New Advances in Geophysics (NAG) meeting 2016
Integrated Imaging of the Earth

Program

11 -12 February, Burlington House, London

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# Schedule

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| **Thursday 11/2** | |
| 9:30 - 10:00 | Registration and Coffee |
| 10:00 - 12:00 | Theoretical developments in integrated imaging |
| 12:00 - 13:30 | Lunch |
| 13:30 - 16:00 | Integrated imaging for natural resource exploration |
| 16:00 - 18:00 | Posters and wine reception |
| **Friday 12/2** | |
| 10:00 - 10:30 | Coffee |
| 10:30 - 12:25 | Integrated imaging for near surface imaging |
| 12:25 - 13:50 | Lunch |
| 13:50 - 14:00 | BGA AGM |
| 14:00 - 15:30 | Integrated imaging from the crust to the deep Earth |

# Oral Presentations

## 11 February

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| 10:00 - 10:10 | | Introduction |
| 10:10 - 10:50 | Javier Fullea | Integrated geophysical-petrological modelling of the upper mantle using terrestrial and satellite data **(Invited)** |
| 10:50 - 11:15 | Romina Gehrmann | Analysis of controlled source electromagnetic data in the Black Sea: Regularized 2-D inversion with seismic constraints and trans-dimensional Bayesian inversion to estimate uncertainties |
| 11:15 - 11:40 | Clifford Thurber | Methods and Applications of Joint Geophysical Inversion |
| 11:40 - 12:05 | Naser Meqbel | Joint 3D inversion of multiple electromagnetic data sets |
| | Lunch | |
| 13:30 - 13:55 | Carl Fredrik Gyllenhammar | Is there space for petrophysics in Rock Physics? |
| 13:55 - 14:20 | Lucy MacGregor | Integrated interpretation of seismic and CSEM data for reservoir characterisation. |
| 14:20 - 14:45 | Michal Stefaniuk | An attempt of application of integrated magnetotelluric and seismic data interpretation for recognizing of geological structure and petroleum traps in Polish Outer Carpathians. |
| 14:45 - 15:10 | Alan Roberts | Integrated imaging of fracture systems from surface outcrop and geophysical data |
| 15:10 - 16:00 | | Discussion – Future Avenues |
| | Wine and Posters | |

## 12 February

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| 10:30 - 11:10 | Niklas Linde | On the value of multiple data types and conceptual geological knowledge in hydrogeophysical inversion **(Invited)** |
| 11:10 - 11:35 | Bedanta Goswami | Joint resistivity and seismic image of an active seep area in the Arctic Ocean |
| 11:35 - 12:00 | Maria Garcia Juanatey | Joint and constrained inversions of magnetic and gravity data in the Skellefte District |
| 12:00 - 12:25 | Richard Hobbs | Bayesian Networks for pore-pressure prediction |
| | | Lunch |
| 14:00 - 14:40 | Tony Lowry | Thermo- & hydration dynamics of the lithosphere from combined seismic, potential field and petrophysical constraints **(Invited)** |
| 14:40 - 15:05 | Max Moorkamp | Using seismically constrained magnetotelluric inversion to recover velocity structure in the shallow lithosphere |
| 15:05 - 15:30 | Amy Gilligan | Seismological structure of the 1.8Ga Trans-Hudson Orogen of North America and comparisons with present-day Tibet |

# Posters

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| Islam Fadel | Joint inversion of surface waves, gravity and gravity gradients |
| Jim Whiteley | A statistical analysis of co-located MASW and ERT data to identify zones of common geophysical parameters within Cretaceous Upper Chalk |
| Björn Heincke | Joint inversion scheme with an adaptive coupling strategy - applications on synthetic and real data sets |
| Giuseppe Provenzano | Combining seismic sediment characterisation and geotechnical data to obtain a quantitative model of shallow marine sediments |
| Alan Roberts | Joint stochastic constraint of a salt-dome |
| Jan Vozar | Joint inversion modelling of geophysical data from Lough Neagh Basin |
| Marion Jegen | Joint interpretation of electromagnetic and seismic data to determine gas and methane hydrate distribution within the Nyegga CN03 seep |

# Abstracts

# CALCULATION OF THE LONG-WAVELENGHT SEISMIC STATIC CORRECTIONS BASED ON VELOCITY-DEPTH MODEL DERIVED FROM JOINT INVERSION OF GRAVITY AND REFRACTION DATA, FOR SEISMIC RESEARCH IN POLISH CARPATIANS

