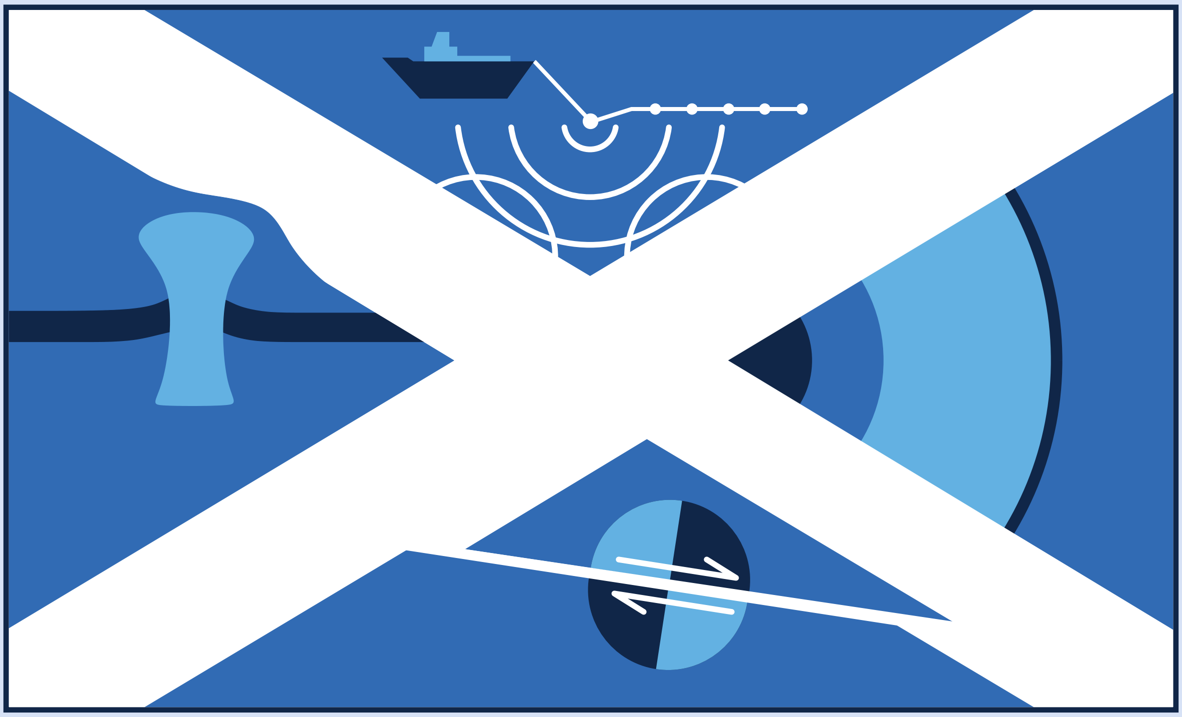
SEISMIX 2016

seismology at the crossroads



ABSTRACT VOLUME

17th International Seismix Symposium
Macdonald Aviemore Resort
Aviemore, Scotland
15-20 May

UNIVERSITY OF ABERDEEN

Dear Colleagues,

Welcome to the 17th International Seismix Symposium, held at the Macdonald Aviemore Resort in Aviemore, Scotland. In this abstract volume, we include all 171 abstracts that have been submitted to the conference for presentation by the approximately 145 delegates who have registered to attend. The origins of Seismix can be traced back to national programs of multichannel seismic reflection profiling of continents and their margins; notable examples include BIRPS in the UK, DEKORP in Germany, BELCORP in Belgium, Lithoprobe in Canada, and FIRE in Finland. A healthy proportion of abstracts submitted to Seismix 2016 document research based on such grand endeavours. However, in recent times, Seismix has diversified from crustal reflection profiling to include most classes of seismic imaging that can be applied to the crust and mantle lithosphere. Hence, methods include those that use active sources or passive sources and applications range in scale from exploration and the near surface through to the lithosphere beneath entire continents. This diversity is clearly present in the abstracts contained in this volume, and helps underscore the unique ability of Seismix to bring together the active/passive source imaging community, and those who work on solid Earth/exploration problems. As such, Seismix 2016 is truly at the crossroads.

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Barents Sea Paleozoic basement and basin configurations: Crustal structure from deep seismic and potential field data

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The Barents Sea is underlain by at least two different basement domains; the Caledonian in the west and the Timanian in the east. The transition between these two domains is not well constrained and contrasting interpretations have been published recently. Interpretations of new high-quality magnetic data covering most of the SW Barents Sea has challenged the Late Paleozoic basin configurations in the western and central Barents Sea as outlined in previous studies. Two regional ocean bottom seismic (OBS) profiles were acquired in 2014. This new dataset crosses the two major directions of Caledonian deformation proposed by different authors: N-S direction and SW-NE direction. Of particular importance are the high velocity anomalies related to Caledonian eclogites, revealing the location of Caledonian suture zones in the northern Barents Sea. One of the main objectives with this project is to locate the main Caledonian suture in the western Barents Sea, as well as the possible Barentsia-Baltica suture postulated further eastwards. The collapse of the Caledonian mountain range predominantly along these suture zones is expected to be tightly linked to the deposition of large thicknesses of Devonian erosional products, and later rifting is expected to be influenced by inheritance of Caledonian trends.

The P-wave travel-time modelling is done by use of a combined ray-tracing and inversion scheme, and gravity- and magnetic modelling will be used to augment the seismic model. The preliminary results indicate high P-wave velocities (mostly over 4 km/s) close to the seafloor as well as high velocity (around 6 km/s) zones at shallow depths which are interpreted as volcanic sills. The crustal transects reveal areas of complex geology and velocity inversions. A low seismic impedance contrast between the sedimentary section and top crystalline basement makes identification of this interface uncertain. Depth to Moho mostly lies around 30 km, except in an area of rapid change in Moho depth, from about 27 km to 32 km. This drop in Moho could indicate a relict subduction zone related to the Caledonian suture zone in the western Barents Sea.

Geologic characterization of Yucca Flat, Nevada, using the Seismic Hammer™

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We present analysis of a multi-component, multi-channel, active-source seismic dataset acquired at the Nevada National Security Site (formerly the Nevada Test Site) using a prototype 13,000-kg weight-drop source. The purpose of the test was to determine the suitability of the source, called the Seismic Hammer™, for basin-scale characterization of Yucca Flat, Nevada. The source generates seismic energy by lifting the mass 1.5 meters before dropping it on a 1.8-m diameter plate. This results in over 190,000 Joules of potential energy being released. My results show that this results in ground motions similar to those produced by 20-kg of TNT-equivalent explosives.

Two intersecting linear transects, 24-km and 14-km long, were acquired in 2015 with the goal of characterizing seismic propagation characteristics and geologic structure in advance of Phase II of the Source Physics Experiments (SPE). The goal of SPE is to use a series of underground chemical explosions at Yucca Flat to understand the mechanisms of shear wave generation from underground explosions.

Our analysis shows that the Seismic Hammer™ is a source with unique properties and was well suited to data acquisition at Yucca Flat. Unlike vibrator sources, the Hammer produces significant energy below 2 Hz, allowing for usable data at source-receiver offsets as far as 11 km. Another benefit, in contrast to explosives, is the ability to hit multiple times at the same source point and stack the data, increasing the signal-to-noise-ratio. P-wave velocity structure was constrained to 2.5-km depth, well below the Paleozoic basement underlying the basin. Correlation of velocity structure to the known geology (Yucca Flat has thousands of boreholes due to underground nuclear testing) is excellent. S-Wave velocity structure was also recovered using the Refraction-Microtremor (ReMi) method. The quality of the shear-wave data was inversely proportional to the proximity to old nuclear tests. In regions of extensive nuclear testing, seismic scattering, multi-pathing, and attenuation destroyed the coherency of the surface-wave wavefield. Using this data as a test case, we propose and present a new metric of ReMi surface-wave quality based on image entropy.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Multi-observable probabilistic tomography for the physical state of the Earth's interior

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The past ten years have been marked by dramatic advances in four seemingly isolated research fields: Thermodynamic modelling of minerals and rocks at high PT conditions, numerical simulation of the thermomechanical behaviour of the Earth's interior, efficient decomposition techniques to solve complex simulation-based problems, and probabilistic inversion methods. All these disciplines have individually created "revolutions" in the way we understand and model natural systems, including our planet. However, a more profound understanding is still ahead of us from the formal combination of these disciplines/techniques into a single operational framework to study the interior of the Earth.

In this contribution, I will present and discuss the concept of multi-observable probabilistic tomography or "thermochemical tomography". This new kind of tomography is particularly designed for studies of the fundamental thermodynamic variables of the Earth's interior, namely temperature, pressure and chemical composition. Once these variables are known, all physical parameters of interest (e.g. seismic velocities, density, viscosity, conductivity, etc) and traditional tomography images are also retrieved in a thermodynamically-consistent way. The method is built on a simulation-based inversion technique where multiple satellite (e.g. gravity gradients, geoid height, etc) and land-based (e.g. seismic, plate motions, heat flow, etc) datasets can be jointly inverted to maximize the physical consistency of the resulting Earth model. Assembling this large problem required a collaborative effort between thermodynamicists, mineral physicists, geophysicists and geochemists, and marks the first step towards a full coupling between geophysics, geodynamics, thermodynamics, and geochemistry. I will present results for both synthetic and real case studies, which serve to highlight the advantages and limitations of this approach.

Where is the fault? – Effect of seismic image quality on fault interpretation uncertainty

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Uncertainty in interpretation of a seismic image is affected by image quality. In this work, we consider the impact of image quality: the range of pixel intensity and reflection continuity in a seismic image on interpretation uncertainty. We analysed fault interpretations carried out by 196 participants (including the attendees to the last Seismix symposium) for a grey-scale seismic image, presented both in two-way travel time (TWT) and as a depth-converted image. Using image analysis techniques we have quantified the differences in contrast and continuity of the TWT and depth images, creating colour maps of image quality to compare with the spread in the interpreted fault populations. Analysis of the results strongly suggest that differences in image contrast and reflection continuity can form artificial (i.e. not data-constrained) boundaries that have an influence on interpretation outcome. The analysis suggests that quantitative assessment of image quality can be used to feed into seismic processing models for the creation of optimal images for interpretation, and to determine areas within seismic imagery that are poorly constrained. This information can identify areas in an interpreter's model where interpretation risk maybe high, and where interpretation and structural modelling efforts should be focused. Our results have implications for the methods used to process seismic data and the subsequent construction of a seismic image; together these affect the uncertainties in seismic image interpretation and hence risk in sub-surface models.

Learning interpretation: time-lapse seismic interpretation experiment with masters students

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The interpretation of reflection seismic image data links seismic reflections observed in the imagery to subsurface rock architecture. Interpretation of seismic image datainvolves a certain degree of knowledge in structural geology, sedimentology and tectonic settings, and an understanding of the physics behind the creation of a seismic image.

Masters degree programmes focusing on petroleum geoscience are an integral part of many geoscientists professional development, such courses are often the students first opportunity to learn in depth 'the art' of seismic interpretation. In bespoke petroleum masters geoscience courses, elements of seismic interpretation will be taught throughout the course and will generally encompass the learning and application of structural models in different tectonic settings to produce a seismic interpretation. It is is assumed that geoscientists with the most training and practice (experience) will achieve better results than one with less experience. However, the impact of seismic interpretation training on interpretation skill is poorly understood.

Here we present the results of an interpretation experiment in which the same group of taught petroleum geoscience masters students interpreted a seismic image containing an extensional fault, before and after completing a two-week course in structural geology and interpretation of seismic image data. The results show that Pre-Course interpretations are mostly extensional, whereas Post-Course interpretations encompass a greater variety in interpreted fault type (i.e., results include more thrust and inversion). Furthermore, the fault geometries interpreted by the Post-Course students are more listric in character than the faults interpreted Pre-Course. In general, the range of fault geometries interpreted increases in the post-course interpretation set.

This work addresses important questions on the way seismic interpretation is taught at the universities at bachelors and masters levels. The overuse of block diagrams and planar faults could be creating a false perception that faults are planar surfaces, which they rarely are. In addition, the overexposure to normal faults, perhaps related to the predominance of extensional basins in oil exploration, and even the terminology used (i.e., the use of "normal" for extensional faults) could produce a strong bias towards interpretation of normal faults in seismic image data.

Can ambient noise energy be used to monitor CO_2 leakage at the Aquistore CO_2 storage facility?

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It has been shown that it is possible to measure the elastic response of the Earth using ambient noise energy by cross correlating recordings of ambient noise in receiver pairs. This process provides us with data which in theory contains the same information as the data which would have been recorded had an impulsive source been located at one of the receivers. The Green's functions produced through the cross correlation of ambient noise are given the name 'virtual seismograms' and provide information about the subsurface as if one of the receivers had been a source, termed a 'virtual source'.

The Aquistore CO_2 storage facility in south-eastern Saskatchewan, Canada is an independent research and monitoring project which aims to demonstrate that storage of CO_2 in deep geological formations is a safe and workable solution for reducing greenhouse gases. CO_2 injection began at the site in April 2015 and so far >35kT have been stored. Part of the monitoring system installed at the Aquistore site is a 2.5 x 2.5km wide array of 630 geophones. These geophones record both active and passive data; in this study we used ambient noise recordings from 304 of the receivers to test whether ambient noise could be used to monitor aspects of the CO_2 storage facility. In particular, we aimed to determine to what depth CO_2 leakage would have to rise before it could be detected by ambient noise.

Ambient noise recordings preceding injection were cross correlated in receiver pairs, then group velocity dispersion curves between periods of 0.5 and 2.2s were estimated using the Multiple Filter Technique. We used periods for which over 10% of the input cross correlations had acceptable travel times, giving the maximum period of analysis as 1.4s. Tomographic maps were then estimated using the Fast Marching Surface Tomography code and a sensitivity analysis was carried out using S-wave velocity data derived from borehole logs.

One of the main factors in removing travel times was the array size; when picking dispersion curves at each period, any travel times for receiver pairs within three wavelengths were discarded. Given the average velocity of $0.35 km.s^{-1}$ across the periods analysed, at period of 1.5s three wavelengths requires a receiver separation of 1.58km, whereas at period of 1s a separation of 1.05km is required. The array is 2.5 x 2.5km so the number of receiver pairs with the required separation for higher periods is low. The sensitivity analysis for 0.5 -1.4s period showed the maximum sensitivity occurs between 100 and 200m, with no sensitivity below 400m. At 400m Gassmann fluid substitution modelling suggests that S-wave velocities will vary 0.5 – 1.0% with a CO_2 saturation of 10 – 30%. CO_2 remains in a dense supercritical state below depths of ~800m. We therefore show that ambient noise surface wave tomography cannot be used to monitor super-critical CO_2 storage reservoirs themselves with this array geometry and standard methods, as the narrow array width precludes the use of longer periods sensitive to depths greater than 800m. Nevertheless, ambient noise might be used to provide a cost-effective early warning system for leakage into the top few hundred metres of the overburden. With a spatially larger array it may be possible to obtain tomography estimates for higher periods, allowing monitoring to greater depths.

Microgravimetric and seismic joint characterisation of the basement in Hontomín (Spain)

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Hontomín (N Spain) hosts the first Spanish CO2 storage research plant. The geophysical characterisation of the site included the acquisition of a 36 km2 3D seismic and a 16 km2 3D microgravimetric datasets. The integration of these data is here used to: (1) reproduce the deep structure and topography of the basement; (2) quantify the thickness of the Triassic Keuper evaporites, located between the sedimentary succession and the metamorphic basement; and (3) establish relationships between the faults interpreted in the seismic data and those inferred from the gravimetric data in the basement. The geometry of the sedimentary succession and structures interpreted from the seismic volume were used to constrain the inversion of the microgravity data: i.e. their gravimetric signature was calculated and then removed from the Bouguer Anomaly, thus reducing the uncertainty in the inversion process. The derived top of the basement geometry was used, along that of the top of the Triassic Keuper, to calculate the salt thickness. The basement structure is characterized by a half-graben setting filled with thick Keuper evaporites (up to 2000 m thick) forming an extensional forced fold. The two datasets clearly identified two main fault systems compartmentalizing the main structural domain into three differentiated blocks: the Central, South and East blocks. Furthermore, another inferred basement fault has been proposed to accommodate the thickening of the pre-rift succession and Triassic Keuper salts towards the NW of the area. These faults have been interpreted to be reactivated normal faults that led to the development of the Hontomín dome. The structural setting proposed for the Hontomín area suggests a thick-skinned configuration, with two main fault systems affecting the basement.

(Research supports: CGL2014-56548-P, 2009-SGR-1595, VATC: 20133830).

Continental rift structure in the Okinawa Trough back-arc basin

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Back-arc basins are a primary target to understand lithospheric evolution in extension associated with plate subduction. Most of the currently active back-arc basins host well-developed spreading centers where active seafloor spreading and creation of the oceanic crust have already occurred. However, rift structure at its initial stage, a key to understand how the continental lithosphere starts to break in a back-arc setting, is poorly documented. The Nansei-Shoto subduction zone forms a trench-arc-back-arc system from Kyushu, SW Japan, to Taiwan and provides a superb site for studying the interaction between the plate subduction and the rifting process in a continental back-arc basin. Behind this ~1,200-km-long subduction zone, an active continental rift named the Okinawa Trough is formed. Although the total length of extension across the Okinawa Trough is estimated no more than 80 km (Sibuet et al., 1995), its along-trough rifting style is significantly variable: The northern and middle Okinawa Trough is characterized by shallow bathymetry (< 1000 m) and has a wide (up to 230 km) basin structure. In the southern Okinawa Trough, on the other hand, the maximum seafloor depth exceeds 2,000 m and a relatively narrow (60-100 km wide) topographic depression is formed along the rift axes. Early seismic studies suggest that crustal separation and active seafloor spreading has occurred in the central and southern Okinawa Trough, whereas recent studies reveal that there exists over-15-km-thick crust beneath the rift axes even in the southern part where the deepest seafloor occurs, indicating that the whole part of the Okinawa Trough is still at a stage of continental rifting (Hirata et al., 1990; Sibuet et al., 1998). Yet the fault system accommodating the crustal extension is little documented. The Okinawa trough is also known for active hydrothermal system discharging high temperature fluids, implying that the crustal rifting enhances the transfer of high-temperature magmatic bodies from the deep mantle up to near the seafloor. However, the relative roles of magmatic input and tectonic stretching in controlling the whole rifting system remain poorly understood.

Toward understanding the tectonic and volcanic processes associated with the continental back-arc rifting, JAMSTEC has been carrying out active-source seismic experiments in the Okinawa Trough. Multichannel seismic (MCS) reflection data and OBS refraction data were collected in the southern Okinawa trough (24-26°N) in 2013 and in the northern Okinawa trough (29-30°N) in 2015. Based on the data set, we present structural models of the Okinawa Trough. The MCS reflection data in the southern part of the trough show an almost symmetric rift system across the rift axis: Within the basin the sedimentary layers are highly cut by inward-dipping normal faults. Just beneath the rift axis a narrow intrusive structure is imaged, but a stable magma chamber is not observed on axis. Instead, a possible melt lens was found ~10 km horizontally away from the rift axis towards the arc. The sedimentary layers overlying the possible magmatic body are deformed, suggesting the off-axis volcanism is young or probably still active. Associated with the rifting process, crust has been significantly thinned from the original ~25-km-thick arc crust and the thinnest crust of ~10 km occurs just beneath the rift axis. We interpret that the southern part of the Okinawa Trough is at a transitional stage from continental rifting to seafloor spreading. The northern part of the Okinawa Trough, on the other hand, exhibits much wider deformed zone. This structural variation may be influenced by the southward increase in rifting rate along the Okinawa Trough.

Structure and seismic behaviour along the weakly-coupled Nansei-Shoto subduction zone from active- and passive-source seismic investigations

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The Nansei-Shoto subduction zone, extending 1,200 km from Kyushu, SW Japan, to Taiwan, has been intensively examined in terms of seismic coupling along the plate boundary and tsunami potentials. On the contrary to other subduction zones nearby, the Nansei-Shoto subduction zone has lacked clear evidence of great megathrust earthquakes (M>8) for the last few hundred years and thus the overall interplate coupling is thought to be weak. Correspondingly, slow slip events and very low frequency earthquakes are ubiquitously distributed in the forearc region (e.g., Nishimura, 2014), supporting the idea that the plate interface is weakly coupled. One of the exceptional great earthquakes is the 1911 Kikai-jima earthquake (M8.0) in the northern part of the subduction zone at 29°N (Usami, 1996). Another devastating event is the 1771 Yaeyama earthquake (M~8) in the southernmost area, which is thought to have ruptured a shallow portion of the plate interface and generated a huge tsunami (Nakamura, 2009). However, background subduction structure generating such events in a weakly-coupled condition remains enigmatic.

Since 2013, JAMSTEC has been carrying out marine seismic experiments in the Nansei-Shoto subduction zone to reveal the fine-scale geometry and nature of subduction faults. This “Nansei-Shoto” project consists of two-dimensional active-source experiments and extensive passive observations to cover the entire subduction zone. Multichannel seismic reflection and refraction/wide-angle reflection data were collected along seismic lines across the potential source region of the 1771 Yaeyama earthquake in 2013 and that of the 1911 Kikai-jima earthquake in 2015. Together with active source data obtained by Japan Coast Guard in the same area, we aim to construct a new seismogenic model in the Nansei-Shoto subduction zone.

The most prominent structural feature in the southern part of the subduction zone is a non-accretionary frontal wedge: The plate interface and the branching fault form a narrow (~40-km-wide) wedge structure. Since the branching fault has a steeper angle of ~15° and overlaps the potential source region of the 1771 Yaeyama earthquake, reverse faulting along this branch is the most likely candidate for the source of the 1771 Yaeyama earthquake tsunami. On the other hand, the frontal wedge becomes much wider up to ~100 km where the 1911 Kikai-jima earthquake occurred. Within the low-velocity frontal wedge multiple landward-dipping reflectors are imaged. This structure is very similar to the accretionary prisms in the Nankai subduction zone and is in a great contrast with the non-accretionary frontal wedge in the south. This difference probably comes from the structural variation of the incoming plate and the amount of sediment supply into the trench: To the north lie a series of volcanic ridges of late Cretaceous to early Eocene ages (Amami Plateau, Daito Ridge and Oki-Daito Ridge), while the more southerly West Philippine basin exhibits a deep seafloor with little amount of sediments on its top. Large bathymetric highs and volcanic products on the incoming plate may have contributed to form the accretionary frontal wedge and anomalous earthquakes in the northern part of the subduction zone.

Thermo-chemical heterogeneity of continental lithospheric mantle: examples from Europe, Siberia, and Southern Africa

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I present models of lithosphere density and the non-thermal part of upper mantle Vs anomalies in different tectonic provinces of Eurasia and Southern Africa. The focus is on compositional heterogeneity of the lithospheric mantle, and therefore the effect of regional temperature variations on density and Vs is removed by applying regional temperature corrections, which are constrained by heat flow data.

Significant parts of Precambrian cratons of Laurasia are characterized by extremely low surface heat flow values (<25-30 mW/m2), which imply the depth extent of the lithospheric keels down to 300-350 km, at least locally. These values are in apparent contradiction with a worldwide compilation of cratonic xenolith P-T arrays, which are usually consistent with surface heat flow of around 40 mW/m2 and the lithosphere thickness of 200-250 km depth. Models of lithosphere density and seismic velocity structure indicate that xenoliths do not sample mantle with the lowest density and the highest velocity.

Density structure of continental lithosphere mantle correlates with crustal structure and surface tectonics. This observation is illustrated by examples from the East European, Siberian and southern Africa cratons, where lateral variations in density structure of the lithospheric mantle are compared with petrological studies of mantle-derived xenoliths from the Fennoscandian, Siberian and Kaapvaal kimberlite provinces. I demonstrate regional correlations between mantle density and kimberlite occurrences, and a striking correlation between Moho sharpness and kimberlites in the Kaapvaal. In Siberia, high lithosphere density in major sedimentary basins suggests the presence of eclogitic material.

Since the depth distribution of density anomalies is unknown, the analysis is complemented by seismic data in order to understand better geodynamic causes of mantle density heterogeneity. Temperature-corrected seismic velocity structure based on published high-resolution tomography models indicates a pronounced stratification of lithospheric mantle in many Precambrian terranes, in agreement with xenolith data. The lateral extent of depleted lithospheric keels diminishes with depth and, below a 150-200 km depth, may be significantly smaller than geological boundaries of the cratons. A comparison of mantle density with mantle Vp, Vs regional tomography models in southern Africa shows a weak negative correlation, which suggests a strongly non-unique correlation between density and velocities, reported earlier based on xenolith studies.

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The Proterozoic Ladoga rift (SE Baltic shield): No evidence for a rift in geophysical data

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Mesoproterozoic mafic magmatism at the southern part of the Baltic Shield (the Lake Ladoga region) is conventionally ascribed to epicratonic rifting. The region hosts a series of mafic dykes and sills of Mesoproterozoic ages, including a ca. 1.53-1.46 Ga sheet-like gabbro-dolerite sills and the Salmi plateau-basalts from the Lake Ladoga region. Based on chiefly geochemical data, the region is conventionally interpreted as an intracratonic Ladoga rift (graben). We question the validity of this geodynamic interpretation by analyzing regional geophysical data (crustal structure, heat flow, Bouguer gravity anomalies, magnetic anomalies, and mantle Vs velocities).

Our analysis of characteristics of continental rifts demonstrates the following.

1. The topography of the region lacks a linear horst-graben structure typical of modern rifts, however this feature might have been lost by surface erosion.

2. The crust has neither shallow Moho, nor magmatic high-velocity underplated material, and thus is not typical of continental rifts.

3. Weakly negative Bouguer gravity anomalies, especially by comparison with adjacent "background" anomalies suggest the presence of high-density material at shallow, near-Moho depths; however, the shape of the anomaly is rounded rather than linear, and may not attest to the paleorifting event.

4. Seismic velocities in the upper mantle show a possible weak low-Pn anomaly near Lake Ladoga, and strong positive (+5+7%) Vs anomaly at 75-125 km depth to the NE of the lake, but not in the region of Mesoproterozoic mafic magmatism.

5. No thermal anomaly or lithosphere thickness anomaly is currently present in the lithosphere of the region, which instead is marked by extremely low heat flow; however, given the age of magmatism any thermal anomaly may have long ceased and thus its absence does not disprove rifting origin of magmatism.

6. The absence of linear magnetic anomalies which are preserved in other paleorifts provides strong evidence that this region has not been affected by rifting.

We conclude that a mechanism other than rifting is responsible for Mesoproterozoic mafic magmatism at the southern part of the Baltic Shield and propose that magma intrusion associated with deformation along the margins of Nuna (Columbia) supercontinent, and its transformation to eclogite facies, locally speeded by fluids, produced a highly heterogeneous density structure of the lithosphere.

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Geodynamics of convergent margins: A global geophysical perspective

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Convergent margins, being the boundaries between colliding lithospheric plates, form the most disastrous areas in the world due to intensive, strong seismicity and volcanism. We review global geophysical data in order to illustrate the effects of the plate tectonic processes at convergent margins on the crustal and upper mantle structure, seismicity, and geometry of subducting slab. We present global maps of free-air and Bouguer gravity anomalies, heat flow, seismicity, seismic Vs anomalies in the upper mantle, and plate convergence rate, as well as 20 profiles across different convergent margins.

A global analysis of these data for three types of convergent margins, formed by ocean–ocean, ocean–continent, and continent–continent collisions, allows us to recognize the following patterns.

(1) Plate convergence rate depends on the type of convergent margins and it is significantly larger when, at least, one of the plates is oceanic. However, the oldest oceanic plate in the Pacific ocean has the smallest convergence rate.

(2) The presence of an oceanic plate is, in general, required for generation of high-magnitude (M N 8.0) earthquakes and for generating intermediate and deep seismicity along the convergent margins. When oceanic slabs subduct beneath a continent, a gap in the seismogenic zone exists at depths between ca. 250 km and 500 km. Given that the seismogenic zone terminates at ca. 200 km depth in case of continent–continent collision, we propose oceanic origin of subducting slabs beneath the Zagros, the Pamir, and the Vrancea zone.

