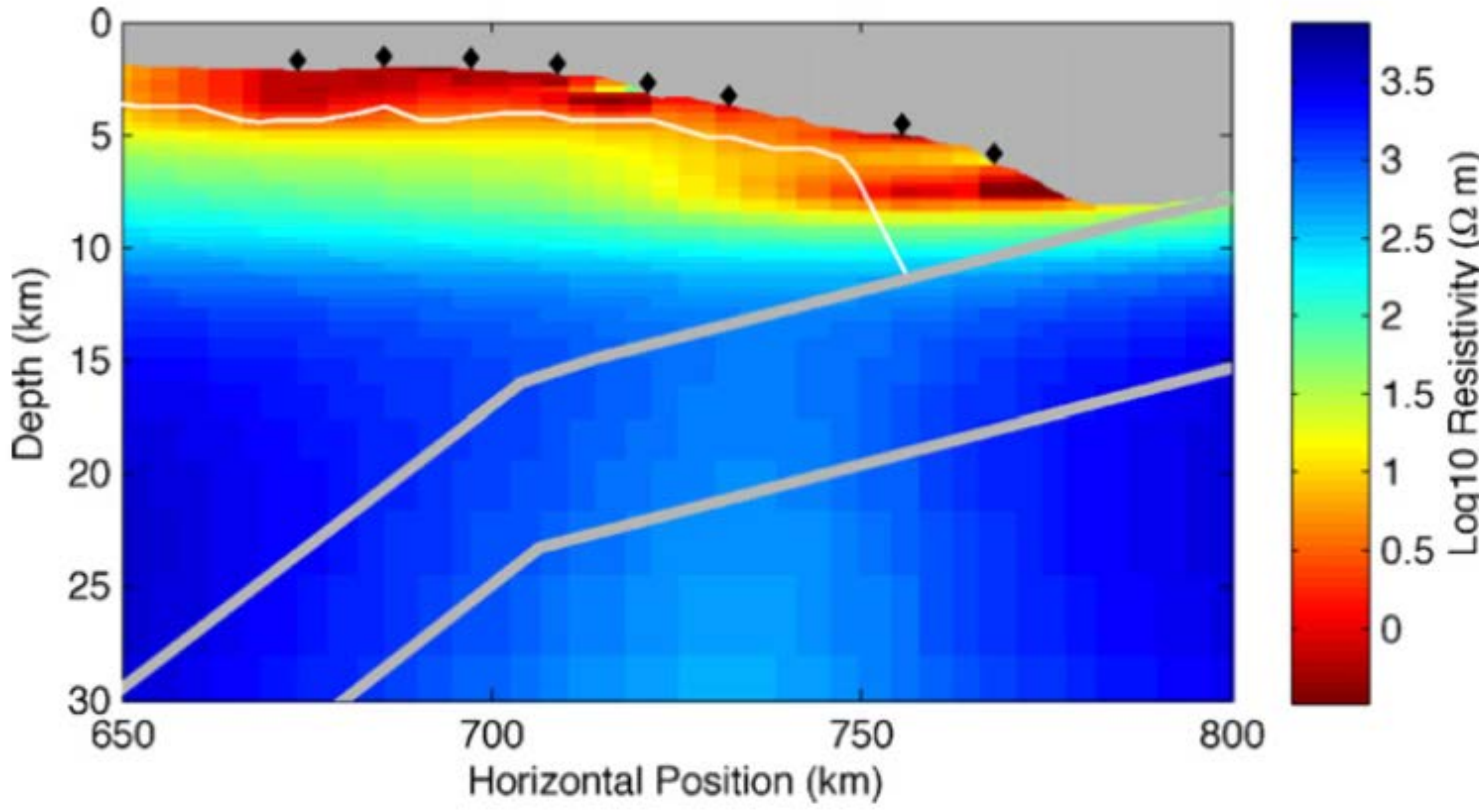
Constable and Heinson, 2004 (re-inverted)

Convergent Margins:

- ● 2000: MT off northeastern Japan
- ● 2010: MT + CSEM offshore Nicaragua (SERPENT)
- ● 2015: MT + seismics Aleutian arc/Okmok volcano
- ● 2018: MT + CSEM Hikurangi (HT-RESIST)
- ● 2019: MT + CSEM Alaska Peninsula (EMAGE)



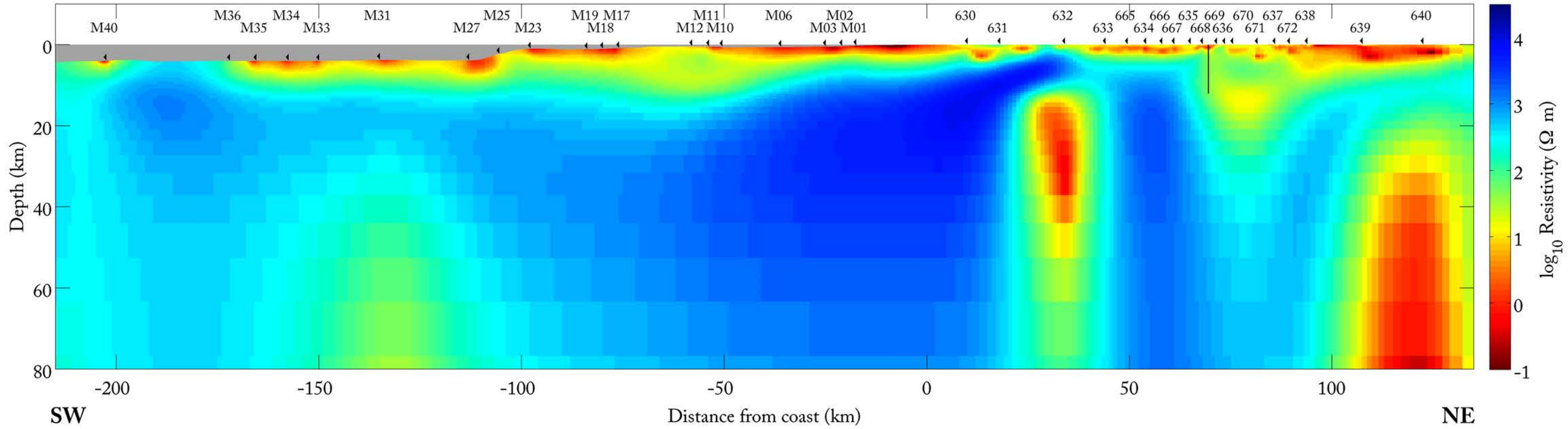
Naif et al., 2016



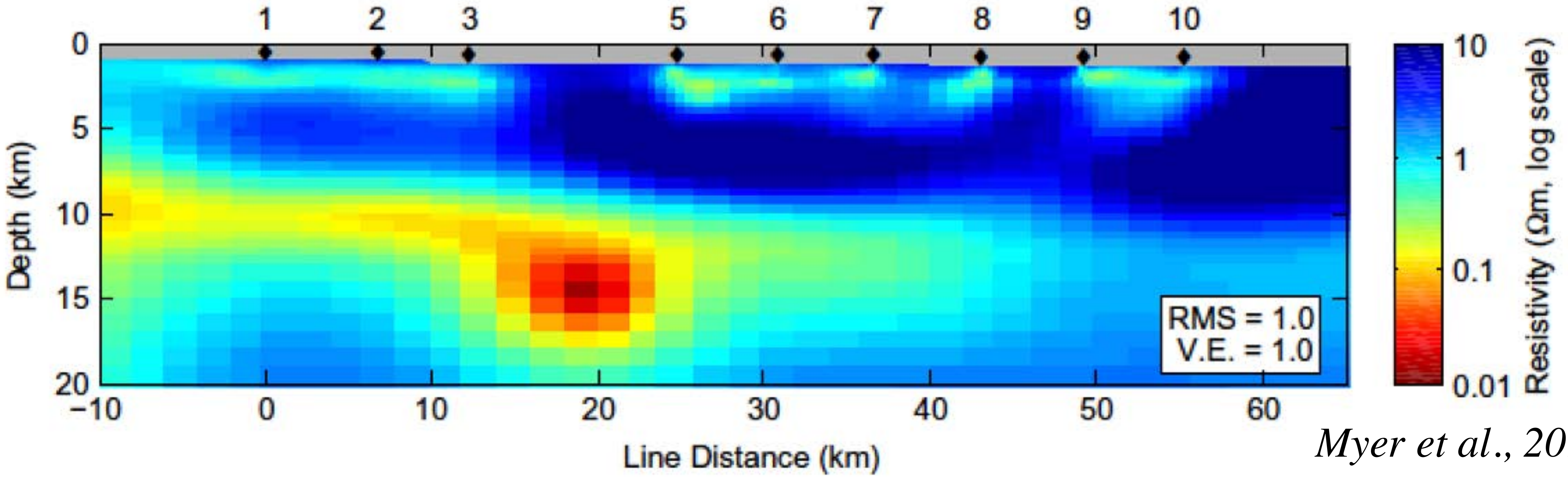
Key and Constable, 2010

Passive Margins:

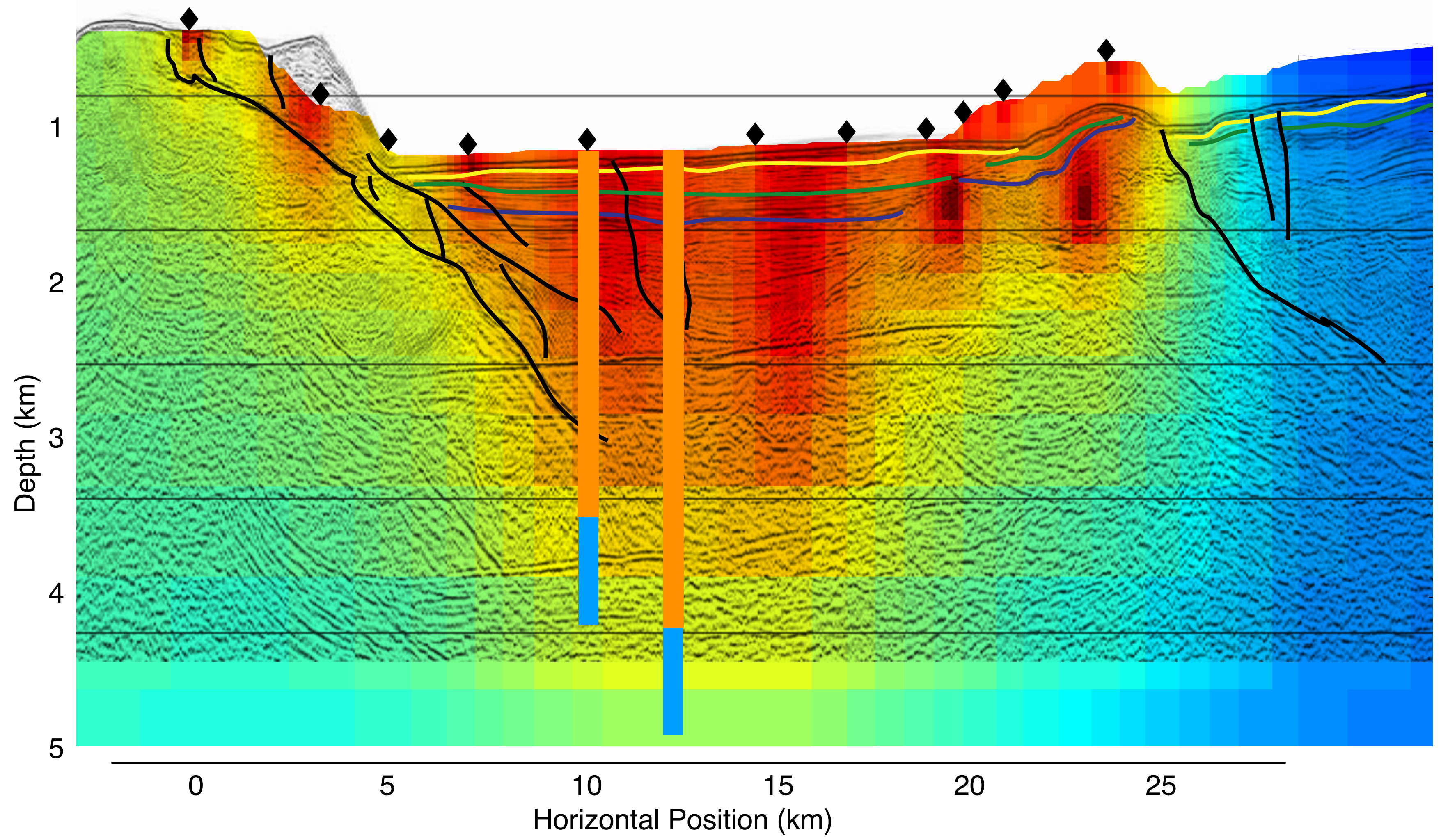
- 🟡 2003/4: MT and CSEM in San Diego Trough
- 🔴 2008/9: MT + CSEM offshore Morro Bay
- 🟣 2010: MT Voring Plateau
- 🔵 2014: MT off Cascadia (MOCHA)
- 🟢 2021: MT in Spencer Gulf