*A.Cygal[1], J. Pilch[1], K. Pieniądz[1], M. Stefaniuk[1], T. Maćkowski[1]*
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The paper presents the results of seismic data processing flow where the integrated seismic-gravity inversion was applied in order to derive long-wavelength static corrections. Research area was located in the SE part of Poland, namely at the boundary of Silesian and Skole Units of the Outer Flysch Carpathians. This is a region of a complex fold-thrust geology with angles of the dipping layers up to 90 degrees. In combination with sharp elevation changes ranging within about 300 m, seismic imaging in this area is exceptionally challenging and the interpretation of its results – extremely ambiguous. Such a variability of geological medium in the presence of complex tectonic structures, creates an opportunity for the existence of so-called negative velocity gradients, whose location is shown in the results. It appears that including them in a near-surface model is essential for an appropriate calculation of static corrections. Tests and analysis performed during this research led to the development of a successful methodology of static corrections computation. It consists of a simultaneous inversion of geophysical data such us: seismic, gravity and borehole (if they are available in the area of interest). Such an integrated approach results in the distinctively better near-surface model solutions than using the classical method alone, be it general linear invesion (GLI) or first-arrival traveltime tomography. Statics obtained from velocity model, being a product of joint inversion along with converted density distribution model, has proven to be more reliable and detailed than velocity model developed without any geophysical data integration. Application of such an advanced static corrections significantly improved the quality of seismic image of the subsurface in the first stage of seismic data processing. There is also evidence that a good initial model is crucial for properly conducted inversion and in each cases it influenced the character of the final model in a decisive manner. It is, therefore, vital that each starting model is geologically interpretable and verified with information such as surface geological maps and wells, what exactly has been done in this study. According to the presented examples of statics calculated from velocity and gravity models and resulting seismic section enhancement, the main conclusion can be drawn that an integration of geophysical and geological data in joint inversion process is the best method for complex fold-thrust geological settings.

**Key words:** joint inversion, traveltime data, gravity data, long wavelength static corrections, seismic processing,

**Acknowledgments.** This paper was based on results of investigations carried out in the framework of the project entitled “Experimental, complexes and multi-variant interpretation of seismic, magnetotelluric, gravity and borehole data as a tool to improve the effectiveness of structural and reservoir research” – Applied Research Program III (In Polish: Program Badań Stosowanych III).

# Joint inversion of surface waves, gravity and gravity gradients

*Islam Fadel[1], Mark van der Meijde[1], Max Moorkamp[2], Hanneke Paulssen[3]*
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Joint inversion is a key player in getting more realistic and self-consistent 3D subsurface models. With the emerging large amount of high-quality seismological data from different seismological networks and the global coverage gravity and gravity gradients measurements provided by recent GOCE satellite mission, a new methodology is needed to exploit the full capability of both datasets and to enhance the 3D subsurface models.

In this study, we will present a synthetic test for jointly inverting surface waves, gravity and gravity gradients. We will test the direct coupling approach using available velocity-density relationships and the structure constraint approach using cross-gradient to enforce structural similarities between shear wave and density models.

The comparison between the results from the two approaches will be used as a guidance for future studies where real data will be used.

# Integrated geophysical-petrological modelling of the upper mantle using terrestrial and satellite data

*J. Fullea, Dublin Institute for Advanced Studies (DIAS), Dublin 2, Ireland*

Surface topography is a paradigmatic example of the degree of entanglement of the different geophysical-petrological parameters commonly used to describe the Earth. The elevation of the Earth's surface depends, according to the isostatic principle, on the average density of the lithosphere that is primarily sensed by gravity methods and, indirectly, by seismic observations on propagating wave speeds. The lithospheric flexural response to variations in the surface elevation depends on the wavelength of the topographic loads and the mechanical strength of the lithosphere, which is primarily controlled by its rheology. Residual, non-isostatic topography has two sources: i) our imperfect knowledge of the crustal and lithospheric mantle density; and ii) a dynamic component. Dynamic topography is related to the vertical stress field (dependent on mantle density heterogeneity) and the rheology of the Earth. In turns, the viscosity of rocks is strongly affected by even a small amount of water (OH- ions structurally linked to the mineral lattice), which is mostly sensed by electromagnetic methods through orders-of-magnitude variations in the electrical conductivity of rocks. Dry and wet rocks have very similar densities but quite different melting points, and this has strong influence on their mechanical strength and rheological behaviour (i.e., viscosity). To close the loop, density, viscosity, seismic velocities, electrical conductivity, water and melt are all non-linearly related and linked to the common temperature, pressure and bulk composition conditions within the Earth. Therefore, an appropriate understanding of even the most straightforwardly measured and apparently simple Earth observable – its present-day surface topography– requires a consistent, complex and holistic integration of gravity, seismic electromagnetic, petrological and geodynamic modelling.