(3) Dip angle of the subducting slab in continent–ocean collision does not correlate neither with the age of subducting oceanic slab, nor with the convergence rate. For ocean–ocean subduction, clear trends are recognized: steeply dipping slabs are characteristic of young subducting plates and of oceanic plates with high convergence rate, with slab rotation towards a near-vertical dip angle at depths below ca. 500 km at very high convergence rate.

(4) Local isostasy is not satisfied at the convergent margins as evidenced by strong free air gravity anomalies of positive and negative signs. However, near-isostatic equilibrium may exist in broad zones of distributed deformation such as Tibet.

(5) No systematic patterns are recognized in heat flow data due to strong heterogeneity of measured values which are strongly affected by hydrothermal circulation, magmatic activity, crustal faulting, horizontal heat transfer, and also due to low number of heat flow measurements across many margins.

(6) Low upper mantle Vs seismic velocities beneath the convergent margins are restricted to the upper 150 km and may be related to mantle wedge melting which is confined to shallow mantle levels.

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BB-ASAP: BroadBand seismic experiment in the Area of Sergipe-Alagoas-Pernambuco, Brazil

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Mountains building and their erosion and peneplanation, sediment and nutriment transfers trough river into continental plate-form and deep ocean, are deeply connected with the growth cycle of the earth, the birth and the evolution of the ocean, the palaeo-climate and the palaoe-oceanography variations, which are all linked with deep earth processes. Probing the strong correlation between deep and surface processes in order to understand the Earth's growing and to model forecasts, needs the multidisciplinary approach proposed in the holistic project "From Mountain to Deep Sea" of the White Paper « an holistic approach of international collaboration in Marine Sciences » (http://marinebrazil.sciencesconf.org/). Considering the complex history of the assemblage of the Brazilian Lithosphere, the understanding of the evolution of the topography and the role of inherited structures from past orogenic episodes need a 3D model of the crust and upper mantle. Recent wide-angle experiment (SALSA cruise) allows high resolution but discrete 2D images of the crust of the NE Brazil margin, but cannot offer a lateral coverage of the lithosphere. We propose a seismic BroadBand (BB) array of stations, deployed both on land and at sea along the coast. The joint analysis of the BB data together with the previous seismic results will allow, by coupling active and passive seismic methods, the construction of a 3D seismic model of the Lithosphere with unsurpassable detail and the detailed and integrated study of the interaction between onshore-offshore (Source to Sink) and surface/deep processes (Mud to Mantle).

Crustal structure variations in the southern Central Iberian Zone: Effects of composition and Alpine reactivation in an internal Variscan domain

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The IBERSEIS and ALCUDIA projects have acquired vertical incidence and wide-angle reflection seismic data in the Variscan Central Iberian Zone of Spain. Together, they present a NE-SW, ~300 km long transect that samples an area going from the Ossa-Morena Zone in the S, through the Central Iberian Zone, to the Alpine Central System to the N.

Although crustal thickness appears to be fairly constant along most of the Central Iberian Zone, the seismic signature of the laminated lower crust suggests that the latest varies in thickness, decreasing from 6 s TWT in the S to 2 s TWT to the N. This implies overall compositional and velocity changes in the crust that may place the crust-mantle boundary at different depths. That, together with a well constrained velocity increase in the upper crust and the existence of the sedimentary basin to the N, configures a complicated pattern when trying to establish the Moho depth.

Wide angle reflection data provides good velocity control in the upper crust and the mantle along the entire transect, imaging a gradual increase of 3-5 km in the Moho depth to the N. There, the amount of Variscan metasediments diminish and the surface geology is characterized by granodiorites, migmatites and by the Madrid Basin, a foreland basin of the Alpine Central System that is part of the bigger Tagus Basin. The increase in crustal thickness identified in the neighborhood of the Central System is also accompanied by a slight increase in the Poisson ratio values, that even though still below 0.25, they are higher than those observed in the southern part of the profile, far from the influence of a late Variscan melting episode and of that of Alpine tectonics.

Two scenarios are considered to take part in the Moho deepening near the Central System: the Alpine reactivation causing this mountain belt has increased the crustal load giving rise to a foreland basin and, probably, to a moderate crustal thickening. Also, a gradual change in crustal composition to the N, triggered by generalized melting, has probably incorporated denser and more basic rocks, contributing to Moho deepening by isostatic readjustment. The importance of each of these processes is, as yet, unknown. However, the next acquisition of the CIMDEF project wide-angle reflection dataset across the Central System will surely shed some light on this issue (Research supports: CGL2014-56548-P, 2009-SGR-1595).

Imaging the subduction megathrust, northern Hikurangi subduction zone, New Zealand

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Along the northern Hikurangi subduction margin, New Zealand, the subduction megathrust between the subducting Pacific plate crust and the Australian plate, is just 10-15 kms deep beneath parts of the coastline, as primarily inferred from deep marine-seismic reflection profiles and earthquake hypocenters. Short-term transient (~2-3 week duration) slow slip behaviour occurs on the megathrust every ca.12-18 months, detected by the New Zealand land-based GeoNet cGPS and seismometer network. The shallow depth of the SSEs along the northern Hikurangi subduction margin means that, in contrast to many other subduction margins, the seismometers and cGPS sites lie in the 'near-field' of the transient slow-slip. The close proximity of the slow slip to the surface means that we have the potential to resolve body-wave seismic properties at a scale useful for constraining and testing some of the theories on fundamental mechanisms governing the slow slip, such as the relationship between slow slip and high fluid content.

Passive seismic tomography studies along the subduction margin offer excellent constraint on the body-wave seismic properties close to the megathrust, due to the relatively high level of seismic activity in the subducting Pacific plate crust, but also due to the dense seismometer networks. Using a modified SIMULPS approach we have obtained 3-D *Vp* and *Vp/Vs* from 8 to 70 km depth along the northern Hikurangi subduction margin, using data from 2600 spatially distributed earthquakes recorded by the permanent GeoNet seismometers and by temporary campaign seismometer arrays recording in 1993-1994, 2001 and 2011-2012. Inversions were constrained offshore by incorporating onshore–offshore travel-time data from marine seismic air-gun sources, which improved constraint of shallow velocities and the plate interface (PI) zone velocity structure.

The results show extensive regions of subducted sediment, but with major variations along strike. Above the shallow plate interface and north of Gisborne there is a 70-km long zone of high *Vp/Vs* and low *Vp*, which is interpreted as subducted sediment with high fluid-pressure. Subducted sediment is also observed at shallower depth offshore in seismic reflection data, in the vicinity of the shallow SSEs. In new analysis we are now exploring the relationship between the zone of high Vp/Vs and clusters of seismic activity observed along the down-dip edge of the SSEs, as well as further improving the density of seismic observations for further tomography inversions by folding in new 2011-2014 earthquake observations.

Structure of Canadian lithosphere obtained from receiver functions

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We present first results of our analysis of the lithosphere and asthenosphere for the area around Slave craton and Big Slave Lake. We calculated P and S receiver functions and obtained velocity model through their join inversion. The inversion provides robust results for the S-wave velocities in the crust and the upper mantle up to a depth of 300 km as well as constraints on the P-wave velocities and the Vp/Vs ratio. The crustal and upper mantle discontinuities (Moho, LVZ, LAB) are characterized by depth, sharpness and lateral spatial variations. Obtained seismic models are complimented by petrological data inferred from mantle xenoliths.

3D joint refraction-reflection travel-time tomography of the Galicia 3D wide-angle dataset

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The Galicia 3D reflection-refraction seismic experiment was carried out in 2013 at the Galicia rifted margin in the northeast Atlantic Ocean, west of Spain. The main geological features within the 64 by 20 km (1280 km^2) 3D box investigated by the survey are the peridotite ridge (PR) composed of serpentinized peridotite, a series of fault bounded, rotated basement blocks and the S reflector, which has been interpreted to be a low angle detachment fault. Forty-four short period four component ocean bottom seismometers (OBS) and 28 ocean bottom hydrophones (OBH) were deployed within the 3D box. 3D multichannel seismic (MCS) profiles sampling the whole box were acquired with two airgun arrays of 3300 cu.in. fired alternately (in flip-flop configuration) every 37.5m.

We present the results from 3D joint refraction-reflection traveltime tomography performed with TOMO3D, that constrains the P-wave velocity structure of the sediments, crust and uppermost mantle and the topography of the S reflector in the 3D box. Results are validated by synthetic tests, by comparisons with the results of previous first-arrival traveltime tomography and with images from the processed Galicia 3D MCS volume. The 3D P-wave velocity structure of the uppermost mantle yields the degree of serpentinisation and permits us to estimate the amount of water reaching the mantle through the higher permeability fault network. The crustal thickness retrieved by the present study allows us to estimate the degree of lithospheric extension, and to test the hypothesis of depth dependent stretching and the faulting, by comparing the wide-angle retrieved thinning with the one estimated from the fault heaves in the upper-crust.

Joint refraction and reflection travel-time tomography of near-vertical and wide-angle seismic data

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Near-vertical multichannel seismic reflection (MCS) and refraction/wide-angle reflection seismic (WAS) data are generally used as separate data sets and processed, modeled and/or interpreted following different approaches. Typical travel-time tomography of just WAS data with sparse acquisition geometries (generally 1 station/OBS/shot every several km) lacks the resolution to define the model properties and the geometry of geologic boundaries (reflectors) with the appropriate accuracy, especially in the shallow layers of a model.

Here we show the improvement achieved by combining these two different data sets into a common inversion strategy. To do so, we have adapted the tomo2d (Korenaga et al, 2000) and tomo3d (Meléndez et al, 2015) joint refraction and reflection travel time tomography codes to implement streamer data and MCS acquisition geometries. The scheme results in a joint travel-time tomographic inversion based on integrated travel-time information from refracted and reflected phases from WAS data and reflected phases identified in the MCS common depth point (CDP) or shot gathers. The high redundancy of MCS data greatly improves the definition of reflector's geometry, whereas the long-offset WAS refractions reduce the velocity-depth trade-off that is inherent to reflection travel-time inversion. As a result, the joint refraction and reflection travel-time inversion scheme drastically increases the accuracy of velocity (Vp) and reflector geometry models as compared with the independent inversion of the two data sets.

To represent the advantages of a common inversion approach we have modeled and compared results for synthetic data sets using two different travel-time inversion strategies: First, we have produced seismic velocity models and reflector geometries following typical refraction and reflection travel-time tomographic inversion of just WAS data with a typical acquisition geometry (one OBS each 10 km). Second, we have performed joint inversion integrating two coincident data sets consisting of MCS data collected with a 8 km-long streamer and the WAS described above data into a common inversion scheme. Our synthetic results of the joint inversion indicate a 5-10 times smaller ray travel-time misfit in the deeper parts of the model, compared to models obtained using just WAS or MCS data.

As expected, there is an important improvement in the definition of the reflector geometry, which in turn, allows improving the accuracy of the velocity retrieval, especially in the area immediately above and below the reflector. To test the joint inversion approach with real data, we combined coincident MCS and WAS data acquired in the northern Chile subduction zone into a common inversion scheme to obtain a higher-resolution information of upper plate and inter-plate boundary.

Linking Tasmania and mainland Australia using passive seismic imaging techniques

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Understanding the tectonic evolution of the eastern margin of Gondwana in an attempt to link mainland Australia (Victoria) and Tasmania has proven to be a challenge to geoscientists. The presence of Bass Strait, which separates the two land masses, and the thick sub-marine sedimentary basins, has largely masked the underlying basement rocks. As a consequence, while a variety of plausible tectonic models have been postulated, they are often incompatible or conflicting. The key to unravelling the tectonic relationship between Tasmania and Australia is an improved understanding of the intervening crust and upper mantle. Therefore, the goal of this study is to develop a unified model of the lithosphere beneath Bass Strait by combining constraints from a variety of classes of passive seismic data recorded by a recent experiment.

The dataset that will be exploited consists of approximately 18 months of passive seismic data recorded by an array of 24 three-component broadband instruments covering southern Victoria, several islands in Bass Strait (Flinders Island, King and Deal Islands) and northern Tasmania. The methodology to be used consists of combining teleseismic traveltime residuals, ambient noise data, receiver functions and shear wave splitting data to jointly constrain the crust and upper mantle structure.

The results obtained from this study are likely to have important implications for models which attempt to explain the tectonic evolution of the region. For example, receiver functions will provide constraints on location and geometry of subhorizontal discontinuities underneath the array and can highlight changes in anisotropy and S-wave velocity. Mantle anisotropy derived from shear wave splitting of teleseismic phases will be crucial in geodynamic modelling. Ambient noise tomography will constrain the seismic structure of the crust and teleseismic tomography will image the lower crust and upper mantle.

The combined seismic model will be integrated with other available datasets in order to develop a comprehensive structural model for Bass Strait, Victoria and Tasmania These include total magnetic intensity and gravity data, seismic reflection profiles, geological field mapping and well data.

Modelling the enemy: A comparison of methods for simulating noise in seismic datasets

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Noise is a persistent feature in seismic data which can result in the introduction of artefacts during the imaging of microseismic events, while it can lead to errors in the estimated velocity model and predicted source parameters during inversion. Synthetic microseismic datasets are often used to test the sensitivity/robustness of imaging algorithms to noise. To do this noise is commonly added to synthetic microseismic datasets. This study aims to identify the noise modelling method that provides the best similarity to recorded seismic noise.

Three months of passive seismic data recorded on a permanent surface array prior to injection at the Aquistore carbon storage site has been used in this study. A noise analysis study identified three different noise signals within the data which were broadly classified as stationary, non-stationary and pseudo-non-stationary depending on the length of their presence in the event detection time window. Five modelling methods have been considered in this study – White, Gaussian Noise modelling (WGN); CONVolution-based modelling (CONV); COVAriance-based modelling (COVA); Individual COVAriance-based modelling (ICOVA); and, a mixture of ICOVA and Linear Prediction Filter modelling (ICOVA-LPF). The first two methods, WGN and CONV, are already applied in seismic noise modelling while the other approaches have been adapted from communication theory. The COVA method requires the recorded noise to be split into many time segments before the sample mean and covariance matrix are computed. The mean and covariance are then utilised to create a multivariate Gaussian matrix with the same statistical properties as the original noise segments.

The ICOVA method involves modelling individual noise signals by selecting noise segments that contain only that noise type. Once all the noise types have been modelled, the models are combined to create a single noise field model. ICOVA-LPF modelling uses the ICOVA method to model signals which have a high presence in the data while a Linear Prediction Filter (LPF) is used for less observed signals.

Unsurprisingly, WGN provides little-to-no similarity to the recorded noise. The CONV model does not accurately represent the non-stationary and pseudo-non-stationary aspects of the noise field due to the modelling conditional that noise must be stationary. A requirement of COVA modelling is that each noise segment must experience the same statistical properties, therefore this method fails to handle noise that is only present in a handful of patches, such as a passing car. By modelling noise signals individually, the ICOVA method provides a close representation of all three noise types identified, quantified using the statistical Mann-Whitney White test. Convergence tests highlighted that a minimum of 200 noise samples exhibiting the same statistical properties are required for each noise signal modelled using the ICOVA method. The ICOVA-LPF model has used an LPF for the highly variable, non-stationary noise signal resulting in a better correlation to the recorded noise.

Through the identification of a noise modelling method that accurately represents the recorded noise field, this study has detailed a path for the incorporation of realistic noise in synthetic seismic datasets.

The Himalayan Seismogenic Zone: A New Frontier for Earthquake Research

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The Mw 7.8 Gorkha, Nepal, earthquake that occurred on April 25 of this year was a dramatic reminder that great earthquakes are not restricted to the large seismogenic zones associated with subduction of oceanic lithosphere. Not only does Himalayan seismogenesis represents important scientific and societal issues in its own right, it constitutes a reference for evaluating general models of the earthquake cycle derived from the studies of the oceanic subduction systems. This presentation reports results of a Mini-Workshop sponsored by the GeoPrisms project that was held in conjunction with the American Geophysical Union on December 15, 2015, designed to organize a new initiative to study the great Himalaya earthquake machine.

The Himalayan seismogenic zone shares with its oceanic counterparts a number of fundamental questions, including:
a) What controls the updip and downdip limits of rupture?
b) What controls the lateral segmentation of rupture zones (and hence magnitude)?
c) What is the role of fluids in facilitating slip and or rupture?
d) What nucleates rupture (e..g. asperities?)?
e) What physical properties can be monitored as precursors to future events?
f) How effectively can the radiation pattern of future events be modeled?
g) How can a better understanding of Himalayan rupture be translated into more cost effective preparations for the next major event in this region?

However the underthrusting of continental, as opposed to oceanic, lithosphere in the Himalayas frames these questions in a very different context:
h) How does the greater thickness and weaker rheology of continental crust/lithosphere affect locking of the seismogenic zone?
i) How does the different thermal structure of continental vs oceanic crust affect earthquake geodynamics?
j) Are fluids a significant factor in intercontinental thrusting?
k) How does the basement morphology of underthrust continental crust affect locking/creep, and how does it differ from the oceanic case?
l) What is the significance of blind splay faulting in accommodating slip?
m) Do lithologic contrasts juxtaposed across the continental seismogenic zone play a role in the rheological behavior of the SZ in the same manner as proposed for the ocean SZ?

Major differences in the study of the continental vs oceanic seismogenic zone include:
a) direct geological observation via field mapping
b) dense and wide aperture monitoring of surface strain via GPS and INSAR
c) extensive sampling of geofluids via surface flows and shallow drill holes
d) cost effective deployment of long term geophysical arrays (e.g. seismic and MT) designed to detect subtle variations if physical properties within the seismogenic zone, and ultimately,
e) a fixed platform for deep drilling of past and future rupture zones

It remains to be established whether the Himalayan seismogenic zone has the potential for earthquakes of the greatest magnitudes (e.g. 9.0+). However, there is no question that future ruptures in this system represent a serious threat to major population centers (megacities) in the Indian subcontinent. For this reason alone the HSZ is deserving of a major new international, multidisciplinary effort.

Benefits for shallow seismic imaging by both P- and S-wave application in the Tannwald basin (Germany)

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Since overdeepened valleys and basins are prominent settlement areas in the European Alps, the ICDP proposal DOVE (Drilling Overdeepened Alpine Valleys) intends to study their sedimentary fill with respect to, e.g., glacial cycles, geohazards, and groundwater. These Quaternary valleys and basins were primarily carved out by glaciers and often refilled with deposits of different facies environments. Their sediment successions constitute an excellent investigation site, e.g., to examine the benefit of combined application of shallow P-wave reflection seismics together with S-wave and multicomponent reflection seismics.

One of the study areas of a DFG-funded project (grants KR2073/3-1, GA749/5-1) is the Tannwald basin, located in Southern Germany about 50 km NE of Lake Constance at the terminal moraine of the last glacial maximum (LGM). Sedimentary deposits of ca. 200 m overlie Molasse bedrock and are locally glaciotectonically disturbed. This lithological setting is confirmed by an older, nearby research borehole. Since 2014 we have accomplished two high-resolution P-wave reflection seismic surveys and one reflection seismic campaign using horizontally polarised SH-waves and multicomponent technique (3-C receivers, SV- and SH-wave sources). In addition, several crosslines were registered to study 3-D effects and to evaluate a 3-D multi-component approach. Here, we present first results from 2-D P-wave and SH-wave seismic imaging.

The seismic sections exhibit high data quality and show the same overall features. In all P-wave seismic sections, we interpret strong reflections as Molasse bedrock, verified by the research borehole. Structures below the bedrock are difficult to determine due to missing coherency. Within the investigated area, the depth of the bedrock ranges from 80 m to maximum 220 m. In the western part close to the LGM terminal moraines, a prominent ramp-like dipping of the bedrock increases the basin depth from 80 m to 160 m. Above the bedrock, reflection segments are spatially spread over the investigated area and delineate the sediment successions within the basin. Close to the LGM moraine, reflections above the bedrock show structures, which we interpret as glacially disturbed sediments.

In the second campaign, we acquired two SH-wave seismic profiles based on results of the P-wave surveys. The seismic SH-wave sections display reflections that we can correlate with the inventory of the P-wave seismics to a large degree. We image the ramp-like dipping of the bedrock but cannot trace the bedrock along all profiles. However, the imaged structures using SH-waves show more details and higher resolution. Possible reasons for varying image quality may be the response to different elastic parameters, damping, or scattering, which results in a lower maximum investigation depth using SH-waves.

In conclusion, P-wave seismics provides a more coherent image and higher penetration depth in overdeepened basins, whereas SH-wave reflection seismics reveals more internal detail of the imaged structures. Further data processing, the evaluation of the multi-component and 3-D data, and new field campaigns at a second project test site are scheduled in 2016.

Focusing prestack depth imaging approaches

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A reliable characterization of the Earth's crust depends strongly on the quality of the corresponding seismic image. Prestack depth migration approaches play an important role for that task and have become a popular tool for deriving high-resolution images even in the case of strongly heterogeneous settings. We present three closely related approaches for increasing the image quality by introducing additional weighting factors into the integral formulation of Kirchhoff prestack depth migration (KPSDM).

KPSDM can be formulated as a weighted diffraction stack, where integration of the temporal derivative of the recorded wavefield is performed along the corresponding diffraction surfaces. The weighting function is given by Kirchhoff theory and accounts among other things for geometrical spreading. The wavefield is smeared along the whole two-way-traveltime isochrones without any inherent restriction, although normally only a small part along the isochrone, i.e. the part that is tangential to the reflector at the specular reflection point, contributes to the image of the corresponding reflector.

For that reason we introduced some approaches which limit the smearing along the two-way-traveltime isochrones to the physically relevant parts around the specular reflection point. In that sense the wavefield is focused to the actual reflection or scattering point in the subsurface. Within the diffraction stack integral, this focusing is expressed as an additional weighting factor. We present three such focusing approaches, Fresnel-Volume-Migration (FVM), Coherency-Migration (CM) and Coherency based Fresnel-Volume-Migration (CbFVM).

In FVM, the migration operator is restricted to the physically relevant part along the two-way-traveltime isochrone by using the concept of Fresnel volumes. The emergent angle of the wavefield recorded at the surface is computed and used to propagate the wavefield along the corresponding ray direction back into the subsurface. Then the smearing along the two-way-traveltime isochrone is limited to the part within the corresponding Fresnel volume of the back-propagated ray.

In CM, the weighting function is computed directly from the input data using the semblance coefficient, i.e. the ratio between the coherent and the total energy within a predefined time window computed over a certain number of neighbouring traces. The focusing characteristics of this approach are similar to FVM, however there is no need for explicit ray tracing which reduces computational costs compared to FVM.

Finally, in CbFVM, both focusing approaches (FVM and CM) are combined and an alternative weighting function is defined which is basically the product of the weighting functions used for FVM and CM. Like in FVM, the smearing is restricted along the two-way-traveltime isochrone using the Fresnel volumes, and additionally the coherency is calculated and used for weighting within this volume, which leads to an increased focusing to the reflection or diffraction point.

The characteristics and performance for these focusing prestack depth imaging approaches are shown for various 2D and 3D seismic data sets from crystalline environments.

Multiple structural interpretations of seismic reflection data – using the Virtual Seismic Atlas to collate and assess uncertainty

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Rarely do seismic datasets lend themselves to unique structural interpretation. Even structural models based on apparently excellent seismic data are routinely falsified by the drill bit. Thus the structural interpretation of seismic data is an exercise in managing uncertainty. Curiously, the published literature rarely suggests the possibility, let alone likelihood, of multiple interpretations satisfying the same data. So although sophisticated seismic datasets and structural modelling tools can specify ever-more precise single interpretations, arguably the geological meaning of seismic reflection patterns still leaves much room for uncertainty. Therefore, the challenges but also the opportunities lie in forming multiple scenarios and investigating their consequences.

The Virtual Seismic Atlas (VSA) is a freely accessible on-line resource which shares the geological interpretation of seismic data. Critically, it provides an opportunity to compare competing interpretations as it supports, indeed encourages, multiple interpretations of individual datasets. Generating interpretations can be aided by applying experience, either personal or communal – commonly by making reference to analogues. However, locating "lookalike structures" for comparison has hitherto been difficult and demands search strategies that maximise serendipity. The VSA search environment deliberately exposes visitors to arrays of products; it is explicitly designed to yield results from multiple search pathways that expose the user to diverse juxtapositions of distinct interpretations – increasing the likelihood of the serendipitous connection. It also acts as a guide to further information including published science and data library portals.

This presentation will illustrate the results of expert interpretations of individual seismic datasets, and examples of analogue searches that reveal comparisons between similar structures (e.g. thrust faults) developed in distinct basin settings. The VSA and all the images of seismic data and their interpretations are openly accessible at: www.seismicatlas.org without subscription or log-in. This latter point is critical for it allows a diverse community to become involved in seismic interpretation – a necessary step if we are to assess the range of the possible. Demonstrations will be available during the course of the meeting.

Constraints on Archean tectonic processes from seismic reflection surveys in the Canadian Superior and Australian Yilgarn cratons

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The nature of Archean tectonic processes, including the timing and nature of the transition from an early, potentially gravity-driven tectonic regime to a proto-plate tectonics, is still widely debated. With their high spatial resolution, deep seismic reflection images provide important constraints on geodynamic models of tectonic processes due to the apparent correlation between reflectors and strain fabrics. Following multi-year seismic acquisition programs in the Yilgarn craton by Geoscience Australia with the Geological Survey of Western Australia and in the Superior craton by the Canadian Lithoprobe program, these two cratons are now the best surveyed Archean regions on Earth.

Integrated interpretation of seismic and geological data show that the Superior craton grew as various island arcs, oceanic plateaux, and micro-continental fragments of Meso-Neoarchean age were accreted to the southern margin of a pre-existing microcontinent (North Caribou superterrane) that gave rise to well-developed east-striking belts of granite-greenstone, metasedimentary, and plutonic rocks. These belts were crossed by the Lithoprobe Western Superior transect. The seismic reflection lines reveal a doubly-vergent orogen in the north and in the south north-dipping mid-crustal reflection fabrics. The latter are interpreted to represent successive episodes of underthrusting with Moho offsets locating relict suture zones. These north dipping mid-crustal reflection fabrics, which are underlain by subhorizontal reflections in the lower crust, correspond to the 3.4-2.7 Ga Winnipeg River and 3.0-2.7 Ga Marmion terranes. The 2-3 s thick unit of subhorizontal reflections in the lower crust, which exhibits 8% azimuthal P wave anisotropy, has been interpreted as a subcreted slab of oceanic crust.

The evolution of the Yilgarn craton is still strongly debated: one of the more prevalent theories interprets the NNE-trending granite-greenstone belts to reflect eastward growth of the craton by accretion to the eastern margin of a microcontinent comprising the Meso-Neoarchean Youanmi terrane. More recently, it has been proposed that these belts arose through repeated episodes of extension and contraction above a west-dipping subduction zone. The Youanmi terrane is characterized by an extensive fabric (> 500 km) of commonly listric east-dipping mid-crustal reflections that sole out into the upper part of a 2-3 s thick region of subhorizontal lower crustal reflections. This observed fabric is similar to that observed in the Marmion terrane, and it is possible that this fabric is a common characteristic of Mesoarchean crust. Originally interpreted as related to shortening, many mid-lower crustal seismic reflectors in the Yilgarn craton are now viewed as arising in an extensional setting, perhaps due to gravitational spreading.

Given their similar geometry, the seismic reflectors in the Mesoarchean Marmion terrane may also have formed by a similar process prior to the terrane being caught up in the accretionary orogeny of the Western Superior craton. In this case, the lower crustal P wave anisotropy arose from ductile flow prior to collision, and the subhorizontal lower crustal reflection fabric does not represent a subcreted oceanic slab; in fact, the reflectors are most likely part of the Marmion terrane, making it thicker than previously thought. This study illustrates the value of comparisons of seismic reflection data from different Archean cratons.