Wheelock, 2012



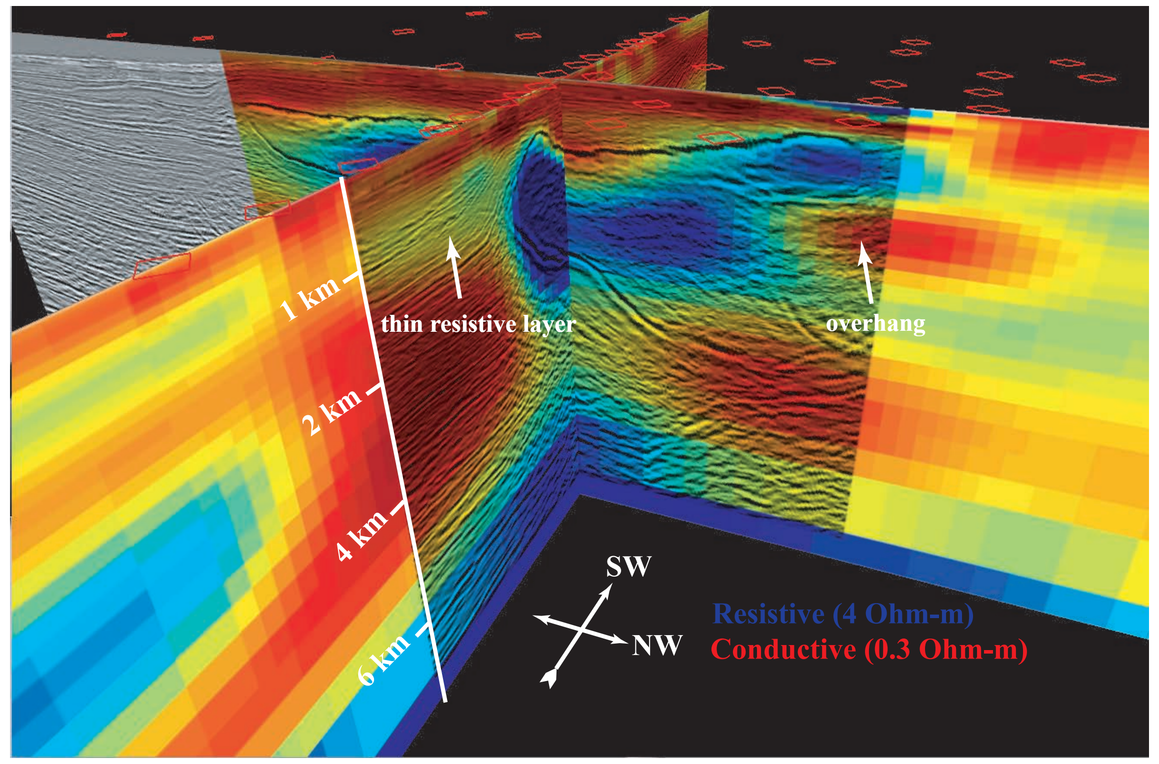
Myer et al., 2013



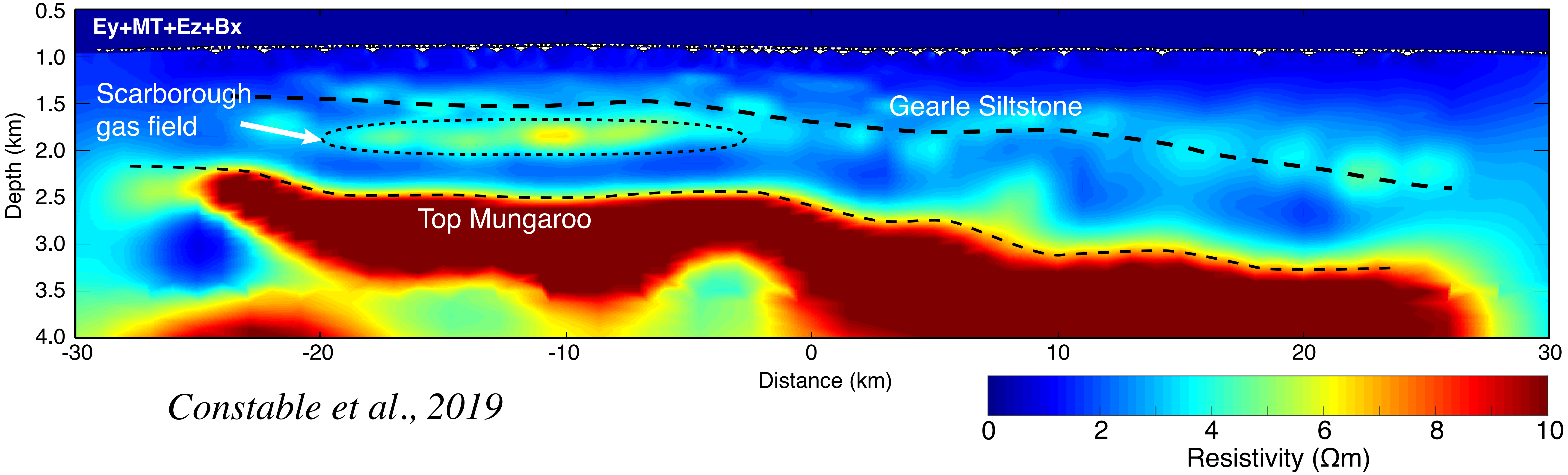
Constable et al., 2009

Resource Exploration:

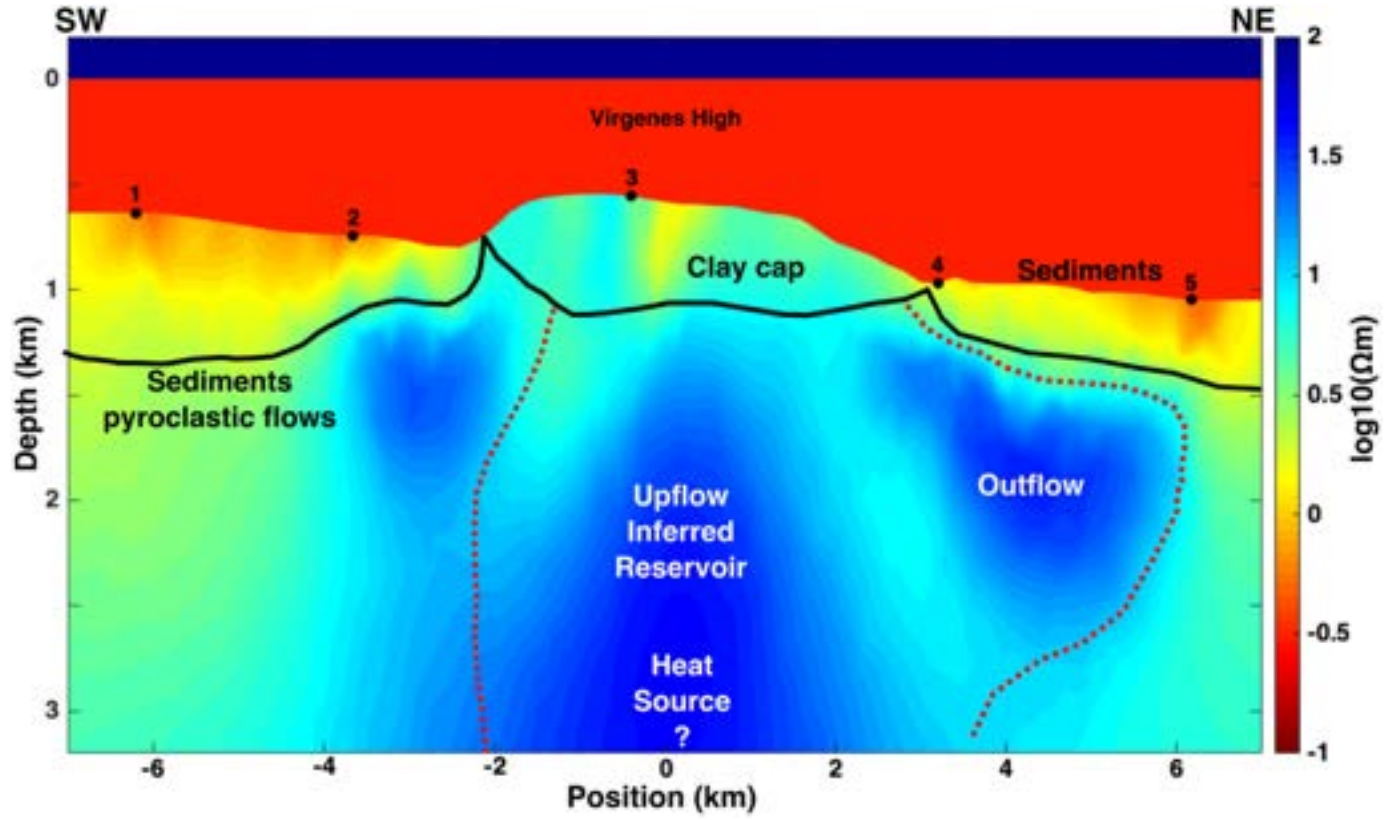
- 🔵 1997-2003: Gemini MT
- 🟠 2000: CSEM Girassol, Angola
- 🔴 2009: Scarborough MT + CSEM
- 🔵 2014: Uruguay MT + CSEM
- 🟢 2015/16: MT + CSEM + Seismics Gulf of California (geothermal)
- 🟡 2019: CSEM Santa Barbara tar seeps



Key, 2003



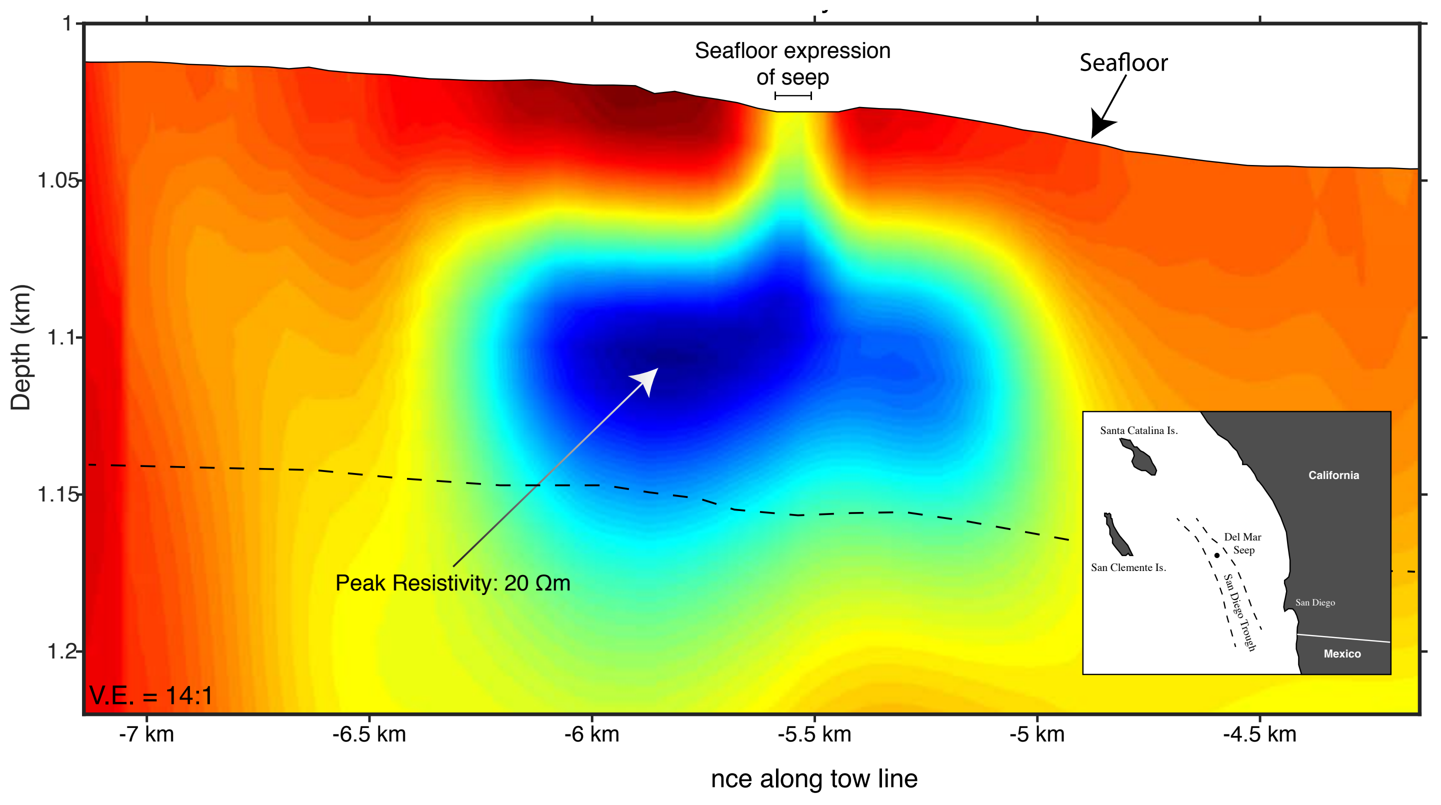
Constable et al., 2019



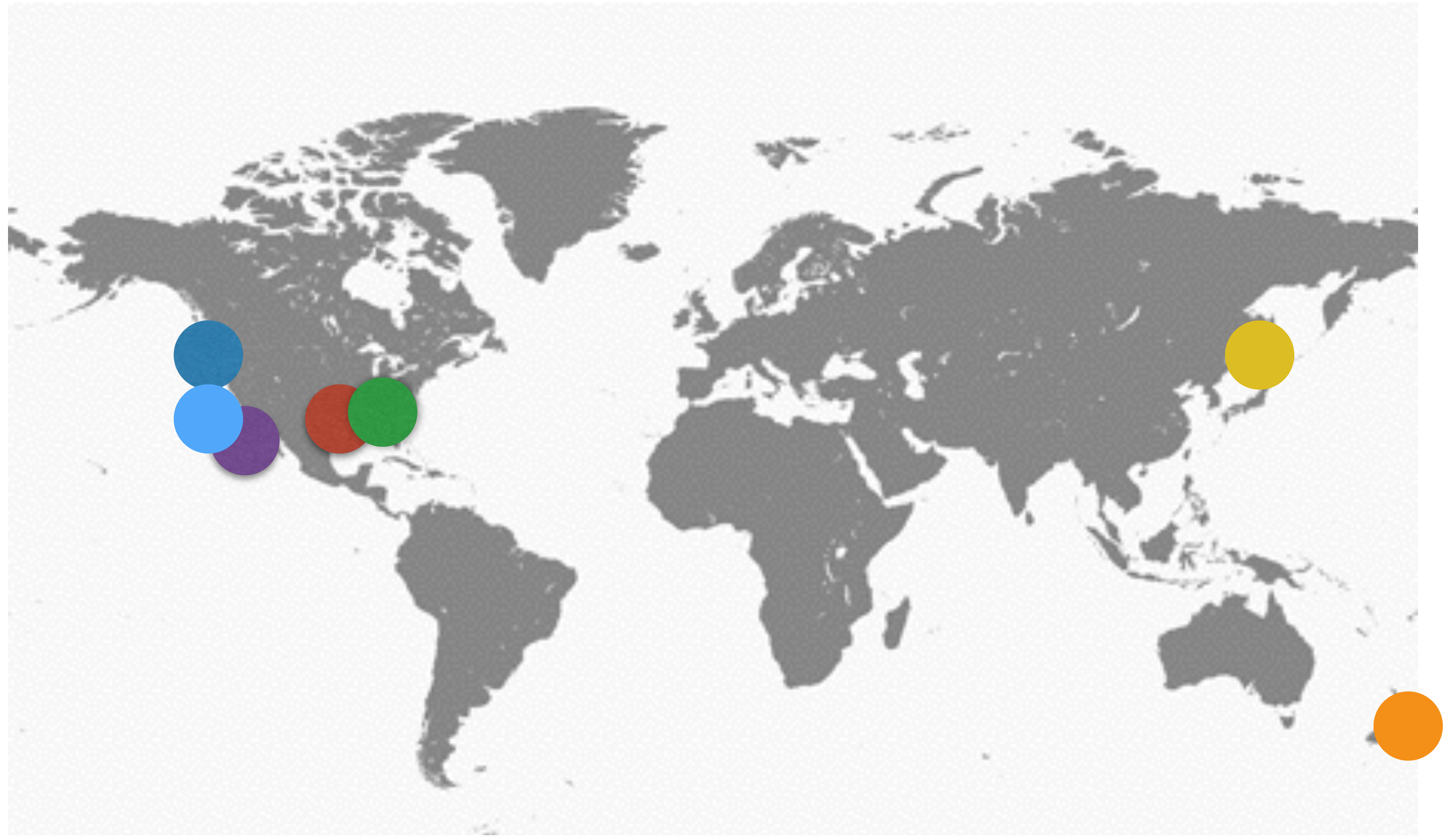
Córdoba-Ramírez et al., 2019

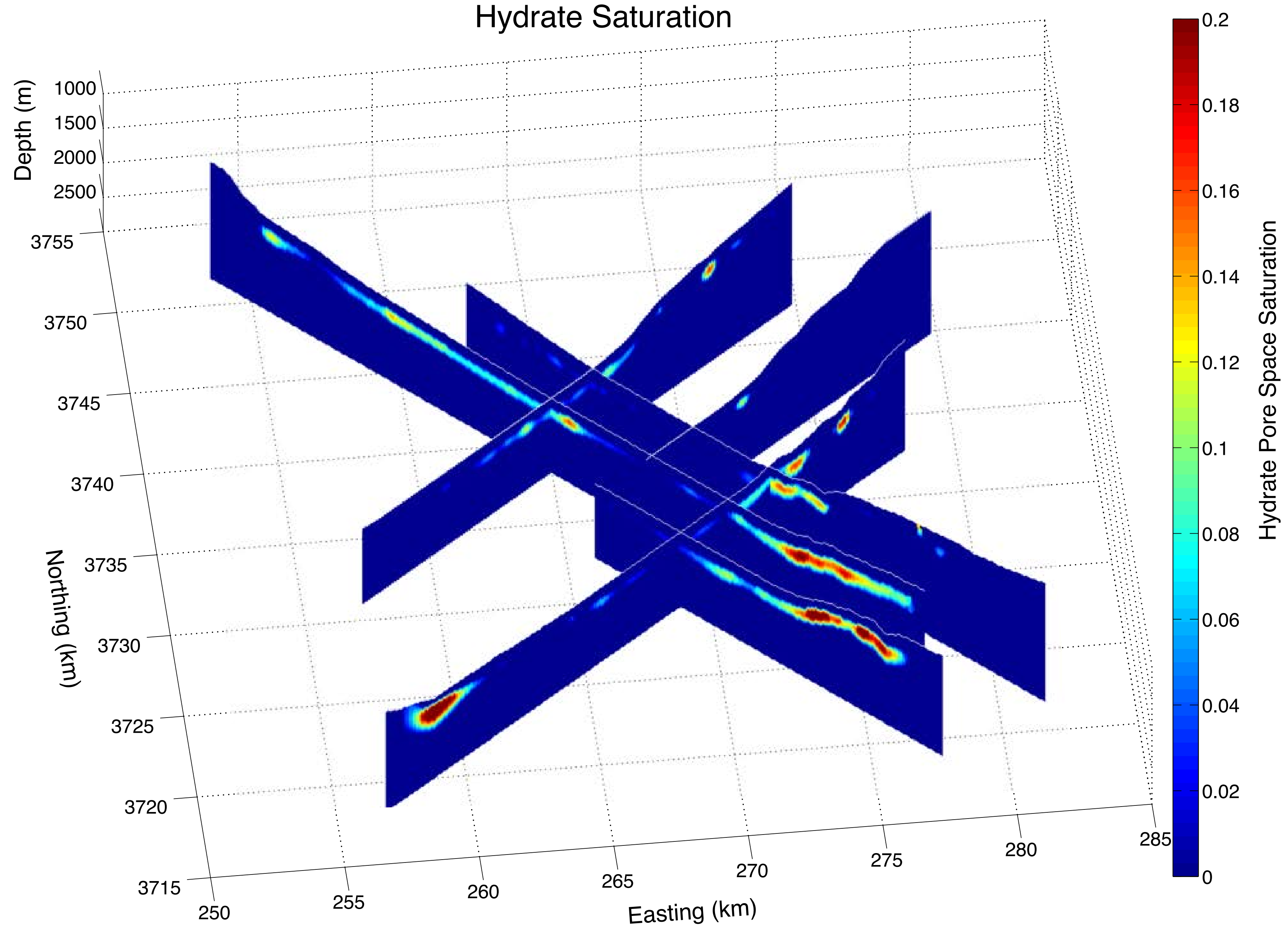
Gas Hydrates:

- ● 2004: CSEM at Hydrate Ridge
- ● 2008: CSEM Gulf of Mexico I
- ● 2014: CSEM Santa Cruz Basin
- ● 2017: CSEM Gulf of Mexico II
- ● 2016: CSEM + SP Del Mar Seep
- ● 2014-2016: CSEM Japan
- ● 2020: CSEM Pegasus Basin

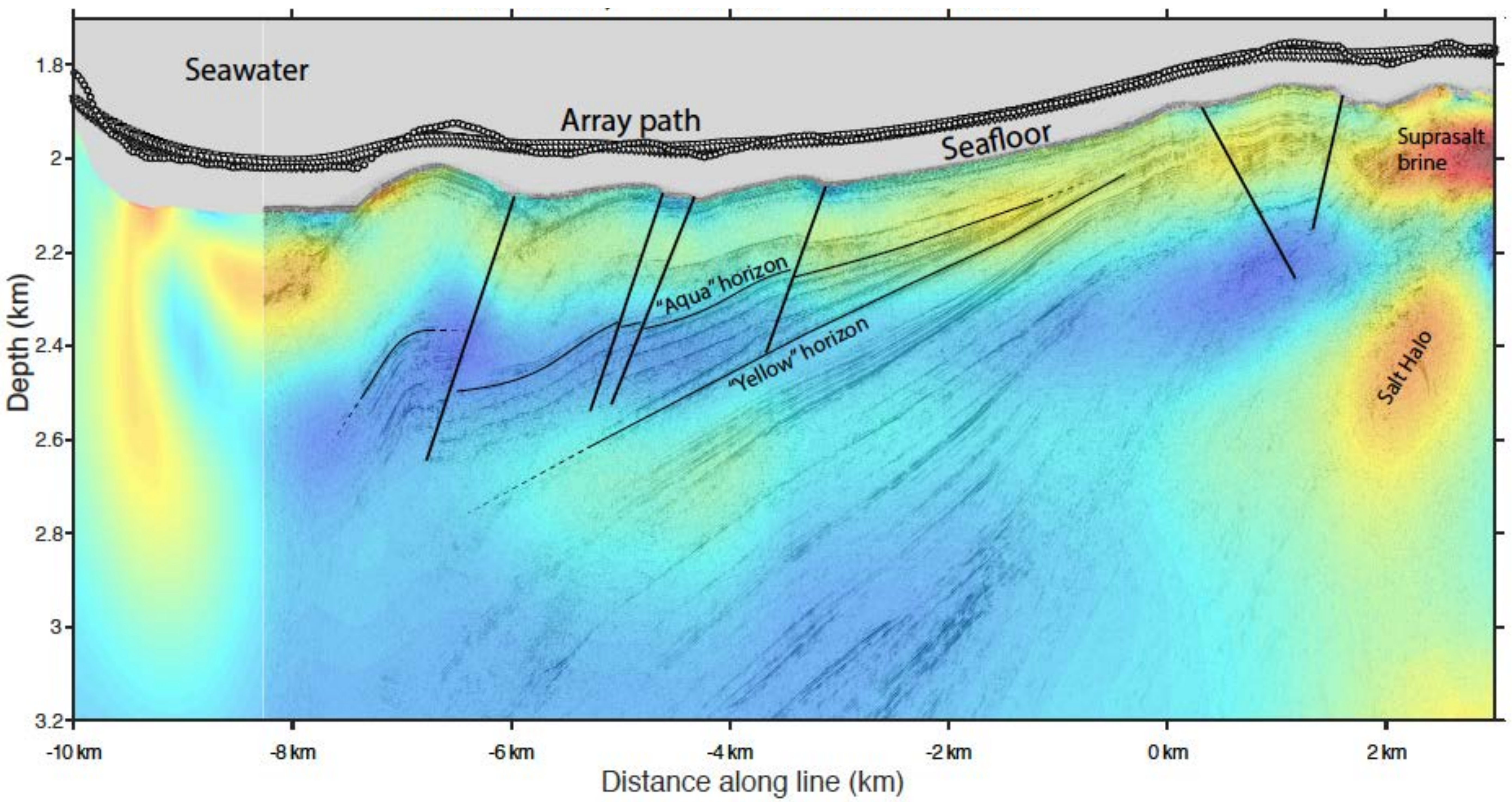


Constable et al., 2020





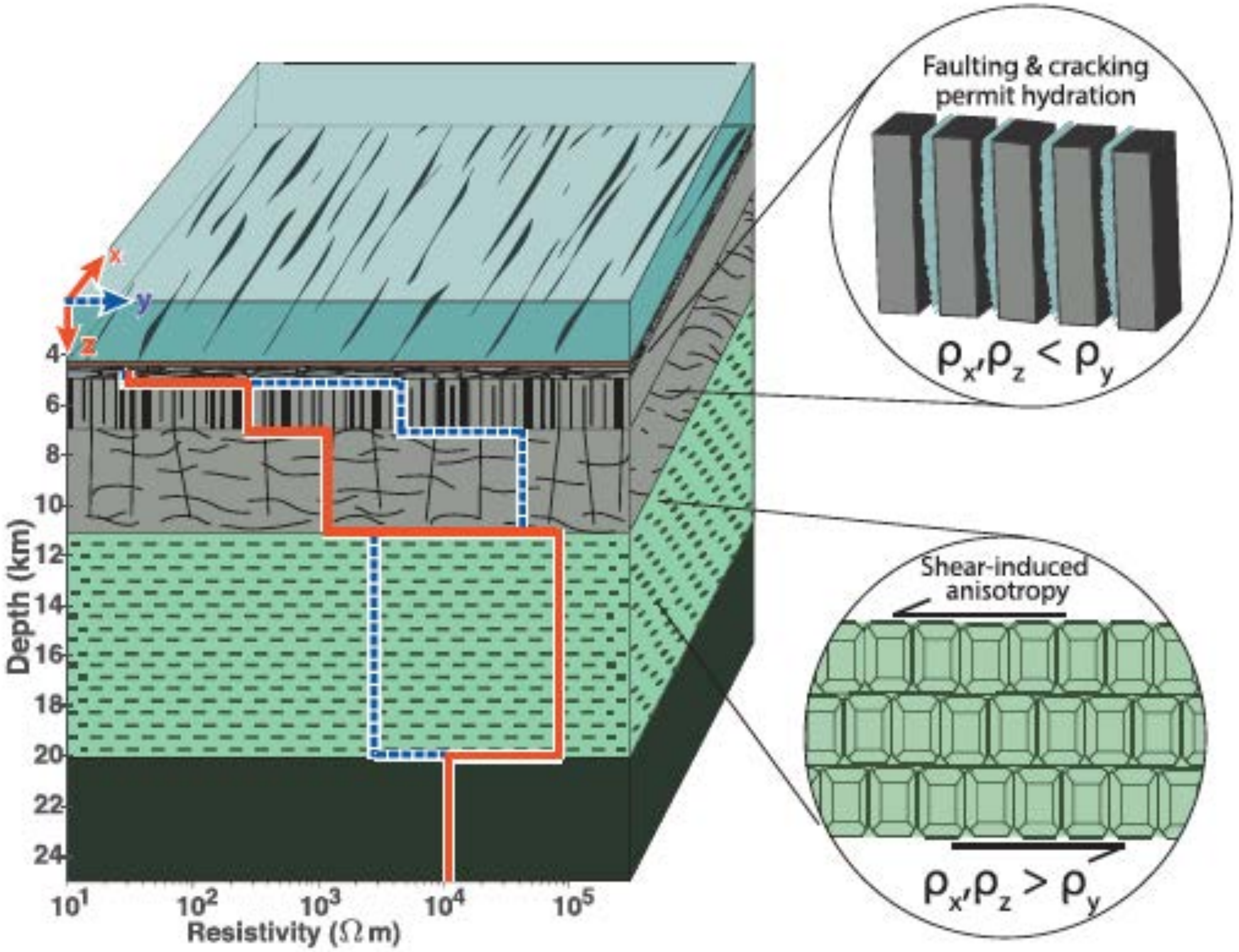
Kannberg & Constable, 2020



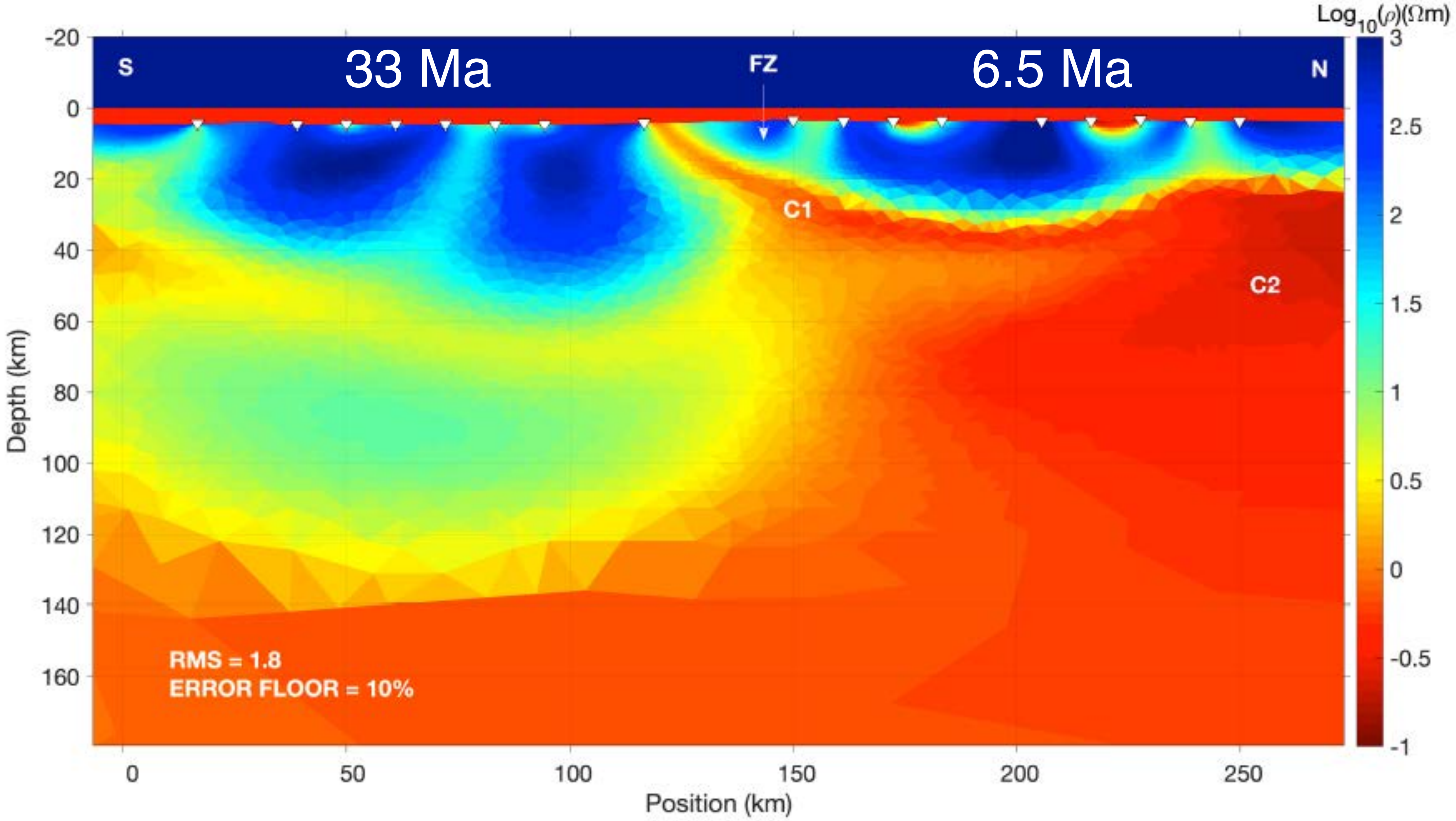
Kannberg et al., in prep

Normal Lithosphere:

- 🟢 1988: CSEM East Pacific (PEGASUS)
- 🟠 2001: CSEM + MT East Pacific (APPLE)
- 🔵 2018: MT Mendocino Fracture Zone