# Joint and constrained inversions of magnetic and gravity data in the Skellefte District

*María A. García Juanatey, Uppsala University*
*Peter Lelièvre, Memorial University*
*Christopher Juhlin, Uppsala University*
*Colin Farquharson, Memorial University*

The Skellefte District is a very rich metallogenic province in northern Sweden. Its complicated structural setting pose a challenge for geophysical and geological investigations in this area. Most recent research efforts have been directed at the construction of 3D geological models through the combined interpretation of independently modeled geophysical and geological data. This approach took advantage of the similarities between the data sets, but could not deal with the inconsistencies between the different data sets. Our aim is to take the integration efforts further by integrating the datasets already at the modelling stage. In this way we intend to address the inconsistencies and reduce significantly the uncertainties associated to the constructed 3D models. The available geophysics in the district includes regional gravity and magnetic data, four seismic reflection lines, and more than 60 magnetotelluric sites. The existing geological data is condensed on interpreted surfaces representing the most important lithological boundaries. Additionally, there are density and susceptibility values obtained from samples across the whole district. At the moment, we are looking for the best way to integrate the different geophysical datasets with geologically-constrained, joint and cooperative inversions. In this contribution we show preliminary results with the magnetic and gravity data.

# Analysis of controlled source electromagnetic data in the Black Sea: Regularized 2-D inversion with seismic constraints and trans-dimensional Bayesian inversion to estimate uncertainties

*Romina Gehrmann, University of Southampton, UK*
*Katrin Schwalenberg, Federal Institute for Geosciences and Natural Resources, Germany*
*Timo Zander, GEOMAR, Germany*
*Jan Dettmer, University of Victoria, BC, Canada*

In 2014 an interdisciplinary survey was conducted as part of the German SUGAR project in the Western Black Sea targeting gas hydrate occurrences in the Danube Delta. Marine controlled source electromagnetic (CSEM) data were acquired with a seafloor-towed horizontal dipole-dipole array. We present inversion results from two different approaches for one CSEM profile co-located with one seismic reflection profile from a high resolution 3-D data set. First, two-dimensional (2-D) regularised inversion (MARE2DEM by Kerry Key) is applied which provides a smooth model of the electrical resistivity distribution beneath the source and multiple receivers. The 2-D approach includes seafloor topography and structural constraints from seismic data. Second, trans-dimensional (trans-D) Bayesian inversion for a layered subsurface is carried out which treats the number of layers as unknown and rigorously estimates parameter uncertainty. To quantify parameter uncertainty, we consider one CSEM data location and apply trans-D inversion via reversible jump Markov-chain Monte Carlo (random) sampling. A non-diagonal data covariance matrix, obtained from residual error analysis, accounts for correlated errors. The thorough uncertainty analysis is relevant to estimate realistic upper and lower bounds on resistivities and subsequently on gas hydrate saturation along the profile.

# Seismological structure of the 1.8Ga Trans-Hudson Orogen of North America and comparisons with present-day Tibet

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The geology of northern Hudson Bay records the Paleoproterozoic (~1.8Ga) Trans-Hudson Orogeny (THO), making it an ideal locality to study Precambrian orogenic processes. Previous studies suggest that the THO was comparable to the present-day Himalayan-Karakoram-Tibet Orogen (HKTO). However, detailed understanding of the deep crustal architecture of the THO, and how it compares to that of the HKTO, is lacking.

Joint inversion of receiver functions and surface wave data provides new Moho depth estimates and shear velocity models for the crust and uppermost mantle of the THO. Archean crust is relatively thin (~39 km) and structurally simple, with sharp Moho. However, the Quebec-Baffin segment of the THO has a deeper Moho (~45km) and a more complex crustal structure. Observations show some similarity to recent models, computed using the same methods, of the HKTO crust. Based on Moho character, present-day crustal thickness, and metamorphic grade, we propose that southern Baffin Island experienced thickening during the THO of a similar magnitude and width to present-day Tibet. Fast seismic velocities at >10km below Southern Baffin Island may be the result of partial ecologitization of the lower crust during the THO, as is currently thought to be happening in Tibet.