Seismic reflection imaging of the heat source of an ultramafic-hosted hydrothermal system (Rainbow, Mid-Atlantic Ridge 36° 10-17'N)

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Most of our understanding of hydrothermal systems and the nature of their heat sources comes from models and observations at fast and intermediate spreading ridges. In these settings, hydrothermal systems are mainly located within the axial zone of a spreading segment, hosted in basaltic rock, and primarily driven by heat extracted from crystallization of crustal melt sills. In contrast, hydrothermal systems at slow-spreading ridges like the Mid-Atlantic Ridge (MAR) show a great variety of venting styles and host-rock lithology, and are located in diverse tectonic settings like axial volcanic ridges, non-transform discontinuities (NTDs), the foot of ridge valley walls, and off-axis inside corner highs. Among MAR systems, the Rainbow hydrothermal field (RHF) stands out as an end-member of this diversity: an ultramafic-hosted system emitting H_2 and CH_4-rich fluids at high temperatures and high flow rates, which suggests a magmatic heat source despite the lack of evidence for recent volcanism and its location within an NTD with presumably low magma budget.

We present 2D multichannel seismic reflection images across the Rainbow massif from the NSF-funded MARINER multidisciplinary geophysical study that reveal, for the first time, the magmatic system driving hydrothermal circulation in an ultramafic setting. Data were acquired in 2013 on board the *RV M. Langseth* with an 8-km-long hydrophone streamer. The images have been obtained from pre-stack depth migrations using a regional 3D *P*-wave velocity model from a coincident controlled-source seismic tomography experiment using ocean bottom seismometers. Our images show a complex system of partially molten and solidified plutonic sills intruding fresh or partially (<15%) serpentinized peridotite centered beneath the RHF. The sill complex occupies an areal extent of ~4.6x8 km^2, with most of the sills at depths between 3-6 km below the seafloor, but some as deep as 10 km below seafloor. Our data also image high-amplitude 35°-45° dipping reflections within the massif coincident with strong lateral velocity gradients that may arise from detachment fault planes, lithological contacts, and/or alteration boundaries. Our results are an important step towards understanding the interactions of detachment faulting, magmatic intrusion, and hydrothermal circulation in sections of the global mid-ocean ridge system dominated by mantle exposures.

Crustal structure across the Okavango continental rift zone, Botswana: Initial results from the PRIDE-SEISORZ active-source seismic profile

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The PRIDE project aims to understand the processes of continental rift initiation and evolution by analyzing along-axis trends in the southern portion of the East Africa Rift System, from Botswana through Zambia and Malawi. The SEISORZ active-source seismic component of PRIDE focused on the Okavango Rift Zone (ORZ) in northwestern Botswana, with the main goal of imaging the crustal structure across the ORZ. This will allow us to estimate total crustal extension, determine the pattern and amount of thinning, assess the possible presence of melt within the rift zone, and assess the contrasts in crustal blocks across the rift, which closely follows the trend of a fold belt. In November 2014 we conducted a crustal-scale, 450-km-long seismic refraction/wide-angle reflection profile consisting of 19 sources (shots in 30-m-deep boreholes) spaced ~25 km apart from each other, and 900 receivers (IRIS/PASSCAL “Texan” dataloggers and 4.5Hz geophones) with ~500 m spacing. From NW to SE, the profile crosses several tectonic domains: the Congo craton, the Damara metamorphic belt and the Ghanzi-Chobe fold belt where the axis of the ORZ is located, and continues into the Kalahari craton. The record sections display clear crustal refraction (*Pg*) and wide-angle Moho reflection (*PmP*) phases for all 17 of the good-quality shots, and a mantle refraction arrival (*Pn*), with the *Pg-PmP-Pn* triplication appearing at 175 km offset. There are distinct changes in the traveltime and amplitude of these phases along the transect and on either side of the rift axis, that correlate with sharp transitions across tectonic terrains and show evidence for shallow faulting. Initial modeling suggests: (1) the presence of a sedimentary half-graben structure at the rift axis beneath the Okavango delta, bounded to the SE by the Kunyere-Thamalakane fault system; (2) slower upper crust and thicker, faster lower crust to the southeast of the ORZ than to the northwest; and (3) 4-6 km thinner crust beneath the ORZ than in the surrounding domains (fold belts and Congo and Kalahari cratons) where the crust is crust 45 km thick.

Magma migration at the onset of the 2012-13 Tolbachik eruption revealed by Seismic Amplitude Ratio Analyses

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In contrast of the 1975-76 Tolbachik eruption, the 2012-2013 Tolbachik eruption was not preceded by any striking change in seismic activity. By processing the Klyuchevskoy volcano group seismic data with the Seismic Amplitude Ratio Analysis (SARA) method, we gain insights into the dynamics of magma transfer prior to this important eruption. We highlighted a clear migration of the source of the microseismicity within the seismic swarm, starting 20 hours before the reported eruption onset (05:15 UTC, 26 November 2012). This migration proceeded in different phases and ended when eruptive tremor, corresponding to lava extrusion, was recorded (at ~11:00 UTC, 27 November 2012). In order to get a first order approximation of the location of the magma, we compare the calculated seismic intensity ratios with the theoretical ones. As expected, the observations suggest a migration toward the eruptive vent. However, we explain the pre-eruptive observed ratios by a vertical migration under the northern slope of Plosky Tolbachik volcano that would interact at shallower depth with an intermediate storage region and initiate the lateral migration toward the eruptive vents. Another migration is also captured by this technique and coincides with a seismic swarm that started 16-20 km to the south of Plosky Tolbachik at 20:31 UTC on November 28 and lasted for more than 2 days. This seismic swarm is very similar to the seismicity preceding the 1975-76 Tolbachik eruption and can be considered as a possible aborted eruption.

New developments in virtual deep seismic sounding

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Virtual deep seismic sounding (VDSS) is a robust variant of wide-angle reflection. Instead of manmade sources, VDSS uses *S*- to *P*-wave conversion from natural earthquakes near each seismic station as powerful virtual sources. VDSS offers several distinct advantages over traditional methods. In particular, at distances between about 30°-55°, the virtual source of VDSS leads to a post-critical reflection off the Moho (seismic phase *SsPmp*) whose large amplitude stands out even when signal-generated noise is present.

The first application of VDSS to dense-spaced array data recorded during Project *Hi-CLIMB* successfully detected a regional trend of northward thinning crust beneath Tibet where the crustal thickness reaches 75 km in southern Tibet [Tseng, Chen & Nowack, GRL, 2009]. Now trace-by-trace comparison of VDSS profiles flanking the *Hi-CLIMB* linear array revealed marked, lateral (east-west) changes of overall crustal thickness under the Bangong-Nujiang suture zone, where a zone of disrupted Moho, characterized by multiple, Moho-like scatters at different depths, was previously detected by Gaussian beam migration of conventional receiver functions [Nowack, Chen & Tseng, BSSA, 2010].

Another important development is that the trade-off between crustal thickness and *P*-wave speed inherent in seismic reflections is negligible for estimating crustal buoyancy based on VDSS, once the relationship between *P*-wave speed and density of crustal rocks is taking into account (the Birch's law). We recently completed high-resolution estimates of crustal buoyancy over the entire western US, thus isolating mantle sources that support high elevation there. Positive residual topography, or the difference between observed elevation and that supported by crustal buoyancy, is particularly pronounced on the edges of the Colorado Plateau (including the northern and southern Rocky Mountains, and the eastern Snake River Plains) and the Basin and Range Province, indicating strong mantle support of elevation, from either thermal buoyancy or dynamic processes.

The phase *SsPmp*, the main stay of VDSS, has a significant move-out relative to the direct *S*-phase (up to 2.5 s between ~30°-55°). As such, when observations over different distances along similar back-azimuths are available, it is straightforward to simultaneously constrain overall crustal thickness and the average *P*-wave speed, overcoming the trade-off between the two important parameters. We have succeeded in applying this approach to data recorded by longstanding broadband seismic stations in Australia.

Internal structure of seaward-dipping reflectors from velocity analysis of ultra-long-offset seismic reflection data from the Uruguay passive margin

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Seaward-dipping reflectors (SDRs) are a key characteristic of transition zones between continental and oceanic crust at volcanic-passive margins. Where SDRs have been drilled, they are found to consist of interbedded sub-aerial tholeiitic lava flows, volcanic tuffs and terrestrial sediment with individual layers typically 10s-100m thick. This combination of alternating layers of basalt and sediment poses many problems for conventional seismic imaging. The high velocity contrast between basalt and sediments means a significant part of the seismic energy appears at large source-receiver offsets (>4 km), while the near offsets are degraded by strong peg-leg multiples. Further, in areas with thick basaltic sequences, high-frequency seismic energy experiences increased scatter compared to the low-frequencies. Here we analyse ultra-long-offset (10,200 m), wide-bandwidth (5-100 Hz) seismic reflection data acquired by ION-GXT offshore Uruguay in 2012 to gain new insights into the internal structure and hence formation of SDRs.

We focus on a single profile which is co-incident with a conventional wide-angle, ocean-bottom seismometer profile collected by BGR. The ION-GXT reflection stack images a zone of SDRs about 80 km wide and 7 km thick that form a series of discrete packages. Whilst the wide-angle profile provides a broad velocity framework it does not provide any detailed information on the internal velocity structure of the SDRs. To conduct the velocity analysis on the long-offset gathers we first performed extensive de-noising and multiple removal to target several types of coherent noise such as internal, water related, and apex shifted multiples. Semblance velocity analysis was then conducted on supergathers made from stacking 10 adjacent CMPs. A long-offset NMO correction was used to take into account the streamer length used. The velocity analysis was completed every 250 m to ensure capturing the lateral velocity variations and the final velocity models were combined with pre-stack time migrated images.

The velocity across the SDRs varies by up to 1 km s^{-1}, with the highest internal velocities observed where the stacked section shows them to thicken at the down-dip end of individual packages. Here velocities reach 6.3-6.8 km s^{-1}. The line displays 5-6 of these velocity highs that are spaced approximately 10 km apart. Beneath the SDRs the velocities reduce to more typical values for upper-mid continental crust (5.5 km s^{-1}). To our knowledge none of this detail has been previously seen at any other volcanic margins. We interpret the zones of anomalously high velocity as depleted mafic or ultramafic solidified magma, intruded within crystalline continental crust. We suggest that the intrusive bodies are the ancient magma chambers that sourced the sub-aerial tholeiitic lava flows that formed the SDRs. This new model is markedly different to the conventional view in which the SDRs erupt from a more-fixed central point that develops into the proto-mid ocean ridge.

Continental strike slip fault zones in geologically complex lithosphere: the North Anatolian Fault, Turkey.

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As part of the multi-disciplinary Faultlab project, we present new detailed images in a geologically complex region where the crust and upper mantle is bisected by a major continental strike-slip fault system. Our study region samples the north Anatolian fault zone (NAFZ) near the epicentres of two large earthquakes that occurred in 1999 at Izmit (M7.5) and Düzce (M7.2) and where estimates of present day slip rate are 20-25 mm/yr. Using recordings of teleseismic earthquakes from a rectangular seismometer array spanning the NAFZ with 66 stations at a nominal inter-station spacing of 7 km and 7 additional stations further afield, we build a detailed 3-D image of structure and anisotropy using receiver functions, tomography and shear wave splitting and illuminate major changes in the architecture and properties of the upper crust, lower crust and upper mantle, both across and along the two branches of the NAFZ, at length scales of less than 20 km. We show that the northern NAFZ branch depth extent varies from the mid-crust to the upper mantle and it is likely to be less than 10 km wide. A high velocity lower crust and a region of crustal underthrusting appear to add strength to a heterogeneous crust and play a role in dictating the variation in faulting style and post-seismic deformation. Sharp changes in lithospheric mantle velocity and anisotropy are constrained as the NAFZ is crossed, whereas crustal structure and anisotropy vary considerably both parallel and perpendicular to the faulting. We use our observations to test current models of the localisation of strike-slip deformation and develop new ideas to explain how narrow fault zones develop in extremely heterogeneous lithosphere.

An inverse method to measure thickness and volume of a thin CO_2 layer at the Sleipner Field, North Sea

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At the Sleipner Carbon Capture and Storage Project, CO_2 extracted from produced natural gas is being injected at approximately 1000 m depth into a pristine saline aquifer. The storage reservoir is a porous sandstone that is 250 m thick in the injection region, sub-divided by 1 m thick shale layers at intervals of about 30 m. Monitoring of injected CO_2 is primarily achieved through time-lapse three-dimensional seismic reflection surveys. Previous studies have shown that injected CO_2 is trapped in nine distinct thin layers within the reservoir. Whilst seismic reflection images obtained from the time-lapse surveys are adequate to measure changes in lateral extent of these layers through time, measuring the volume of CO_2 trapped within each layer has proved difficult. These layers are generally too thin to be resolved by direct measurement of the separation between reflections from the top and bottom of each CO_2 filled layer. Here, we present an inverse method to measure thickness of thin CO_2-saturated layers by exploiting the repeatability of time-lapse seismic surveys. Our approach combines measurements of reflection amplitude from the top of a layer with measurements of relative changes in two-way-travel-time down to the same reflection between time-lapse surveys to give estimates of layer thickness. A series of synthetic forward models, to which varying levels of ambient noise is added, are used to test the robustness of our method and to quantify uncertainties. This method is applied to the shallowest layer at Sleipner (Layer 9). By measuring CO_2-layer thickness on all time-lapse surveys, temporal changes in the volume of CO_2 in Layer 9 can be calculated. The volume of CO_2 in Layer 9 grows at a quadratic rate with time, despite an approximately constant injection rate at the base of the reservoir. The relationship between CO_2-thickness and trap topography is explored, and potential CO_2 migration pathways through the aquifer are identified.

Seismic imaging without a source: Towards cost effective and low environmental impact hydrocarbon exploration

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Long term recordings of ambient seismic noise can be cross-correlated to produce empirical Green's functions between all station pairs in an array/network. The application of dispersion analysis to these waveforms allows period-dependent surface wave group and phase velocities to be extracted and combined to create tomographic images of the crust and upper mantle.

Recently, it has been demonstrated that seismic structure at the exploration scale can be revealed using this method, but much more work is required before it could be used as a routine tool in the commercial sector. In this project, I will develop a data-processing workflow that enhances ambient noise signal with a particular emphasis on high frequency energy. Methods will focus on pushing the boundaries of what is currently possible in terms of spatial resolution of near surface structure. This will include exploiting the ellipticity of Rayleigh wave particle motion, which has the potential to greatly improve the recovery of structure in sedimentary basins and implementation of advanced Bayesian tomography methods.

The new techniques will be applied to datasets collected in Australia and elsewhere. For instance, large volumes of ambient noise data have been recorded by stations located in Tasmania and SE mainland Australia as part of the WOMBAT transportable array experiment. This is an ideal location for ambient noise tomography as Bass Strait and the Southern Ocean provide a strong source of diffuse seismic energy. Furthermore, the ability of ambient seismic noise methods to delineate the structure of sedimentary basins beneath Bass Strait can be tested against a vast repository of seismic reflection data collected by industry.

Interpretational Uncertainty

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Critical questions about the natural world are very rarely 'what do these data show?' and more frequently 'what can these data tell us about the thing we want to know?' We refer to the latter as our *target* information. Under conditions of both high complexity and high uncertainty it is often impractical to relate the data directly to the target using physical (process) models. Experts are then needed for their judgements, interpretations, future forecasts, and their uncertainty estimates for risk assessments or worst-case scenarios.

Experts vary, having experienced different situations during their professional history. Expertise is thus inherently subjective, and results of previous assessments of geoscientists reflect a concomitant variation in performance. Expert variation in itself may not be problematic, provided that its effects can be included within an estimate of uncertainty in the experts' results. Uncertainties can then be included within subsequent risk analyses and decision-making processes. This paper concerns the analysis of interpreters' uncertainties.

Bayesian statistics are used to describe how prior beliefs about a parameter of interest should be updated given subsequent information or data, and to propagate prior uncertainty estimates through to that updated position. In geoscience, the prior is usually inherently subjective as it describes a set of beliefs or assumptions based on uncertain information. This subjective knowledge is expert dependent. Additionally, how subsequent data is processed in order to illuminate information about the parameter of interest is also typically expert dependent. Further uncertainties may arise from the order in which data is obtained or analysed, as well as potential deviations from optimum human performance (cognitive biases). All such sources of uncertainty may be described and propagated within our novel Bayesian framework.

Particularly when making decisions using seismic data, interpretation is often required before information within the data can be used. Furthermore, data interpretation is often divided into distinct hierarchical phases. For example, prior information together with regional data may be interpreted initially to try to assess the overall geological settings or concepts that may pertain (e.g., purely extensional setting, reactivated faulting, salt intrusion, etc.). Within each of these concepts, the detailed interpretation of the seismic data may vary from that in other concepts; thus, the interpretation of the concept can be regarded as hierarchically before a more detailed interpretation that follows thereafter in order to estimate the parameter of interest. Other examples of using hierarchical interpretation include the extrapolation of annual temperature data to the next 100 years (using a variety of modelling concepts) before estimating future sea-level rise, or the creation of a model of tephra (volcanic ash) fall distribution by smoothing spatially discrete measurements to constrain possible models that estimate future eruption volumes.

This work applies a novel application of Bayesian statistics to the problem of interpretational uncertainty estimation. It addresses commonly observed issues surrounding expert variation and subjectivity, as well as various pathways available to experts for cognitive processing of data. This is illustrated by applying the theory to geological interpretation of geophysical data. Through this research, it becomes clear why approaching an interpretation in different ways may produce different results; it thus brings the community closer to a better understanding and quantification of interpretational uncertainty. By improving uncertainty estimation, and by applying the same method to other sources of uncertainty, decision-makers may take better-informed decisions with more accurate representation of the risks involved.

Marchenko imaging of primaries and multiples in elastic media

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The classic approach to image subsurface structures assumes that the seismic reflection data contains no multiples. Thus the data must either undergo multiple removal before their use, or the classic approach must be modified. Eliminating internal multiples represents a challenge, especially for elastic data. Nonetheless, a method for imaging primaries and internal multiples has been devised for acoustic media. The so-called Marchenko imaging method uses internal multiples in the data during imaging, bypassing any need for internal multiple attenuation. Tests on complex models and field data have shown its effectiveness. An extension of these methods to elastic data has been recently proposed by the authors, which has established a Marchenko theory for elastodynamic waves in solid media, and validated it in isotropic elastic media with horizontal and vertical density variations.

Elastic Marchenko methods have been developed which allow reconstructions of directionally decomposed (up- and down-going) elastodynamic wavefields at arbitrary subsurface points. It requires the single-sided multicomponent reflection response data obtained at the surface of the earth, which has been processed to have the direct wave as well as ghosts and free-surface effects removed. It also requires estimates of the P and S direct waves which may be provided by smooth background velocity macromodels frequently available at the migration step of seismic processing. The required data is then used in an algorithm which solves a 3D vector-valued Marchenko-type equation, which gives it its name. Upon convergence of the algorithm, we obtain multicomponent estimates of the up- and down-going wavefields “measured” at each image point from sources at the surface without having placed actual receivers there.

The fields provided by Marchenko redatuming may be used in several different ways, including internal multiple removal, primary estimation and imaging. We focus on the latter, providing an imaging framework for elastodynamic data which does not require any internal multiple removal. The imaging framework provides a straightforward connection to conventional imaging using Marchenko fields; in conventional imaging, the backwards extrapolated (up-going) data is crosscorrelated with the forward-propagated (down-going) wavefield to obtain the zero-time lag image. Therefore, we propose an imaging condition for Marchenko fields which consist of the zero-time lag crosscorrelation of the estimated up- and down-going fields. However, we show that this imaging condition, while suppressing some artifacts, creates others. Consequently, we also propose another imaging condition which uses only the direct-wave and the up-going field to generate the data. Additionally, our framework states that the true image should be obtained by a multi-dimensional deconvolution (MDD) of the up- and down-going fields. However, because of computational requirements, we show results obtained by approximating the MDD by a single-channel deconvolution.

We demonstrate our results using an isotropic, elastic model with a synclinal interface and several velocity and density contrasts. The numerical experiments contrast several of the proposed imaging conditions with a conventional imaging method for elastic data.

2D pre-stack full-waveform inversion of multichannel seismic data to retrieve thermohaline ocean structure. Application to the Gulf of Cadiz (SW Iberia)

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This work demonstrates the feasibility of 2D, time-domain, adjoint-state full-waveform inversion (FWI) to retrieve high-resolution models of ocean's water physical parameters such as sound speed, temperature and salinity. The proposed method is first described and then applied to pre-stack multi-channel seismic reflection (MCS) data acquired in the Gulf of Cadiz (SW Iberia) in 2006; in the framework of the GO (Geophysical Oceanography) project, intended to test the oceanographic potential of seismic data and funded by the EU.

The proposed inversion strategy includes specifically-designed data pre-conditioning for acoustic noise reduction, and then source wavelet inversion for each individual shot, followed by sound speed inversion, all in the shotgather domain. The inversion is performed in two steps. In the first we invert frequencies between 10-15 Hz using a coarse initial model constructed with coincident eXpendable Bathy Thermograph (XBT) data. The resulting model of the first step is used as initial model in the second one (10-25 Hz). We show that the final sound speed model has a horizontal resolution of 70 m, which is two orders of magnitude better than that of the original XBT-derived model, and close to the theoretical resolution of O(λ).

Temperature (T) and salinity (S) are also retrieved with the same lateral resolution as sound speed by combining the inverted sound speed model with the thermodynamic equation of seawater and a local, depth-dependent T-S relation derived from regional conductivity–temperature–depth (CTD) data of the National Oceanic and Atmospheric Administration (NOAA) compilation.

The comparison of the inverted T and S models with XBT and CTD casts deployed simultaneously to the MCS acquisition shows that the thermohaline contrasts are accurately resolved with an uncertainty of 0.15 ºC for temperature and 0.1 PSU for salinity. These high-resolution T, S models display numerous features and details corresponding to oceanic finestructure with lateral continuity over tens of kilometers that cannot be observed in the models obtained with conventional, probe-based oceanographic techniques. The combination of oceanographic and MCS data into a common, pseudo-automatic inversion scheme allows to quantitatively resolve submeso-scale features and incorporate them into larger-scale ocean models of ocean's structure and circulation.

Seismic anisotropic fabrics in eastern and northern Canada: evidence from shear wave splitting measurements

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Shear wave splitting measurements are used to determine the orientations and strength of anisotropic fabric in the upper mantle. Whether this anisotropy is caused primarily by "fossil" fabrics preserved in the continental lithosphere or by present-day sublithospheric flow, or some combination thereof, has been the subject of debate for several decades. With the increase in seismograph station coverage in eastern and northern Canada, new data sets are able to contribute to the evidence for lithospheric vs sublithospheric anisotropy.

We examine the variation in fast-polarisation orientations and splitting delay times across eastern and northern Canada in the context of geological and geophysical constraints such as major tectonic boundaries, potential-field anomalies, "absolute" plate motion and geodynamic models of sublithospheric mantle flow.

In some regions, notably the Canadian Maritimes and northernmost Canada, fast-polarisation orientations exhibit a strong correspondence with tectonic boundaries. In these areas, plate-scale lithospheric deformation related to past tectonic processes such as the Appalachian and Eurekan orogenie, respectively, appear to dominate the anisotropic fabric. Splitting measurements at long-term Arctic Canadian seismograph stations, though incomplete in back-azimuthal coverage, suggest systematic variations that likely indicate multiple anisotropic layers. Across much of central-eastern Canada, we observe partial correlation both with tectonic structures and with present-day mantle flow directions. Variations in splitting parameters between closely-spaced stations indicate the presence of lithospheric fabrics via Fresnel-zone considerations, but it is also likely that sublithospheric mantle flow plays a significant role. Given the thickness of the lithosphere beneath the Canadian Shield, it is reasonable to expect that our measurements would record contributions from multiple sources of seismic anisotropy.

Delimiting the continent-ocean transition at the ultra-slow Deep Galicia rift margin: new insights from wide-angle seismic data

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Anomalously thin oceanic crust and expanses of exhumed and serpentinised mantle material at magma-poor rift margins are now a globally observed phenomenon that characterises the seaward limit of the continent-ocean transition at ultra-slow rift margins. Hyperextension of continental crust at the Deep Galicia rifted margin in the North Atlantic has been accommodated by the rotation of continental fault blocks, which are underlain by the S-reflector, an interpreted detachment fault, beneath which serpentinised mantle peridotite is inferred to be present. West of these features, the enigmatic Peridotite Ridge has been suggested to delimit the western extent of the continent-ocean transition. An outstanding question at this margin is where oceanic crust begins, with little existing data to constrain this boundary and a lack of clear seafloor spreading magnetic anomalies.

Here we present results from a 160-km-long wide-angle seismic profile (WE-1), consisting of 34 ocean bottom instruments recording arrivals from coincident multichannel seismic surveying. Forward modelling and travel time tomography models of the crustal compressional (P wave) velocity structure reveal highly thinned and rotated crustal blocks overlying the S-reflector, which generally correlates with the 6.0 – 7.0 kms-1 velocity contours, corresponding to peridotite serpentinisation of 60 – 30 %, respectively. West of the Peridotite Ridge we observe a basement layer which is 2.8 - 3.5 km thick in which P wave velocities increase smoothly and rapidly from ~4.6 kms-1 to 7.3 - 7.6 kms-1, with an average velocity gradient of 1.00 s-1. Below this, velocities slowly increase toward typical mantle velocities with an average velocity gradient of 0.14 s-1. Such a downward increase into mantle velocities is attributed to decreasing serpentinisation of mantle material with depth. However, the presence of sparse Moho reflections indicates the onset of an anomalously thin oceanic crustal layer, ~20 km west of the Peridotite Ridge, which increases in thickness from ~0.5 km to ~1.5 km over a distance of 35 km, seaward. We infer that mantle exhumation continued up to 25 km west of the Peridotite Ridge, before the onset of the formation of anomalously thin crust overlying serpentinised mantle material.

Crustal structure of the Barreirinhas Basin, NW Brazil, from a 3-D wide-angle seismic survey

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The deep structures of the North-East equatorial Brazilian margin, was investigated during the MAGIC (Margins of brAzil, Ghana and Ivory Coast) joint project, conducted in August-September 2012 by Ifremer (Institut Francais de Recherche pour l'Exploration de la Mer), UnB (University of Brasilia), FCUL (Faculdade de Ciências da Universidade de Lisboa) and Petrobras. The main objectives of the cruise are to understand the fundamental processes, which lead to the thinning and finally to the breakup of the continental crust, which is still one of the main challenges for the Earth Science community, in a specific context of a pull-apart system with two strike-slip borders.

To probe the crustal structure of the offshore Barreirinhas Basin, a set of 5 intersecting deep seismic wide-angle profiles were carried out, with the deployment of short-period OBS's from the IFREMER pool. Three of the profiles were extended into land using land stations from the Brazilian pool. The experiment was devised to obtain the 2D structure along the profiles, from tomography and forward modelling, and thus not optimised for a 3D study; however, some of the profiles the OBS's recorded also the shooting from the nearby intersecting profiles, giving the opportunity to extend the crustal image from 2D to 3D.

This marine dataset, acquired over an area of 330x480 km^2 with a varying bathymetry from 100m to 4000m, generated several problems for the generation of a 3D tomogram. The water column and the strong variation of the sea bottom revealed to be complicated to deal by some of the available codes; in addition, the location on a continental margin with an associated strong variation of the Moho depth and lateral crustal structure, showed that pure 1D models were inadequate to use as initial input model. Several types of models were tested, the ones with best response being derived from 1D models derived at each OBS and later lateral interpolated to create a lateral smooth varying model. Several additional tests were performed to adjust the parametrisation, the results being compared with the models obtained from forward modelling.