Chesley et al., 2019

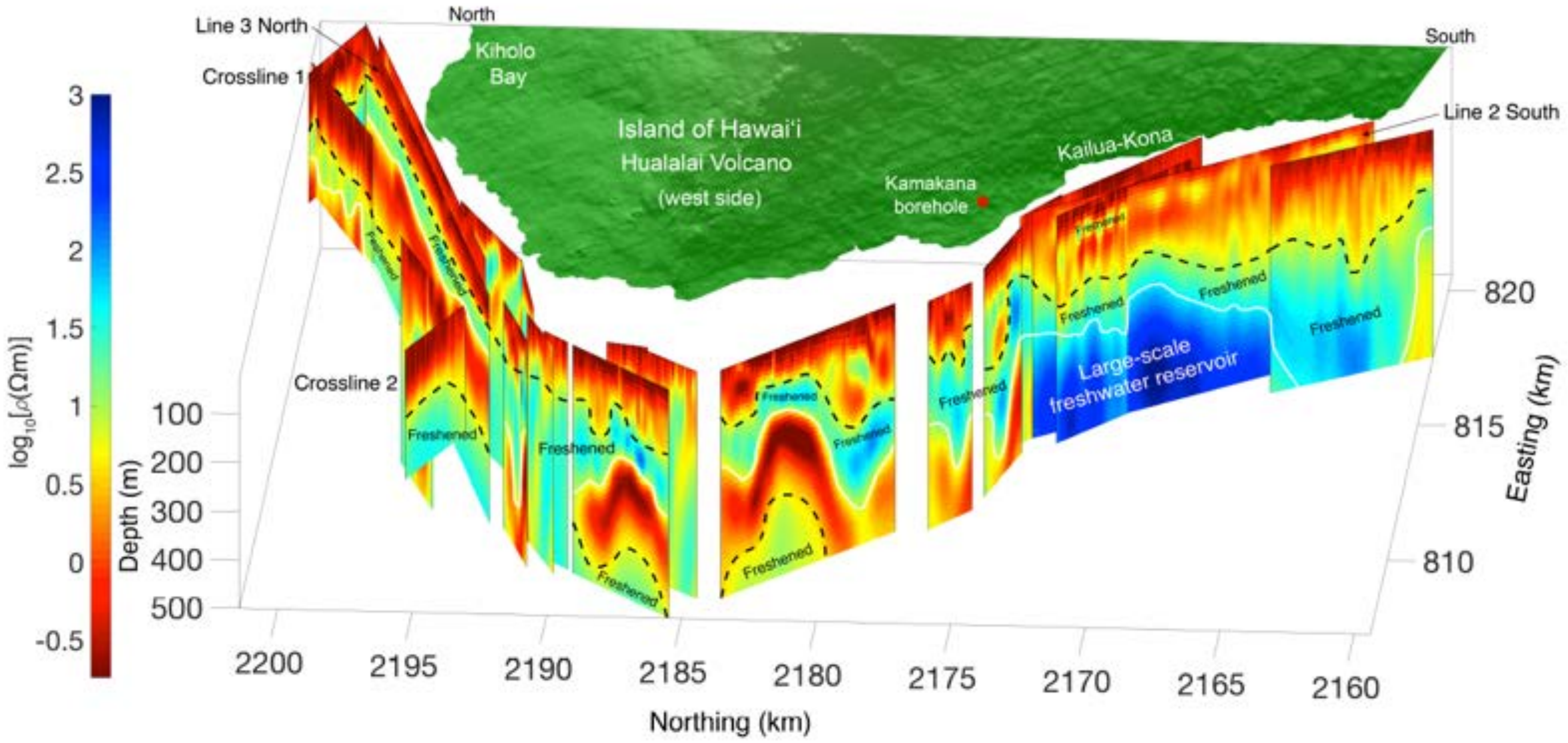


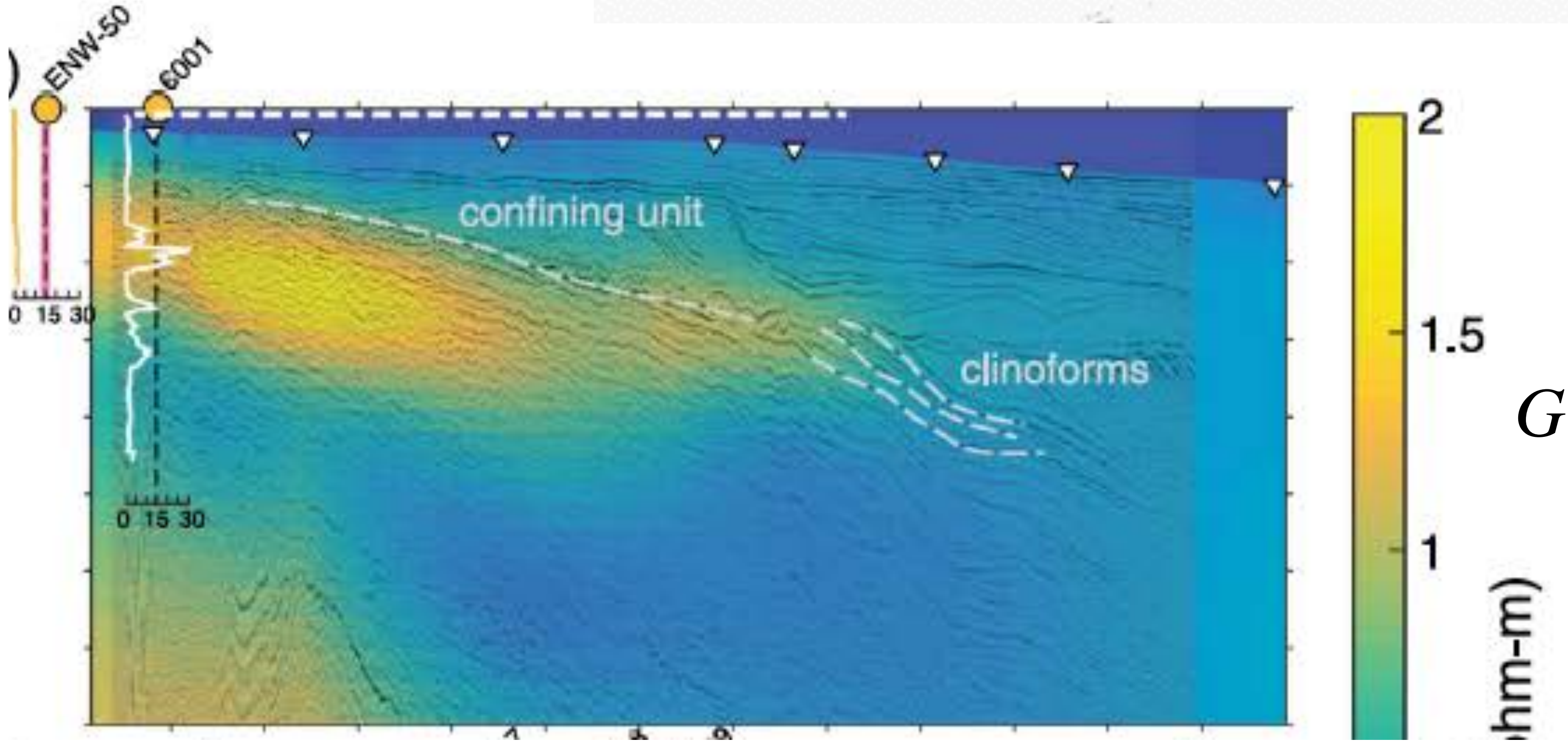
Reyes-Ortega et al., in prep

Offshore Groundwater and Permafrost:

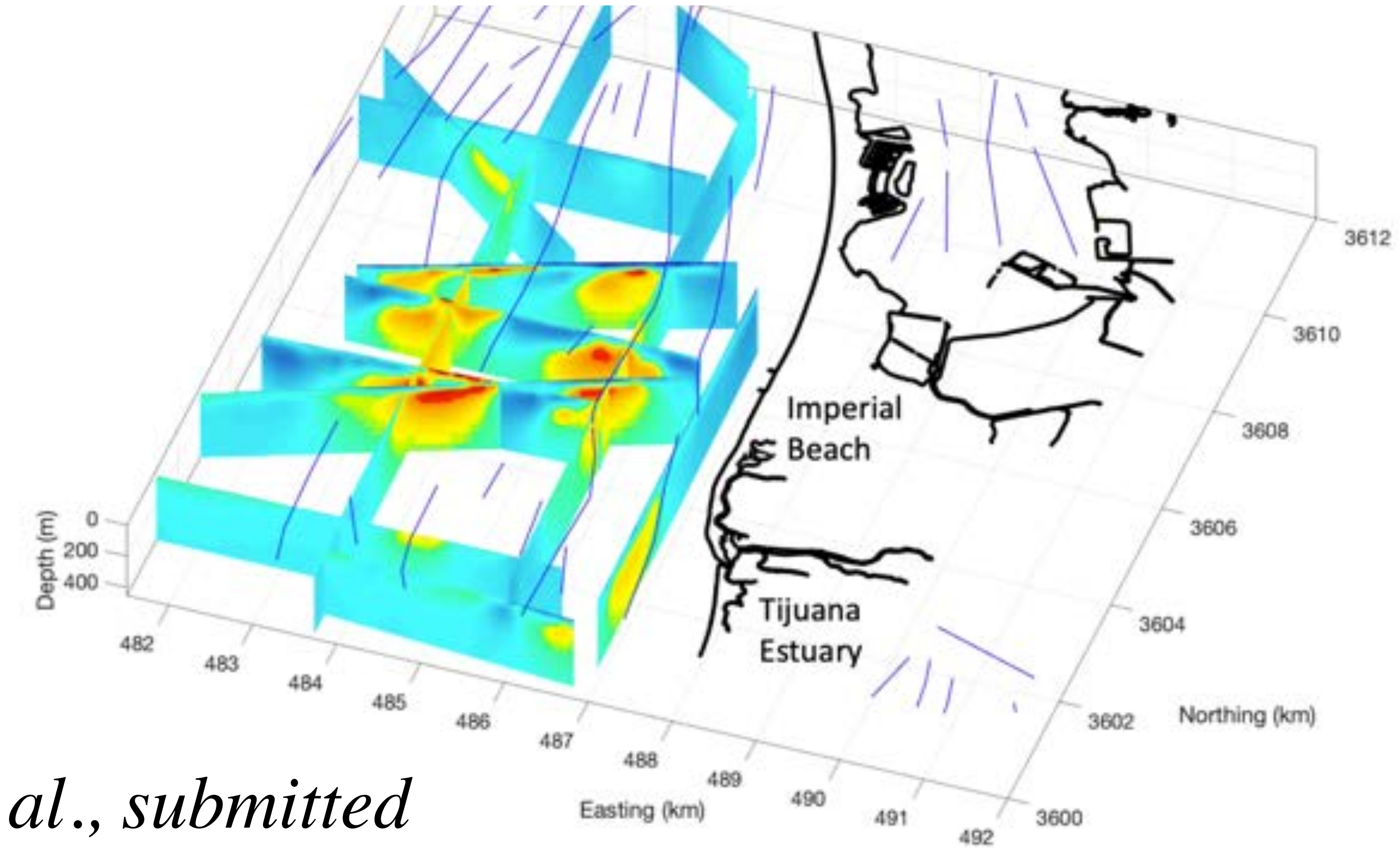
- 🟠 2014/5: CSEM Prudhoe Bay (permafrost)
- 🔴 2015: CSEM Atlantic continental shelf
- 🔵 2018: CSEM Offshore Hawaii
- 🟢 2018-2020: CSEM San Diego Aquifer