# Joint resistivity and seismic image of an active seep area in the Arctic Ocean

*Bedanta Goswami, University of Southampton*
*Karen Weitemeyer, University of Southampton*
*Timothy Minshull, University of Southampton*

The Arctic continental margin contains large amounts of methane within hydrates. The west Svalbard continental slope is one of the areas where active methane seeps have been reported near the landward limit of the hydrate stability zone. The presence of bottom simulating reflectors (BSRs) on seismic reflection data in water depths deeper than 700 m provides evidence for the presence of hydrate. Resistivity obtained from marine controlled source electromagnetic (CSEM) data provides a useful complement to seismic methods for detecting shallow hydrate and gas. We therefore acquired two CSEM lines in the west Svalbard continental slope, extending from the edge of the continental shelf to water depths of around 800 m. High resistivities (5-12 Ωm) observed above the BSR support gas hydrate presence in deep water depths. High resistivities (3-4 Ωm) at 700-390 m water depth also suggest possible hydrate occurrence within the gas hydrate stability zone (GHSZ) of the continental slope. Additionally, high resistivities (4-8 Ωm) landward of the GHSZ are coincident with high-amplitude reflectors and low velocities reported in seismic data that indicate the likely presence of free gas. The joint interpretation also suggests lateral free gas migration beneath the GHSZ to the active seep area.

# Is there space for petrophysics in Rock Physics?

*Dr. Carl Fredrik Gyllenhammar, Independent Consultant, Valkyrjegaten 22, 4011 Stavanger, Norway*

Petrophysics has evolved since the first e-log in 1927. The calculation of Vcl, porosity and Sw to calculate the volume of hydrocarbons in place has been achieved by adding as many independent measurements as possible.

Rock Physics is more recent, evolving from the seismic industry. Limited to velocity, density and elastic moduli, to detect hydrocarbons.

The different elastic moduli of most minerals are documented by lab experiments. By taking the average of each constituents, one can predict the Voigt upper bound (max stiffness) and Reuss lower bounds (softness before fluid).

The data is often presented in a cross-plot, P-velocity versus porosity.

The author has just completed a study where 220 wells, between 58 and 62 degree north in the Norwegian sector, have been interpreted using all available wireline logs. A model for volume of clay using the sonic-density cross-plot will be presented. Cross-plotting P-velocity versus porosity shows that shale often fall below the Reuss lower bound. The author suggests that the source for porosity calculation could be the error.

If the petrophysical interpretation are accurate the resistivity of brian can be calculated. A preliminary Rw map at TD in all 220 wells has given a surprising result.

# Joint inversion scheme with an adaptive coupling strategy – applications on synthetic and real data sets

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*Max Moorkamp, University of Leicester, UK*

Joint inversion strategies for geophysical data have become increasingly popular since they allow to combine complementary information from different data sets in an efficient way. However, for joint inversion algorithms that use methods that are sensitive to different parameters, it is important that they are not restricted to specific survey arrays and subsurface conditions. Hence, joint inversion schemes are needed that 1) adequately balance data from the different methods, 2) ensure a stable convergence behavior and guarantee adequately low data misfits, 3) consider the different resolution powers of the methods and 4) use links between the parameter models that are suited for a wider range of applications.

We present a cell-based non-linear petrophysical 2-D joint inversion of MT, seismic tomography and gravity data that that accounts for these critical issues. To avoid relative scaling a cooperative joint inversion strategy is used, in which the inversion steps are performed separately for each method and the otherwise independent inversions are linked by employing constraints that account for parameter relationships. To ensure that the inversion convergence for all methods is not profoundly disturbed by the coupling, the strengths of the associated constraints are re-adjusted at each iteration. For the adaption of the coupling strengths a criterion is considered that is based on the variations of the objective functions at successive iterations. The different resolutions of the involved methods are considered by making the behavior of the coupling constrains dependent on the relative resolution power of the methods. Fixed relationships between seismic velocities, densities and resistivities in this scheme is an assumption that is surely only valid for certain subsurface conditions. However, in the case that an inadequate relationship disturbs the convergence towards an acceptable low data misfit, the adaption procedure reduces the coupling strengths. This means that the impact of the link is weakened and that the relationships between the finally obtained physical parameter models can deviate significant from the assumed parameter relationships if it is required to receive adequately low data misfits.

Results from synthetic models and a real data example from the Faroe-Shetland Basin, where different geophysical data are combined for subbasalt imaging, demonstrate that the scheme works very robust and provides much more reasonable an better resolved models than the corresponding individual inversions.

POSTER CONTRIBUTION

# Joint interpretation of electromagnetic and seismic data to determine gas and methane hydrate distribution within the Nyegga CN03 seep.