Most of the tested parameters tended to have similar values regardless of the grid or the initial input model used. The main velocities anomalies tend also to be located roughly at the same zone, with the initial input model affecting mainly the exact shape and position. Checkerboard tests were also performed to define the model areas with good resolution. The overall final model anomalies are in agreement with the expected crustal structure. The Barreirinhas sedimentary basin appearing as a general low velocity area, its extension being clearly defined by the transition from continental to oceanic crust. The position of several sedimentary basins is also marked, the anomalies signal clearly delimiting different compositions. Old volcanic cones present also low velocities at the lower crust-upper mantle. The transition between a proto-oceanic crust and a transitional crust, composed by exhumed lower continental crust, is also clearly defined.

Crustal structure of Portugal from passive and active seismic methods

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Portugal lies on the south-westernmost tip of Europe, next to the boundary between Eurasia and Africa. The slow oblique convergence between Iberia and Nubia is accommodated along a broad region of diffuse deformation rather than along a single plate boundary. The geology of Portugal documents a protracted history from Paleozoic basement formation to the Mesozoic opening of the North Atlantic Ocean. It constitutes a key area for accretionary terrane and basin research, providing the best opportunity to probe a crustal formation shaped by the Paleozoic Variscan orogeny followed by the Mesozoic-Cenozoic extensions. The inheritance of such complex geologic history is yet to be fully determined, playing an important role in the current geodynamic framework, influencing the current crustal deformation and observed regional seismicity.

The first attempts to measure the physical properties of the crust of this area of Western Iberia were performed by several wide-angle active seismic profiles, conducted in the 70's and 80's by private companies or international projects like ILIHA. The compilation of these deep seismic reflection/refraction surveys showed a relatively homogeneous crust, although with some hints of anisotropy located in some areas. Since the data was mainly restricted to P-waves analysis and the profiles were unevenly distributed along the country, these studies did not provided a comprehensive knowledge on the crustal structure.

From 2010 to 2012, a temporary seismic broadband array project called WILAS was carried in Portugal, following similar initiatives like the TOPOIBERIA project in Spain. Taking advantage of an increase in the number and quality of the permanent BB network operating in Portugal, with the collaboration of the GFZ-Potsdam, this project deployed several temporary stations across Portugal, covering the country with a dense network of 65 stations with a maximum station spacing of approximately 50 km. The data compiled has since being analysed by several passive imaging techniques to increase the knowledge of the crust and uppermost mantle structure, namely P-Receiver-Functions (PRF), local–earthquake (LET) and ambient noise (ANT) tomographies, filling the gaps in the image provided by the active methods.

The PRF's results overall confirm the results of the deep-seismic sounding profiles, of an overall smooth Moho, with the variations usually associated with suture zones. However, there some local discrepancies between active and passive results.

The anomalies provided by LET and ANT results both point to a structure influenced by the tectonic zonation of Portugal: an arcuate shape influenced by the shape of Ibero-Armorican Arc, with the several suture zones delimiting the main anomalies. The presence of several basins associated with the opening stages of the Atlantic affect the anomalies, showing the distribution in depth of the crustal extension.

Velocity variations at Kīlauea and Bárðarbunga volcanoes measured using ambient seismic noise

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The continuous and pervasive nature of ambient seismic noise allows the extraction of interstation seismic signals in a repeatable fashion. Small fluctuations in these signals allow the measurement of tiny relative velocity variations, of less than 0.1%, in the top few kilometres of the crust. This has the potential to be both a powerful monitoring tool for volcanoes and a novel way of studying subsurface volcanic processes.

We use ambient seismic noise to investigate velocity variations at volcanoes in Iceland and Hawai'i. By cross-correlating the vertical component of day-long records between pairs of stations, coherent seismic waves can be extracted from the ambient seismic noise. Two common techniques are used to calculate the time delays between the daily cross-correlation functions and a reference function: the moving-window cross-spectral method (in the spectral domain) and the 'stretching' method (in the time domain).

In Iceland in 2014 a 48 km long dyke propagated away from Bárðarbunga volcano and breached the surface at Holuhraun producing a 6-month long eruption. The intrusion of this 5 m wide dyke was captured by a network of ~75 broadband stations. This provides an unprecedented opportunity to study the response of both the crust and neighbouring Askja volcano to the interplay between intrusion, deformation and eruption. At Kīlauea, the summit is continually inflating and deflating as the 2008 eruption from the vent at Halema'uma'u persists. We study continuous records between 2011-2015. Extensive instrumentation at the summit allows comparison between time series of velocity variations and deformation data. Results show a remarkable correlation between the apparent velocity variations and the inflation state of the summit. Both these case studies have the potential to further our understanding of the origin of such velocity changes.

The main source of ambient seismic noise in both areas is the ocean-generated secondary microseism at a predominant period of 7.5 seconds. Potential contaminating sources are present in both case studies. Over 30,000 micro-earthquakes were detected during the Bárðarbunga-Holuhraun dyke intrusion as the magma forced its way through the country rock. A source of near-constant tremor and long-period events (< 1 Hz) is present at Kīlauea. Distinguishing between true velocity variations and spurious measurements due to such contaminating sources is necessary. The source of the volcanic tremor at Kīlauea is very stable and so has the potential to be used as an alternative passive source for this cross-correlation technique.

The mantle transition zone beneath central Tibet: Seismic evidence for lithospheric detachment

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It is widely accepted that the Tibetan plateau, with the highest mountains and largest flat plateau on Earth, is generated by the continental-continental collision between the Indian and Eurasian plates as well as the subsequent convergence which is estimated to be 1800-2800 km long. As a result of this convergence, the crust has thickened to twice the thickness of normal continental crust. However, the lithosphere under the plateau has not thickened. Although many seismic projects have been conducted to study the collision mechanism, there hasn't been convinced coherent image of the lithospheric mantle in Tibet. The spatial and temporal observed in volcanic activity suggest removal of the deep part of the lithosphere. Research reveals that Qiangtang terrane (QTT) was above 5000 m by at least the middle Oligocene and maintained this high elevation from then on. But the mechanism remained highly controversial.

Teleseismic P waveforms were collected by 53 broadband seismic stations which was built around the Bangong-Nujiang Suture. We select events with epicentral distances ranging from 30° to 90° and with magnitudes of greater than 5.3 from November 2013 to November 2015. We calculate receiver functions in the time domain with a band-pass filter of 0.03-0.2Hz. We totally obtain 6420 high signal-to-noise ratio RFs and the stack one of every station then we can determine the thickness beneath every station. We also conduct the images of mantle transition zone of 15 profiles using the common conversion points time to depth migration. Then we achieve the 2-D thickness of the mantle transition zone.

Our results show that a thickening of the MTZ appears under QTT from 32° to 34°N. According to a triplicate waveform study, we infer that it is the deeper 660-km discontinuity that causes the MTZ thickening under central Tibet. The geochemistry study reveals that the volcanic rocks which were K-rich alkaline 30 Ma were distributed broadly in the QTT, we speculate that the detachment began 30 Ma ago. The thickened MTZ is approximately located in the uppermost mantle under the low-Pn velocity zone (where there is also inefficient Sn propagation) 30 Ma ago. And the upwelling of the asthenosphere followed by the lithospheric detachment caused the uplift of the QTT before at least late Early Oligocene (~30 Ma).

Tracking stress and hydrothermal activity along oceanic spreading centers using three-dimensional tomographic images of seismic anisotropy

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Marine controlled-source seismic tomography experiments now utilize dense arrays of 50-100+ ocean-bottom seismographs with spacings of the order of 2-10 km and source grids consisting of many tens of seismic lines with <500 m shot spacing. These dense experiments focus on the upper 10 km of the lithosphere over areas approaching 10,000 sq-km. Because of the dense spatial and azimuthal sampling of ray paths (500,000+ travel time measurements possible), it is now feasible to solve for 3-D images of P-wave anisotropic structure with lateral resolving lengths of up to 1 km. Seismic anisotropy is a common feature of the uppermost ~3-4 km of the lithosphere near oceanic spreading centers. P-wave speeds of shallowly refracted waves vary with the azimuth of the seismic ray path, a type of anisotropy produced by stress-aligned lithospheric cracks and microcracks. The fast axes of anisotropy are generally oriented parallel to the trend of spreading centers, as expected for ridge-parallel cracks that form by means of the anisotropic ambient stress fields associated with seafloor spreading. Three-dimensional imaging of seismic anisotropy using P-wave speeds has potential for estimating components of the stress field over large regions of oceanic lithosphere, with enough detail to examine regional and local distributions of stress.

Recent examples of dense experiments include the L-SCAN and MARINER studies performed along the Eastern Lau Spreading Center and Mid-Atlantic Ridge (36N), respectively. These two spreading centers represent high magma supply and low magma supply end-members. In each case, background anisotropy of ~4% is found in the upper 4 km of lithosphere with the fast axes generally oriented parallel to the trend of the spreading center as expected for cracks that form in association with seafloor spreading. Along the Eastern Lau Spreading Center, the study encompassed four individual spreading segments. Near the ends of ridge segments, where the neo-volcanic zone jumps from one spreading center to the next, anisotropy is high with orientations that are out of alignment relative to the background trend, a pattern that is retained at greater lithospheric ages. This agrees with numerical models and seafloor morphology that suggest tensile stress concentration and brittle crack formation in these areas. Anisotropy also increases in areas along the ridges where the underlying magma supply and hydrothermal output are greater. This is opposite the trend expected if simple tectonic stress models govern anisotropy. Instead, increased hydrothermal activity, due to increased magma supply, can explain the high anisotropy as resulting from hydrofracturing above the magmatic system. Along the Mid-Atlantic Ridge, seismic anisotropy exceeds 10% in an isolated area surrounding an oceanic core complex that is both underlain by intruded melt sills and hosts at its surface a long-lived high-temperature hydrothermal vent field (the Rainbow field). The high-anisotropy region is broad and semi-circular at depth, focusing upwards in a funnel-like manner just beneath the vent field. Both studies indicate that ambient crack distributions are overprinted by local hydrofracturing above regions of relatively high melt supply. These studies provide the first evidence that images of seismic anisotropy can be used to map variations in hydrologic activity along the crests of oceanic spreading centers.

Deep structure of the Santos Basin-São Paulo Plateau System, SE Brazil

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The structure and nature of the crust underlying the Santos Basin-São Paulo Plateau System (SSPS), in the SE Brazilian margin, is discussed based on six wide-angle seismic profiles acquired during the SanBa experiment in 2011, conducted by Ifremer, FCUL, UnB and Petrobras. Velocity models allow us to precisely divide the SSPS in seven domains from unthinned continental crust (Domain CC) to normal oceanic crust (Domain OC). Beneath the continental shelf, a ~100 km wide necking zone (Domain N) is imaged where continental crust thins abruptly from ~40 km to less than 15 km. Most of the SSPS (Domain A and C) shows velocity ranges, velocity gradients and a Moho interface characteristic of thinned continental crust. A central domain (Domain B) has, however, a very heterogeneous structure. While its southwestern part still exhibits extremely thinned (7 km) continental crust, its northeastern part depicts a 2-4 km thick upper layer (6.0-6.5 km/s) overlying an anomalous velocity layer (7.0-7.8 km/s) and no evidence of a Moho interface. This structure is interpreted as atypical oceanic crust, exhumed lower crust or upper continental crust intruded by mafic material, overlying either altered mantle in the first two cases or intruded lower continental crust in the last case. Lastly, in a seventh domain (Domain D), forming a triangular shape region in the SE of the SSPS, the crust is only 5 km thick, characterised by high seismic velocities between 6.20 km/s in the upper crust and 7.4 km/s in the lower crust. As seismic velocity gradients seem to rule out a continental origin, and clear Moho reflections argue against serpentinised upper mantle, we propose that the crust underlying this region to be of oceanic origin. Deviations from normal oceanic crustal velocities in the lower crust (6.70-7.00 km/s) could be explained by accretion at slow spreading rates leading to the inclusion of serpentinite into the lower crust at the onset of organised seafloor spreading. Overall, the v-shaped segmentation of the SSPS confirms an initial episode of rifting oblique to the general opening direction of the South Atlantic central segment.

Characterization of the Ventaniella fault from top to bottom through a multidisciplinary geophysical study

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The Ventaniella fault, also called Cantabrian fault, is a crustal structure that runs NW-SE through the Cantabrian margin and Cordillera in the Northern Iberian Peninsula.

The fault has a very long cartographic expression exceeding 300 km onshore and 150 offshore. The current structure acts mainly as a strike-slip with some inverse component. In some parts along its trace it reworks some Mesozoic rifting faults that are suitably oriented to accommodate north-south shortening during the alpine cycle. However, its role in the development of the Pyrenean Cantabrian mountain chain is not fully understood. The existence of lingering seismicity at its tips and the suggestion that separates different geodynamical domains provides good arguments for further investigation of this fault.

A novel project has been funded to study this structure from different points of view, including several geophysical approaches, together with geological characterization of the fault zone and a better mapping of its main trace and associated structures.

Several shallow geophysical lines across the fault zone have been planned at the NW, central and SE segments to compare with geological and petrological studies that will give information about the uppermost character of the fault. At the same time, a small seismic network of 10 stations within 20 km of radius from the fault trace has been deployed within the seismically active southern segment to analyze seismicity, ambient noise and integrate with other neighboring seismic networks and former deep studies to propose a crustal model of the fault zone.

Preliminary data from this network together with complementary studies are being gathered with the aim of improve our understanding of its significance within the crustal structure of the Northern Iberia.

Lessons from Nodal Acquisition in South Gippsland, Victoria

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2D seismic vibroseis reflection data were acquired in the South Gippsland region of Victoria in June-July 2015 as part of a collaborative project between the Geological Survey of Victoria and Geoscience Australia. The purpose of the survey was to gain an understanding of the geometry and internal structure of the Cretaceous Strzelecki Group that includes up to 100m of volcanics (Older Volcanics) and the underlying Palaeozoic basement of the Melbourne Zone. The depth to the basement varies across the four transects from 400 m to 7 km maximum. The survey was designed to image shallow near surface groundwater targets and basin down to 7 km depth as well as deeper crustal structures. The potential deterioration of seismic data quality due to the presence of the shallow volcanics also required investigation.

The Fairfield Zland cableless Nodal system was used with 15 m spacing of point receiver nodes rather than the cable acquisition system previously used by Geoscience Australia with an array of 6-geophone strings with 20m spacing. The advantages of using the nodal system are (a) more flexibility in design of the survey, especially in rugged terrains, or urban areas, and (b) significantly easier deployment of the equipment with much less downtime. A number of tests were carried out prior to the acquisition program to compare various sweep parameters and to optimise the acquisition parameters for a range of targets, both shallow and deep. These tests included linear sweeps with expanded bandwidth and non-linear customised high-dwell sweeps. High fold seismic reflection data (nominal fold 600) were collected to improve signal to noise ratio using two 50,000 lb vibroseis units for the source array. In an attempt to overcome the shallow volcanic layer issue data were recorded to long offsets up to 10 km, and not less than 4.5 km where the roads in the area were crooked.

Despite the effort of collecting the high fold data and long offsets, the quality of seismic data was significantly degraded due to several reasons including acquisition issues, and, more likely, geology of the region that is not easy to image using conventional seismic techniques. Attenuation appears to have had a substantial effect on seismic data quality, resulting in a loss of energy. The most significant issue seems to be a high level of noise observed in the data, especially at far offsets. This noise is more likely related to environmental noise in the region and due to nodes not being fully buried. However, the seismic data previously acquired in the same area using a cable system also exhibits poor data quality. This suggests a 'geological factor' as a major issue for good quality imaging of the crust in this area.

During the acquisition stage some general issues with the current nodal system were experienced, such as delays and problems of data harvesting and re-construction of shot gathers. This created a problem with real time monitoring of the data quality and resulted in difficulties in modifying acquisition parameters or calling shutdowns due to poor weather conditions. One example of lack of real time monitoring was a leap second event that caused timing errors that was identified only a few days after the event.

The data processing is currently being undertaken and is expected to be completed in June 2016. The advanced processing stream includes Pre-Stack Time and Depth Migration, DMO, Common Reflection Surface and Post-Stack Migration processing. The preliminary results show good images of the basin in the shallower section but little reflectivity observed in middle and low crust.

Constraining Crustal and Lithospheric Structure via Transfer Function Analysis of Teleseismic Data

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Seismograms from distant (teleseismic) earthquakes represent a combination of source-side and receiver-side effects. Various approaches have been used to separate out receiver-side structural information, including traditional receiver function deconvolution for the teleseismic P coda, and grid searches for one-layer splitting parameters for the SKS pulse. These approaches yield new observables (receiver functions and single-event splitting parameters) that are then examined or inverted in various ways to recover more complex structure.

The common flaw in these approaches is that they are based on inverting the result of a previous non-unique inversion. Receiver functions are prone to deconvolution artefacts, particularly in the presence of sedimentary basins; single-event splitting parameters are not robust observables, and multi-layer interpretations of parameters derived from assuming a single layer are inherently contradictory. I propose an alternative methodology applicable in principle to any teleseismic phase: the generation of transfer functions relating data components. For the teleseismic P wave, the transfer function between vertical and radial ground motion depends only on the receiver-side structure, and may be used to predict the radial component from the vertical; for an SKS pulse, the radial-to-transverse transfer function may be used in a similar way. In either case, we can evaluate how well a particular subsurface model predicts the actual observed waveform, and directly derive a meaningful misfit; inversion may be performed through Monte Carlo or grid search approaches.

I will present examples of applications to crustal and sedimentary-basin thickness measurement from the P coda in the Williston Basin and Mid-Continent Rift, USA, as well as across the North Anatolian Fault, Turkey. I will also present early results of shear-wave splitting analysis using a transfer-function approach. Finally, I will introduce the use of transfer functions in a possible layer-stripping technique for removing basinal artefacts from receiver functions.

Crust and Moho Structure Across the North American Midcontinent Rift System via Receiver Function and Transfer Function Analysis

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The Mid-Continent Rift (MCR), a failed Proterozoic rift structure in central North America, coincides with the Mid-continent Geophysical Anomaly (MGA), a gravity high that is a dominant feature of North American gravity maps. The MCR underwent a combination of extension, magmatism, and subsequent compression, and it is difficult to predict how these events affected the overall crustal thickness and bulk composition in the vicinity of the rift axis, though the associated gravity high indicates that large-volume mafic magmatism took place. The Superior Province Rifting Earthscope Experiment (SPREE) project instrumented the MCR with Flexible Array broadband seismographs from 2011 through 2013 in Minnesota and Wisconsin, along two lines crossing the rift axis as well as a line following the axis.

We examine teleseismic P-coda data from SPREE and nearby Transportable Array instruments using two complementary techniques: receiver-function and transfer-function analysis. Receiver functions were generated using time-domain iterative deconvolution (Ligorria and Ammon, 1999) and examined using waveform fitting as well as H-k stacking, to examine crustal layering as well as the depth and character of the Moho. Outside of the MGA, the Moho is found to be sharp and fairly flat beneath both the Archean Superior Province and adjacent Proterozoic orogens. The receiver functions become much more complex along the MGA, where the Moho Ps conversion weaker and more variable; at several stations, multiple arrivals are seen within the expected time window for the Moho conversion. Strong conversions from sedimentary basins are also observed, with particularly thick sediment present in basins flanking the rift axis.

We also apply an alternative approach to the P coda at these stations: modelling the transfer function between the vertical and radial components, and so directly fitting the waveform data without deconvolution. We use the transfer-function approach to perform a grid search over three crustal properties: crustal thickness, crustal P/S velocity ratio, and the thickness of an overlying sedimentary basin. Transfer-function results indicate that the crust is significantly thickened along the rift axis, with maximum thicknesses approaching 50 km; the crust is thinner (ca. 40 km) outside of the rift zone. The crustal thickness structure is particularly complex beneath southeastern Minnesota, where very strong Moho topography is present, as well as up to 2 km of sediment; further north, the Moho is smoother and the basin is not present. The P/S velocity ratio varies along the rift axis, indicating a more mafic crust (higher ratio) in southern Minnesota.

The two methods used have complementary strengths and weaknesses; receiver-function data allows direct evaluation of the nature of individual Ps conversions, while the transfer-function approach is robust in the presence of strong sedimentary-basin reverberations. We conclude that the MCR has a complex Moho with a transition from crust to mantle occurring over a 10-20 km interval; the transfer-function thickness measurement may be capturing the base of this transition, and so incorporating a significant underplated mafic component into its P/S ratio estimate.

Seismic characterization of the Alhama de Murcia Fault (Epicentral area of the Lorca 2011 earthquake)

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The Alhama de Murcia fault (AMF) is one of the most active faults of the Iberian Peninsula and the source of the Lorca 2011 earthquake that caused significant damage including several casualties. This NE-SW oblique (strike slip-reverse movement) fault, extended up to 100 km, has been extensively mapped to characterize its surface structure but almost no information is available of the structure and geometry at depth. As a result of the Lorca 2011 earthquake and its devastating effects in the population a need for better knowledge of the AMF became mandatory. Accordingly, InterGEO project pursues to understand the seismic behaviour of the fault and determine its relevance in seismic hazard. In order to achieve this, a multidisciplinary approach is used including detailed geological mapping, paleoseismic trenches, borehole logging and geophysical characterization. The main aim is to characterize the AMF in the sorroundings of the Lorca city ,from surface to depth, in the most interesting fault segments. In this work we present the very first results of the 2D high-resolution seismic reflection acquisition experiment carried out in 2015 along the AMF. The seismic reflection profiles were designed to reach target depths close to 1 km. These profiles provide the first structural image in depth of the AMF which is specially significant in the Lorca-Totana area where its structure becomes more complex splitting in several branches. The seismic images will contribute to determine if those branches are connected in depth or they correspond to differentiated structures which is required to understand the geodynamics of the AMF and to evaluate its seismic potential (Research supports: CGL2014-56548-P, 2009-SGR-1595 , CGL2013-47412-C2-1-P)

The location of Indian lithosphere beneath Tibet: Insights from group and shear wave velocity structure

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Processes occurring in large, hot, orogenic settings are not yet well understood. From the seismic properties of the lithosphere in areas of active continental collision we can gain insights into deformation processes occurring in present-day orogenies and make inferences about ancient orogenies. Tibet is an excellent natural laboratory for investigating collisional processes: it is the largest and highest orogenic plateau on Earth today.

New dispersion curves, measured from region earthquakes received at stations in West Tibet, Pakistan, and Southern India, and those measured from ambient noise cross-correlations for networks in India and the whole of the Tibetan Plateau, are used together with older dispersion measurements to obtain new fundamental mode Rayleigh Wave group velocity maps for Tibet for periods from 5-70s. The dense path coverage at the shortest periods due to the inclusion of ambient noise data allows features of ~100km scale to be resolved. The group velocity variations seen in these maps correspond well with known geological and tectonic features. In particular there is a strong correlation between low velocity group velocity at short periods and areas of thick sediments.

The Rayleigh wave group velocity maps are used to invert for shear wave velocity profiles to a depth of 120km. A mid crustal low velocity layer (~10% decrease in velocity) is observed throughout much of Tibet, with the exception of the northern part of West Tibet. We attribute this to radiogenic heating of the crust. The transition from the crust to the mantle occurs at lower shear velocities in the eastern part of the plateau than in the western part. This cautions against the use of a velocity proxy for mapping out crustal thickness in this region, and suggests that there may be important differences between East and West Tibet. These differences are emphasized by the elevated velocities, similar to those beneath India and the Tarim Basin, observed west of 84^{o} at depths exceeding 90km, i.e. in the upper mantle, across the entirety of West Tibet. We interpret this as Indian lithosphere underthrusting all the way across the plateau in the west, but not in the east. These differences may be the result of difference in the composition of the leading edge of India prior to collision: potential pre-collisional differences in the composition of the lower plate along the length of the orogen have strongly influenced the deep crustal and upper mantle structures that developed in other, older orogenic belts.

Do earthquakes contaminate marine reflection data?

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'Seismology at the crossroads' is the basic theme of Seismix 2016 Symposium that brings together researchers from the active and passive source imaging communities. In development of this theme, we present results of the first-pass analysis of the interaction between active (airgun) and passive (ambient noise, earthquakes) source signals. In 2014-15 the Australian National Ocean Bottom Seismograph (OBS) Fleet was utilised by the petroleum industry on a number of seismic surveys, including Shell Australia's Dirk-Adventure-Bart (DAB) seismic survey over the Exmouth Plateau on the Australian Northwest margin. Signal from a magnitude 6.6 MS earthquake in the Solomon Islands was recorded at several OBS sites during the Shell DAB survey concurrently with the airgun generated signal.

The airgun signal dominates when the distance between the OBS and airguns is small. In this case earthquake energy is often undetectable by visual inspection of the time series. The airgun signal amplitude decreases with increasing distance, and when the distance between the OBS and airguns at the time of earthquake energy arrival exceeds 70 km, the airgun signal becomes undetectable to the background of surface waves from the earthquake. Analysis of the spectral composition of the vertical component seismogram at this location shows a very prominent microseismic peak at low frequency values (≤ 0.5 Hz). This high amplitude feature has a rather narrow frequency range: its power spectral density at 3-4 Hz drops from peak values by ~5 orders of magnitude. From 3-4 Hz and above the airgun signal contribution becomes noticeable. The power spectral density at ~50 Hz is ~2 orders of magnitude greater than that at 3-4Hz. We conclude that within the frequency range from 3-4 to ~40 Hz the earthquake signal contributes enough energy for the resulting interference signal (earthquake plus airguns) to have a greater power spectral density than when earthquake energy is absent.

Non-earthquake energy contribution at small OBS-airguns offsets is strong enough to almost close the spectral gap between the microseismic peak (≤ 0.5 Hz) and the broadband airgun signal frequency range which was designed to have a flat signature from 5 to 90 Hz. There is a possibility that this non-earthquake energy is one of, or a combination of: airgun generated signal, shooting vessel noise, and/or noise generated by the array of ten 10-km long streamers towed behind the seismic vessel. Surprisingly, the earthquake energy at some OBS locations appears to make a noticeable contribution not only near the microseismic peak frequencies (≤ 0.5 Hz), but also up to frequencies as high as 50 to 60 Hz. We argue that in some instances earthquake energy may contaminate marine reflection data in the frequency pass-band needed for petroleum exploration.

Ongoing analysis suggests that under certain conditions seismic vessel noise and/or noise induced by a towed array of streamers produce *low frequency* spectral effects similar to the ones attributed to the energy of the Solomon Islands earthquake discussed above. Australian OBS data from the Shell DAB survey are unique by global standards, allowing further research into the full marine seismic wave field from active and passive sources.

Crustal-scale Imaging of a complex subduction system from dense OBS data by Full Waveform Inversion.

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The Nankai Through region (Japan) is one of the best sites for studying factors controlling segmentation of the earthquake rupture zones in subduction systems. Enormous number of high quality data, including multi-channel reflection seismic (MCS) and wide-angle reflection/refraction seismic (WARR), were acquired in the region. Ocean bottom seismometers (OBS) were used by JAMSTEC (Japan Agency for Marine-Earth Science and Technology) to collect WARR data with an unprecedented density (down to 1-km spacing). Redundant illumination of underlying structures enables crustal-scale seismic imaging using those data. In particular, one is able to exhaustively exploit their potential using full-waveform inversion (FWI). FWI is being intensively developed both by the oil and gas industry as well as by academia, driven by the fact that it offers derivation of the multi-parameter high-resolution earth models by starting from almost raw field data. Not only the imaging algorithms are developed – new acquisition technologies and a growing pool of OBS instruments available to the academic community make it now possible to acquire dense WARR OBS data even in 3D. Therefore, as it was presented during the 2014 SEISMIX conference, derivation of a 3D crustal-scale velocity model by FWI becomes now feasible.

Still, though, majority of the WARR OBS data is acquired along 2D profiles. Hence, here we investigate the crustal-scale FWI-based imaging of the real 2D OBS data acquired in the exceptionally complex subduction zone of the Nankai Through. We present how this type of data and imaging lead to automation of the high-resolution crustal velocity model building at the same time focusing on possible pitfalls of FWI, when not enough care is taken to quality-control the inversion process.