Attias et al., 2020

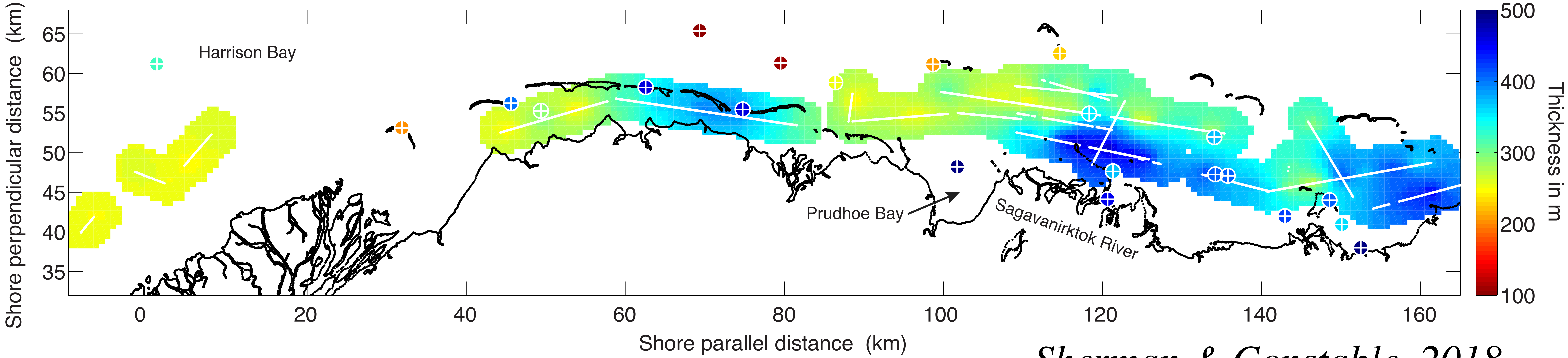




Gustafson et al., 2019



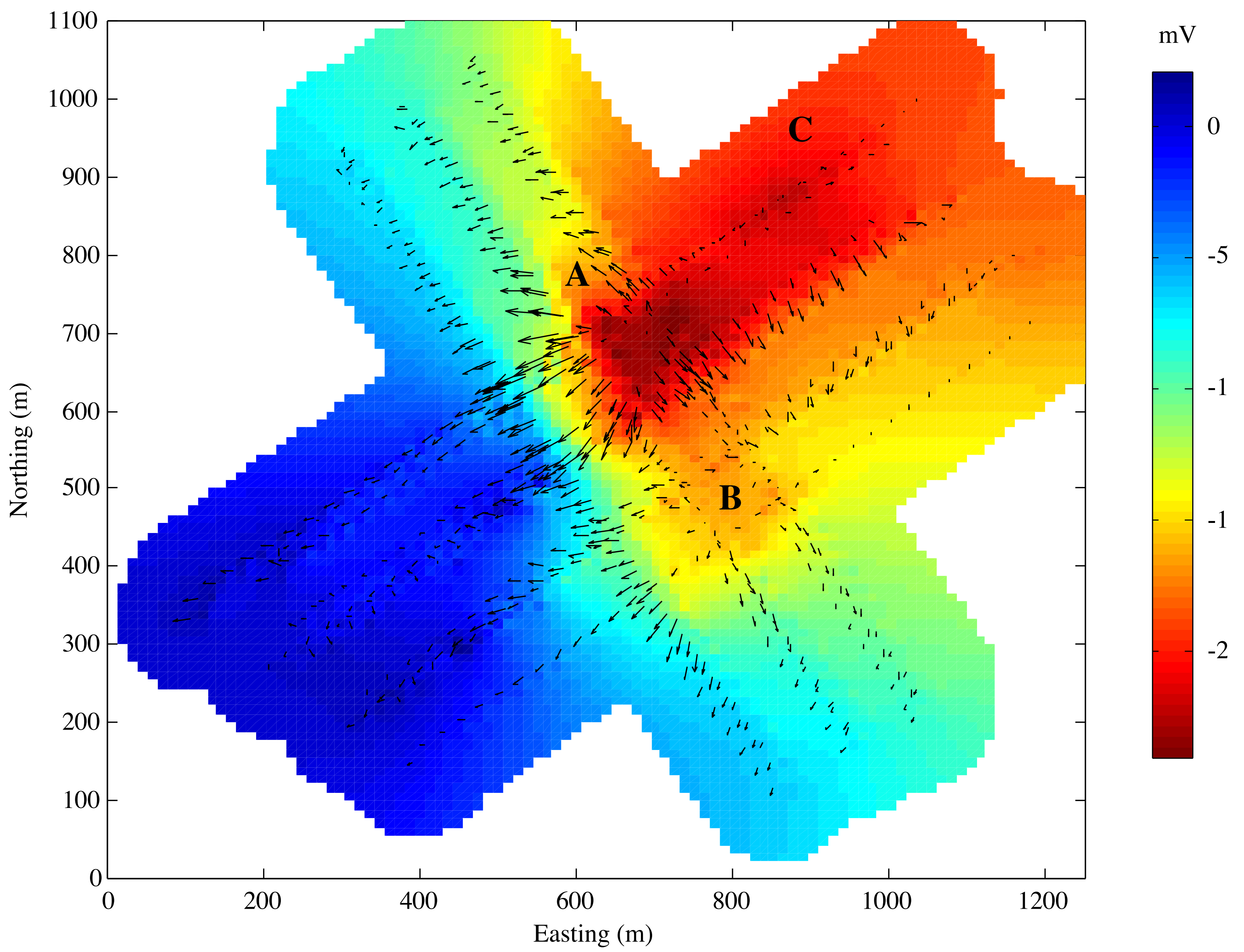
King et al., submitted



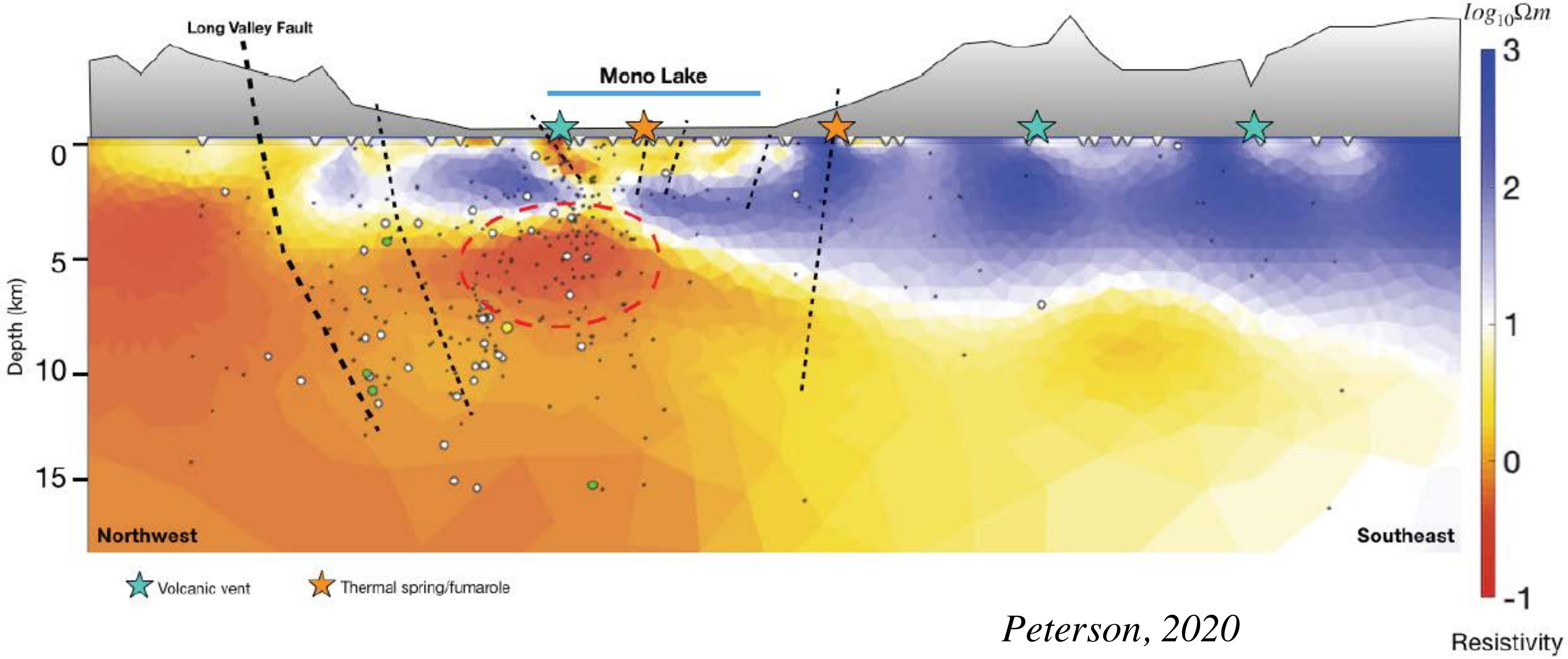
Sherman & Constable, 2018

Other Stuff:

- ● 2017: MT Mono Lake (volcanics)
- ● 2019/20: MT geothermal lakes, NZ
- ● 2016: AUV CSEM + SP, Okinawa Trough



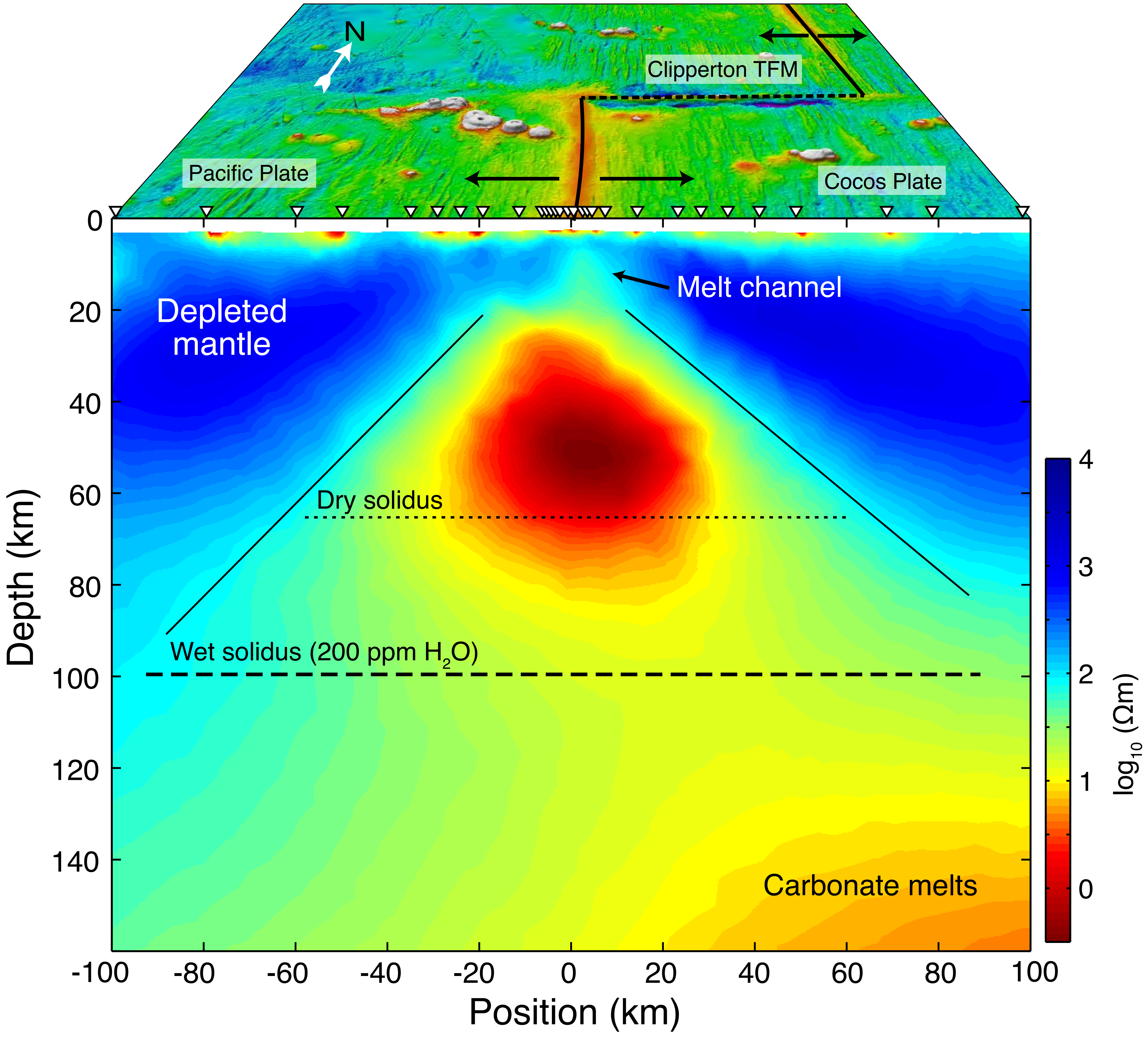
Constable et al., 2018

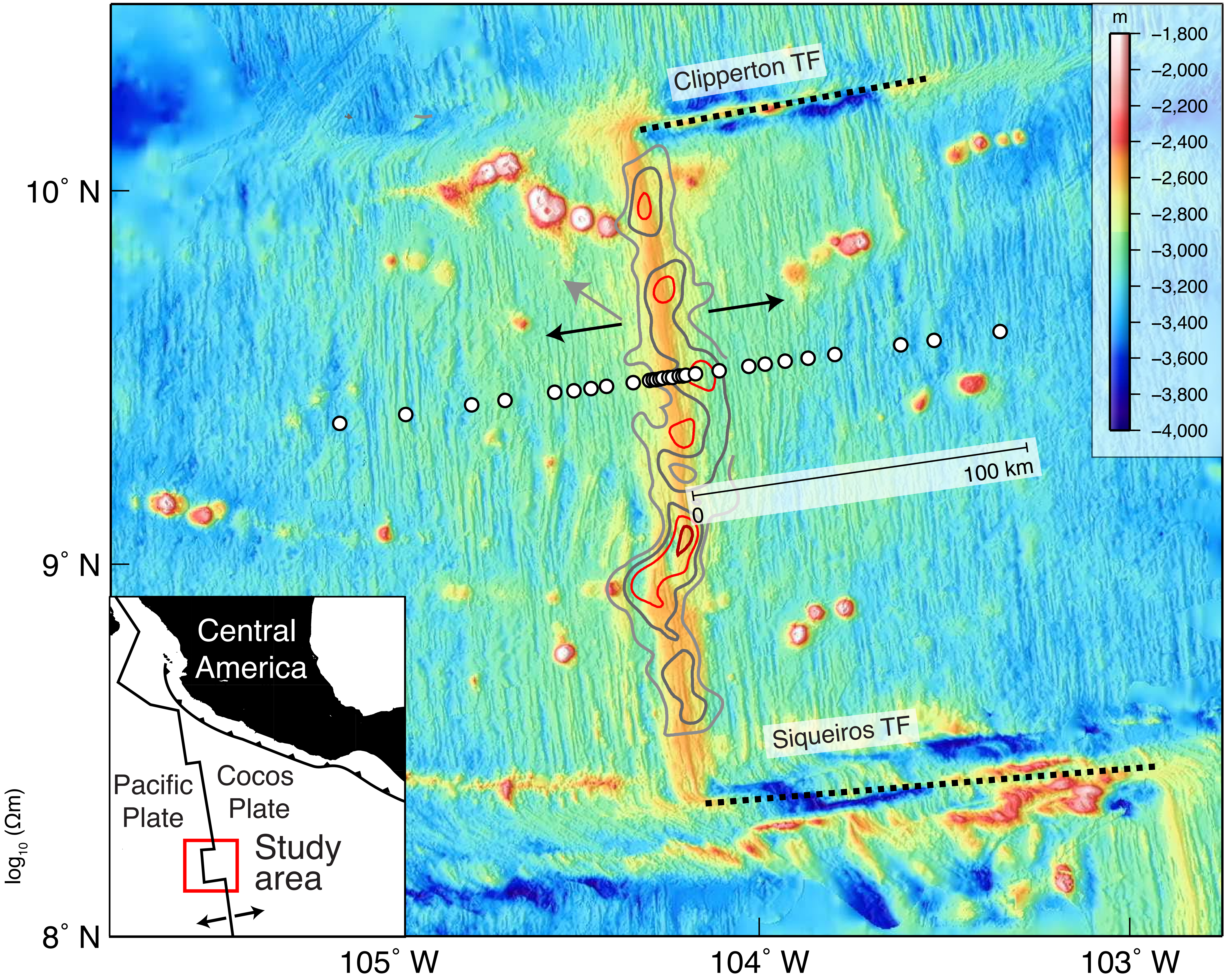


Peterson, 2020

East Pacific Rise: 69 sites of marine MT data collected south of Clipperton transform fault in February 2004.

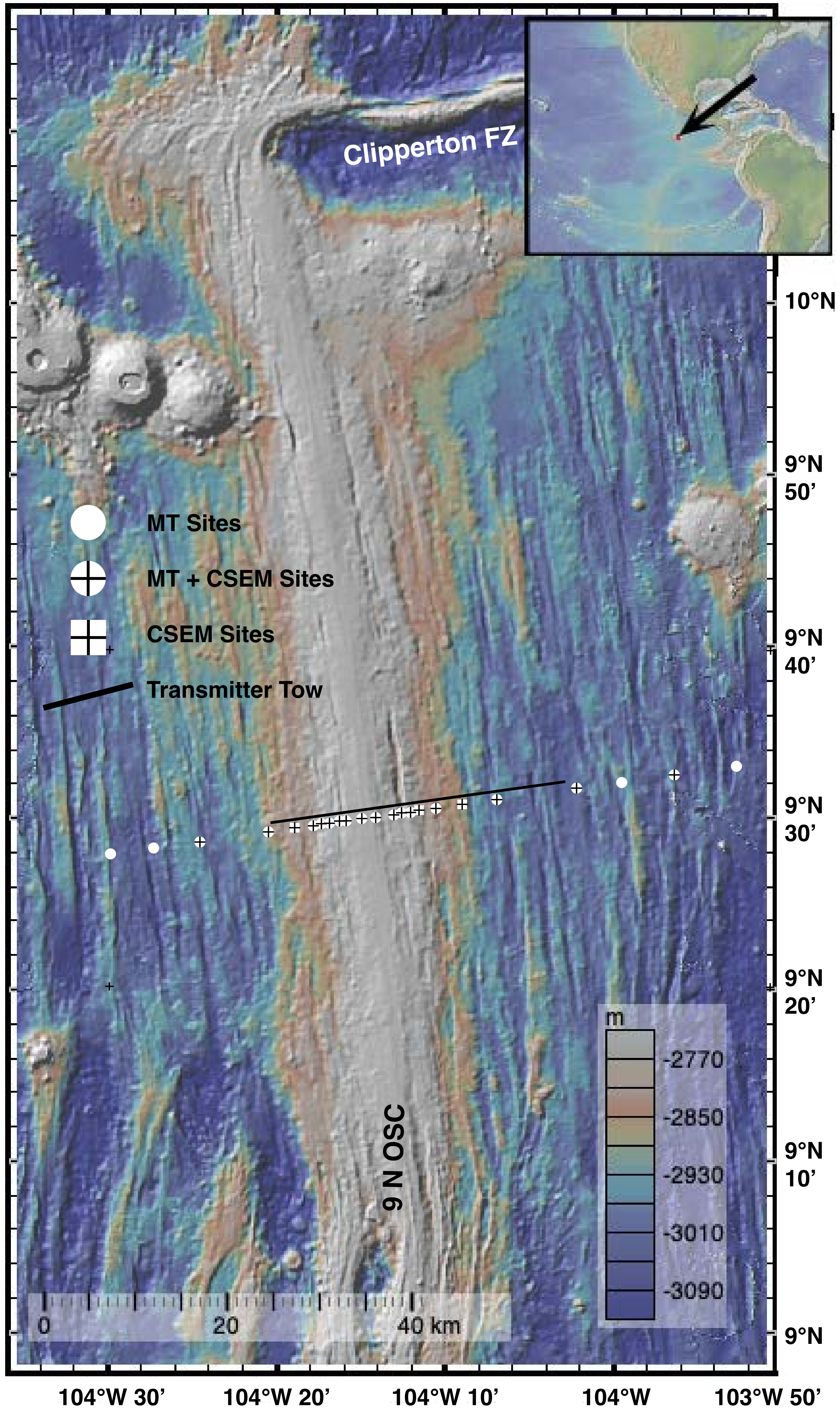
Funded by NSF. Kerry Key co-PI.