*S. Hoelz, M. Jegen-Kulcsar, D. Cukur, M. Sommer, E. Attias, K. Weitemeyer and C. Berndt.*

The presence of the Nyegga pock marc field within the gas hydrate stability field on the Norwegian continental slope points to possible methane release through cold seeps. It is, however, not clear how the methane may migrate through the still existing hydrate stability zone as the gas should form new hydrate further up in the section. In an effort to better understand the physical processes and quantify the hydrate/gas distribution in the area, GEOMAR and the University of Southampton collected different types of electromagnetic data sets with different depth ranges and resolution in a region, which has been extensively covered by seismic investigation.
The presence of hydrate within seafloor sediments causes an increase in both the bulk modulus, and hence the seismic velocity, and in the electrical resistivity. The presence of gas decreases seismic velocity but increases electrical resistivity.
Both seismic and controlled source electromagnetic methods can and have been used to estimate hydrate and gas content. Since seismic velocity and the electrical resistivity are sensitive also to a range of other parameters such as lithology, porosity and pore fluid salinity, single rock property parameter investigations are hampered by many uncertainties. However, since the sensitivities are different for the two properties, determination of both velocity and resistivity for the same volume of sea bed provides a powerful tool for distinguishing the contribution of hydrate or gas from that of other parameters.
In this work we report on a new type of 3D electromagnetic high resolution tomography experiment which was focused on the CN03 chimney in the centre of the region. The data indicates the presence of a highly resistive zone, where seismic travel time tomography has shown the presence of gas hydrates within the chimney. The distribution of methane hydrate concentrations are derived based on a joint interpretation of seismic velocity and electrical resistivities.

# On the value of multiple data types and conceptual geological knowledge in hydrogeophysical inversion

*Niklas Linde, University of Lausanne, Institute of Earth Sciences, Applied and Environmental Geophysics Group, Géopolis 3779, 1015 Lausanne, Switzerland*

A single geophysical property field obtained by smoothness-constrained inversion is often insufficient for robust and reliable inference of hydrogeological or reservoir state variables and properties. Information can be added to the inverse problem either by new data sources or by including information about the geological setting. Joint inversion improves the model resolution and the resulting model realizations are generally better suited for quantitative interpretations. To obtain high-resolution property fields that display realistic connectivity patterns (essential for subsurface mass transfer) it is necessary to work within a framework that accounts for the underlying geological setting. A well-suited tool to achieve this is multiple-point statistics that generate multiple (conditional or unconditional) subsurface realizations that are in agreement with a training image that defines the underlying conceptual geological model. The numerical challenges of conditioning to indirect geophysical or hydrogeological data (especially for discontinuous property fields) will be exemplified by crosshole ground-penetrating radar examples. Model uncertainty is ideally quantified by sampling multiple conditional realizations in proportion to the posterior distribution, but the resulting uncertainty estimates obtained by Markov chain Monte Carlo methods are often overly optimistic.

# Thermo- & hydration dynamics of the lithosphere from combined seismic, potential field and petrophysical constraints

*Anthony R. Lowry, Utah State University, Logan UT USA*
*Derek L. Schutt, Colorado State University, Ft Collins CO USA*
*Marta Pérez-Gussinyé, Universität Bremen, Germany*
*Janine Buehler, Scripps Institute of Oceanography, San Diego CA USA*
*Xiaofei Ma, Utah State University, Logan UT USA*
*Michael A. Berry, New Mexico Tech, Socorro NM USA*
*Dhananjay Ravat, University of Kentucky, Lexington KY USA*

By coupling joint inversion methodologies to mineral physics, we find evidence that water plays a more important role in tectonism than previously realized. Among the observations,
• Thermodynamical modeling suggests hydration promotes crustal mineral assemblages with lowered $v_P/v_S$, shedding new light on low crustal $v_P/v_S$ measured in the western U.S. Cordillera from joint inversion of USArray receiver functions and gravity. $v_P/v_S$ is strikingly low throughout the high-elevation regions of the western Cordillera.
• Rheological modeling of flexural rigidity measurements can map water variations in the uppermost mantle. Mantle hydration inverted from flexural rigidity exhibits similar spatial distribution to crustal hydration inferred from $v_P/v_S$, with notable exception that the Wyoming craton has mostly dry mantle lithosphere but a hydrous crust.
• In hydrated lithosphere of the high-elevation western U.S., Moho temperatures derived from Pn velocities are systematically colder than predictions from surface heat flow modeling. These differences implicate a previously unrecognized advective contribution to thermal transfer.
Lithospheric hydration may result from dehydration of subducted slab or entrainment of water into upwellings from the mantle transition zone. Conceptualizing hydration as a large-scale process that increases buoyancy, decreases ductile strength and changes lithospheric mineralogy, mass and energy transfer may illuminate enigmatic processes of uplift and strain.