Our dataset comes from 2001 SFJ-OBS survey involving 100 OBS deployed along a 100-km long profile with 1 km spacing recording airgun shots extended along 140-km long profile with a 100 m spacing. Despite the good data quality, the complex geodynamical context involving subduction of topographic highs makes this dataset extremely challenging for FWI. We go through the whole procedure beginning from processing of raw data including Discrete Curvelet Transform, manual first break picking, starting model building by iterative FATT&FWI, designing FWI strategy and parametrisation ending with a validation of the final model including Dynamic Image Warping to quantify mismatch between real and synthetic data.

Resolution improvement from the FATT to the final FWI model is significant from shallow sediments down to the deep crust. In particular, the FWI model shows a sharp LVZ atop the oceanic crust. This anomaly might represent a damage fault zone created by subducting ridges colliding with the backstop. The top of this LVZ might correspond to a splay fault along which the co-seismic slip can occur during the next large earthquake in the area. More low velocity anomalies associated with thrusts suggest evidence of high-pressure fluid circulation along fault paths. Other interpretation highlights includes large-scale stacked thrust sheets in the backstop, major thrusts in the Miocene wedge (Kodaiba and Tokai thrusts) and layered sediments filling the trench.

Feasibility analysis of travel-time tomography of downward continued streamer data followed by full waveform inversion in limited-low frequency recordings

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Seismic tomography methods are useful techniques to retrieve the physical properties of the subsurface. In particular, adjoint-state full waveform inversion (FWI) of controlled source data is considered to be one of the most powerful tools to obtain accurate, high-resolution models. However one of its main drawbacks is the strong non-linearity of the problem, which makes the solution strongly dependent on the initial model and on the low frequency content of the data set. A common strategy to mitigate these issues is to combine the robustness of Travel Time Tomography (TTT) to obtain an appropriate reference model that is subsequently refined by FWI.

The combination of TTT and FWI is often used for long-offset acquisition geometries, where refracted waves are present as first arrivals. Conversely, its application to streamer-type multichannel seismic (MCS) data is infrequent, because these data are intrinsically short offset so the presence of refractions is very limited. In this case, Downward Continuation (DC) or redatuming of the MCS data to simulate an ocean bottom experiment allow recovering the refracted waves as first arrivals, so it is possible to perform TTT. In this work we use synthetic data to show that such TTT-based velocity models are suitable initial models for FWI even when data lack frequencies below 4 Hz; a realistic value in field data recordings.

In summary, the strategy proposed, implemented and tested consists of several processing and inversion steps. First we compute the downward continued wavefield using a finite difference solution of the acoustic wave equation in time domain. The solver used for the propagation, developed at BCSI, is parallelized and incorporates a multi-shooting strategy to back-propagate the wavefield. The chosen datum level is the sea bottom. Then we pick the first arrivals of the DC data and we perform the TTT. We show that, in contrast to other possible choices for the initial model, the TTT solution is kinetically correct to start FWI at 4 Hz, in the sense that it allows to overcome cycle-skipping.

Ongoing work is the application of this strategy to field data acquired in the Alboran basin with a 6 km-long streamer (TOPOMED experiment). The goal is to characterize the shallow structure in a tectonically active area the east Alboran basin volcanic arc. This includes the geometry of the sedimentary layers and basement outcrops and mapping large active faults that may represent a regional earthquake hazard.

Seismic velocity structure of active rifts and a mid crustal low velocity zone in the Icelandic crust

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Iceland is the product of long lived hotspot volcanism in the North Atlantic region, and it is widely believed that this is caused by a hot convective mantle upwelling. The structure of the Icelandic crust, with anomalously elevated thickness, peaking at 37 km beneath central Iceland, is key to this interpretation of an underlying mantle plume.

Here we undertake a study of the crustal structure across the whole island using ambient noise tomography to produce a seismic model of the crustal rift systems at previously unseen resolution. We use continuous broadband records from a high density seismic array deployed by Cambridge University which over the last 10 years has covered the whole of the northern and eastern neo-volcanic zones, with a typical station spacing of 5-10 km. The dataset is augmented by 48 sites from the permanent monitoring network of the Icelandic Meteorological Office (IMO), 30 sites from the HOTSPOT experiment of 1996-98, and further short term deployments to complete coverage of the whole island. Rayleigh waves are extracted from the continuous ambient noise and used to measure group velocity dispersion curves for interstation pairs. Errors in the observations are estimated from the temporal repeatability of the measurement for multiple stacks of the noise correlation function. Group velocity tomographic maps are generated across a range of periods from 5 to 25 seconds. Pseudo-dispersion curves are then extracted from the well constrained cells of the group velocity maps, and are inverted for a shear wave velocity structure.

We find low wavespeed anomalies which are extremely well correlated with the active volcanic rift zones of the plate boundary. As much as 0.5 km/s wavespeed variation is observed between the slower rifts and the faster non-volcanically active regions. The slow anomalies demarcate each of the neo-volcanic zones, and even delineate a linking branch between the Western Volcanic Zone with the Eastern Volcanic Zone near the Bárðarbunga-Grimsvötn volcanic complex. Within the rifts slower wavespeeds are concentrated along the western side of the Vatnajökull ice cap, and the very slowest velocities are centred beneath the Bárðarbunga-Grimsvötn volcanic complex, where the crust is thickest and the centre of the mantle plume is believed to lie.

A striking feature of the shear velocity inversions is a clear low velocity zone in the mid crust, which is consistently resolved across the entirety of the model. The layer of slow velocities occurs between 14-20 km depth with a reduction of up to 0.3 km/s. The topography of this zone shallows into the active volcanic rifts, where an elevated geotherm and higher degree of melt extraction is expected.

The magmatic plumbing system of the Askja central volcano, Iceland, as revealed by local earthquake tomography

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Using a dense seismic network, we have imaged the plumbing system beneath Askja, a large central volcano in the Northern Volcanic Zone, Iceland. Local and regional earthquakes have been used as sources to solve for Vs, Vp and Vp/Vs ratios beneath the volcano. Travel-time tables were created using a finite difference technique and the residuals used to simultaneously solve for both the earthquake locations and velocity structure. In addition to the background seismicity, we have used the earthquakes generated by the 2014-15 Bárðarbunga dike intrusion. These provided a 45 km long, distributed source of large earthquakes which are well located and provide accurate arrival time picks. Together, these data provide excellent illumination of the Askja volcano from all directions.

The main seismic velocity anomaly imaged is a low-velocity body immediately beneath Askja caldera at a depth of ~6 km. The anomaly is ~10% slower than the initial best fitting 1D model and has a Vp/Vs ratio higher than the surrounding crust, suggesting the presence of increased temperature or partial melt. We use simple relationships between mineralogy and seismic velocities to estimate that this region is ~10% partial melt, similar to observations made at other volcanoes such as Kīlauea. This low-velocity body is significantly deeper than the depth of a deflating body beneath Askja as suggested by the observed subsidence. Synthetic tests show that any such shallow low-velocity body must be smaller than 15 km^3, significantly smaller than the imaged body at 6 km depth. We conclude that if there were a shallow body which is below our imaging resolution, it cannot be a significant storage area for magma in the Askja plumbing system.

Beneath the large low-velocity zone, a region of high Vp/Vs ratios extends into the lower crust and is coincident with seismicity in the lower crust. This is suggestive of a high temperature channel in the lower crust which could be the pathway for melt rising from the mantle. This melt either intrudes into the lower crust or stalls at the brittle-ductile boundary at ~6 km depth in the imaged body. Above this, melt can travel into the fissure swarm through large dikes or erupt within the Askja caldera itself.

Fracturing and alteration in young oceanic crust from 3D seismic velocity structure and anisotropy analysis

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Fracture and fault networks in the upper oceanic crust influence the circulation of hydrothermal fluids and the transfer of heat and mass between crust and ocean. These fractures form with a predominant orientation parallel to the ridge axis, creating porosity- and permeability-derived anisotropy that can be measured using geophysical methods. As the crust ages, its porosity and permeability evolve due to cooling, alteration and sedimentation. The rate at which these changes occur and their effects on oceanic crustal structure and hydrothermal flow patterns are currently not well constrained.

An extensive geophysical survey was conducted in 2015 over DSDP/ODP borehole 504B, located ~200 km south of the Costa Rica Rift in ~6 Ma crust. A three dimensional grid of seismic reflection and wide-angle refraction data combined with potential field measurements, underway bathymetry, and passive magnetotellurics enables comprehensive analysis of the lithosphere from the sediments through the crust to the upper mantle.

We present the three dimensional p-wave velocity structure of ~6 Ma crust at borehole 504B from inversion of first arrivals using FAST. The 35 x 35 km^2 velocity model reveals the seismic structure of the ~5 km thick crust, which is related to lithological and alteration changes through calibration at the borehole. The drilled section comprises 571.5 m of extrusive lavas overlying a 209 m transition zone of mixed pillows and dykes containing an alteration boundary, which grades to >1050 m of sheeted dykes. Depth-dependent seismic anisotropy is investigated by comparing velocities at different shot-receiver azimuths. Results reveal a ridge-parallel fast direction within the crust, due to aligned fractures, and a ridge-perpendicular fast direction within the upper mantle, attributed to directional mantle shearing. These results combined with other findings from this new, comprehensive dataset lead to an improved understanding of how this ~6 Ma crust has developed and the active processes which continue to alter its structure and composition.

Integrated Geophysical Study on the Deep Structure of Bohai Bay Region

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The North China Craton (NCC) is the only place where intensive destruction of thick Archaean lithosphere on earth. It is considered by scientists as "a best example of ancient lithosphere destruction". The process and mechanism of the NCC destruction becomes research hot point and two destruction models are under debate. One is the Thermal Erosion Model (TEM) and another is the Delamination Model (DM). The first one usually occurs in the circumstance of mantle plume and mushroom shape seismic velocity anomaly where radiated faults distribution can be found. The second model, where geophysical spatial variation can be usually found, for example large-scale low seismic velocity in the upper mantle.

The Bohai Bay in the north China belongs to the eastern block of the NCC, and several important fault zones exist there. It's been considered to be the center of lithosphere thinning of the NCC. However, until 2009 no seismic survey profile is in this region offshore even if there are numerous profiles on land around the Bohai Bay. Hense, we conducted two onshore-offshore deep seismic reflection/refraction profiles in 2009 and 2011 in this region with a tuned air-gun arrays as large as 9000 inch^3 and 80 ocean bottom seismometers to get the deep structure in the Bohai Bay. Besides, we employed various potential field and earthquake data to study the hot debated NCC destruction models in even larger scale.

Based on the results of two onshore-offshore deep seismic profiles, earthquake tomography and gravity-magnetic inversion in the Bohai Bay region, we find the lower crust anisotropy and small-scale high velocity zones do exist in the region and no large-scale undulance of the Moho, and we propose lithosphere thinning is mainly caused by the upper mantle extension. The result indicates that lateral variation of the Moho interface and the crustal P-wave velocity are affected mostly by the existence of large-scale faults nearby, and lower crust was underplated and transformed by the Moho. There is no geophysical evidence support the TEM or DM of the NCC destruction based on our experiment. Therefore, we suggest that the crustal structure of the region shows "a relatively normal crust and thinned mantle" and instability phenomena shows P-wave velocity anomalies in the crust may represent a combined effect of North China Craton -Yangtze collision at the early stage and the distal effect of the Pacific plate subduction at the late stage.

SS waveform splitting: Theoretical analysis and tentative applications

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An anomalous SS waveform splitting time (up to ~10 s) has been observed between radial and transverse components, which cannot be explained by the seismic anisotropy along SS ray-path alone. Our theoretical analysis reveals that such a large time is a consequence of SS radial waveform's contamination by crustal reverberations beneath its bounce point. Given an isotopic model, the splitting time is a function of crustal thickness and averaged crustal Vp of SS bounce point, as well as horizontal slowness. The anatomized SS waveform characteristic not only suggests that caution must be taken about appropriate analysis of SS waveform, but also in turn promotes us to constrain upper-mantle seismic anisotropic parameters and crustal thickness beneath its bounce point in light of SS waveform splitting.

FIRE for free (FFF) – how to make large and valuable seismic reflection data sets easily available

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The data from FInnish Reflection Experiment FIRE are like the data from many other similar large seismic reflection programs. After the first years, the use of the data is rather limited, despite the fact that the acquisition was expensive and the scientific value of the data is high. Often the main reason is not that the data are unavailable in principle, they are just too complicated to use in practice.

The Institute of Seismology of the University of Helsinki has started - with the financial support of the Ministry of Education of Finland – the FFF project to overcome these obstacles by building up a data base and a related interactive web site for easy downloading of seismic data and supporting material of the FIRE program. We hope that this will encourage our colleagues everywhere to use the data and help our students, by using the data, to learn the great importance of seismic imaging of the crust. The project started in March 2016 and by the end of the year we assume that there will be a prototype available for testing. After feedback from users, the upgraded data base and the web site will be ready by the end of 2017.

The seismic files in the data base will include raw field data, edited field data, DMO and NMO stacks as well as migrated sections. Additional material includes for example coordinate files, observer's logs, line maps and, as much possible, other relevant geological and geophysical material. Our goal is also to make available plots of the sections in different scales, so that a person not familiar with seismic data, could use them easily. An important step is the creation of the edited field data in which the headers of the SEG-Y shot gathers already include all relevant parameters, like coordinates, station numbers etc...,which usually are in the auxiliary files. These gathers include only proper shot gathers with reliable observer's log information, no tests or misfires. As this phase usually consumes most of the work time, especially if you are not familiar with details of acquisition, we hope that the availability of these shot gathers would lower the threshold of scientific use of the data.

Whereas the handling of the seismic data is quite straightforward, creation of a good interactive web site may produce some challenges. We are sure that we can manage these and hopefully in the end, link our data base with the extensive EPOS-ERIC seismic data base in the future.

Seismic landstreamer data in challenging mining environment: lessons learned from Siilinjärvi apatite-bearing open-pit mine, Finland

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As a part of the ERA-MIN sponsored Start-GeoDelineation project, reflection seismic data were acquired in the Siilinjärvi open-pit apatite-bearing mine in central Finland during July 2014. Data were acquired simultaneously using a newly developed (Brodic et al., 2015) digital-based landstreamer system (80-3C sensors) and wireless recorders (52 connected to 10 Hz geophones). The landstreamer consisted of, at the time of the survey, 4 segments, each having 20 sensors placed 2-4 m apart. For wireless stations, receiver spacing of about 10 m (fixed during the survey) was used. To generate the seismic signal, a bobcat mounted drop-hammer was used. Shot points were spaced 4 m apart and each point was recorded 3 times and stacked vertically to improve the signal quality. Two seismic profiles were acquired inside the open pit, and two in its vicinity outside. The main goals of the Siilinjärvi seismic survey were first to check the performance of the seismic streamer for open-pit mine planning and further to better understand the relationships between the carbonatite-apatite mineralization and different generations of basic dykes in connection to fracture and shear zones. In addition to the seismic profiles, down-hole logging including full waveform sonic, magnetic susceptibility, natural gamma and various laboratory measurements including density were performed in three boreholes to constrain the seismic interpretations.

Despite the highly noisy environment of an active mine, most shot gathers show high quality first breaks for all offsets but lack noticeable reflections. Geology of the Siilinjärvi mine is rather complex with diabase dykes crosscutting the ore formation in different directions. Careful inspection of the first arrivals suggests velocities as low as 3000 m/s at near offsets and clear refracted arrivals of more than 5000 m/s at far offsets. This observation by itself is interesting and may imply a zone of weakness (e.g., blast-damaged) or poor quality rocks (carbonatite and mica rich) where the profiles were placed in the pit. Seismic tomography was carried out to complement some of the short reflections observed in the data. Joint reflection and tomography results in conjunction with the borehole data allowed us to interpret some of the major shear zones at shallow depths but also suggested possible contact with a major intrusion south of the Siilinjärvi complex limiting the southern extent of the mineralization. 3D swath processing was also carried out to overcome the geological complexities and the crookedness of some of the profiles. Our results suggest that combining tomographic and reflection imaging suites best extracting new information about geological structures in the Siilinjärvi case and same approach is likely to be efficient in other open-pit mine planning seismic projects as well. Further analysis of the data is currently on-going.

Brodic, B., Malehmir, A., Juhlin, C., Dynesius, L., Bastani, M., and Palm, H., 2015. Multicomponent broadband digital-based seismic landstreamer for near surface applications. Journal of Applied Geophysics, 123, 227–241.

Stepping stones to reconstruct the Archean-Paleoproterozoic boundary of Central Fennoscandia: insights from deep seismic reflection profiles

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The Finnish Reflection Experiment (FIRE) was carried out in 2001-2005 to comprehend subsurface geophysical characteristics of Archean-Paleoproterozic crust. During FIRE project, more than 2000 km of seismic reflection data were acquired throughout Finland along roads. These profiles cross the major geological units of the country and provide glimpse to the deep geology and crustal architecture. Rapid development of 3D-modeling capabilities in the past years has enabled new insights to the deep bedrock through facilitated visualization and integration of different data sets. In case of crooked seismic reflection profiles, plotting a profile to its true 3D location simplifies the correlation of surface features with observed reflections. In the present work, we have integrated east-west oriented seismic profiles FIRE3 with aerogeophysical maps, gravity and magnetotelluric data, and diverse geological data in order to decipher the crustal architecture of the Archean-Proterozoic boundary in central Finland.

FIRE seismic reflection data were acquired with split spread geometry consisting of 362 active channels with 50 m spacing. Five Geosvip 15.4 ton vibroseis trucks were used as a seismic source, and sweep was linear upsweep from 12-80 Hz. Data has been commercially processed by using standard processing flow including band-pass filtering, geometrical spreading corrections, static corrections and deconvolution. The data acquired portray crustal structures down to the uppermost mantle, to the depths of about 80 km.

FIRE3 seismic profiles image the present crustal structures of the Archean bedrock and its Paleoproterozoic cover in the east and the Paleoproterozoic Central Finland Granitoid Complex in the west. The profile FIRE3 crosses the historical mining district of Outokumpu, providing more information about the crustal structures possibly influencing the mineralising system. It is apparent from the seismic images that Paleoproterozoic Outokumpu allochton is strongly reflective due to material contrasts of the upper crust, while more homogenous Archean crust mainly consisting of gneisses, granites and granodiorites is non-reflective. By combining the surface geology with the subsurface seismic reflectors, we have correlated and extrapolated large-scale tectonic boundaries and geophysical signatures in 3D along the profiles using the Paradigm GoCad software. Deep structures without surface expressions are inferred using apparent dip directions interpreted from the seismic profiles, winding profile providing 3D control of the interface. This procedure enables a 3D modelling of the strike and dip of major geological units, such as rock type contacts or faults. Modelling of crustal architecture is a key to understand tectonic processes that have shaped the bedrock.

Data mining to discover the causes of reflectivity within the Kevitsa intrusion and associated Ni-Cu-PGE deposit in northern Finland

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Data mining approaches, such as SOM (Self-Organizing Maps), can be used for objective analysis of the complex and disparate geophysical and geological data sets typical for mining camps, to understand the underlying relationships between the different data. The SOM analysis is based on vector quantization and measures of vector similarity. It is unsupervised, so no prior knowledge is required on the nature or number of groupings within the data. Here we have used SOM to study the causes of observed internal reflectivity within the Ni-Cu-PGE-bearing Kevitsa intrusion, and its relationship to the disseminated sulfide mineralization. The Kevitsa Ni-Cu-PGE deposit is hosted by the Kevitsa mafic-ultramafic intrusion located within the Central Lapland Greenstone Belt in northern Finland. The Kevitsa deposit is currently being mined by First Quantum Minerals Ltd.

At this stage, only borehole data was used for the SOM analysis. In total, hundred and thirty-four boreholes, constituting 64 999 samples, were selected for the SOM analysis, which was conducted with CSIRO`s SiroSOM software. Eight different geophysical, twelve geochemical, as well as lithology and alteration variables were included into the analyses in different combinations. Sonic logs were available from 16 boreholes. One major strength of the SOM analysis is that it can be used to infer missing data values, i.e., in particular in this context sonic logs that in mining and exploration camps are typically only available from a few boreholes. With the Kevitsa borehole data, we tested how well simulated SOM data values for seismic velocity correlate with the actual measured values. The results show that just a few strategically placed sonic logs are enough for SOM to reliably infer the sonic logs for the rest of the boreholes. In the case of Kevitsa, a combination of geochemical, specific gravity, rock-quality designation, resistivity and induced polarization data was found to be the best for predicting the seismic velocities. This ability of SOM provides a powerful tool for seismic interpretation, in particular when the results of the SOM analysis are visualized in 3D and directly compared to the seismic data.

The main objective of the SOM analysis was to study the causes of reflectivity observed in the Kevitsa 3D seismic reflection data within a constrained area inside the intrusion. In earlier studies, it has been suggested that the rather continuous reflectors are due to contacts between the tops and bottoms of smaller-scale magmatic layers within the intrusion, which also control the extent of the Kevitsa ore deposit (sulfides deposited at the bottoms of the layers). Our initial SOM results show that the data is inconclusive about the contacts between the tops and bottoms of the magmatic layers being the cause of the observed reflectivity. However, with increasing sulfide contents (the trend visible with respect to S-, Ni-, and Cu-contents), the seismic velocities drop significantly (pyrrhotite, chalcopyrite and pentlandite, the main ore-bearing sulfide minerals, lower the velocities), but the densities stay about the same as for the barren host rocks (pyrrhotite, chalcopyrite and pentlandite should also increase the densities, but there is no clear trend to this effect). The velocity drop caused by the increased sulfide content is enough to cause a reflected signal, and the observed internal reflectivity within the intrusion could arise from this. We will show evidence to support this interpretation and discuss other possible scenarios.

Using realistic 3D geological models based on triangulated surfaces in parallel seismic finite difference simulations

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Seismic simulations are among other things used to study effects of wave propagation in complex geological media and to optimise acquisition geometries during the planning of seismic surveys. The parallelisation of the corresponding software makes it possible to simulate the wave propagation also in large 3D models. While a simple geological structure, such as a layered half space, can be expressed with simple mathematical functions, more complicated geometries are often described by triangulated surfaces that represent boundaries between neighbouring formations or that enclose geological bodies. In order to use these complex model geometries for parallel seismic finite difference simulations, they have to be converted into a regular 3D Cartesian grid. The software Skua-Gocad by Paradigm comprises a function for the conversion of models that consist of triangular meshes into a 3D voxel grid. However, the applicability of this routine is limited when large grids with a very high spatial resolution are required. This is often the case with finite difference simulations in order to avoid artefacts like grid dispersion or unwanted diffractions at dipping layers caused by the staircase effect. Furthermore, generating the voxel grid before the simulation utilises a lot of hard disk space, and reading as well as writing this voxel-based model from hard disk into memory can be very time-consuming. For this reason, we choose an approach where a rasteriser is incorporated in the parallel seismic simulation software. The rasteriser assigns a specific geological body uniquely to each grid point. Its input is a triangulated, watertight surface model that represents the different geological units. At the beginning of the seismic simulation, this model is read by all involved processes of the parallel computation. The parallelisation is based on a domain decomposition of the 3D finite difference grid where each process computes the wavefield within its subgrid. Accordingly, the processes rasterise the model only within their subgrids and assign identifiers to the grid points that correspond to certain geological bodies of the geometry model. With these identifiers, it is possible to assign material parameters, i.e. the seismic velocities and the density, to all points of the finite difference grid. The values that correspond to certain identifiers are listed in a look-up table. Each of the parallel processes keeps only the rasterised model parameters in the memory that are needed for the simulation. Such finite difference simulations are not restricted to a sequence of homogeneous geological bodies. The identifiers can also be used to alter the material parameters of the model constituents depending on the coordinates of each individual grid point. Thus it is for example easily possible to add a velocity trend with depth.

As a proof of concept, we show snapshots of the seismic wavefield and seismograms from a 3D elastic simulation with a spatial grid consisting of 1100 x 860 x 700 grid points. It is based on the model of a complex salt structure. The computing time for 6000 time steps is approximately 48 minutes on 125 processors of the high performance computing cluster of TU Bergakademie Freiberg. Of the computing time, rasterising the model requires less than a minute. This example illustrates that the presented method makes it possible to include complex, realistic 3D structures into seismic simulations in an efficient way.

A new generation of ocean-bottom seismometers

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Numerous geophysical instrument pools worldwide have been developing portable ocean bottom seismometers (OBS) for several decades. Research projects using these instruments have shed new light on the internal structure of the Earth and the nature of earthquake sources. As a result of these successes, Güralp has taken advantage of its 30 years of expertise in manufacturing and installing seafloor instrumentation to launch a new OBS product range. Each instrument is designed for specific deployment methods and installation depths. The instruments are engineered to meet current challenges for ocean bottom seismography, including withstanding high pressures, minimising power consumption, improving recovery rates and maximising battery time.

Broadband OBS provide the flexibility to perform seismic monitoring at all scales and for a range of applications, from teleseismic earthquake monitoring, to detection of microseismic events. Additional geophysical sensors can be included into the OBS systems, including accelerometers for strong-motion applications, such as earthquake early warning, and absolute/differential pressures gauges (APGs/DPGs) for detecting changes in the overlying water column and in seafloor displacement. In this poster, we explain the main benefits and advantages of each OBS instrument, and describe some key results that have arisen from their use.

Cabled OBS systems have the advantage of transmitting data in real-time to an onshore data centre, as well as maintaining a permanent power supply. Typical applications of cabled systems include permanent ocean observatories, as well as earthquake and tsunami early-warning systems. A Güralp cabled OBS system installed in the Sea of Marmara, Turkey has been used to shed light on microseismicity along the Northern Anatolian Fault. In addition, sensors located in the Cascadia subduction zone captured the fine details of the Axial Seamount eruption in May 2015. Güralp portable OBS have been used for a wide range of applications, including permanent reservoir monitoring (PRM) for hydrocarbon production, and monitoring seismicity along undersea faults in central California. A recent wide-azimuth 3-D seismic survey off the north-western coast of Australia was able to extend the aperture of traditional streamer active-source seismic surveys and shed new light on the deep structure of continental margin.

Improved detection of induced seismicity using beamforming techniques: application to traffic light systems

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Unconventional methods of hydrocarbon extraction, such as hydraulic fracturing, have the potential to reactivate existing faults, causing induced seismicity. Traffic Light Schemes have been implemented in some regions; these systems ensure that drilling activities are paused or shut-down if seismic events larger than a given magnitude are induced. In particular, the United Kingdom has imposed a traffic light scheme based on magnitude thresholds of Ml = 0.0 and Ml = 0.5 for the amber and red limits, respectively. Therefore, an effective traffic light scheme in the UK requires monitoring arrays capable of detecting events with Ml < 0.0. However, achieving such low detection thresholds can be challenging where ambient noise levels are high, such as in the UK.

We have developed an algorithm capable of robustly detecting and locating small magnitude events, which are characterised by very low signal-to-noise ratios using small arrays of surface broadband seismometers. We compute STA/LTA functions for each trace, time shift them by theoretical travel-times for a given event location, and combine them via a linear stack.

We test our method using a dataset from a surface array of Güralp 3T broadband seismometers that recorded hydraulic fracturing activities in the central United States. Our beamforming and stacking approach identified a total of 20 events, compared to only 4 events detected by traditional picking methods. We therefore suggest that our approach is suitable for use with low magnitude traffic light schemes, especially in noisy environments.

Reflections on BIRPS

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In the late seventies and early eighties, the Royal Society, Natural Environment Research Council (NERC) and a group of academics lead by Derek Blundell and Drum Matthews were keen to follow recent research in the United States to use reflection imaging methods to map the deep structure of the Earth's crust around the UK. Plans were developed for a on-land transect to cross major tectonic structures in Scotland. In 1981, Dave Smythe, with some funds from the Institute of Geological Sciences (now BGS) and a guiding hand from the oil industry acquired a marine seismic profile off the north coast of Scotland – MOIST. The results were spectacular and the British Institutes Reflection Profiling Syndicate (BIRPS) was born. The NERC initially funded BIRPS for four years during which time four surveys were shot providing a network of marine profiles from the Shetland Isles in the north to the South-west approaches (partly in collaboration with the French group ECORS); and two surveys in the North Sea (through collaboration with GECO). Within this flurry of activity BIRPS acquired its 'signature' profile DRUM. DRUM – Deep Reflections from the Upper Mantle – ensured BIRPS success and remains an iconic reflection image of not only faults in the crust but structures in the upper mantle down to depths of nearly 100 km.