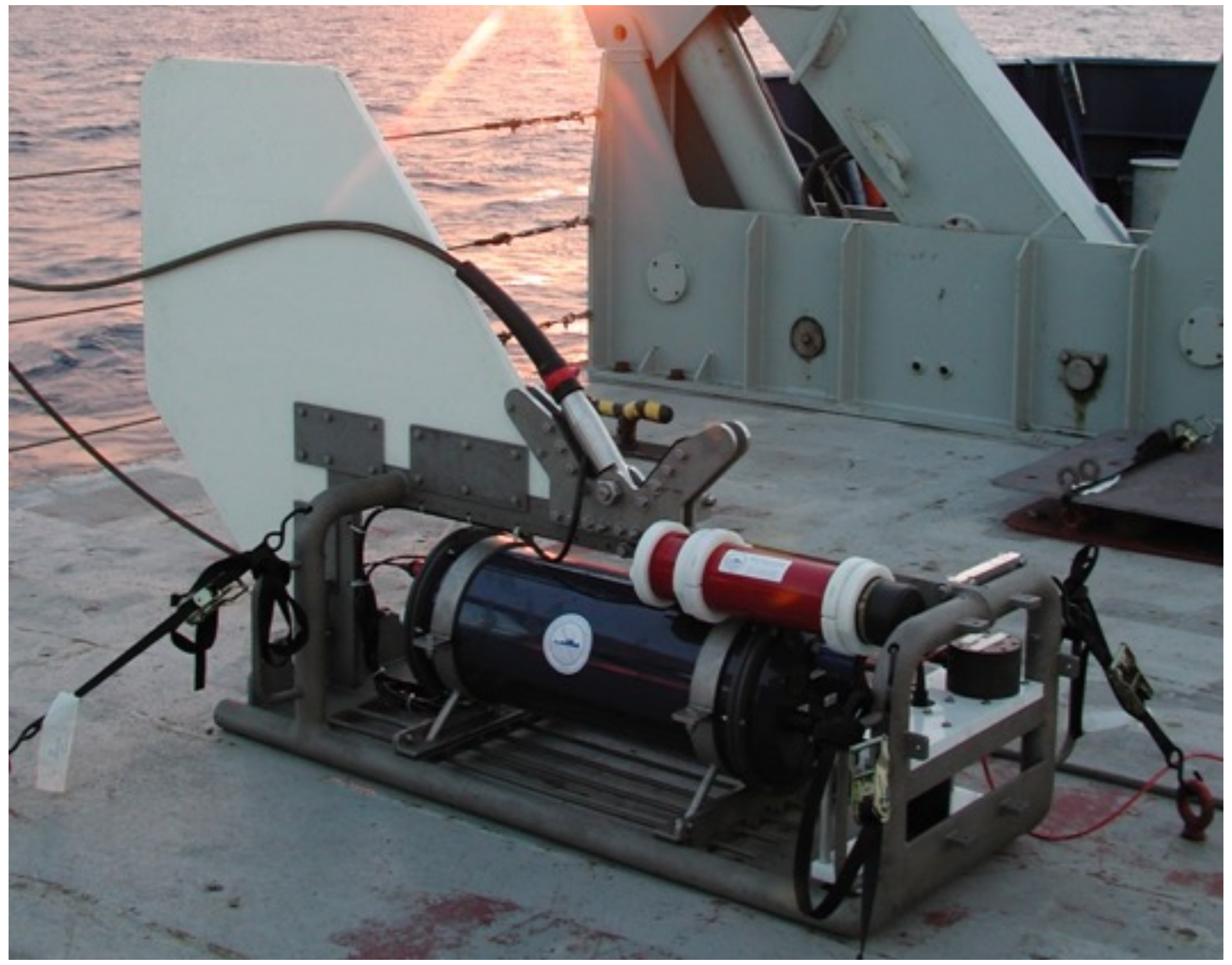




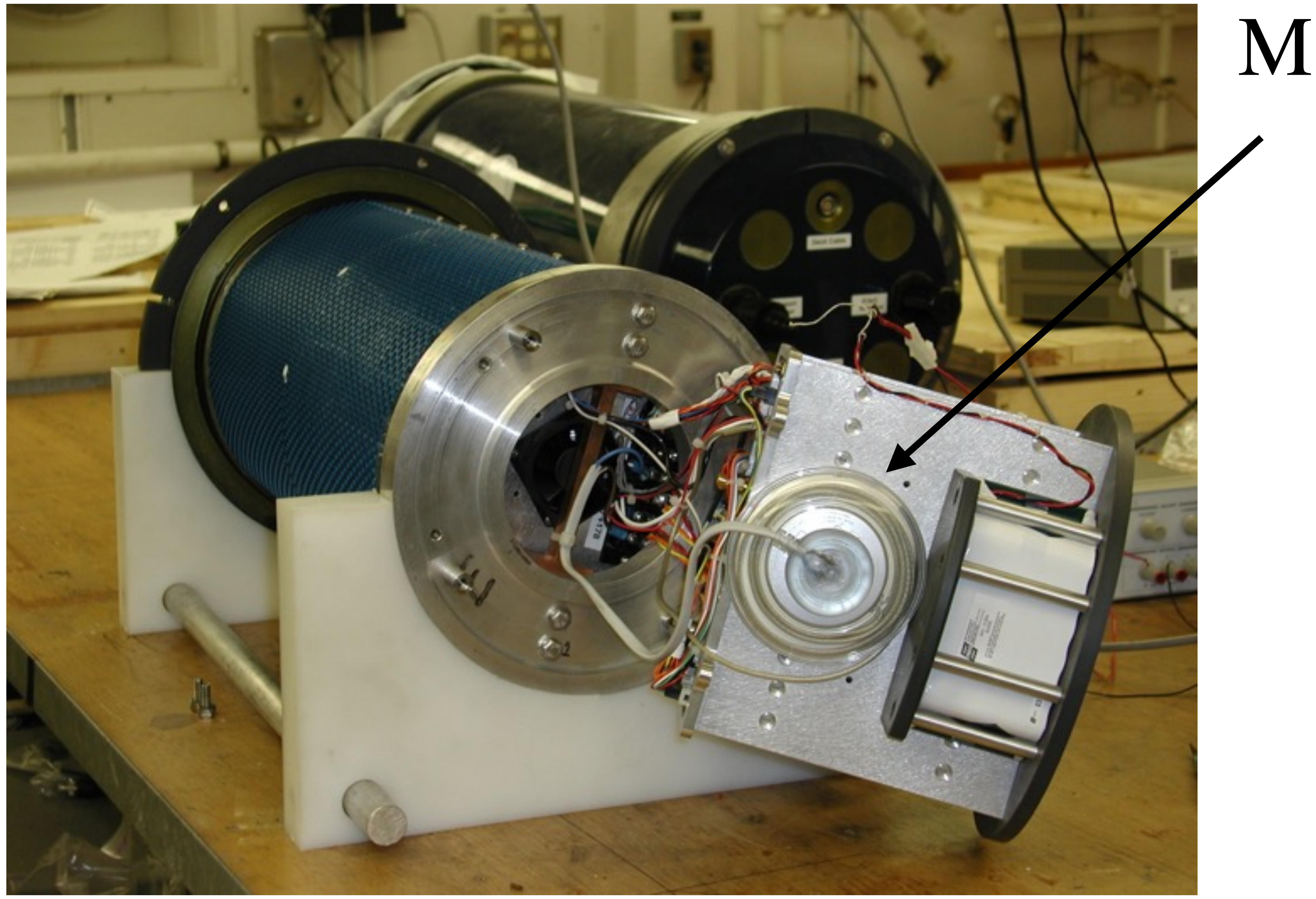
Key, Constable, Liu, and Pommier, 2013

A bit of a party…



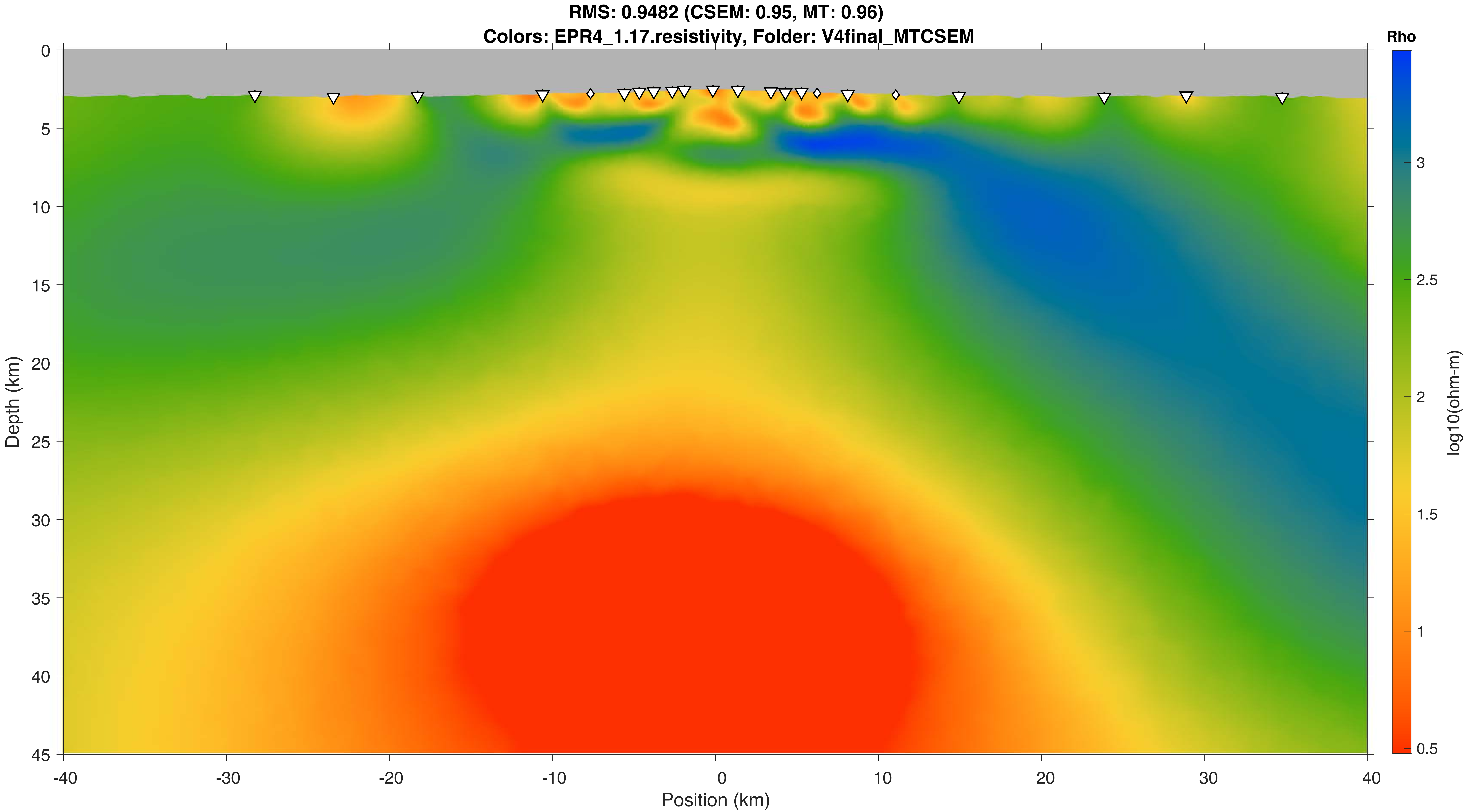


SUESI-200

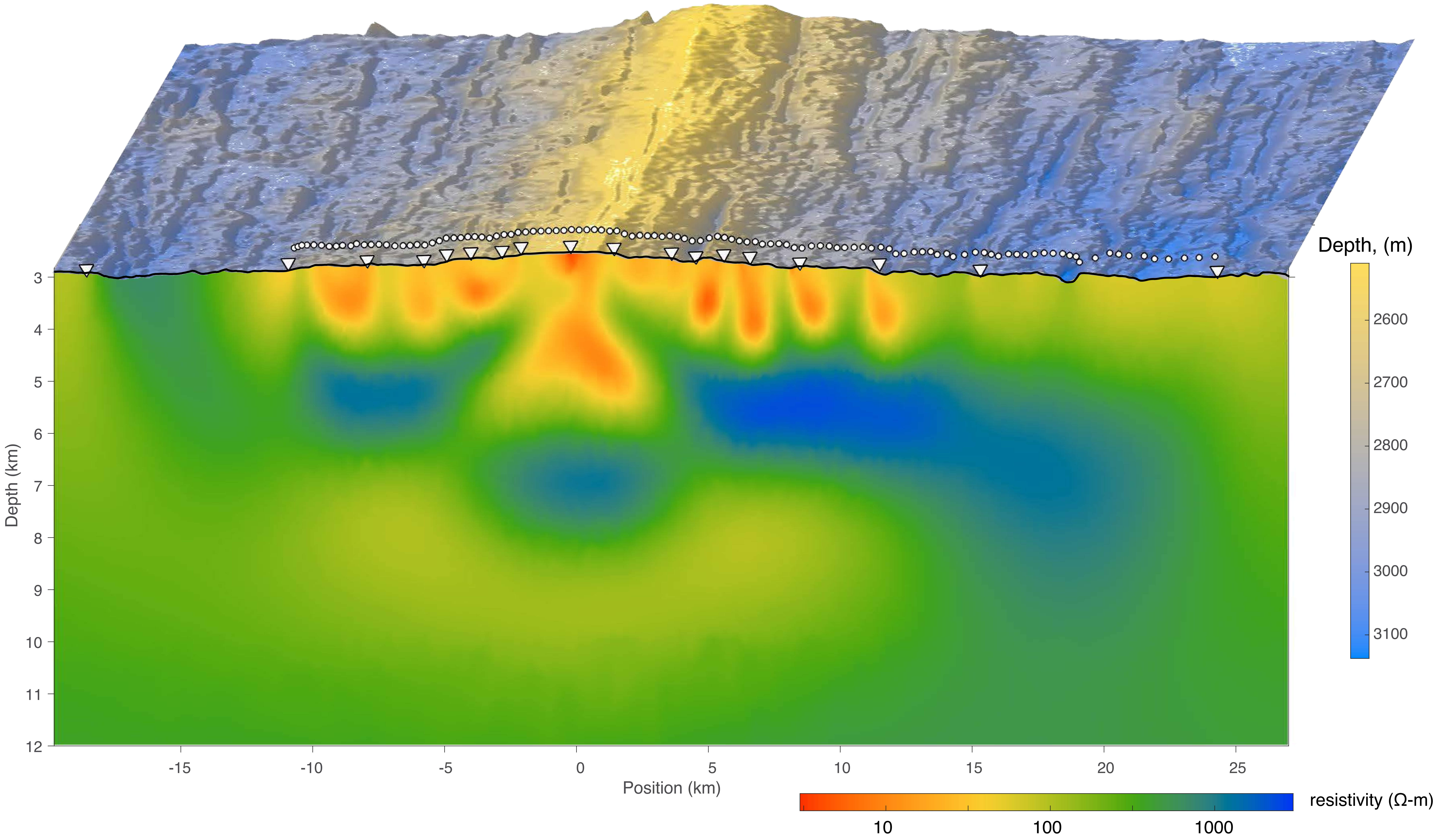


Mac power supply

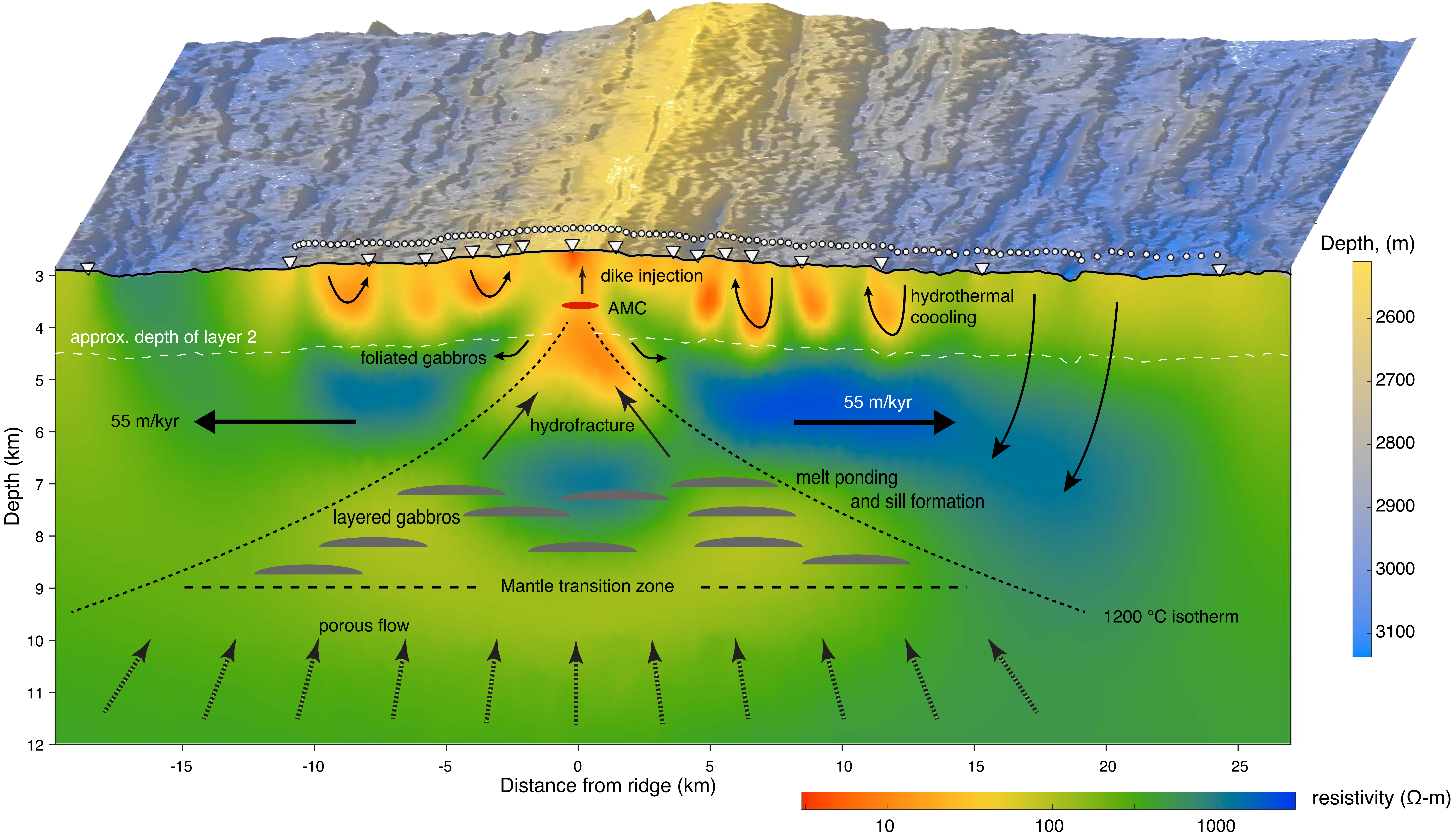
MT+CSEM Inversion



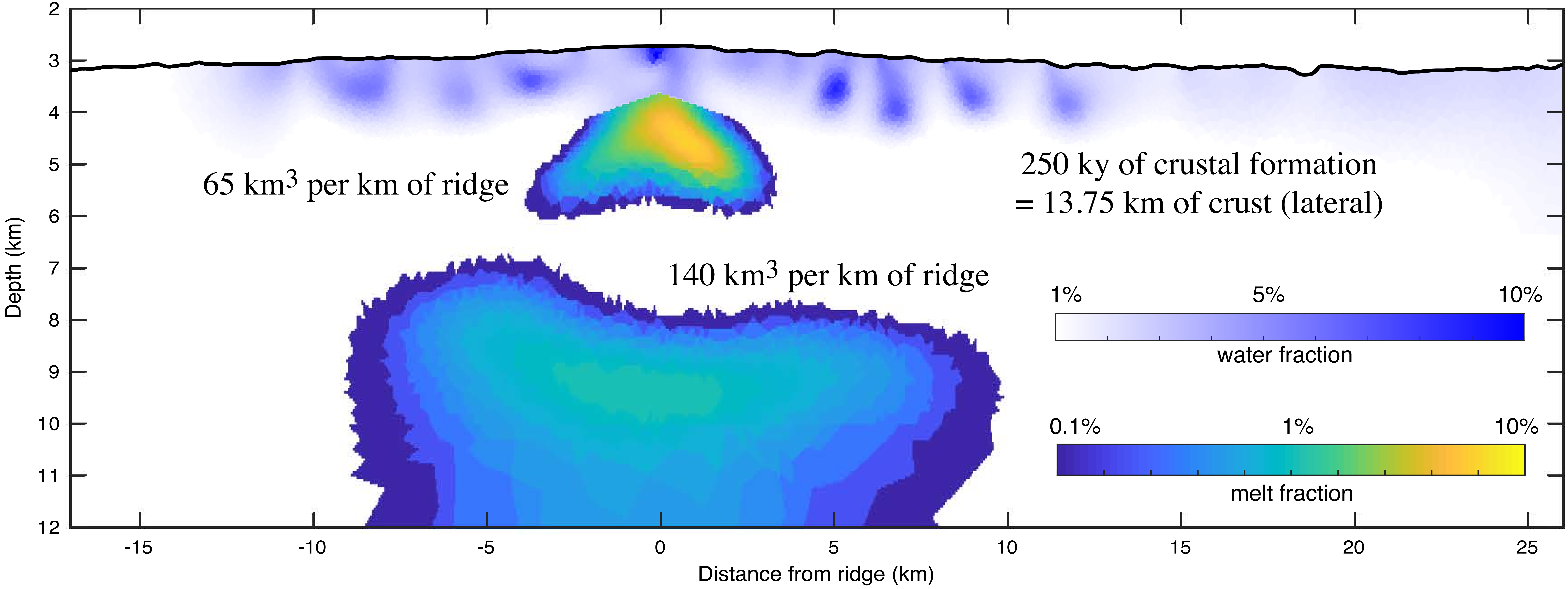
CSEM Inversion



CSEM Inversion



Melt and porosity



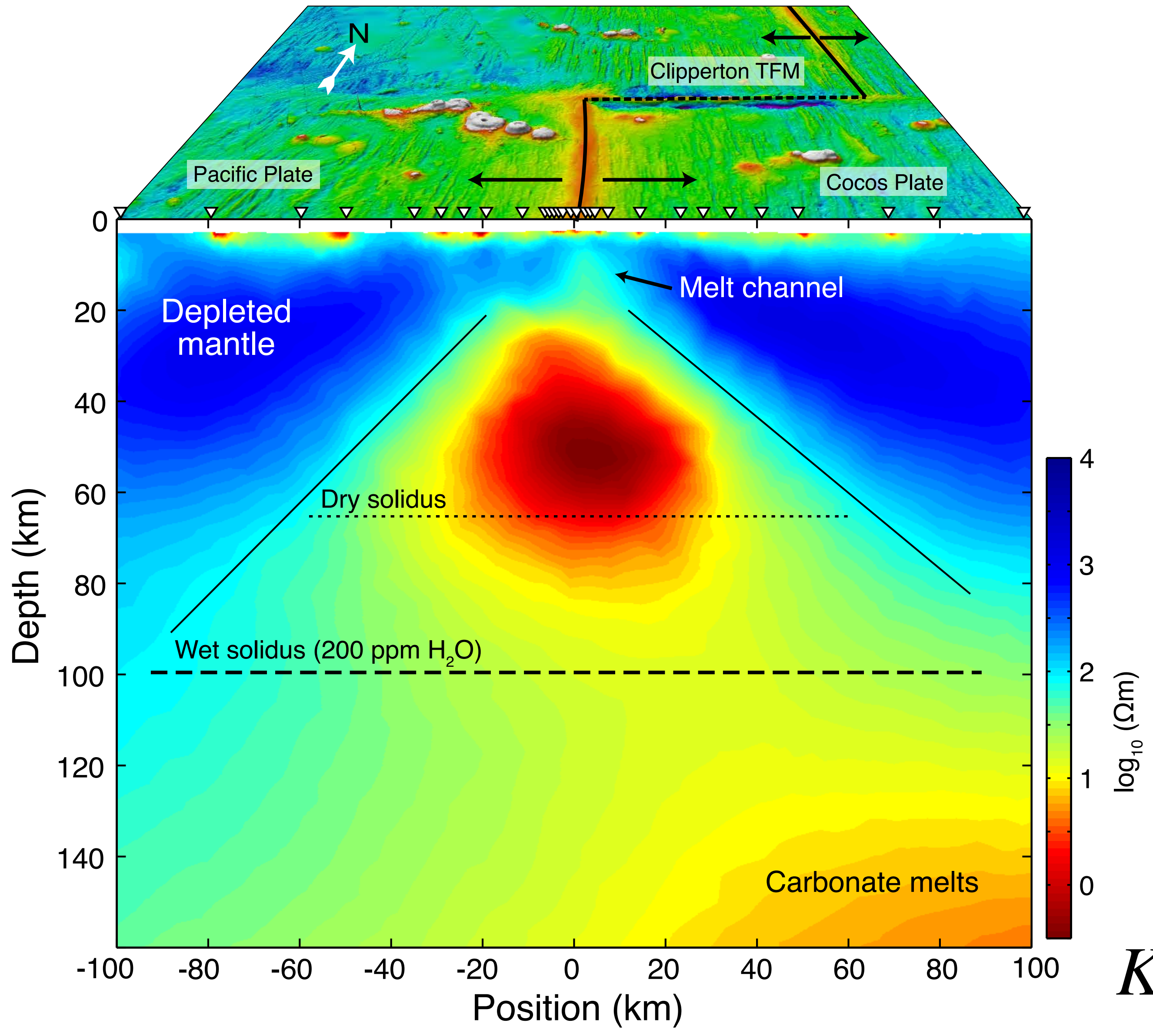
65 km^3 per km of ridge

140 km^3 per km of ridge

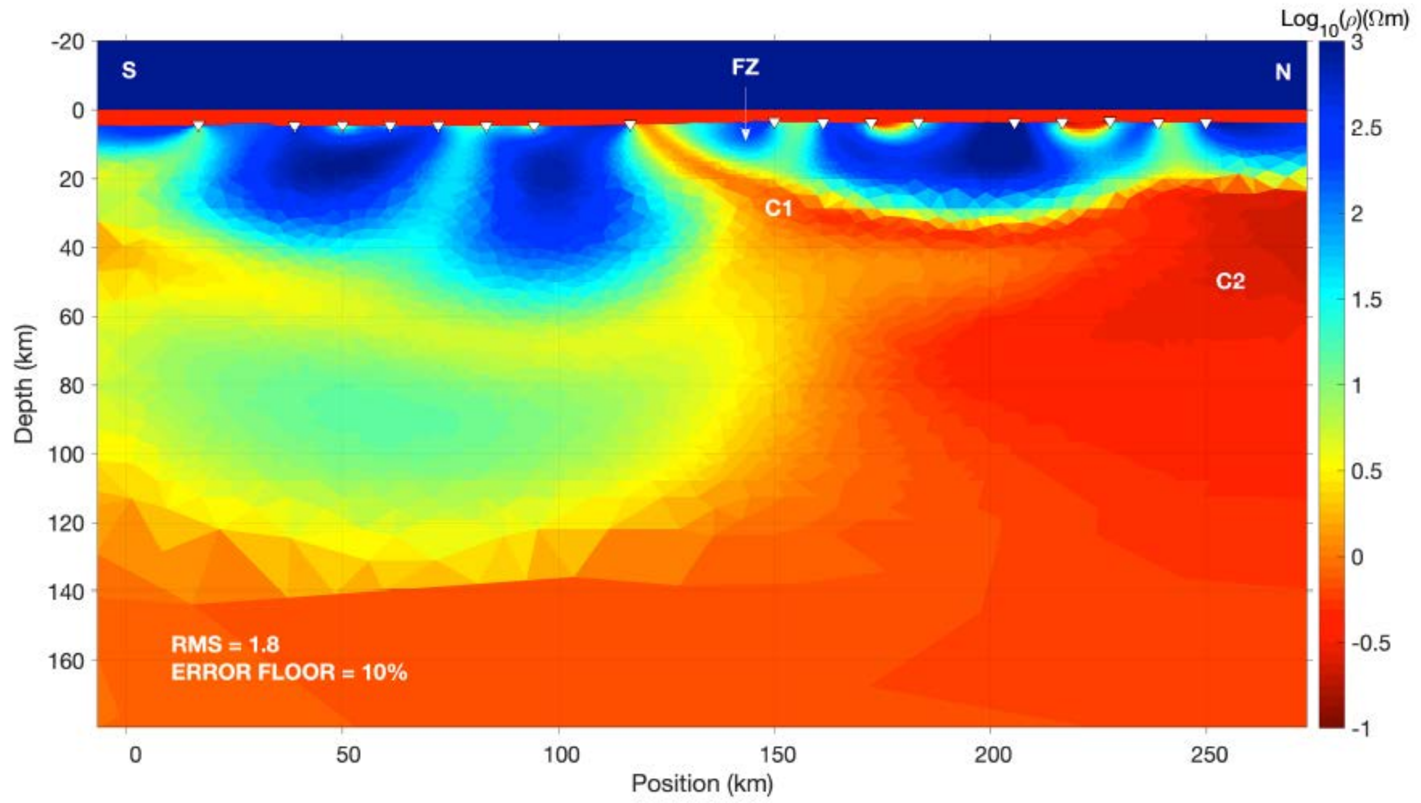
