Porosity estimates from marine controlled source electromagnetic dipole-dipole data at the Scanner Pockmark in the North Sea

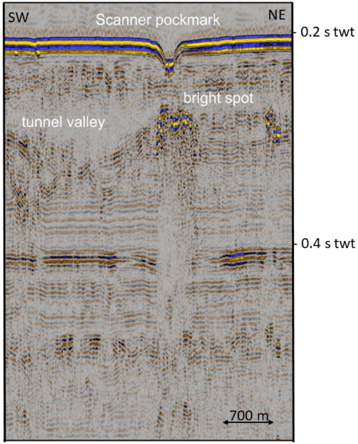
Romina A. S. Gehrmann, Giuseppe Provenzano, Christoph Böttner, Héctor Marín-Moreno, Ian Y. Tan, Naima K. Yilo, Gaye Bayrakci, Jonathan M. Bull, Timothy A. Minshull and Christian Berndt

7th May 2020

Introduction

Scanner Pockmark in Witch Ground Basin in the Central North Sea

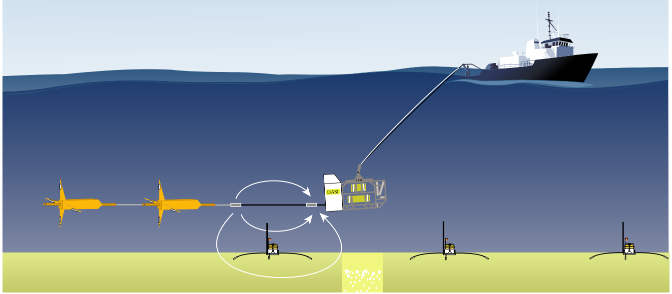
- Area with abundant pockmarks (Gafeira and Long, 2015)
- Scanner Pockmark up to ∼17 m deep and about 100 to 300 m wide
- Vertical fluid conduit connecting deeper methane sources to surface (Karstens and Berndt, 2015)
- Seismic reflector indicating gas reservoir in ∼40 mbsf (Bright spot, Böttner et al., 2019; Berndt et al., 2017)



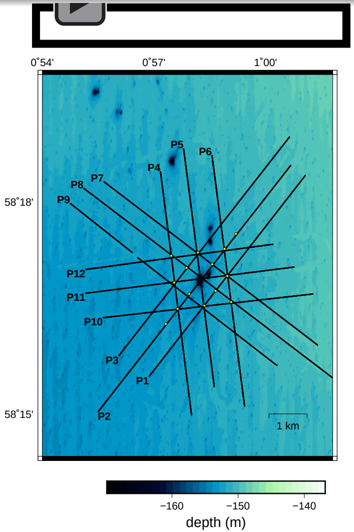
adapted from Berndt et al. (2017)

Controlled-source electromagnetics (CSEM)

- Sensitive to porosity and pore content (Edwards, 1997)
- Experiment with electric dipole source (DASI, Sinha et al., 1990) and three-axis dipole electric field receivers (Vulcan, Constable et al., 2016)

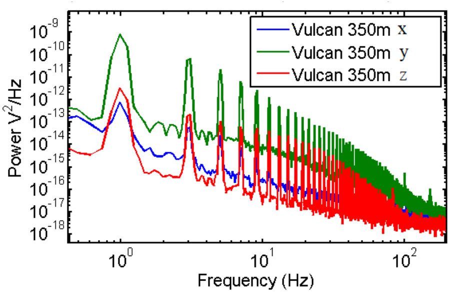


adapted from a version by Karen Weitemeyer and finalised by Kate Davis

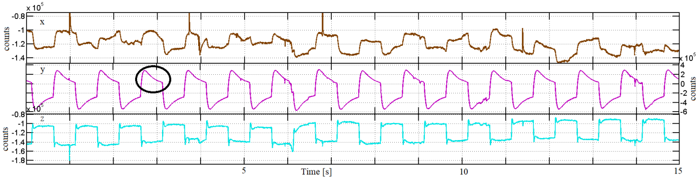


CSEM DATA PROCESSING

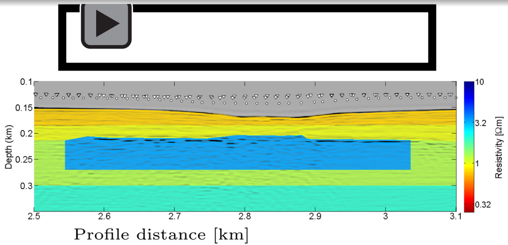
- Source: ∼90 A square wave signal
- Receiver: x - crossline, y - inline, z - vertical
- High energy in high frequencies due to energy guided along air-water boundary (Weidelt, 2007)
- Processing: 1-s long time windows transformed into frequency domain, divided by source dipole moment, stacked over 30 s and clock drift corrected (Myer et al., 2011)