# Integrated interpretation of seismic and CSEM data for reservoir characterisation.

*Lucy MacGregor, James Tomlinson, RSI Geophysical Ltd.*

Combining multiple geophysical data types using integrated interpretation can provide information on earth properties that is ambiguous when only a single data type is considered. The combination of seismic and CSEM data within a rock physics framework has the potential to improve the certainty with which reservoir lithology and fluid properties are constrained. Although integrated interpretation brings many benefits, there are a number of challenges to be overcome before such approaches can be robustly applied. Firstly, measurements made using very different physical processes must be combined and linked to the underlying rock and fluid properties in a consistent fashion. This requires a rock physics framework to be either numerically derived or empirically calibrated at well locations. Secondly seismic and CSEM techniques sample the earth at very different scale. These different scales must be reconciled in an integrated interpretation or joint inversion approach. Finally in order for an integrated interpretation approach to be successful, both seismic and CSEM methods must be sensitive to the interval of interest and changes in properties within it. The solutions to these challenges are case dependent and must be considered with care. This presentation will illustrate approaches to addressing these challenges in reservoir characterization.

# Joint 3D inversion of multiple electromagnetic data sets

*Naser Meqbel, Helmholtz-Centre Potsdam - GFZ*
*Oliver Ritter, Helmholtz-Centre Potsdam - GFZ*

Electromagnetic (EM) methods are routinely applied to image the subsurface from shallow to regional structures. Individual EM methods differ in their sensitivities towards resistive and conductive structures as well as in their exploration depths. If a balance between different EM data can be found, joint 3D inversion of multiple EM data sets can result in significantly better resolution of subsurface structures than the individual inversions. We present a weighting algorithm to combine magnetotelluric (MT), controlled source EM (CSEM), and geoelectric (DC) data. Our new scheme is based on weighting individual components of the total data gradient after each model update. Norms of individual data residuals are used to determine weighting parameters. Synthetic inversion tests demonstrate advantages of joint inversion in general and also the influence of the weighting. In our tests, the CSEM data gradients are several orders of magnitudes larger than those of the MT and DC data sets. Consequently, direct joint inversion of CSEM, MT and DC data results in models which are dominated by structures required by the CSEM data. Applying the new adaptive weighting scheme results in an inversion model which resembles better the original model and which has better data fit.

# Using seismically constrained magnetotelluric inversion to recover velocity structure in the shallow lithosphere

*Max Moorkamp, University of Leicester*
*Stewart Fishwick, University of Leicester*
*Alan Jones, Self Employed*

Typical surface wave tomography can recover well the velocity structure of the upper mantle in the depth range between 70-200km. For a successful inversion, we have to constrain the crustal structure and assess the impact on the resulting models. In addition, we often observe potentially interesting features in the uppermost lithosphere which are poorly resolved and thus their interpretation has to be approached with great care.

We are currently developing a seismically constrained magnetotelluric (MT) inversion approach with the aim of better recovering the lithospheric properties (and thus seismic velocities) in these problematic areas. We perform a 3D MT inversion constrained by a fixed seismic velocity model from surface wave tomography. In order to avoid strong bias, we only utilize information on structural boundaries to combine these two methods. Within the region that is well resolved by both methods, we can then extract a velocity-conductivity relationship. By translating the conductivities retrieved from MT into velocities in areas where the velocity model is poorly resolved, we can generate an updated velocity model and test what impact the updated velocities have on the predicted data.

We test this new approach using a MT dataset acquired in central Botswana over the Okwa terrane and the adjacent Kaapvaal and Zimbabwe Cratons together with a tomographic models for the region. Here, both datasets have previously been used to constrain lithospheric structure and show some similarities. We carefully asses the validity of our results by comparing with observations and petrophysical predictions for the conductivity-velocity relationship.

# Bayesian Networks for pore-pressure prediction

*Rachel Oughton, Richard Hobbs, David Wooff*
*Durham University*

When drilling a borehole to reach a hydrocarbon reservoir it is crucial to understand the pressure regime in the rock. If an overpressured area is encountered unexpectedly it can have costly and dangerous results. Predictions of pressure are made using a variety of sources of information; some is osberved data made whilst drilling, or from nearby wells, while some comes from the experience of the geologists. The standard prediction workflow involves a combination of ad hoc empirical formulae using limited subsets of the data and adjusting according to understanding of the area, with no rigorous or coherent framework for quantifying the uncertainty. We have developed a Bayesian network model that combines the available data with experts' knowledge in order to produce pore-pressure predictions with an uncertainty estimate that takes into account the whole process.