BIRPS continued work until 1998. Its outputs and future programme where reviewed every four to five years by an international visiting group. Project selection was initially through directed research and then later through open submission and review. Day-to-day operations, which included detailed planning, contract evaluation, data acquisition, processing and initial interpretation was by a Core Group headed up by Drum Matthews and from 1991 by myself. During the project lifetime, BIRPS completed a ring of deep seismic profiles around the British Isles including several repeat visits to the north of Scotland were it all began. In the later years BIRPS worked increasingly on international projects. One of these not only provided new and exciting science, that is still an area of active research, but also caught the imagination of the public. The CHIXULUB project surveyed the now buried 65 Ma multi-ring crater that straddles coast of the Yucatan Peninsula in Mexico, a date that is known to dinosaur enthusiasts of all ages!

Transient Lithospheric Deformation after a Megathrust

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The Korean Peninsula was dislocated laterally by 1-6 cm after the 11 March 2011 M9.0 Tohoku-Oki megathrust at a distance of ~1300 km. These lateral displacements produced apparent tensional stresses of 1-7 kPa in the crust of the peninsula, perturbing the medium. Temporal variation of seismic velocities is investigated to assess the lithospheric responses to the megatrust. The Green's function over inter-station paths are retrieved from ambient noises recorded at broadband seismic stations that are densely deployed over the peninsula. The ambient noises are bandpass-filtered for various frequency ranges, and spectral whitening and one-bit normalization are applied. The fundamental-mode Rayleigh waves are retrieved by stacking the cross-correlation functions of 10-days-long ambient noises from 2010 to 2015. The traveltime changes of Rayleigh waves with respect to the reference traveltimes are calculated by comparing the stacked cross-correlation functions. The reference Rayleigh waves are calculated by stacking the cross-correlation functions for 4 to 6 months before the megathrust. The traveltime changes are normalized by the inter-station distances. Abrupt traveltime delays are observed right after the megathrust, which are particularly strong along paths subparallel to the great-circle direction to the megathrust. The peak traveltime delay reaches 0.028 s/km, which corresponds to shear velocity decrease of 8.9 %. The traveltime delays are weak along the paths deviated from the great-circle directions. The observation suggests that the transient tension stress field caused longitudinal lithospheric perturbation with preferential mineral orientation and fluid migration, decreasing the seismic velocities. The traveltime delays were recovered with rates of 0.000025 to 0.000059 s/km per day, completing the recovery in several hundred days after the megathrust.

Exploring the seismic expression of fault zones in 3D seismic volumes: some examples from thrust and normal faults systems.

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Mapping and understanding distributed deformation is a major challenge for the structural interpretation of seismic data. However, volumes of seismic signal disturbance with low signal/noise ratio are systematically observed within 3D seismic datasets around fault systems. These seismic disturbance zones (SDZ) are commonly characterized by complex perturbations of the signal and occur at the sub-seismic to seismic scale. They may store important information on deformation distributed around those larger scale structures that may be readily interpreted in conventional amplitude displays of seismic data scale. In a complementary contribution we introduce a method to detect fault-related disturbance zones and to discriminate between this and other noise sources such as those associated with the seismic acquisition (footprint noise). Here instead two case studies, from the Taranaki basin and deep-water Niger delta are presented. We show how the workflow can These resolve fault within SDZs using tensor and semblance attributes along with conventional seismic mapping and a discussion of their possible significance is also proposed.

Exploring seismic facies within fault zones in 3D seismic volumes: an image processing workflow model.

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Mapping and understanding distributed deformation is a major challenge for the structural interpretation of seismic data. Volumes of seismic signal disturbance with low signal/noise ratio are systematically observed within 3D seismic datasets around fault systems. These volume of low signal/noise ratio are commonly characterized by complex perturbations of the signal and occur at the sub-seismic to seismic scale. They are here termed as a seismic disturbance zones (SDZ). Their origin seems partly related to the acquisition design and uncertainty of the velocity model used during migration processes but partly to the summative signal response sub-seismic structure and to the petrophysical nature of the large scale fault zones. Investigation using signal attributes (through image processing techniques) can unravel important information and help to elucidate their origin and significance. We propose here a workflow to map those feature and cross-plot seismic waveform signal properties extracted from the fault seismic expression as a tool to investigate the seismic signature and explore seismic facies of a SDZ. The method require an initial preconditioning of the dataset to reduce random noise unrelated to the fault structure of our interest; a selection of the main geobodies including the SDZ using opacities property related to the signal attributes (using semblance and eigenstructure attributes); calculation and a cross-plot analysis of amplitude-azimuth – Dip to attenuate footprint noise or unrelated geological feature; calculation and a cross-plot analysis of phase-frequency and coherency attributes on the attenuated volume to explore the correlation between signal properties and possible signal texture having a statistical significance across the selected geobodies volume; finally a facies classification distribution using a probability threshold based on statistics of a sampled area is proposed.

Can rotational ground motion observations help us solving seismic inverse problems?

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Broadband seismic data acquisition is dominated by translational ground motion measurements (displacements, velocities, or accelerations). To completely characterize the deformation of an elastic body, in general strain and rotational motions should also be measured. While strain measurements have been routinely used in borehole experiments or observatory settings, rotational ground motion observations are sparse, primarily due to the fact that they are difficult to observe. In the absence of (but hope for) sensors that satisfy the needs of broadband seismology we investigate theoretically whether additional rotation measurements help us solving seismic inverse problems.

Seismic ground rotation velocity is a vectorial quantity, the curl of the elastic wavefield. The three components are linear combinations of the ground velocity gradients. A simple plane harmonic wave analysis highlights an extremely interesting property: some components of the translational wavefield (e.g., transverse acceleration) and rotational velocity (e.g., around a vertical axis) have the same waveform and their amplitude ratio scales with phase velocity. In other words, the combined observation of collocated translations and rotations contains information about the seismic velocity structure in the vicinity of the measurement point. Application of adjoint methods to this problem allows us to quantify this sensitivity to near-receiver structure and develop a tomographic scheme based on this family of observations. Similar measurement and inversion techniques are possible with combinations of strains and translations.

What about the seismic source? Using realistic point and finite-source inversion setups we investigate how source parameters can be recovered by a classic seismic experiment with N 3-component sensors compared to N/2 sensors measuring 6 components (i.e., 3 additional rotations) keeping the overall number of observed traces constant. Surprisingly, in almost all cases the latter experimental setup leads to better resolved source parameters in both point- or finite-source scenarios. Obviously the benefit would be the substantially reduced logistics.

Finally, we report on progress on developing portable sensors using fibre-optic technology that should soon enable us to support these theoretical concepts by observations.

Large heterogeneous structure beneath the Atotsugawa Fault, central Japan, revealed by seismic refraction and reflection experiments

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A high-strain-rate zone termed the Niigata Kobe Tectonic Zone, which was detected by GPS array, is located in central Japan. This zone has been the location of numerous historical large earthquake-related disasters. It contains an active right-lateral fault called the Atotsugawa Fault. This fault trends ENE–WSW (~060°), is subvertical (90° ± 10°) near the surface, has a length of 63 km. The fault has been associated with several large historical earthquakes. One of the largest events was the 1858 Hietsu earthquake, with an estimated magnitude of ~7.0 that was determined from the distribution of the seismic intensity

The artificial source seismic experiment near the Atotsugawa Fault used seven explosive sources and 1108 seismic stations, and was conducted in October 2007. The seismic stations were spaced along a NNW–SSE-oriented 170-km-long profile line that was perpendicular to the strike of the Atotsugawa Fault. The explosive charge size was 500 kg for two shot points and 300 kg for five shot points. The average interval between seismic stations was 153 m.

We present the results of an explosive-source seismic experiment that focused on identifying the formation mechanisms of the fault. The data showed lateral variations in velocity structure within the upper crust and revealed the geometry of a sedimentary layer. This sedimentary layer is very thin in the central part of the profile line, where many seismogenic faults occur. In addition, a horizontally layered reflective zone was identified at depths of 15–25 km beneath the Atotsugawa Fault; the characteristics of this zone were determined using physical parameters and the results of previous research. This zone has a relatively low P-wave and extremely low S-wave velocity, and is located in the upper part of a low-velocity zone. This zone also hosts three low-resistivity zones (Usui et al., 2011), all of which extend from the lower crust to the bottom of active faults. The reflective zone is probably caused by the presence of isolated water-filled cracks, whereas the low-resistivity zones are associated with interconnected water-filled cracks. The lower-crustal reflective zone is also probably a weak zone that is responsible for concentrating deformation within the upper crust. The presence of abundant fluids beneath the Atotsugawa Fault may have reduced the strength of the fault, leading to earthquakes in this area, thereby strongly suggesting that the low-velocity reflective layer in the study area influenced the formation of the Atotsugawa Fault. All of these seismological, geomagnetic, and numerical modeling data support the existence of fluids in the lower crust in the area. These fluids are released by the dehydration of subducting slabs and ascend into and pass through the mantle wedge, eventually reaching the lower crust to form a low-velocity zone that is weak, concentrates deformation within the upper crust, and reduces the strength of the Atotsugawa Fault, resulting in earthquakes.

Structures and active tectonics of reactivated back-arc rift revealed by multiscale seismic profiling: Hokuriku region, central Japan

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Reactivation of back-arc failed rift and its mechanism that mobilize active tectonics remains well unexplored. We show results and interpretation of new onshore-offshore deep seismic reflection profiles across Toyama sedimentary basin located within the Sea of Japan back-arc rift, to illuminate their deep to shallow images of crustal structures and reactivated active faults. Seamless data acquisition connecting onshore with offshore seismic signals by use of ocean bottom cables, and densely spaced (~25 m) shot and receiver points successfully provide high resolution crustal images of the failed rift of this region. Supplemental higher resolution seismic reflection data with denser shot-/receiver intervals were simultaneously collected to define recent activity of reactivated structures. Similar to other Neogene back-arc sedimentary basins in the Sea of Japan, Neogene sediments thicker than 5 km underlain by P-wave velocity >5 km/sec, correlated with top of the pre-Neogene basement rocks, indicates significant syn- and post-rift subsidence. High velocity anomaly in P-wave perturbation underlying this region suggests the formation of sedimentary basin were presumably associated with concentrated crustal stretching and basalt intrusion into the lower crust near the rift axis. Sedimentary basin structures revealed by deep seismic reflection profiles also indicate that thick basin-fill sediments are strongly faulted and folded by thrust faults that are reactivated normal faults formed during the Miocene rifting stage. In addition, shallower, high-resolution seismic reflection profiles clearly imaged structural growth signatures of these reactivated structures during Quaternary and hence their recent fault activity, which are also recorded by tectonic geomorphology of marine and fluvial terraces. These survey results provide great contribution to construct seismic source fault models for Tsunami and seismic hazard estimation that has strong inheritance on crustal structures of the back-arc rift formed during the middle Miocene opening of the Sea of Japan. We find that seamless, onshore-offshore survey is a powerful tool to identify and locate active faults near coastlines that would be elusive only with onshore and offshore surveys. We also emphasize that, combining multi-scale seismic reflection profiles with tectonic geomorphology allows us to depict complicated structural characters and recent activities of reactivated normal faults that are mostly blind due to dynamic subsidence of the failed rift structures.

Lithospheric structures and their formation process at the northwestern border region of the Izu collision zone, central Japan

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Several seismic profiling studies have been made widely from the Central Japan Alps to the southwestern foot of the Mt.Fuji cross the Median Tectonic Line, the Southern Japan Alps, the Itoigawa-Shizuoka Tectonic Line, and so-call "the South Fossa Magna". Their main purpose are to reveal the lithospheric structures at the northwestern border region of the Izu collision zoneand their formation process since Middle Miocene. The significant results of the studies are summarized as follows:

1. Most materials of the colliding Izu arc on the Philippine Sea Plate (PHS) have been subducting beneath the Japanese island arc since middle Miocene. Only three buoyant huge blocks were exfoliated from the upper crust of the Izu arc and have accreted to the Japanese island arc. Thus nearly 50-km thick materialsderived from the Izu archave been underplated to the Japanese island arc.

2. The initial stage of the colliding process produced two major left-lateral faults: the southern segment of the Itoigawa-Shizuoka Tectonic Line (ISTL) and the Akaishi Tectonic Line (ATL). The former was originally formed as a major thrust in the subduction zone of the PHS, and then changed into a high-angle left-lateral fault associated with the colliding process. The latter displaced the structure of the Outer zone at about several tens km in a left-lateral slip sense. Its northern extension cut the gently dipping original Median Tectonic Line (MTL) and newly constructed the present high-angle MTL. In that sense, the present, that is, new MTL is a part of the ATL.

3. The Outer zone exhibits extraordinary structures only between the new MTL and the northern part of the southern segment of the ISTL. That is, the verging direction is opposite to that of the accretionary complexes in the Outer zone in southwest and central Japan. This suggests the Outer zone there has been overturned by the collision.

4. At the present northwestern border region of the Izu collision zone, the active faults in the Fujikawa-kako fault system are spraying directly from the upper surface of the PHS at about several km in depth. Their vertical slip rate is estimated to be about 4 mm / year. Considering that the fault system forms a small-scale nappe structure in the shallower part, their net slip rate must be more than the vertical one.

Fundamental structure model of island arcs and subducted plates in and around Japan

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The eastern margin of the Asian continent is a well-known subduction zone, where the Pacific (PAC) and Philippine Sea (PHS) plates are being subducted. In this region, several island arcs (Kuril, Northeast (NE) Japan, Southwest (SW) Japan, Izu-Bonin and Ryukyu arcs) meet one another to form a very complicated tectonic environment. The 2011 Tohoku earthquake (M=9.0) caused a large amount of coseismic and post-seismic crustal deformations in broader region from the trench area to the island arc. Such phenomena are regarded as "response of trench-arc system" controlled by plate motion through highly heterogeneous material properties. At 2014, we started to construct fundamental structure models for island arcs and subducted plates in and around Japan. Our research is composed of 6 items of (1) topography, (2) plate geometry, (3) fault models, (4) the Moho and brittle-ductile transition zone, (5) the lithosphere-asthenosphere boundary, and (6) petrological/ rheological models.

This paper is mainly related with the results of items (1) and (2). The area of our modelling is set 12°-54° N and 118°-164° E to cover almost the entire part of Japanese Islands together with Kuril, Ryukyu and Izu-Bonin trenches. The topography model and trench axis models were constructed from the 500-m mesh data provided from GSJ, JODC and GINA, Alaska University.

Plate geometry models are being constructed for the Pacific and Philippine Sea plates through the two steps. In the first step, we constructed "base" models with rather smooth boundaries in our whole model area using 41,892 earthquake data from JMA, USGS and ISC. For 7,853 cross sections taken with several directions to the trench axes, 2D plate boundaries were defined by fitting to the earthquake distribution (the Wadati-Benioff zone), from which we obtained equi-depth points for each boundary. These equi-depth points were approximated by spline interpolation technique to make equi-depth lines with longer wave lengths (>75-150 km). The 3-D "base" plate models of the PAC and PHS plates were constructed from these equi-depth lines. Although such a base model provides only crude plate geometry, the PHS plate subducted beneath the SW Japan arc shows significant undulation.

As the second step, regional plate configuration with shorter wave-length (<50-100 km) is being constrained in the vicinity of Japan from recent results by seismic tomography, RF analysis and active source experiment. We have collected 59 references, from which plate position data were sampled. These data are used as "correction terms" to the "base" plate models described above. Preliminary analysis indicates that the plate boundary of the PAC plate from the controlled source experiments is systematically shallower than that from natural earthquakes in a depth range of 10-50 km, which may indicate the difference between the structural and mechanical boundaries of the subducted plate.

The most important problem still unclarified is the geometry of the intersection between the PAC and PHS plates in the southernmost part of the Northeast Japan arc. Now, we are collecting new results from active source seismic experiment and tomography results to constrain shallower part of the eastern margin of the PHS plate.

Arc-arc collision structure in the southernmost part of the Kuril trench region -Overview of results from integrated reanalyses for controlled source seismic data in the Hidaka Collision Zone

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The southernmost part of the Kuril trench is known as an arc-arc collision zone. Since the middle of the Miocene, the Kuril forearc has been colliding against the NE Japan arc to form very complicated and unique tectonic environment in the middle part of the Hokkaido Island (the Hidaka Collision Zone (HCZ)). In this region, several seismic reflection/refraction experiments were undertaken (Arita et al., 1998; Tsumura et al., 1999; Ito et al., 2000, Iwasaki et al., 2004). Our integrated reinterpretation for these data sets, which started in 2012, revealed detailed and new structural features within the HCZ.

In the southern part of the HCZ, the crustal delamination associated with the collision was clearly imaged by applying CRS/MDRS method to the seismic reflection data (Tsumura et al., 2014). Namely, the upper 22-23 km crust of the Kuril arc is off-scrapped and obducted along the Hidaka Main Thrust (HMT), while the lower part of the crust is descending down to reach the subducted Pacific plate. In the northern part of the HCZ, the HMT is also well imaged both by seismic reflection processing and refraction/wide-angle reflection analysis, but the delamination structure as obtained in the southern HCZ is not clearly seen. Around the HMT, the crystalline basement is almost outcropped. In the west of the HMT, several eastward dipping layering is found down to a depth of 7-8 km, probably corresponding to fragments of Cretaceous subduction/arc complexes or deformation interfaces branched from the HMT. The relatively higher velocity in the uppermost crust just east of the HMT represents the base of the obducted middle or (upper part of) lower crust of Kuril arc.

The most important finding in the northern HCZ is a clear image of the NE Japan arc crust descending eastward to a depth of about 40 km under the hinterland side. Our refraction/wide-angle reflection analysis revealed the strong dipping reflectors with a velocity contrast of 0.5-1 km/s at depths of 10-35 km west of the HMT. Our result shows that the subducted NE Japan arc meets the Kuril arc 20-40 km east of the HMT at a depth of 20-30 km.

The obduction of the upper Kuril crust starts at a deeper crustal level of at least 27-30 km and more easterly (~20 km) of the HMT as compared with the case in the southern HCZ. If the metamorphic rocks outcropped east of the HMT are the same crustal materials shallower than 22-23 km depth as in the case of the southern HCZ, the deeper crustal portion originally situated at 23-27~30 km depth must exist in the western side of the present HMT. The very strong and deep reflectors found west of the HMT might result from the mixture of upper crustal (low velocity) materials of the NE Japan arc and middle/lower crustal (high velocity) materials of the Kuril arc.

Joint inversion of P- and S-wave receiver functions and surface-wave dispersion velocities: Case studies in Arabia

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We have modified an existing procedure for jointly inverting P-wave receiver functions and surface-wave dispersion velocities to incorporate additional constraints from S-wave receiver functions. This combination bridges resolution gaps between the data sets, as dispersion velocities are sensitive to absolute S-wave velocity averages within frequency-dependent depth-ranges while P-wave receiver functions constrain vertical S-P travel-times and S-wave velocity contrasts across subsurface seismic discontinuities. Constraints on the lithosphere-asthenosphere boundary (LAB), however, are generally weak due to the interference of P-to-S refracted waves across the base of the lithosphere with crustal reverberations and relatively small amplitudes associated with the velocity increase across the LAB. S-wave receiver functions also constrain P-S travel-times above and S-wave velocity contrasts across subsurface seismic discontinuities, but S-to-P conversions never interfere with crustal reverberations. Thus, addition of S-wave receiver functions into the joint inversion scheme effectively decouples the signatures of the base of the lithosphere and the crust, and provides more robust constraints on the S-wave velocity structure of the lithospheric and the sublithosperic mantle.

The modified methodology is demonstrated at a number of select broadband stations in the Arabian shield and platform. The Arabian shield spans the western third of the Arabian Peninsula and consists of rocks of Precambrian age dotted with Cenozoic sedimentary rocks and volcanics, while the Arabian platform consists of a widespread Phanerozoic cover that encompasses the remaining two-thirds of the peninsula. Seismic data is routinely collected by the Saudi National Seismic Network, consisting of around 150 operational broadband stations, as part of the country's effort to monitor seismic activity throughout the kingdom. Additional seismic data is available from past and ongoing temporary experiments. The joint inversion approach succeeds in producing 1D velocity models that simultaneously match all three sets of observations, providing robust S-wave velocity-depth profiles down to ~250 km depth. The crustal and lithospheric-mantle portion of the models agree well with independent estimates found in the literature and confirm the thickening trend of the Arabian crust towards the East. Perhaps more interestingly, the new approach images a relatively shallow - in the 60-170 km depth-range - asthenospheric low-velocity channel under the stations located along the Red Sea margin and Gulf of Aqaba.

Elucidation of the lithosphere/asthenosphere system of "normal" oceanic mantle via broadband ocean bottom seismology

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Although plate tectonics started as a theory of the "ocean" nearly 50 years ago, the detail of the mechanism how it works is still poorly known. It has been hampered partly by our inability to determine in-situ the structure of the lithosphere/asthenosphere system in the ocean. Recent advances in ocean bottom broadband seismometry, together with advances in the seismic analysis methodology, have now enabled us to resolve the regional 1-D structure of the entire lithosphere/asthenosphere system, from the surface to a depth of ~150km, including seismic anisotropy (azimuthal), with deployments of ~15 broadband ocean bottom seismometers (BBOBSs) for 1~2 years (Takeo et al., 2013, 2016). We have thus succeeded to model the entire oceanic lithosphere/asthenosphere system without a priori assumption for the shallow-most structure, the assumption often made for the global surface wave tomography. We will cover the background of the research, our new multi-band approach for the "broadband ocean bottom seismology" and findings, preliminary results from our Normal Mantle project in which we conducted a broadband seismic and EM array survey in the northwest Pacific and found abnormal, as well as perhaps normal, mantles, and hopefully convince the audience that we are now at an exciting stage that a large scale array experiment in the ocean (e.g., Pacific Array) is becoming approachable to elucidate how plate tectonics might have worked in the past ~200 Ma beneath the ocean.

Reference:

Takeo, A., K. Nishida, T. Isse, H. Kawakatsu, H. Shiobara, H. Sugioka, and T. Kanazawa (2013), Radially anisotropic structure beneath the Shikoku Basin from broadband surface wave analysis of ocean bottom seismometer records, J. Geophys. Res., 118 (6), 2878–2892, doi:10.1002/jgrb.50219.

Takeo, A., H. Kawakatsu, T. Isse, K. Nishida, D. Suetsugu, H. Shiobara, H. Sugioka, and A. Ito (2016), Intensity of seismic azimuthal anisotropy in the oceanic lithosphere and asthenosphere from broadband surface-wave analysis of OBS array records at 60 Ma seafloor, J. Geophys. Res., accepted.

Common Reflection Point Body Wave Imaging by Interferometry of Earthquake Sources

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Jon Claerbout (1968) first suggested that the reflection response of a flat layered sequence of materials can be recovered by correlating the transmission response with itself. Thus for body-wave sources that are sufficiently numerous and suitably distributed, the reflection profile can be processed from such ambient noise using this approach. However, the real world has strong 3D structural and velocity complexity, and source distributions are not vertically aligned with recording stations nor sufficiently randomly distributed in space.

Here, we explore an imaging procedure that is generalized for two non-coincident receivers that record subsurface sources that are offset from the receivers. In this regard, the geometries favorable to body wave imaging are investigated using synthetic seismograms for various source distributions in subsurface. We test these methods using high spatial density recordings (i.e. 200m) collected after the Mw 5.8 Mineral, Virginia earthquake of 2011. As the result, the reflection sections processed show clear coherency in the same depth range indicating the southeast dipping thrust structures as a nearby conventional deep seismic line.

These results, and the modeling behind them, suggest that this methodology would be more effective with recording by true 2D surface arrays by using 3 component sensors to separate P and S wave energy and, of course, by using a much larger number of sources. Most aftershock sequences involved hundreds, if not thousands of sources. The combination of natural sources with high resolution represents a potentially low cost approach to 3D and even 4D imaging of crustal structure in seismically active areas.

3D reflection imaging of an extensive, thick Proterozoic layered basement complex in southeastern New Mexico from reprocessing of “discarded” nodal oil exploration recordings

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Due to advances in recording capabilities, seismic data for land oil-industry surveys is now often recorded continuously using very large (>1000 channel) areal arrays. A large portion of these data is usually discarded since it is not directly used for conventional imaging purposes. However, there is a growing consensus that these “surplus” recordings contain a variety of useful information about the subsurface, especially for academic seismologists but also for oil explorers. Here we report results of processing two nodal datasets from a major, ongoing exploration effort in the Permian Basin of southeastern New Mexico and west Texas. Extended correlation of normally harvested, pre-correlation recordings provided excellent 3D imaging of a massive, extensive layered sequence in the upper basement. Nearby wells indicate the top of this layered sequence consists of granitic material, and link it to the well-known 1.37 Ga granite-rhyolite province that underlies much of the south-central U.S. Although portions of this sequence have been reported from previous 2D COCORP and oil industry seismic surveys in New Mexico, Texas, Oklahoma, Illinois and Ohio, these new data are the first true 3D seismic imaging of this geotectonic units. These results unequivocally demonstrate the value in preserving and reprocessing continuous nodal recordings that would normally be ignored or discarded during conventional oil and gas exploration analyses, but the value of true 3D imagery in the interpretation of complex basement reflection patterns.

Active-source seismic studies from ocean basin to trench in the Northwestern Pacific; imaging from sediment to lithosphere-asthenosphere boundary

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In order to examine uniformity and diversity of formation, alternation and deformation processes of the oceanic lithosphere, JAMSTEC has been carrying out active-passive seismic studies from an ocean basin to a trench through an outer-rise in the Northwestern Pacific. Previous seismological and petrological studies obtain a general consensus indicating that an oceanic lithosphere formed along a first spreading center away from a transform fault and a hot stop is characterized by a uniform oceanic crust and mantle structure as well as the clear Moho. However, recent large-scale long-offset active-source seismic studies report several seismological evidences suggesting a variation of lithospheric structures which reflect formation, alternation and deformation processes of the oceanic lithosphere.

As one of those surveys, we acquired active-source seismic data along a series of profiles running from the Kuril-Japan Trench, the Northwestern Pacific, to the ocean basin at ~600 km seaward from the trench. Ages of the seafloor in the survey area are 121-125 Myr old. From seismic reflectivity and velocity images, we found clear seismological evidences showing structural alternation/deformation in the outer-rise region due to bending plate before subduction. For instance, reduction of Vp and increase of Vp/Vs toward the trench are observed from ~150 km away from the trench, and comparing in the Japan Trench and Kuril trench, degree of those structural changes toward the trench are more significant in the Japan Trench where larger bending-related faulting is observed than that in the Kuril Trench.

We also acquired long-offset (~ 1000 km long) active-source seismic data in the ocean basin at about 2000 km away from the Kuril-Japan Trench, between the Emperor Seamounts and the Shatsky Rise. The profile was taken perpendicular to the magnetic anomalies, and seafloor ages are varied from 123 to 149 Myr old along the profile. The seismic reflection data show obscure or even no Moho imaged, although the clear seafloor magnetic anomalies indicating first spreading rate are identified. From travel-times and waveforms modelling of wide-angle reflection phases observed at large offsets (150-500 km offsets) in the OBS data, we found thin low velocity patches at mid-lithosphere (35 to 60 km deep in the mantle). The mid-lithosphere patches are interpreted as frozen (or fossil) melts which were formed as ancient melts ponded around past lithosphere-asthenosphere boundary. This ancient magmatic activity may be also a cause for modifying a physical property (i.e., reflection character) of Moho.

Aforementioned seismic studies demonstrate that combined seismic reflection and long-offset wide-angle OBS refraction/reflection survey are powerful way to obtain a structural image from sediment to lithosphere-asthenosphere boundary.