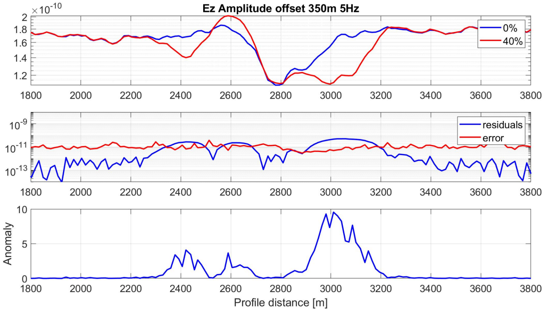


- Power spectra (top) of 60-s time series for channels x, y and z.



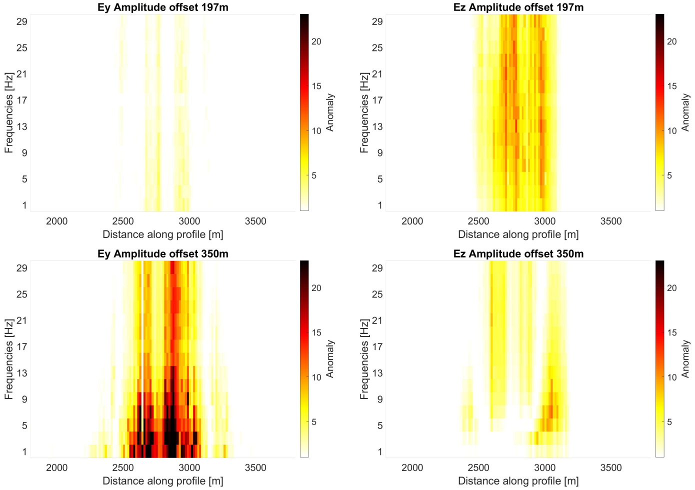
Data information - Forward modelling study





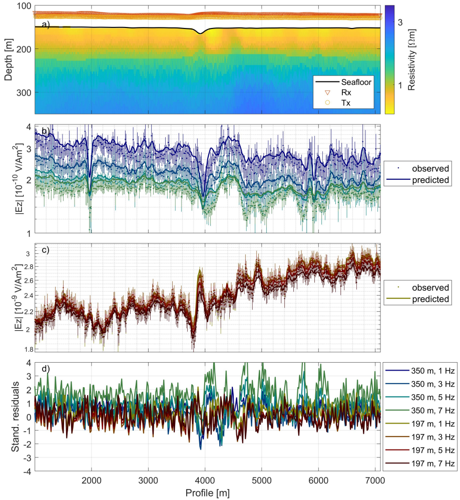
- Analysing the effect of 40% gas pocket underneath seismic reflector
- Predicted data for model with and without gas pocket
- Difference in predicted data (residuals) vs data error σ (based on stacking and navigational uncertainties Gehrmann et al., 2019)
- Data anomaly for datum i $(F(\mathbf{m}_{0\%})_i - F(\mathbf{m}_{40\%}))_i/\sigma_i$, where $F(\mathbf{m})$ is the forward operator on model $\mathbf{m}$.

Data information - Forward modelling study

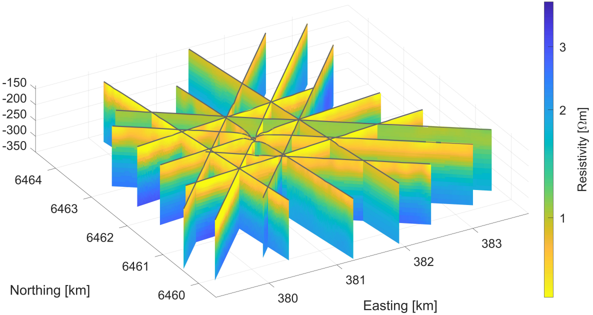


- Data anomaly for inline E_y and vertical E_z electric field response for $f < 30$ Hz
- Anomaly for short offset (197 m) similar for all frequencies
- Anomaly for long offset (350 m) more diverse (different information) in the $f < 13$ Hz
- Higher frequencies seem to contain similar information and would therefore bias the result if included into inversion