# Combining seismic sediment characterisation and geotechnical data to obtain a quantitative model of shallow marine sediments

*Giuseppe Provenzano, Ocean and Earth Sciences, National Oceanography Center Southampton, University of Southampton, European Way, Southampton, SO14 3ZH*

*Mark E. Vardy, Marine Geosciences Group, National Oceanography Center Southampton, European Way, Southampton, SO14 3ZH*

*Timothy J. Henstock, Ocean and Earth Sciences, National Oceanography Center Southampton, University of Southampton, European Way, Southampton, SO14 3ZH*

Quantitative models of near-surface marine sediments are important for geo-hazard and offshore engineering purposes. Characterisation these shallow marine sediments currently relies on direct sampling via cores, boreholes and CPTUs. This approach suffers from its inherent mono-dimensionality and becomes time-consuming and expensive for large areas. Furthermore, the sampling process mechanically alters the soft sediments, introducing systematic errors. In this framework, high-resolution seismic reflection data is traditionally limited to providing information about the geometry of the discontinuities, combined with a predominantly qualitative interpretation of the amplitude and polarity of the seismic phases.

Here I will present a pre-stack seismic inversion methodology custom-tailored for very-high-frequency (*VHF*) marine data to obtain decimetre-resolution elastic model of the near-seabed. Tests on synthetic data and a real marine dataset show how *VHF* seismic can be effectively combined with geotechnical measurements, providing a horizontal resolution unfeasible via direct sampling. The role of the geotechnical data is two-fold: on one hand it provides the seismic inversion with a low-frequency trend, on the other hand is valuable to validate the inversion results. The independent estimates of P-wave velocity and Poisson's ratio obtained from the seismic inversion strongly correlate to the core and the CPTUs measurements. The proposed inversion method opens the way to the three-dimensional mapping of geotechnical properties across large areas in terms of soil stiffness, undrained shear strength, compressibility and overpressure ratio, significantly limiting the need of extensive coring campaigns.

# Joint stochastic constraint of a salt-dome

*Alan W. Roberts, Durham University, Durham, UK.*
*[Current: Geospatial Research Limited, Durham, UK]*
*Richard W. Hobbs, Durham University, Durham, UK.*
*Michael Goldstein, Durham University, Durham, UK.*
*Max Moorkamp, Geomar, Kiel, Germany.*
*[Current: University of Leicester, Leicester, UK.]*
*Marion Jegen, Geomar, Kiel, Germany.*
*Bjorn Heincke, Geomar, Kiel, Germany.*
*[Current: GEUS, Copenhagen, Denmark.]*

Understanding the uncertainty associated with large joint geophysical surveys, is both a conceptual and practical challenge. Through the use of emulators, we adopt a Monte Carlo forward screening scheme to globally test a prior model space for plausibility. This approach means that the incorporation of all types of uncertainty is made conceptually straightforward, by designing an appropriate prior model space, from which to draw candidate models. We test the methodology on a salt-dome target, over which three datasets have been obtained; wide-angle seismic refraction, magneto-telluric and gravity data. We consider the datasets together using an empirically measured uncertain physical relationship connecting the three different model parameters; seismic velocity, density and resistivity, and show the value of a joint approach, rather than considering individual parameter models. The results are probability density functions over the model parameters, together with a halite probability map. The emulators are shown to give considerable speed advantage over running the full simulator codes, and we consider their use to have much potential in the development of geophysical statistical constraint methods.

# Integrated imaging of fracture systems from surface outcrop and geophysical data

*Alan W. Roberts, Geospatial Research Limited, Durham, UK.*
*Ekaterina A. Vsemirnova, Geospatial Research Limited, Durham, UK.*
*Richard R. Jones, Geospatial Research Limited, Durham, UK.*
*Jonathan J. Long, Geospatial Research Limited, Durham, UK.*
*Richard W. Hobbs, Durham University, Durham, UK.*

A thorough understanding of the fracture systems associated with reservoir structures is crucial to the effective hydrocarbon field production. Extensive surface mapping by geologists affords detailed and reliable understanding of the near-surface structures, however the depth to which this understanding can typically be applied is very shallow. Seismic and other geophysical techniques provide considerable, yet lower resolution, structural information about the subsurface. However, understanding the observed structural variations requires associated geological understanding to which the structural information can be tied. In this study we show how inference may be made as to fracture characteristics from seismic data and how the use of geophysical data can extend a detailed understanding of surface fracture data to the sub-surface.