250 ky of crustal formation
= 13.75 km of crust (lateral)

A lot of a party…

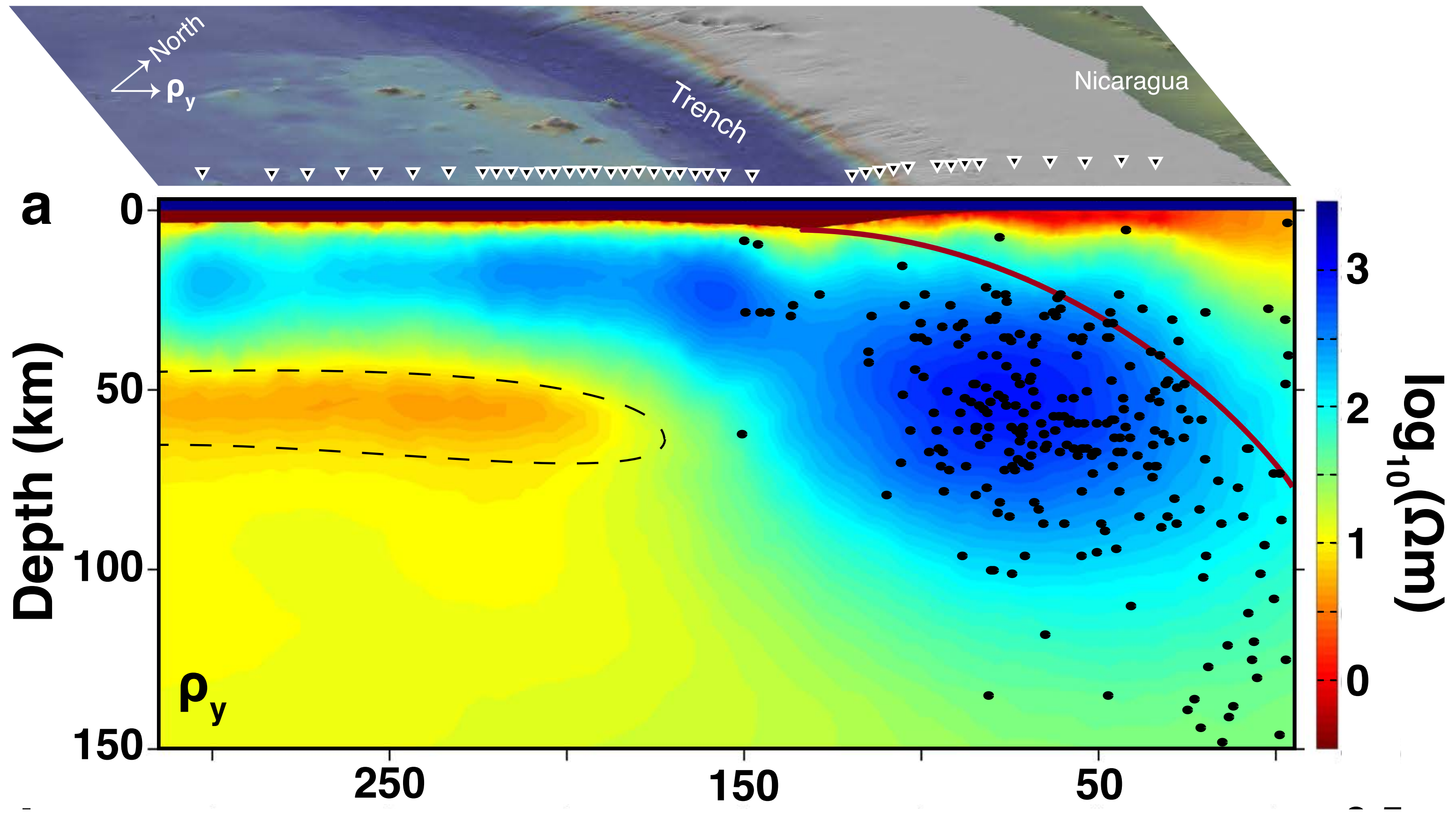
(3) What are the internal structures associated with spreading ridges, transform faults, subduction zones, island arcs, back arc basins, active and passive margins of continents? What is the variation of asthenospheric depth with age and location? These topics list some of the subjects which are becoming open to examination by EM methods and should be actively pursued in conjunction with modern methods. *Cox, 1980*