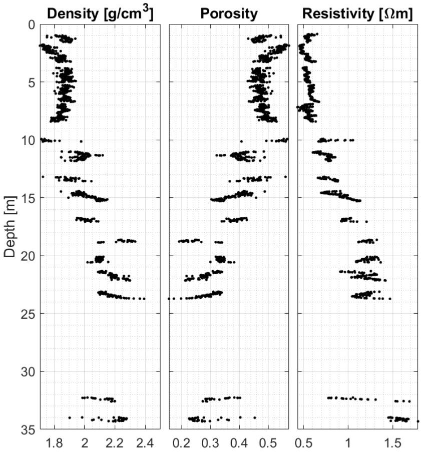
CSEM data inversion results



- Optimal resistivity models from inversion (MARE2DEM, Key, 2016) for vertical electric field component for 1 to 7 Hz
- Background resistivities vary between 0.6–1 Ωm at the surface and 2–2.6 Ωm at 200 mbsf.



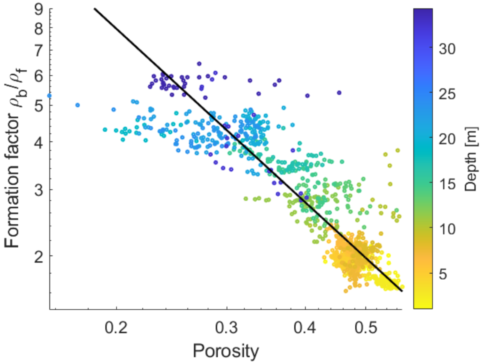
Physical parameters from RD2 core MSCL data



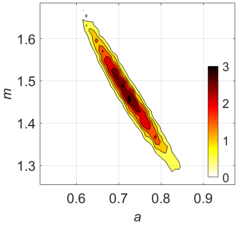
- Rock Drill 2 (BGS) cores at reference site about 6 km to the North East of Scanner (Karstens et al., 2019).
- Bulk density and resistivity are measured with the multi-sensor core logger by BOSCORF using gamma ray attenuation (Evans, 1965) and electromagnetic induction (Jackson et al., 2006) respectively
- Porosity ϕ is estimated from density d using $\phi = d_{\text{bulk}} - d_{\text{grain}}/d_{\text{fluid}} - d_{\text{grain}}$ with d_{grain}=2.65 g/cm^3 and d_{fluid}=1 g/cm^3 (Geotek, 2016)

Resistivity-Porosity relationship

- Logging data shows a distinct trend for resistivity vs porosity with depth



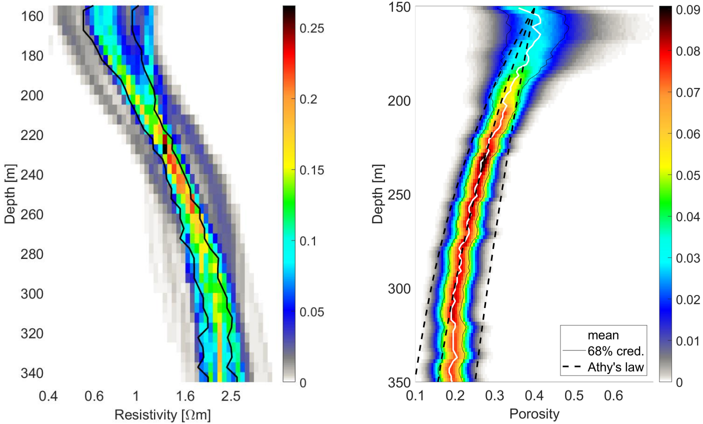
- The empirical Archie's law (Archie, 1942) $\rho_{\text{bulk}}/\rho_{\text{fluid}} = a\phi^{-m}$ can be fit to the logging data
- Archie parameters a and m can be calibrated
- Best fit from non-linear optimisation (Dosso et al., 2001) for $a = 0.73$ and $m = 1.46$.