Seismic ore exploration in the Outokumpu area, eastern Finland: Constrains from 3D seismic full waveform modeling and processing considerations

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Seismic forward modeling is used to get better understanding of the seismic signature of the Outokumpu assemblage rocks (serpentinite, carbonate, skarn and quartz rocks) and associated Outokumpu-type semi-massive to massive sulphide Cu–Co–Zn–Ni–Ag–Au deposits, and to develop tailored hard-rock reflection seismic data processing schemes for aiding seismic ore exploration in the Outokumpu area. Reflection seismic line OKU1 at the southwestern end of the Outokumpu area was chosen to be the main focus of the forward modeling efforts because it is located in the close vicinity of 2.5 km deep Outokumpu Deep Drill Hole, which provides direct lithological control for the observed reflectivity and well-documented acoustic properties of the Outokumpu rocks. Thus, a detailed geological model could be built based on the Outokumpu Deep Drill Hole data and OKU1 reflection seismic line. SOFI3D full waveform finite-difference code was used to calculate theoretical shot gathers which were then processed with the same processing schemes as the real OKU1 reflection line.

We conclude that within mica schist hosting them, the Outokumpu assemblage rocks (and black schist enveloping them) form internally strongly reflective packages typically characterized by numerous diffraction hyperbolas in the stacked sections. The reflectivity characteristics can be used to target the potentially ore-bearing Outokumpu assemblage rocks at depth, and the reflection seismic data provide a good basis for setting regional exploration targets in the Outokumpu area. Based on the results of this study, it seems also possible that the Outokumpu-type sulphide mineralizations could be even directly observed as high-amplitude anomalies in the reflection seismic sections. However, the physical properties of the Outokumpu assemblage rocks and Outokumpu-type sulphide mineralizations significantly vary across the Outokumpu area, and new seismic velocity measurements across the Outokumpu area, as well as more and better constrained density data, are required to study the seismic response of the Outokumpu assemblage rocks and the Outokumpu-type sulphide mineralizations in more detail. Nevertheless, careful crooked-line data processing sequence should be able to preserve the direct signals, if present in the data, except for very shallow signals that are more likely to get distorted by the crooked-line effects. The crooked-line effects can also potentially produce high-amplitude anomalies and care is required when interpreting the high-amplitude anomalies in light of ore exploration.

Determination of parameters of the Earth's crust types in the Eastern Black Sea Basin based on complex interpretation of reflection plus refraction seismic data and potential fields.

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The considered territory covers the eastern part of the Black Sea, where the Eastern Black Sea (EBS) basin is main structural element. This work is based on new results of reprocessing seismic lines (multichannel seismic) acquired in 2011 within the international project Geology Without Limits and wide–angle seismic profiling (WASP) (University of Southampton). Two lines of WASP have been chosen for reprocessing one of them - line 1 is orientated approximately parallel to the axis of the EBS basin. Besides, gravity/magnetic measurements have been interpreted to study a deep geological structure.

The major elements of the Black Sea Region are the two basins - the Western Black Sea (WBS) and the Eastern Black Sea basins with thin crust. These basins are separated by the Andrusov and Arkhangelsky ridges (Mid-Black Sea High) with thick crust. Other structural elements include the Shatsky Ridge with continental crust and the Tuapse, Sorokin and Gurian foredeep basins. The nature of the thin crust within the centre of the EBS basin has been the subject of much discussion.

New processing of reflection/refraction data and integrated interpretation of seismic and gravity datasets enables an assessment of the full crustal structure of the EBS basin. The EBS basin is the large graben – rift structure, where the thickness of sedimentary cover up to 12,5 km. The boundaries of the basins are strongly influenced by large NW - trending normal faults and their systems emphasizing their rift origin. To the south a block of the Ordue Pitsunda flexure transversally to the basin's trend is fixed. It testifies to that the axis of the rifting-spreading could not extend further to the south.

The EBS basin is surrounded by platform area (Shatskiy to east, and Andrusov, Arkhangelsky ridges to west), where Upper Jurassic – Cretaceous carbonate and terrigenous sediments form a base of sedimentary cover. Carbonate build-ups and reefs are recognized in seismic record, a large of them is fixed in the northern part of the Shatsky Ridge. The sedimentary succession of the EBS basin is composed mainly of Upper Cretaceous and Cenozoic terrigenous deposits. The lower part of the succession is characterized by high velocities of 5,2-6,0 km/s. Basalts and mafic rock may present at the base sedimentary cover, they form volcanic structures.

Analysis of seismic and gravity datasets allows to trace the Moho boundary. Within EBS basin the average crustal thickness is 16–18 km that corresponds oceanic or highly rifted continental crust. In the basin centre synrift and postrift sediments are bedded on basaltic layer (oceanic crust) with thickness of 7-8 km conforming that rifting culminated in seafloor spreading. By the Moho surface EBS basin has a shape as back-arc basin. Many researches (Zonenshain, Nikishin and others) assume that the EBS basin together with WBS basin were formed as back-arc basins behind the Pontide volcanic arc. Geophysical data revealed that the transition between oceanic and continental crust is abrupt (~20-25 km) and coincides with one a series of basement scarps, complicated large faults and volcanic structures.

Pathways between reservoir and surface - advanced seismic fault imaging at the CO2CRC Otway Project site, Australia

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At the CO2CRC Otway Project Site, Australia, we collected shear (SH) wave reflection seismic data in the framework of the project PROTECT (PRedition Of deformation To Ensure Carbon Traps) in November 2013. The aim was to prove whether or not faults that were interpreted at larger depths continue to the surface, and to detect possible smaller-scale faults. As secondary goal we wanted to complement the existing 3-D exploration seismic data set in the uppermost 400 m.

Using LIAG's equipment for SH-wave seismic acquisition (hydraulic vibrator MHV4S with source point spacing of 4 m, and SH-geophones mounted on a 240-m long land streamer with 1 m spacing), three profiles were acquired. The data processing comprised geometry setup, elevation statics, surface-wave noise suppression via fk-filtering, velocity determination after DMO-correction, pre-stack time migration, and 1-D depth conversion. During pre-processing of the data, the application of spectral balancing and fk-filtering proved to be fundamental. Refraction statics enhanced the imaging of one of three profiles drastically. This was unexpected, because the survey had been carried out on a paved road. Presumably the relatively high refractor velocity of more than 700 m/s in the survey area caused this effect.

The deep fault zones, interpreted in the exploration volume on profiles PROTECT 1 and PROTECT 2, are shown with the new data that actually reaches the surface. On profile PROTECT 1, a reverse fault is imaged that can be linked to a normal fault structure at ca. 400 m depth. This reverse fault could correlate with a step in surface topography. On profile PROTECT 2 the expected near-surface trace of the interpreted deep normal fault was detected. Finally, profile PROTECT 3 reveals an unexpected fault zone above 400 m depth, which appears unlinked to greater depth.

Pre-stack time migration and subsequent depth conversion yielded the best images so far, with a vertical resolution of ca. 5 m in the upper part. Nonetheless, pre-stack depth migration including reflection tomography will be tested in the future since tomographic velocity models are more horizon-oriented than DMO-/NMO-based ones, which may better resolve depth sections.

With this detailed study, we obtain a better overview of possible fluid migration pathways and communication between reservoir and overburden. As such we provide a validation tool within a workflow for pathway monitoring strategies for subsurface storage in general.

Late Paleozoic crustal-scale wrenching or thin-skinned thrusting in SE Poland and W Ukraine?

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Two deep seismic datasets, POLCRUST-01 profile and the PolandSPAN survey, have been recently acquired in SE Poland above the SW slope of the East European Craton (EEC) that transect the Teisseyre-Tornquist Zone (TTZ) – a crustal boundary between the Precambrian EEC and the Palaeozoic W European Platform, and two geological units: (1) the Radom-Kraśnik Block built of deformed lower Palaeozoic to Devonian strata, and (2) the Lublin Basin filled by Neoproterozoic – Carboniferous strata. Both these Palaeozoic units are covered by a mostly undeformed Permo-Mesozoic sedimentary sequence. One of key problems regarding the regional crustal-scale structure of this area is a position and tectonic characteristics of a boundary between the Palaeozoic Platform and the EEC. Narkiewicz et al. (2015) proposed, using POLCRUST-01 profile, a sharp contact along the TTZ that corresponds to the subvertical strike-slip Tomaszów Fault at shallow depths. Krzywiec et al. (2016) proposed, using PolandSPAN and industry data, that the Radom–Kraśnik Block is a thrust stack that imbricates ?Neoproterozoic to Devonian sediments of the EEC margin. Its leading edge corresponds to a triangle zone related to the jump of the basal detachment from a basement-cover interface to Silurian shales. A minor amount of slip that has been conveyed to the Lublin Basin was accommodated by gentle thin-skinned deformation of the post-Silurian series. Reinterpretation of the POLCRUST-01 profile proved that the Tomaszów Fault of Narkiewicz et al. (2015) is a thin-skinned thrust located within the Radom–Kraśnik Block, and should not be regarded as a shallow expression of the TTZ. The data available from W Ukraine suggest that key elements of the Variscan thin-skinned thrust system continue south-eastward, where they ultimately plunge under the Carpathians.

Reinterpretation of the POLCRUST-01 profile has been completed as part of the Polish National Centre for Research and Development grant BG1/GAZGEOLMOD/13 (BLUE GAS – Polish Shale Gas Program).

Narkiewicz et al., 2015, Transcurrent nature of the Teisseyre–Tornquist Zone in Central Europe: results of the POLCRUST-01 deep reflection seismic profile. Int. J. Earth Sci. (Geol. Rundsch.), DOI 10.1007/s00531-014-1116-4.

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Advanced seismic imaging techniques characterize the Alpine Fault at the DFDP-2 drill site in Whataroa (New Zealand)

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The plate-bounding Alpine Fault in New Zealand is an 850 km long transpressive continental fault zone that is late in its earthquake cycle. The Deep Fault Drilling Project (DFDP) aims to deliver insight into the geological structure of this fault zone and its evolution by drilling and sampling the Alpine Fault at depth.

We have acquired and processed reflection seismic data to image the subsurface around the drill site. The resulting velocity models and seismic images of the upper 5 km show complex subsurface structures around the Alpine Fault zone. The most prominent feature is a strong reflector at depths of 1.2-2.2 km with a dip of ~40° to the southeast below the DFDP-2 borehole, which we assume to be the main trace of the Alpine Fault. The reflector exhibits varying lateral reflectivity along its extent. Additionally, subparallel reflectors are imaged that we interpret as secondary branches of the main fault zone. The derived P-wave velocity models reveal a 400-600 m thick sedimentary layer with velocities of ~2.3 km/s above a schist basement with velocities of 4.5-5.5 km/s. A pronounced low-velocity layer with velocities of approximately 3.5 km/s can be observed within the basement at 0.8-2 km depth. Small-scale low-velocity anomalies appear at the top of the basement and can be correlated to the location of the fault zone strands.

Finally, the results provide a detailed basis for a seismic site characterization at the DFDP-2 drill site and correlate with preliminary cutting and logging results from the drilling. However, the more complex 3D structure of the fault zone has not yet been clearly imaged in detail. Thus, we acquired a 3D-VSP seismic data set at the DFDP-2 drill site in January 2016. Besides a zero-offset VSP, we conducted a walk-away VSP survey with a vibroseis source and 1C- and 3C-receivers in the borehole as well as at the surface. This extensive data set is expected not only to improve the existing velocity model, but also to enhance the 3D structural image of the fault zone. Since the existing borehole did not intersect the Alpine Fault at depth, detailed seismic images will be of crucial importance for further structural and geological investigations of the architecture of the Alpine Fault in this area.

Seismic Interferometry and Monitoring of the Earth's Background Seismic Field

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MSNoise is an Open and Free Python package known to be the only complete integrated workflow designed to analyse ambient seismic noise and study relative velocity changes (dv/v) in the crust. It is based on state of the art and well maintained Python modules, among which ObsPy plays an important role. To our knowledge, it is officially used for continuous monitoring at least in three notable places: the Observatory of the Piton de la Fournaise volcano (OVPF, France), the Auckland Volcanic Field (New Zealand) and on the South Napa earthquake (Berkeley, USA). It is also used by many researchers to process archive data to focus e.g. on fault zones, intraplate Europe, geothermal exploitations or Antarctica. We first present the general working of MSNoise, originally written in 2010 to automatically scan data archives and process seismic data in order to produce dv/v time series. We demonstrate that its modularity provides a new potential to easily test new algorithms for each processing step. For example, one could experiment new methods of cross-correlation (done by default in the frequency domain), stacking (default is linear stacking, averaging), or dv/v estimation (default is moving window cross-spectrum "MWCS", so-called "doublet"), etc.

We present the last major evolution of MSNoise from a "single workflow: data archive to dv/v" to a framework system that allows plugins and modules to be developed and integrated into the MSNoise ecosystem. Small-scale plugins will be shown as examples, such as "continuous PPSD" (à la McNamarra & Buland) or "Seismic Amplitude Ratio Analysis" (Taisne, Caudron). We will also present the new MSNoise-TOMO package, using MSNoise as a "cross-correlation" toolbox and demystifying surface wave tomography! Finally, the poster will be a meeting point for all those using or willing to use MSNoise, to meet the developer, exchange ideas and wishes!

Crustal velocity structure and density model beneath a temporary broadband seismic array in the Gyeongju Area of Korea

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Gyeongju has been the capital of the long lasting Silla Dynasty which keeps abundant histories (57 B.C. – 935 A.D.). The historical record so called Samguksagi has reported many seismic activities in the Gyeongju area. Gyeongju is located in the Cretaceous Gyeongsang Basin situated in the southeastern part of the Korean Peninsula. The basin is bounded on the west and north by the Precambrian metamorphic rocks (i.e., the Yeongnam Massif) as well as the Jurassic granitoids, and is overlapped on the east by the Early Tertiary calc-alkaline volcanic succession intercalated with minor amounts of sedimentary rocks. An aggregate thickness of more than 9,000 m of siliciclastic and volcanic strata is preserved in the basin. The initiation of major sedimentation in the basin was mainly attributed to an E-W crustal extension that resulted from the sinistral, brittle shearing in the southeastern part of the Korean Peninsula during the Early Cretaceous. This sinistral, brittle shearing might be due to the northward (oblique) subduction of the Izanagi Plate underneath the eastern margin of the Eurasian Plate during the Early Cretaceous. The Cretaceous Gyeongsang Supergroup is extensively intruded by granitoids that are collectively termed as the Bulgugsa Granite. They are in general fine- to medium-grained and are composed of granite, granodiorite, and tonalite. The Late Cretaceous granitoids in the Gyeongsang Basin are correlated with the granitoids in the southwestern Japan that have similar intrusion ages. The intrusive ages of granitoids in both areas cluster between 100 Ma and 50 Ma. It is generally agreed that the Late Cretaceous to Early Tertiary magmatism in the Gyeongsang Basin and the southwestern Japan took place by the subduction of the proto-Pacific (Izanagi) Plate.

A temporary seismic array was in operation between October 2010 and March 2013 in the Gyeongju area of Korea. Teleseismic records of the seismic array appropriate for receiver function analysis were collected and selected seismograms were split into five groups based on epicenters—the Indonesia, Malaysia, Iran, Alaska, and Vanuatu groups. 1D velocity structures beneath each seismic station were estimated by inverting the stacked receiver functions for possible groups. The genetic algorithm was utilized and the surface wave dispersion was used as constraints to avoid non-uniqueness in inversion. The composite velocity structure was constructed by averaging the velocity structures weighted by the number of receiver functions in stacking. The three-dimensional (3D) velocity structure was modelled through interpolation of 1D composite velocity structures. Moho depths were determined in each composite velocity structure based on the AK135-F velocity model. The deepest Moho depth in the study area was found to be 31.9 km and the shallowest 25.9 km. The Moho discontinuity dips southwestwardly beneath the area. A low velocity layer was also detected at a depth between 4 and 14 km. Gravity modelling was carried out using the density structure based on the velocity structure, and was compared with the Bouguer anomalies obtained in this area. The Bulgugsa Granite less dense than the sedimentary strata by 0.08 g/cc optimally presented the Bouguer anomalies. A low circular anomaly which might indicate the intrusion root was also found. Adakitic intrusions related with the slab window and/or a high geothermal gradient appear to be the causes of this low velocity layer.

Structure of Upper Mantle Discontinuities beneath Japan Sea and Adjacent Regions revealed by Multiple-ScS Waves

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The behavior of subducting oceanic lithosphere and its interaction with the deep mantle is an important issue in order to understand the scale of mantle circulation. Northwest Pacific region is one of the ideal locations to study the interaction between a subducting slab and the upper mantle discontinuities. Seismic tomography images show that beneath Japan Sea, the subducting slab has entered the depth of 400 km and interacted with the upper mantle transition zone. Due to limited spatial coverage of seismic stations in the ocean, fewer studies have been done to reveal topography of the upper mantle discontinuities beneath Japan Sea.

In this study, we applied the multiple-ScS reverberations analysis to waveforms recorded by F-net. We took advantage of the dense distribution of stations and spatial clusters of intermediate and deep earthquakes occurred beneath Okhotsk Sea, Russia and Northeast China, and conducted a common-reflection-point (CRP) stacking to the data, that allows us to map the topography of the 410-km and 660-km discontinuities beneath Japan Sea, Kuril, and adjacent regions in detail. The comparison with previous studies for profiles in common region shows that the array stacking technique to long-period signals is effective in extracting the robust features of the upper mantle discontinuities. It can be used not only as a complimentary method to short-period waveform analysis, but also as an independent way which can be applied to regions with limited station coverage. This is the first time to show systematically a complete view of the topography of the 410-km and 660-km discontinuities beneath the broad sea regions in the Northwestern Pacific Subduction zone. A broad depression of the 660-km discontinuity and local complex pattern of uplift and depression of the 410-km discontinuities are observed, and a thermal structure and composition of the upper mantle are investigated based on this map.

The relationship between lithospheric deformation and intermediate-depth seismicity beneath the Pamir revealed by surface wave tomography

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The Pamir, located at the western Himalayan Syntaxis, is one of the most active orogen on earth with ongoing lithospheric deformation. The Pamir and Tibet, both formed by the continuous India-Eurasia collision since about 55 Ma, have similar terrane structure and evolution history. But the Pamir has absorbed about 55-64% shortening of Cenozoic India-Eurasia convergence, which is two to three times of that of Tibet. The significant lithospheric shortening and thickening would have caused lateral extrusion and deep subduction of lithosphere in the Pamir. An evidence indicating the continental subduction in the Pamir is the striking intermediate-depth seismicity, extending down to > 250 km. In contrast, Tibet is essentially aseismic at depths greater than 80 km. Therefore, the Pamir would be an ideal place for understanding the subduction of buoyant continental lithosphere and the formation of intermediate-depth seismicity in the intracontinental setting.

We conducted Rayleigh wave tomography of the Pamir and adjacent regions. The data were initially collected from 106 regional events with magnitude Ms ≥ 5.0 and depth < 100 km, which were recorded by 157 broadband seismic stations of TIPAGE (Tian Shan-PAmir GEodynamic program) and several other networks (MANAS, GENGHIS, and FERGANA, etc.). Rayleigh wave group velocity dispersions of each source-station path were measured at periods of 10-100 s by applying the frequency-time analysis. Then we constructed group velocity maps with 0.8° × 0.8° grids with a damped least-squares method and inverted them to obtain the 3-D S-wave velocity structure.

Our images show a pronounced low-velocity zone (LVZ) in the middle crust of the southern Pamir at depths of 15-35 km and a high-velocity zone at depths shallower than 15 km in the Cenozoic gneiss domes in northern front of the LVZ. We also imaged the subducting Eurasian plate with high velocities in the mantle of the Pamir. In the mantle, an S-shaped LVZ has been imaged at depth of 70-150 km at the place of the intermediate-depth earthquakes, suggesting that the crustal materials may be involved in the subduction of Eurasian plate and the dehydration embrittlement may be the primary trigger of the earthquakes. This study indicates that subduction of continental crust plays an important role in the formation of the intermediate-depth seismicity in an intracontinental setting.

Seismic attributes and their use in interpreting structural and sedimentological relationships in sedimentary basins.

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Seismic attributes, since their first introduction in the late 1980s, are routinely used in the interpretation of 3D seismic datasets. By seismic attribute I refer mostly to those attributes that are generated from a fully processed seismic volume and that an interpreter as opposed to a geophysicist can generate easily using modern software. These attributes include those used to extract more information from an interpretation of a single reflection event (horizon) across a dataset such as edge, dip, azimuth, curvature and those applied to a volume of data, that include amplitude extractions, coherence or semblance algorithms and spectral decomposition techniques. Those applied to horizons are essentially an image processing technique similar to analogous algorithms used with other land surface, remote sensing datasets. Volume-related attributes in contrast, attempt to extract more information from the seismic trace over a time/depth interval and may yield information that can be directly related to subsurface rock properties such as lithology, and when calibrated with well-data, fluid content and even porosity.

In general these attributes have three main uses: structural interpretation, sedimentological analyses ('seismic geomorphology') and rock property information. For example dip and azimuth attributes can be used to extract information on small-scale faults close to the seismic resolution, whereas amplitude attributes allow an interpreter image sedimentary facies, such as channels, mass transport complexes, reefs etc. I will illustrate examples from my research spanning the last two decades where a range of these attributes has been used to help elucidate the nature of polygonal faults, find the first geomorphic evidence for a Quaternary ice-stream in the North Sea and investigate the interaction between deep-water slope sedimentary systems and actively growing structures in west Africa.

Geophysicists have long used complex seismic trace attributes (e.g. Tanner & Sheriff, 1977) and these are not generally those used by interpreters when they refer to seismic attributes. However the power of modern 3D seismic interpretation systems means that these attributes can be generated by an interpreter at the click of a button; perhaps they should be used to greater effect, and I will show some examples of data to which they have been applied. Another very important set of 'geophysical' attributes that are increasingly used by geoscientists is 'elastic impedance' volumes, where post-stack inversion algorithms are used to extract acoustic impedance directly from the seismic volume. With adequate well calibration these attribute cubes can be calibrated to net-to-cross cut-offs, sand content, or oil-bearing sands. An example of the application of elastic impedance to sand and fluid visualization in a producing reservoir from the Foinaven-Schiehallion area will be shown.

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Monte Carlo approach to assess the uncertainty of wide-angle layered models

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The interpretation of wide angle seismic refraction models must take into account the uncertainties of the resulting models, as different modelling approaches may lead to dissimilar models with overlapping uncertainties. Model uncertainties are difficult to estimate, as the problems are generally ill-constrained and trans-dimensional (we are unable to determine the correct number of parameters that define the minimum structure discernible in the data). Uncertainty estimations must be an integral part of modelling results to avoid disparaging interpretations of the same structure imaged at opposite ends of each model's uncertainty bounds, or the exclusion of alternative hypothesis that the model is unable to undoubtedly reject.

We developed VMONTECARLO, a tool to assess model uncertainty of layered velocity models using a Monte Carlo approach and simultaneous parameter perturbation that considers all picked refracted and reflected arrivals; providing insights into the acceptable geological interpretations allowed by data and model uncertainty through velocity-depth plots that provide:

a) the velocity-depth profile range that is consistent with the travel times;
b) the random model that provides the best fit, keeping most of the observations covered by ray-tracing;
c) insight into valid models dispersion;
d) main model features unequivocally required by the travel times, e.g., first-order versus second-order discontinuities, and velocity gradient magnitudes;
e) parameter value probability distribution histograms.

VMONTECARLO is seamlessly integrated into a RAYINVR-based modelling work-flow, and can be used to assess final models or sound the solution space for alternate models, and is also capable of evaluating forward models without the need for inversion, thus avoiding local minima that may trap the inversion algorithms and providing information for models still not well-parametrized.

VMONTECARLO has been successfully applied to two parallel profiles in the Santos Basin (Brazil) where the different crustal structures imaged on both profiles are show to be indeed geologically different and are not due to different interpretations of the same features within the uncertainty bounds of each model.

Mantle heterogeneity in the oceanic lithosphere of the southeast sub-basin, South China Sea, from wide-angle seismic and gravity study

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The southwest sub-basin (SWSB) of the South China Sea (SCS), an oceanic basin, locates in the southwestern part of the SCS, separated by rigid blocks (Macclesfield Bank and Reed Bank), formed by ridge propagation southwestward until the asthenosphere stopped upwelling around 16Ma. The processes of seafloor spreading through a series of mantle lithospheric dynamics in the oceanic lithosphere is generally considered to be the consequence of melt extracting and crustal accretion in the upper mantle structure. lateral crustal heterogeneity only plays a minor role in geophysical attributes, the upper-mantle structure can be revealed by the modeling of wide-angle seismic traveltime and amplitude. Besides, the residual mantle gravity anomaly (RMA) will show the mantle density changes across the axis. Taking account of the crustal structure, cold thermal structure with a strong lithosphere means anisotropic magma distribution along the slow-spreading ridge, which leads a heterogeneity mantle's density structure across the ridge. Therefore, the upper mantle structure, inferred from wide-angle seismic and gravity can thus provide us with knowledge of the processes that have formed oceanic lithosphere at different times and under a variety of conditions which is a straightforward response of the deep mantle structure of the lithosphere.

During the National Basic Research Program of China Project "South China Sea continental margin geodynamics", an 880km wide-angle seismic transect "OBS973" ocean bottom seismometer (OBS) profile across the SWSB from the Paracel (Xisha) Islands region to Spratly (Nansha) Islands from 2009 to 2011. This transect was conducted by two legs of South China Sea scientific exploring cruise, which were performed by R/V SHIYAN 2 of the South China Sea Institute of Oceanology, Chinese Academy of Sciences and M/V TANBAO of Guangzhou Marine Geology Survey with a tuned air guns array and a 480-channels streamer, respectively. We also re-interpreted 8 Multi-channels seismic profiles in light of the result of IODP expedition 349 drilling hole U1433B to construct a refined sediment thickness model for oceanic basin of the SWSB.

The main features of geophysical evidence of the SWSB in the SCS are distinct RMA low over the fossil spreading centre, little RMA variation along the direction of the paleo-spreading axis direction, and relatively wider area of gravity high on the southeast side, the seismic traveltime and amplitude modelling of the crustal structure favors a homogeneity oceanic crust. Therefore, the asymmetric RMA on each sides of the ridge is considered as key evidence for asymmetric pattern of the mantle upwelling and magma flux. It also indicates excess melting of the primitive mantle material which was redistributed differently along the final detachment fault zone at the time of lithosphere broke up. The fracture may work as a brittle-ductile transition for melt injection, which indicates that the latest final detachment rifting of the continental margin of the SWSB may have resulted in different lithosphere isostatic condition on either side of the fossil spreading ridge.

Local earthquake tomography of Scotland

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Scotland is a relatively aseismic region and so local earthquake tomography is a less obvious method to use than in many regions. However, 40 years of earthquakes recorded by the British Geological Survey (BGS) make it possible. Starting with the BGS catalogue a careful selection process maximises arrival time accuracy and ray path coverage. A large number of 1-D velocity models with different layer geometries are considered and differentiated by employing quarry blasts as ground-truth events. Then, SIMULPS14 is used to produce a robust 3-D tomographic P-wave velocity model for Scotland. In areas of high resolution the model shows good agreement with previously published interpretations of seismic refraction and reflection experiments. However, the model shows relatively little lateral variation in seismic velocity except at shallow depths, where sedimentary basins such as the Midland Valley are apparent. At greater depths, higher velocities in the northwest parts of the model suggest that the thickness of crust increases towards the south and east. This observation is also in agreement with previous studies. Quarry blasts used as ground truth events and relocated with the preferred 3-D model are shown to be markedly more accurate than when located with the existing BGS 1-D velocity model.