**An attempt of application of integrated magnetotelluric and seismic data interpretation for recognizing of geological structure and petroleum traps in Polish Outer Carpathians.**

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The polish part of Outer Carpathians is the historical zone of petroleum exploration. Many oil and gas fields were discovered and is still exploited there, mainly located inside relatively shallow but highly complex flysch structures. The Carpathian overthrust is built of intensely deformed flysch sediments of different elastic parameters. It generates complex seismic wave field pattern. Therefore, the interpretation of geological structures and deriving potential petroleum traps is uncertain and wells cannot be reliably located. As recognizing the intra-orogenic structures based on seismic data is difficult, an attempt of integrated interpretation of geophysical data with use of magnetotelluric and seismic data joint to nearby borehole data was made. The presented example of interpretation is based on magnetotelluric data scaled by sounding made close to deep borehole. Initial model for constrained 2D magnetotelluric data inversion was constructed based on reflection seismic cross-section and results of electric well-log profiling interpretation. As a result, a geological model of the Carpathian orogenic structures was proposed. Based on integrated data interpretation, structural outlines of major high and low – resistivity structures were obtained. In general high resistivity complexes are correlated with zones predominated by sandstones that could make structures considered as hydrocarbon traps. Low resistivity areas are connected with layers predominated by silty – clayey lithotypes.

**Key words:** Outer Carpathians, integrated interpretation, constrained inversion, reflection seismic, magnetotellurics, reservoir traps.

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# Methods and Applications of Joint Geophysical Inversion

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We present two examples of joint geophysical inversion. In one case, two different seismic data types, body wave arrival times and surface wave dispersion data, are fit to the same model parameters, compressional and shear wave velocity. In the other case, two different data types, compressional wave arrival times and magnetotelluric (MT) data, are fit to two different sets of model parameters, compressional wave velocity and electrical resistivity, with a structural constraint to link the two. The joint inversion of body wave and surface wave data takes advantage of their complementary resolving capability, with surface waves better resolving the near surface and vertical variations in structure versus body waves better resolving the deeper structure and lateral variations in structure. We will describe two different ways to carry out this joint inversion. Joint seismic-MT inversion is far more complex, due to the lack of a direct theoretical or empirical connection between seismic velocity and electrical resistivity, the dramatic differences in resolving power of the two data types with depth, and the extremely different scaling of the sensitivity factors (Frechet derivatives) in the equations for the forward and inverse problems. We will show example applications of the two types of joint inversion.

# Joint inversion modelling of geophysical data from Lough Neagh Basin

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The Permo-Triassic Lough Neagh Basin, situated in the south-eastern part of Northern Ireland, exhibits elevated geothermal gradient in the exploratory drilled boreholes and indicates good geothermal exploitation potential in the Sherwood Sandstone aquifer. We have used a 3-D joint inversion framework (JIF3D code) for modelling the magnetotelluric (MT) and gravity data collected to the north of the Lough Neagh to derive robust subsurface geological models in the frame of the IRETHERM project. Comprehensive supporting geophysical and geological data (e.g. borehole logs, reflection seismic images, and Tellus Project airborne EM data to constrain MT data and the uppermost part of MT models) have been used in order to analyse and model the MT and gravity data.

Preliminary 3-D joint inversion modelling reveals that the Sherwood Sandstone Group and the Permian Sandstone Formation are imaged as a conductive zone at the depth range of 500 m to 2000 m with laterally varying thickness, depth, and conductance. The conductive target sediments become shallower and thinner to the north and they are laterally continuous. The layer is thickening and deepening in south-east direction. The conductivities vary from 0.1 to 1 S/m, which indicates high concentration of fluids.

# A statistical analysis of co-located MASW and ERT data to identify zones of common geophysical parameters within Cretaceous Upper Chalk

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Imaging dissolution features and rockhead in chalk using geophysical methods can be challenging. The typical massive bedding found within chalk often presents a scenario in which a unit may be lithologically homogenous, but differential dissolution has created localised chemical and physical heterogeneities. Using Multi-channel Analysis of Surface Waves (MASW) and Electrical Resistivity Tomography (ERT), this work aims to quantifiably assess the condition of an area of Cretaceous Upper Chalk in the south of England.

MASW provides subsurface shear-wave velocities, which are directly related to the shear strength of materials, whilst ERT provides resistivity values for subsurface materials, primarily identifying variations in the moisture content and/or chemical composition of a material. Both are commonly used in near-surface geophysical surveys and both methods provide cross-sectional information, allowing for the co-location of these survey types. While no universal rule exists determining the relationship between shear-wave velocity and resistivity, it may be possible to determine localised relationships between these properties using statistical analysis. This presentation demonstrates the use of *k*-means clustering to determine zones of common geophysical parameters prior to further intrusive investigation. This approach aims for quantitative analysis of data to allow for improved interpretation of difficult to interpret geophysical cross-sections.