Porosity estimation

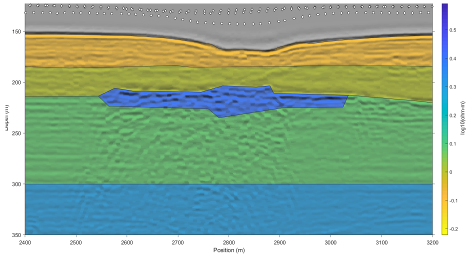
- Sampling from resistivity, Archie's parameter relationship to estimate background porosity
- Comparison to Athy's law of compaction (Athy, 1930) $\phi = \phi_0 e^{-\beta\sigma'}$, where the compressibility is represented by β, for clay-rich, plastic sediments is chosen here between 2–6 $\cdot 10^{-7}$ 1/Pa the effective stress σ' depends on lithostatic pressure and therefore on depth and density

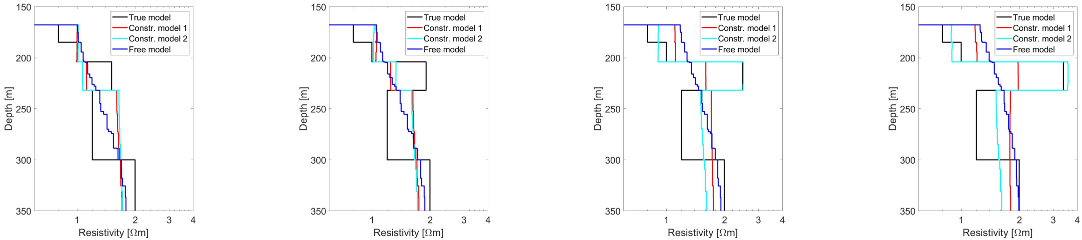
- Probability density for resistivity and porosity



Forward modelling and inversion study

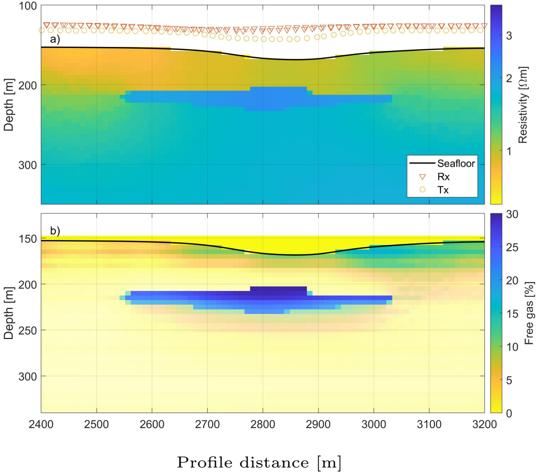
- Synthetic data (realistic data error) for models with different gas saturation using seismic constraints
- Background is 1.2 Ωm, 10% gas → 1.5 Ωm, 20% gas → 1.9 Ωm, 30% → 2.5 Ωm, 40% → 3.4 Ωm using Archie's law
- Vertical profiles show that about 20–30% of gas required to be resolved





Gas estimation

- Resistivity model with seismic constraints (top) shows background resistivity increase from below 1 Ωm to 1.8 Ωm at 200 mbsf
- Gas pocket with up to 30% free gas estimated (bottom). Caution: Errors as large as estimation!
- However, synthetic data study suggests at least 20% are required to cause resistivity anomaly
- Interdisciplinary data and modelling also back up shallow gas pocket required to explain the active venting



Summary

- We estimate a background resistivity trend from 0.6–1 Ωm at the surface and 2–2.6 Ωm at 200 mbsf from towed CSEM vertical electric field amplitude data.
- Using structural constraints from seismic data reveals a resistive area at about 40 mbsf below the pockmark, a potential shallow gas pocket.
- With forward modelling we estimate that frequencies from 1 to 7 Hz have the most diverse information content about the gas pocket.
- A synthetic data study shows that at least 20–30% gas are required to cause an anomaly in the CSEM data above the data error.
- We calibrate the rock physics relationship Archie's law with sediment core logging data to predict porosity and free gas.
- Porosities decrease from about 40$\pm$9% at the seafloor to 19$\pm$3% at 200 mbsf, which matches porosity estimates from sediment compaction.
- Gas estimates are up to 30% with equally large uncertainties and require comparison to the geophysical, geochemical and modelling studies done in the STEMM-CCS project.
- The towed CSEM data resolves the upper 100-200 mbsf, but resolving physical parameters of the chimney at greater depth requires adding more data, for example, from the ocean bottom instruments.

Acknowledgements

- Special thanks to the Ocean Bottom Instrument Consortium team and Laurence North for technical support.
- Thanks to the MSM63 and MSM78 cruise crew and scientific party.
- Thanks to the BGS Rock Drill 2 and the BOSCORF team.
- Thanks to Steven Constable from Scripps for advice and eight loggers.
- Thanks to David Myer and Kerry Key for processing and inversion routines.
- Many thanks to the European Commission for funding the Horizon2020 project STEMM-CCS (Project no 654462).
- Thanks for being able to use the IRIDIS High Performance Computing Facility at the University of Southampton.
- Thank you for viewing the presentation and please comment plentifully.