Key, et al., 2013

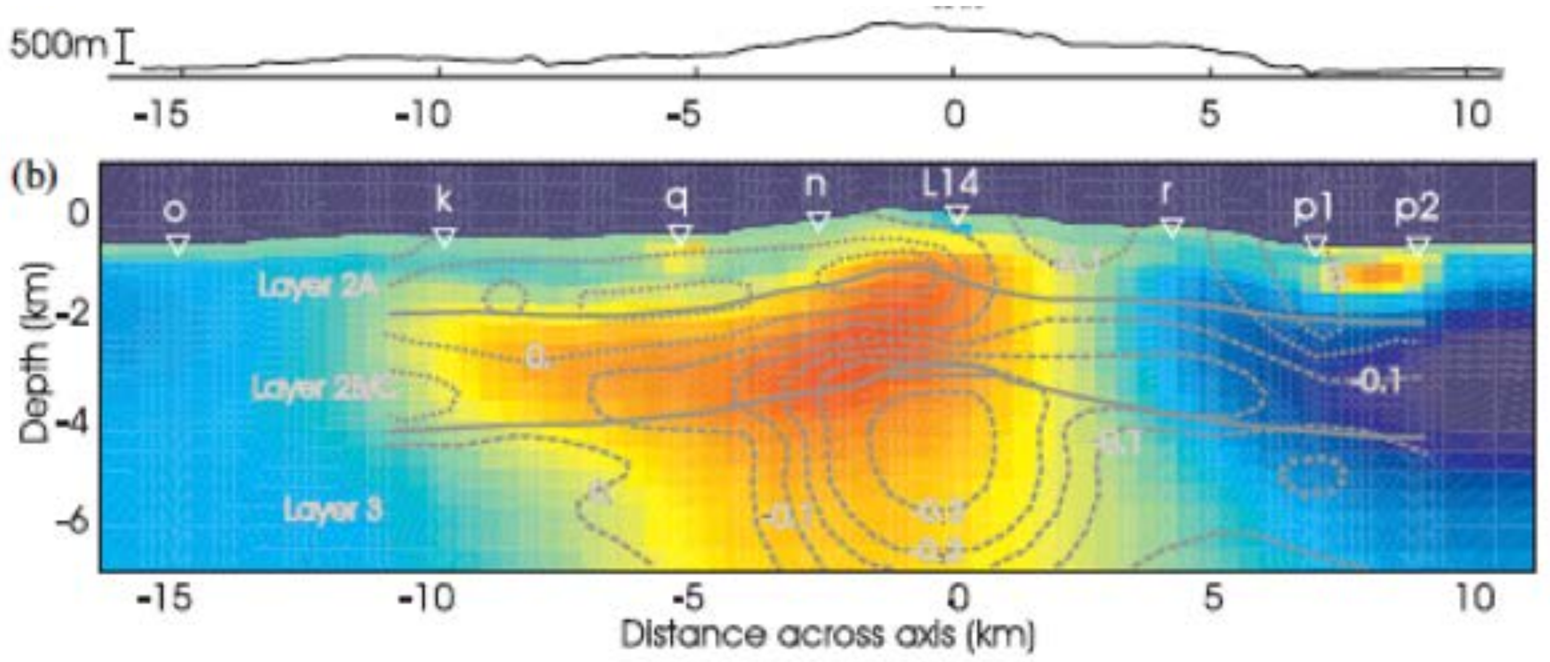


Reyes-Ortega et al., in prep

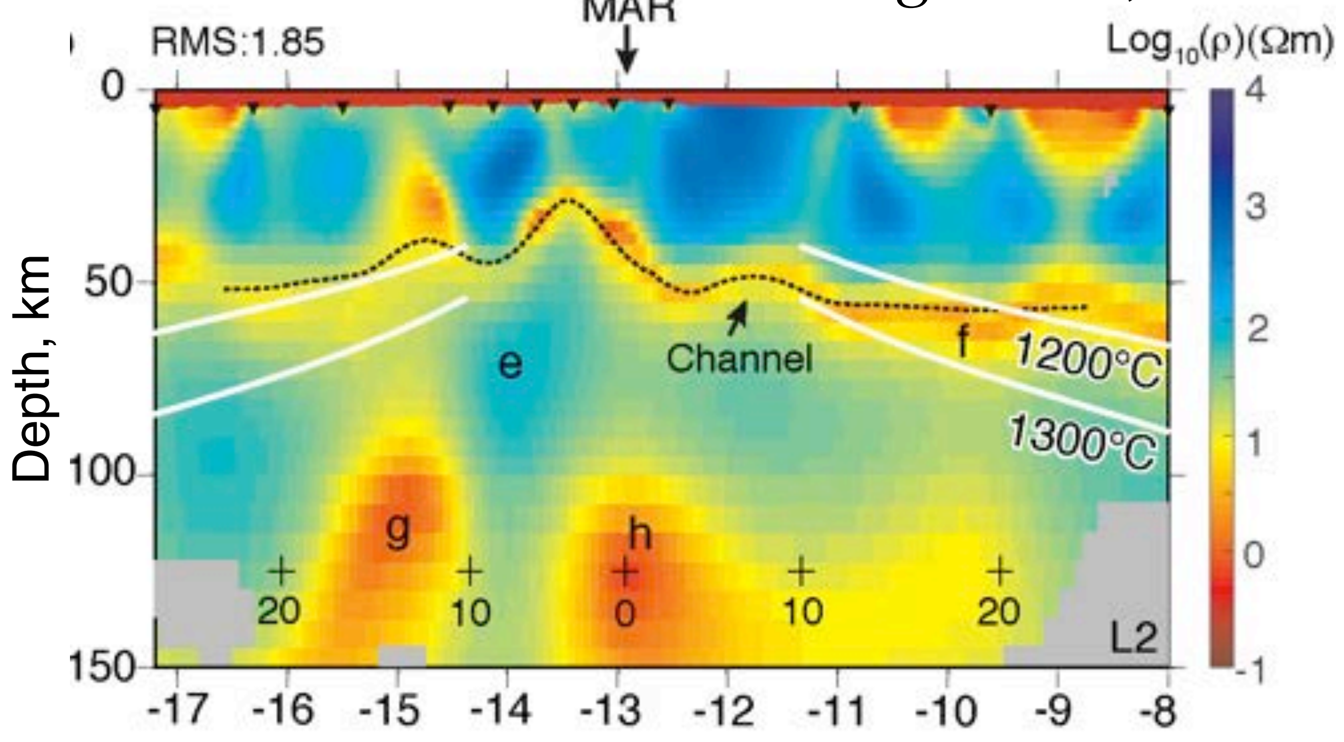


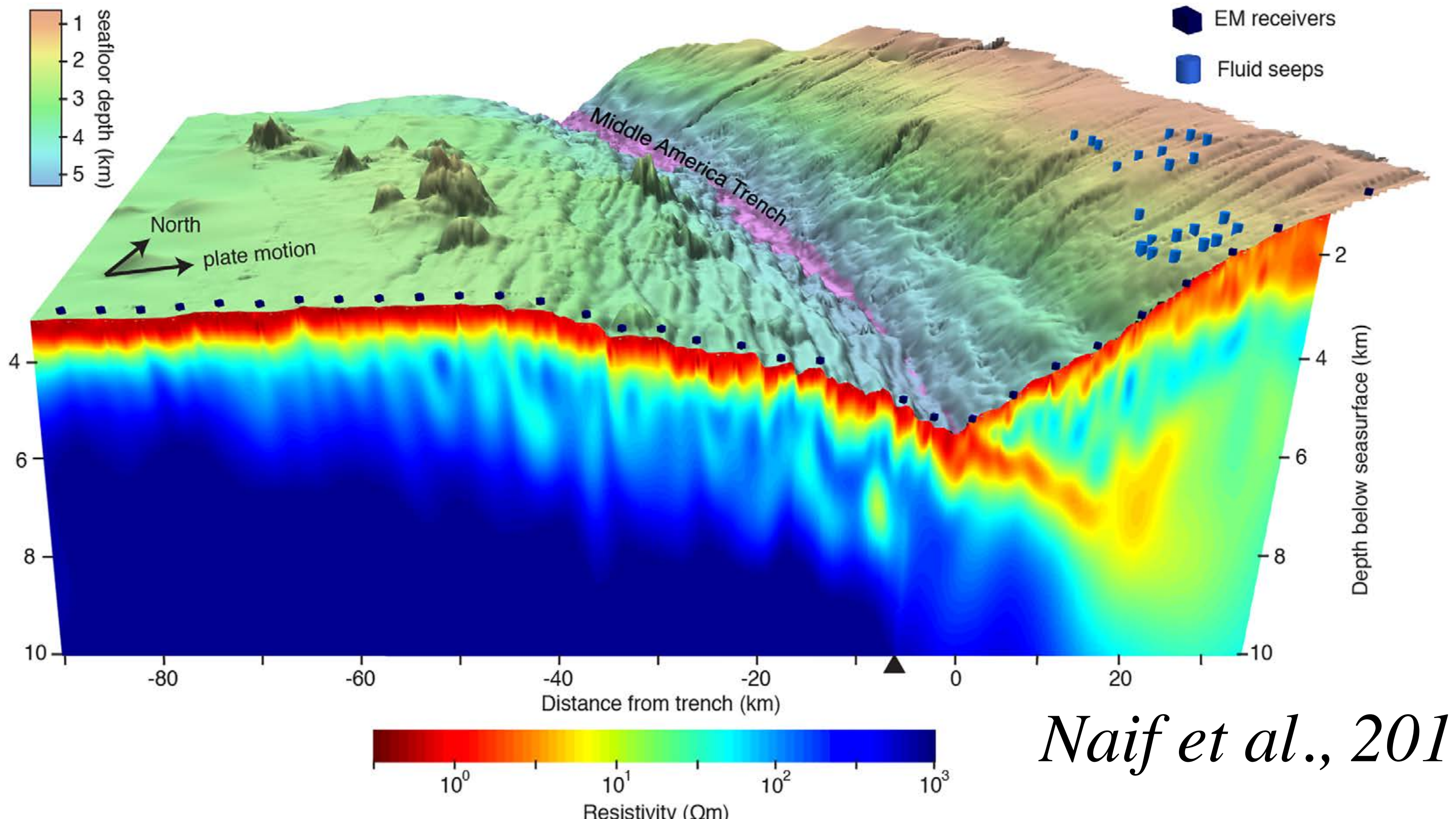
Naif et al., 2013

MacGregor et al., 2001



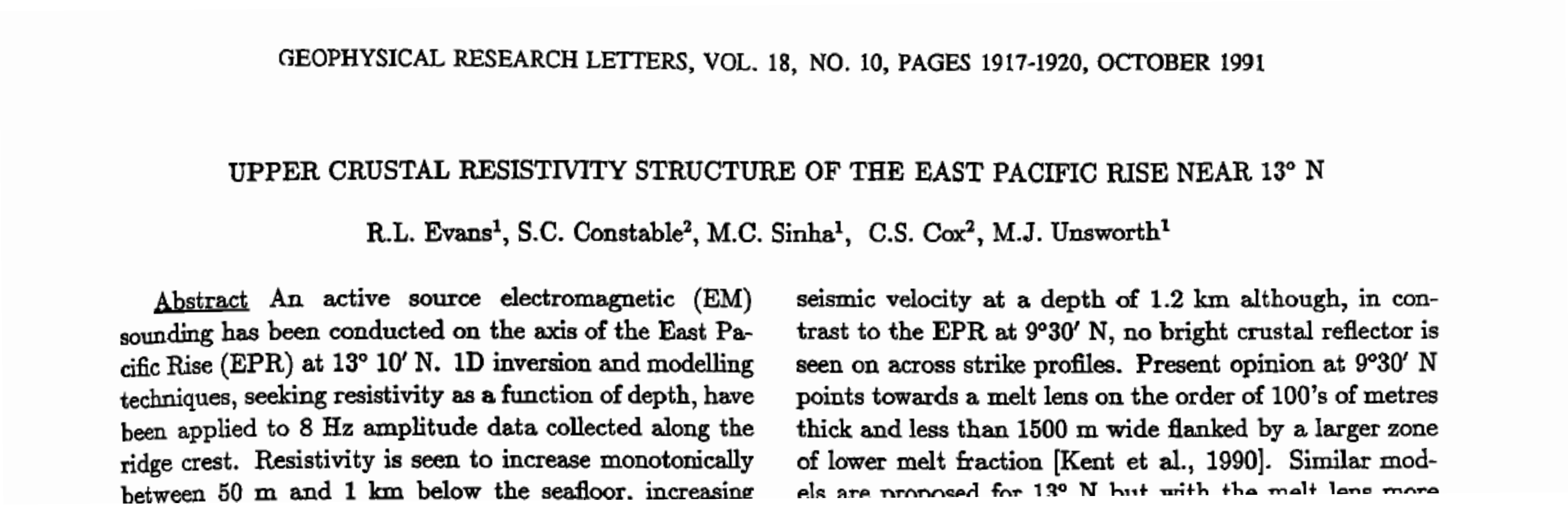
Wang et al., 2020





Naif et al., 2016

A June 1989 cruise on the RRS Charles Darwin was the last marine EM project the Chip participated in.



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UPPER CRUSTAL RESISTIVITY STRUCTURE OF THE EAST PACIFIC RISE NEAR 13° N

R.L. Evans[1], S.C. Constable[2], M.C. Sinha[1], C.S. Cox[2], M.J. Unsworth[1]

Abstract An active source electromagnetic (EM) sounding has been conducted on the axis of the East Pacific Rise (EPR) at 13° 10′ N. 1D inversion and modelling techniques, seeking resistivity as a function of depth, have been applied to 8 Hz amplitude data collected along the ridge crest. Resistivity is seen to increase monotonically between 50 m and 1 km below the seafloor, increasing seismic velocity at a depth of 1.2 km although, in contrast to the EPR at 9°30′ N, no bright crustal reflector is seen on across strike profiles. Present opinion at 9°30′ N points towards a melt lens on the order of 100's of metres thick and less than 1500 m wide flanked by a larger zone of lower melt fraction [Kent et al., 1990]. Similar models are proposed for 13° N but with the melt lens more

Maybe he trusted me to carry the method forward. I suspect that really he had decided that he'd done the difficult, interesting work in marine CSEM, and was no longer interested. He returned to an old love of his — wave microstructure at the ocean surface.

I would like to thank everyone I have had the pleasure to work with, but especially Chip, who taught me so much…