G. E. Archie. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Trans. Am. Inst. Min. Metall. Pet. Eng.*, 146:54–62, 1942.

L.F. Athy. Density, porosity, and compaction of sedimentary rocks. *Am. Assoc. Pet. Geol. Bull.*, 14:1– 22, 1930.

C. Berndt, J. Elger, C. Böttner, R. Gehrmann, J. Karstens, S. Muff, B. Pitcairn, B. Schramm, A. Lichtschlag, and A. Völsch. RV MARIA S. MERIAN Fahrtbericht / Cruise Report MSM63 - PERMO, Southampton – Southampton (U.K.) 29.04.-25.05.2017. GEOMAR Report N.Ser. 037, 2017.

Christoph Böttner, Christian Berndt, Benedict T.I. Reinardy, Jacob Geersen, Jens Karstens, Jonathan M. Bull, Ben J. Callow, Anna Lichtschlag, Mark Schmidt, Judith Elger, Bettina Schramm, and Matthias Haeckel. Pockmarks in the witch ground basin, central north sea. *Geochemistry, Geophysics, Geosystems*, 20(4):1698–1719, 2019. doi: 10.1029/2018GC008068.

S. C. Constable, Peter K. Kannberg, and Karen Weitemeyer. Vulcan: A deep-towed CSEM receiver. *Geochemistry, Geophysics, Geosystems*, 17(3):1042–1064, 2016. ISSN 1525-2027. doi: 10.1002/2015GC006174.

Stan E. Dosso, Michael J. Wilmut, and A.-L. S. Lapinski. An Adaptive-Hybrid Algorithm for Geoacoustic Inversion. *Oceanic Engineering, IEEE Journal of*, 26(3):324–336, 2001.

R. Nigel Edwards. On the resource evaluation of marine gas hydrate deposits using sea-floor transient electric dipole-dipole methods. *Geophysics*, 62(1):63–74, 1997.

H.B. Evans. Grape - a device for continuous determination of material density and porosity. In *Proceedings of 6th Annual SPWLA Logging Symposium. Dallas, TX.*, volume 2, pages B1–B25, 1965.

Joana Gafeira and David Long. Geological investigation of pockmarks in the scanner pockmark sci area. *JNCC Report*, 570, 2015.

Romina A S Gehrmann, Amir Haroon, McKinley Morton, Axel T Djanni, and Timothy A Minshull. Seafloor massive sulphide exploration using deep-towed controlled source electromagnetics: navigational uncertainties. *Geophysical Journal International*, 220(2):1215–1227, 2019. doi: 10.1093/gji/ggz513.

Geotek. Multi-Sensor Core Logger - Manual, 2016.

P.D.J. Jackson, M.A. Lovell, J.A. Roberts, P.J. Schultheiss, D. Gunn, R.C. Flint, A. Wood, R. Holmes, and T. Frederichs. *New Techniques in Sediment Core Analysis*, volume 267, chapter Rapid non-contacting resistivity logging of core, pages 209–217. Geological Society London, Special Publication, 2006.

Jens Karstens and Christian Berndt. Seismic chimneys in the Southern Viking Graben – Implications for palaeo fluid migration and overpressure evolution. *Earth Planet. Sci. Lett.*, 412:88–100, 2015.

Jens Karstens, Christoph Böttner, Mike Edwards, Ismael Falcon-Suarez, Anita Flohr, Rachel James, Anna Lichtschlag, Doris Maicher, Iain Pheasant, Ben Roche, B. Schramm, and Michael Wilson. RV MARIA S. MERIAN Fahrtbericht / Cruise Report MSM78 - PERMO 2, Edinburgh – Edinburgh (U.K.) 16.10.-25.10.2018. GEOMAR Report N.Ser. 048, 2019.

Kerry Key. MARE2DEM: A 2-D inversion code for controlled-source electromagnetic and magnetotelluric data. *Geophysical Journal International*, 207(1):571–588, 2016.

David Myer, Steven Constable, and Kerry Key. Broad-band waveforms and robust processing for marine CSEM surveys. *Geophys. J. Int.*, 184:689–698, 2011.

MC Sinha, PD Patel, MJ Unsworth, TRE Owen, and MRG MacCormack. An active source electromagnetic sounding system for marine use. *Marine Geophysical Researches*, 12(1-2):59–68, 1990.

P. Weidelt. Guided waves in marine CSEM. *Geophys. J. Int.*, 171:153–176, 2007.