Advanced concepts in full wavefield imaging and inversion: active, passive, and real-time 4D seismology

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Time-lapse seismic imaging of the earth's interior, and inversion for dynamic rock and fluid physical property changes, has produced many spectacular results over the past two decades; however we are still making many theoretical approximations, and extracting only a small percentage of the information available in the data. We present advanced concepts in full wavefield imaging and inversion with application to active-source, passive, and real-time 4D seismic data, in order to improve time-varying images of the subsurface, and quantitative estimates of the earth's time-varying physical properties.

4D seismology has now become a mainstream technology to monitor subsurface fluid flow... provided we have certain optimal conditions. However, there are many rock and fluid combinations which are currently nearly impossible to monitor in typical noise environments, with state-of-the-art seismic acquisition systems. These "4D-impossible" cases include conditions for which the 4D signal is extremely weak, for example stiff reservoir rocks (cemented sandstones, carbonates...), and/or reservoir fluids with similar compressibility properties (saltwater versus freshwater, low-GOR oil versus water, high-GOR oil versus gas or CO2...). In such cases the primary 4D seismic response is much weaker than the typical non-repeatable noise levels encountered, and therefore cannot be detected. In other cases the time-varying change in physical properties is so large that the 4D signal is easily observed, but the complex time-lapse scattering is so strong that the simplifying assumptions underlying our imaging and inversion methods become invalid. We will show that we may be able to overcome such difficult challenges by making use of the full complex time-varying scattered wavefields, which we term "4D Coda waves".

In parallel with the 4D seismic developments above, semi-permanent Large N sensor arrays capable of long-term continuous recording are bringing new ideas and science together from the exploration and earthquake seismology communities. I will discuss how advanced wave-equation imaging and inversion methods can be applied to continuous array data including natural and induced seismicity, and ambient noise wavefields. Full wavefield imaging and inversion of continuous passive seismic recordings can bring a step change in our ability to detect, locate, image, and characterize (micro) seismic source events. In addition, the information in the passive seismic wavefields can be used to estimate the detailed velocity structure of the earth, and how it changes over time. Continuous passive seismic recording also allows us to isolate ambient noise body waves for subsurface imaging and inversion. In some cases we are able to achieve ambient noise image convergence in less than 60 minutes of recording time, which allows the possibility to make time-lapse movies of the subsurface with a frame rate of about 1 hour. Since these arrays have a low environmental footprint and require no manmade source energy, we may be heading for a future of low-cost real-time monitoring of the subsurface by harnessing the natural ambient noise that is continuously generated and scattered within the earth.

Simultaneous joint inversion of disparate geophysical observations for 3D geophysical modelling

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When an earthquake or underground explosion occurs, the seismic waves that are generated propagate through the earth, reflecting and refracting at different interfaces and illuminating its 3D structure, while also carrying the signature of the source. The wavefield recorded for many events at many stations around the world can be used to image the structure of the Earth using tomographic approaches. Seismic tomography, first introduced more than 30 years ago, is still a rapidly developing field, which provides the most important constraints to unravel our planet's present and past dynamics, and the driving forces for plate tectonics. In the last years, with the advent of new numerical methods, unprecedented data sets and more commonly available high performance computing resources, we have seen an outburst of 3D geophysical models and techniques for seismic imaging. This talk will present recent developments and application of advanced multivariate inversion techniques to generate a realistic, comprehensive, and high-resolution 3D model of the seismic structure of the crust and upper mantle that satisfies several independent geophysical datasets - surface wave dispersion measurements, gravity data, teleseismic receiver functions, and seismic body wave travel times. Surface wave dispersion measurements are primarily sensitive to seismic shear-wave velocities, but at shallow depths it is difficult to obtain high-resolution velocities and to constrain the structure due to the depth-averaging of the more easily-modeled, longer-period surface waves. Gravity inversions have the greatest resolving power at shallow depths, and they provide constraints on rock density variations. Moreover, while surface wave dispersion measurements are primarily sensitive to vertical shear-wave velocity averages, body wave receiver functions are sensitive to shear-wave velocity contrasts and vertical travel-times. Addition of seismic travel-time data helps to constrain the seismic velocities both vertically and horizontally in the model cells crossed by the ray paths. To avoid mapping broad, possibly dynamic features in the gravity field into variations in density and body wave velocity, we apply a high-pass wavenumber filter to the gravity measurements. P-wave velocities and density variations are related to shear-speed using empirical velocity ratios and relations so that all datasets may be combined in a single inversion. We constrain the 3D variations to be laterally and vertically smooth.

We apply the method to investigate the seismic velocity structure underneath several regions of interest and at different scales; from continental scale (USA) to regional (Colombian and Iranian regions) to more local scales (Alaskan volcanoes). The final optimized 3D velocity models allow us to explore how multi-parameter tomography addresses crustal heterogeneities in areas of limited coverage and improves travel time predictions as well as to address general tectonic and geodynamic questions.

Uncertainty in layered models based on seismic travel times

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The estimation of uncertainty for any geophysical model is important to determine how reliable the model is. It is especially important for subjective trial and error modelling techniques like forward ray-tracing modelling of wide-angle seismic data when the final result is very dependent on the interpreter's knowledge of the area and experience. In this kind of modelling, it is common to encounter over interpretation of the seismic data without checking the uncertainty of the result, especially in the deep parts that are not constrained with other a priori knowledge.

This presentation propose a method of estimating the uncertainty of the final models based on a 1D method of small error propagation generalized for 2D profiles. This method translates picking precision of each refraction and reflection phase to uncertainties in inverted velocities and boundary shapes, and propagates them further to deeper layers. Presented are estimations of previously published models from seismic experiments in the Central Europe. This presentation also discuss the effects of uncertainty propagation in two modelling techniques: layer-stripping and joint inversion, showing the advantage of the last one. Also a specific case of sedimentary layers is presented where combination of refractions and reflections traveltimes are used to find the velocity structure and the shapes of boundaries with special focus on the post-critical reflections effects on the uncertainty of velocities.

Depth migration uncertainty based on seismic velocity estimation from wide-angle reflections in layered structures

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Reflection tomography is a well-known method used for velocity estimation in reflection seismic imaging. It is based on observations of seismic energy that is propagating almost vertically. We propose an extension of standard reflection tomography to wide-angle observations. In typical sedimentary structures with relatively small velocity differences, wide-angle reflections, and especially one observed at large offsets for post-critical angles, are dominant in observed amplitudes, thus easy to recognize and utilise.

A case study is presented in this presentation, of a joint interpretation of conventional reflection seismic with reflection imaging, combined with the wide-angle travel time inversion of additional long offset, so called full-spread observations. A joint interpretation results in a precise recognition of the seismic velocity distribution, that is further used for the seismic depth conversion with the uncertainty analysis of the depth of the reflecting horizons. Velocity field is a crucial factor determining precision of the depth migration. Presenting example of the Braniewo experiment shows that easy to perform extension in standard seismic observations can significantly improve the final image. Despite the salt layer in the studied structure we were able to precisely recognize the seismic velocities of the sub-salt structures, and give the depth migration uncertainty for main reflecting horizons.

Preliminary P- receiver function imaging on the crustal structure of Scandinavia

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Scandinavian geological composition is represented by 2 geological domains: The Palaeoprotorozoic Svecofennian Domain in the east and the Caledonian Deformed Domain in the west (Gorbatschev and Bogdanova, 1993). The Palaeoprotorozoic unit consists of the metasedimentary and metavolcanic rock sequences, massifs of granite, Ljusdal Batholith, bounded by ductile shear zones, part of Transscandinavian Igneous Belt (Högdahl et al.,2004).

Our initial results based on the data from 20 stations deployed over the central part of Norway and Sweden between 60°N and 66°N. The stations used here are part of the ScanArray experiment, which has started in 2012 as an international collaboration between Danish, Norwegian, Swedish, German and British universities. The whole network consists of 79 stations.

To investigate the crustal structure, we use the P-receiver function technique (RF) with the rays oriented in the LQT coordinate system (Vinnik, 1977). The technique allows us to determine the Moho depth around the stations by modeling the differential arrival timing of Ps converted phase. This technique has an advantage of rather high vertical resolution of the depth to seismic discontinuities due to conversion between P- and S-waves.

The whole dataset is uniformly filtered and the deconvolved signals are stacked using appropriate moveout corrections. We have used events with a magnitude ≥ 5.5 Mw, with epicentral distances range from 25° to 100°.

Further studies will include P-receiver function and S-receiver function for all stations of the ScanArray. It's planned to make a joint P-wave and S-wave inversion, which will to investigate the upper mantle beneath the stations.

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Uncertainty in microseismic event location

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Microseismic data are of increasing importance for applications that range from hydraulic fracturing monitoring to geothermal energy production to volcano monitoring. This is typically done primarily via the location of the events. These locations are then correlated with production data and known geologic structures to infer flow patterns. Each stage of this process adds to the uncertainty of the final interpretation, but neither the total uncertainty nor the uncertainty in each step is well quantified.

We begin to tackle this problem using a Bayesian approach to location uncertainty. This allows us to compare different location methods to see which method produces the smallest uncertainties for a given set of conditions. We then carry this analysis further, to show how we can use these uncertainties to characterize the uncertainty in a simple flow model. This analysis has its limitations, however, in that it works primarily from known traveltimes and uses the resulting locations as a priori information for flow analysis.

Much more information is contained in waveforms than simply travel times and much more can be learned about the Earth when looking into more details about seismic events than their location. To that end, we look at so-called Source Scanning Algorithms (SSA). These algorithms work by scanning the discretized model space for best-probability source parameters and allow for the analysis of full-waveforms and the recovery of both source locations as well as source mechanisms. This part of our work focuses on the recovery of source mechanisms and how this can be done in a robust way that takes into account all of the uncertainties present in the data.

Using OBS data during regional seismic surveys: a case study from the Exmouth Plateau, offshore NW Australia

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The Australian Government has recently acquired 20 state-of-the-art broadband Ocean Bottom Seismographs (OBS) units. During the summer of 2014-2015, Shell Australia conducted the Dirk-Adventure-Bart (DAB) seismic survey over the Exmouth Plateau on the NW Australian margin. The placement of the OBS instruments was carefully planned to achieve the desired resolution and depth of investigation (full crustal thickness). High quality data were recorded at all OBS deployment sites, often to offsets sufficiently large to detect Moho refractions (P_n phase), therefore both the seismic velocity distribution and the crustal thickness can be determined from these data. The survey consisted of three conventional 3D reflection surveys and four dedicated OBS 2D refraction lines. The shooting interval for the 2D OBS refraction lines was 100 m, or ~45 s to ~64 s depending on the speed of CGG's Viking Vision 3D seismic vessel. This rather large, by marine reflection seismic standards, shot interval was defined on the basis of pre-survey modelling to minimise contamination of useful signal by noise from previous shots. The seismic airgun source utilised during the Shell DAB survey was an industry standard 4630 cubic inch broadband array, which is a much smaller volume array compared to what is commonly used for deep crustal OBS refraction studies. Several dedicated OBS refraction lines were recorded during the survey, including 280-km long 2D OBS line, known as the BART 2D line, which coincides with the ION Geophysical Westralia SPAN deep reflection line AU1-1050. A number of prominent deep crustal (15+ km depth) features have been interpreted in the reflection data, including possible crustal underplating (or intruded mantle), and Permian/Triassic Sea-floor spreading. Identification of the Moho in the reflection data set is challenging because there is a number of competing deep high-amplitude discontinuous events, and each of them, in the lack of reliable velocity controls from the reflection data, can be taken as a marker of the bottom of the crust. Here we use OBS data from the BART 2D deployment to build the crustal velocity model and independently constrain the Moho depth using wide-angle P_mP arrivals. We manually picked first-arrival travel times for all 14 OBS gathers (mostly P_{sed} and P_g phase with some P_n arrivals). Subsequently, we run first-arrival travel time tomography using the FAST package (Zelt and Barton, 1998). Interestingly, strong PmP reflected phases are observed in the NW segment of the line, where some increased reflectivity around the expected Moho depth (~25 km) is observed. We use those P_mP phases to constrain Moho depths using reflection tomography approach (Moho as a floating reflector) and the tomographic velocity model. Top of the Permian/Triassic Sea-floor spreading interpreted in the reflection data appears to correspond to OBS-derived velocities ~6.2 km/s, with velocity increase to ~7.0 km/s at the bottom of that layer, consistent with interpreted petrology of the rocks in that depth interval. Within the layer interpreted as possible crustal underplating (or intruded mantle) in the reflection data, OBS-derived velocities appear to be identical to those within the Permian/Triassic Sea-floor spreading layer, thus questioning the validity of identification of crustal underplating/intruded mantle in the reflection data set. Inversion of P_mP arrivals allows to identify Moho in the reflection image with greater confidence and also suggests occurrence of some deeper mantle reflections.

Shallow subsurface 3D seismic velocity structure (Záncara river basin, Iberian Peninsula)

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Traveltime tomography provides a very useful tool to characterize in detail the uppermost deposits of a shallow sedimentary sequence. Nevertheless, if the stratigraphic succession presents a complex internal structure, such as diffused lithological boundaries or a large variability for properties within the same lithology, the direct geological interpretation becomes very difficult. In this case, the integration of all the geophysical parameters available is mandatory to better characterize the subsurface. The study area corresponds to a Miocene syncline located in the Záncara River Basin (Cuenca, Spain). The sedimentary sequence consists in a transition from shales to massive gypsums. A 3D traveltime tomography were acquired within a 500x500 m area using a regular grid distributed in a North-South alternated shot and receiver lines. A final inversion grid of 10x20x5 m provided a detailed velocity model of the first hundred meters. The interpretation of the resulting model have been done integrating the numerous well logs available in the area ((including gamma ray, resistivity and sonic logs) Four different units are identified according to their physical properties distribution: gypsiferous shales, shales-gypsum transition and two different gypsum layers, providing the required constraints to interpret the final 3D velocity model. Seismic velocity clearly images the defined domains showing that the gypsum layers gently dips to the W with the shales laying on them in this western sector of the study area. The correlation with the geological profiles shows a good agreement along the the top of the massive gypsum layer characterized by strong velocity contrast. The correlation is not that good for the shale-gypsum transition, featuring low velocity contrast, especially in the very shallow surface where gypsum layer outcrops. The absence of confident log values for this upper part and the strong weathering effects observed makes difficult for the velocity model to differentiated between both lithologies (Research supports: CGL2014-56548-P, 2009-SGR-1595).

Seismic profiles in NW Spain help to constrain orogenic evolution during Variscan crustal thickening and extensional collapse

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Four vertical incidence seismic profiles, two of them shot on land (ESCIN-1.1 and ESCIN-1.2), and two offshore (ESCIN-3.2 and ESCIN-3.3), are welded together to show a composite profile across NW Iberia, representative of the Variscan crustal structure. The profile, roughly oriented W-E, cuts across the more internal and allochthonous Galicia-Trás-os-Montes Zone (GTMZ) in the W, through the internal but autochthonous Central Iberian Zone (CIZ) and West Asturian-Leonese Zone (WALZ), and the external Cantabrian Zone (CZ) in the E.

The seismic composite profile is compared with a W-E geological section depicting the main Variscan structures, including early overturned and recumbent folds, subsequent thrust faults, extensional domes and detachments, late steep folds, and high-angle transcurrent shear zones, characteristic of the hinterland. The external thin-skinned foreland thrust belt forming the CZ is also shown.

The Moho seems located at the base of one or more bands of reflective lower crust covering an interval from 8-14 s TWTT in profile ESCIN-1.1, 9-13 s in profile ESCIN-1.2, 7-13 s in most of the ESCIN-3.3 profile, 8-9 s at its W edge and 8-10 s in profile ESCIN-3.2. Accordingly, a 3-4 s Moho step, Variscan in age, separates the more internal and thinner crust under the GTMZ and CIZ (ESCIN-3.2) from a thicker crust to the E, beneath the WALZ and CZ (ESCIN-3.3 and ESCIN-1.2).

The upper part of the marine profiles reflects the geometry of the Mesozoic and Cenozoic sediments of the Cantabrian margin. The basement is in general transparent in the upper crust, but in the middle crust, the seismic profiles show subhorizontal and dipping, narrow reflective stripes that correlate with crustal scale shear zones, either thrust faults or extensional detachments. A series of them in ESCIN-1.1 can be interpreted as imbricates and the sole thrust of the CZ, a foreland thrust belt characterized by thin-skinned tectonics and more than 50% shortening. The sole thrust continues westward joining in ESCIN-1.2 several W-dipping imbrications suggesting a ramp-related, hinterland dipping duplex. To the W, it continues at the base of a reflective band between 7-10 s under the WALZ, the CIZ and the GTMZ. But while beneath the two latter zones this reflective band represents the lower crust, under the WALZ there are another 3-4 s of reflective crust beneath, interpreted as the basement of the CZ underthrust to the W. Its westernmost edge forms the Moho step in the W part of profile ESCIN-3.3. Modelling of the Bouguer anomaly shows that the Moho step strikes roughly N-S, parallel to the Variscan structures. So, the deep Moho reaching 13 s under the WALZ results from lower crustal duplication, a relict of Variscan shortening.

The thinner crust under the GTMZ and CIZ reflects strong, late-orogenic re-equilibration, linked to thermal relaxation after having experienced a large amount of crustal thickening, as the allochthonous GTMZ alone added ca. 30 km to the Variscan crust. Re-equilibration was less intense in the more external domains to the E (WALZ and CZ), where crustal thickening was limited. Remobilization and extension erased other possible crustal-scale thrusts, and removed the wedge geometry that should be expected for this imbricated part of the Variscan belt.

Seismic structure of the Southern Costa Rica convergent margin

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In 1995, a German-U.S. team carried out the TICOSECT refraction and wide-angle reflection seismic (WAS) survey off- and on-shore Costa Rica, onboard the R/V Maurice Ewing. The main objectives of the TICOSECT project were to investigate the crustal structure of the active continental margin and to understand the geodynamic processes within the subduction system. During the survey three different experiments were carried out to investigate the upper plate response to different segments of the subducting Cocos plate: a) the relatively smooth segment of the Cocos plate in the North, offshore Nicoya Peninsula; b) the central segment dominated by the presence of numerous seamounts; and c) the southern segment characterized by the subduction of the thickened crust of the Cocos Ridge.

In this work we present a 2D P-wave seismic velocity (Vp) model and the geometry of the main geological boundaries obtained along a WAS transect that crosses the southern segment of the margin, West of Osa Peninsula. The WAS transect is 104 km-long, and it includes 19 OBS/OBH with an average separation of ~5 km. We have performed a joint refraction and reflection travel-time inversion of the WAS data following a five-step layer-stripping procedure, consisting of adding the data sequentially (one layer at each step), starting from the shortest offsets/uppermost levels (i.e. the sedimentary phases of the overriding plate) and finishing with the longest offsets/deepest levels (i.e. the mantle arrivals of the subducting plate). Beneath a sedimentary cover of variable thickness, the seismic structure of the overriding plate could be divided into three different domains:

1) the frontal domain; a 30 km-wide zone from the trench towards the coast characterized by velocities ranging between 4.0 and 4.5 km/s;

2) a 15 km-wide transition zone with velocities between 4.5-5.0 km/s; and

3) a 9 km-thick and 40 km-wide crustal section in the NE with velocities between 5.0 and 6.5 km/s.

The subducting plate shows a rough topography and a laterally-varying oceanic-like velocity structure, with a crustal thickness decreasing from 12-13 km just below the trench to 6-7 km-thick below the mid continental slope.

We have converted the WAS velocity model to two-way-time to compare it with a coincident multichannel seismic profile. A remarkably good fit is obtained between the different geological boundaries imaged by the MCS data and those inverted from WAS reflections (i.e. the base of the sediments, the intraplate reflector, and the Moho of both plates). In the same way, characteristic features can be identified in the previously described overriding plate domains:

(1) low-dip imbricated units with internal stratification in the frontal domain (referred as margin wedge);

(2) the highly fractured transitional zone showing active deformation in the sedimentary cover; and

(3) the northern domain showing small extensional basins and tilted blocks overlaid by ~2 km of sediments.

Geophysical data integration for a joint interpretation in a shallow gypsiferous context.

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As every geophysical technique suffers from its own limitation, a proper survey has to combine different geophysical methods. The integration of different geophysical data in order to derive a joint geological interpretation is complicated beyond qualitative (subjective) correlations. We propose a new numerical method (less subjective) to integrate three separated datasets: seismics, electrics and well logging. The study area is the shallow subsurface of a planned singular facility in Villar de Cañas (Cuenca, Central Spain). Lithology down to 100 m deep consists of a transition from shale to massive gypsum. In 2013, we acquired a3D Traveltime Tomography to characterize this transition. After data processing, the velocity model showed, in general, a good correlation with geological profiles, being able to identify the three main layers: shales, transition gypsum and massive gypsum. The correlation for the massive gypsum limit (high velocity contrast) is very good, but is not that good for the transition shale-gypsum (low velocity contrast). As electrical resistivity is a good tool to characterize shale-gypsum transitions, we decided to improve our resolution capacity by integrating resistivity data from a collection of ERT panels. By means interpolation IDW, we built a new 3D bi-parametric grid that nests velocity and resistivity values in every node. In order to derive from de grid a geological interpretation benefiting from both seismic and electrical resolution capacities, we applied a supervised statistical classification (Linear Discriminant Analysis, LDA). The LDA algorithm was fed with velocity, resistivity and lithology values from wells and it classified every node lithologically according to its velocity-resistivity pair, resulting in a new 3D lithological model. This new model joins seismic and electrics resolution capacities, showing for the two limits under discussion a better geological fitting than those techniques separately. (Research supports: CGL2014-56548-P, 2009-SGR-1595 , CGL2013-47412-C2-1-P)

Seismic imaging of the Source Physics Experiment site using interferometry

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We use several methods of seismic interferometry to obtain highly detailed images at the site of the Source Physics Experiment (SPE). The objective of SPE is to obtain a physics-based understanding of how seismic waves are created at and scattered near the seismic source. The records of the SPE shots vary dramatically along different azimuths. To separate source-specific effects from those due to geological structure, we need a precise 3D seismic model at scales ranging from tens of meters to tens of kilometers.

We apply several interferometric techniques: Shot interferometry (SI) uses the SPE shots as rich sources of high frequency, high signal energy. Coda interferometry (CI) isolates the energy from the scattered wavefield. Ambient noise correlation (ANC) uses the energy of the ambient background field. In each case, the data recorded at one seismometer are correlated with the data recorded at another to obtain an estimate of the Green's function (GF) between the two. These GFs are then inverted to obtain the final seismic image. Our objective is to obtain a 3D model that is precise enough to calculate synthetics matching the scattering effects seen in the data.

ANC is the most computationally intensive of the three methods, requiring long, continuous records. Typically, months of data were required at this site. Because the spectrum of ANC is determined by the Earth's background noise field, it also has the lowest frequency content (5-15 Hz along the geophone lines). It's power is that it can be applied to any two seismometers at any offset. This is the best of the three for recovering the deepest structures along the longest paths. In contrast, SI and CI are very fast, requiring only short data segments. Because they contain the same spectral content as the original shot, they result in very high frequency estimates of the GF (up to 30 Hz along the main geophone lines). SI is constrained to paths along directions radially outward from the shot, limiting it's coverage. CI has lower SNR than the SI method, but because it includes both forward and backward scattering arrivals, it can be used to image paths across the seismic lines, in particular, across the source point. These high frequency methods are excellent at resolving the shallow low velocity features that dominate the observed near-field scattering

The SPE site is covered by a dense network of mixed geophone and broadband instruments. Nearly 200 lie within 100 km of the shot point and more than 100 of those lie within 2 km. Using interferometry, we calculate over 10,000 GFs for paths sampling the site. The final result is a model of the P and S velocity structure of the upper crust, with resolution increasing dramatically in the vicinity of the shot point.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Crustal-scale Reflection Seismic or Why we Learned to Stop Worrying and Love the Continental Margins

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Prior to the acquisition and publication of the now legendary BIRPS seismic database in the 1980's and 90's, investigations into the structure of Earth's crust relied on taking a holistic approach. Wide-angle seismic, potential field data, and what available (short record length) reflection seismic data existed were used to create crustal scale geological models. The BIRPS dataset revealed the previously unknown heterogeneity within the continental and oceanic crust. For the first time the structures responsible for basin, or margin formation could be tied to features imaged deep in the crust, and in some cases to structures that were imaged within the mantle lithosphere.

Since 2002, ION has taken the ethos of the BIRPS campaigns, and acquired the global BasinSPAN™ database consisting of long-offset, depth migrated, trans-crustal 2D reflection seismic data on many of the world's continental margins and petroleum provinces. These data provide high-fidelity imaging of the sedimentary section in addition to the entire crust, , allowing workers to interrogate the crustal structure and depositional history of an entire margin and provide critical insights to the mega-regional petroleum system.

The BasinSPAN™ data library covers many tectonic settings and margin types including magma-rich, magma-poor and transform margins. We present seismic examples from each of these tectonic settings from around the globe including Australia's North-West Shelf, the conjugate South Atlantic system, the East African margin and the East Indian margin. Using these examples we demonstrate the observations and some of the key insights that an integrated mega-regional understanding of the crustal structure and depositional architecture can provide to proposed models that describe the evolution of continental margins.

A new model for the formation of seaward-dipping reflectors in the South Atlantic Ocean

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We present a new model for the formation of South America's seaward-dipping reflectors (SDRs) using ~33,000 km of regional seismic reflection data integrated with constraints from velocity analysis of pre-stack data and potential field data. SDRs are erupted during the transition between continental rifting and sea-floor spreading and are a key characteristic of volcanic-passive margins. Where drilled, they are shown to be made of packages of thick sub-aerial tholeiitic lavas and tuffs interbedded with thin layers of terrestrial sediment. The thick accumulation of basalt and interbedded sedimentary rocks poses many problems for conventional seismic imaging as seismic energy is refracted within the SDRs to long-offsets, resulting in a loss of internal and sub-basalt imaging. Our interpretation uses ~18,000 km of long-offset (10,200 m), pre-stack time and depth migrated, low-frequency 2D seismic reflection data acquired between 2009 and 2012 by ION-GXT together with ~15,000 km of conventional (3,000 m offset) seismic data acquired by the German Federal Institutes of Geosciences and Natural Resources (BGR) in 1987 and 1998. The former has a line spacing of 150 km in the south and 80 km in the north but extends the entire margin from southern Argentina to Brazil whilst the latter has a line spacing of just 12.5 km mainly in the south of the study area. This ION-GXT data is capable of imaging the SDR geometry to great depths. A new velocity analysis of three pre-stack dip-lines offshore Argentina, Uruguay and SE Brazil has been conducted.

Based on seismic character and correlation with magnetic and velocity data we identify 4-6 separate fault-bounded SDR packages across margin. These individual packages thicken and diverge ocean-wards, towards a bounding fault. It is suggested that eruption of SDRs was episodic as many individual packages are superimposed by younger more ocean ward volcanic wedges. Offshore Argentina and Uruguay, the earlier land-ward SDR packages have long, 25-30 km, reflections with dips between 15°-25° while later more ocean ward packages are shorter, 10-15 km long, with shallower dipping reflections between 5°-10°. Similar along-dip reflection-length reduction is observed between the volcanic packages within the more massive SDRs of the Pelotas basin (SE Brazil). It is suggested that the reduction in reflection length and steepening in dip represents a switch from sub-aerial to sub-aqueous eruption, reflecting subsidence along the continental margin.

Within the SDR packages the seismic velocities vary by up to 1 km s^{-1}, with the highest internal velocities observed where they are thickest at the down-dip end of individual packages. Here velocities reach 6.3-6.8 km s^{-1}. Beneath the SDRs and the high-velocity bodies the velocities reduce to more typical values of metamorphic continental crust (5.5 km s^{-1}). We interpret the zones of anomalously high-velocity as depleted mafic or ultra-mafic solidified magma, intruded within crystalline continental crust. We propose that the intrusive bodies are the original depleted sources for the sub-aerial tholeiitic lava flows that formed the SDRs. The model we describe shows how the thickest sub-aerial SDRs are erupted onto continental crust by along-margin point sources instead of the more conventional view that SDRs erupt from a fixed central source which develops into the proto-mid-ocean ridge.

No more multiple removal: Construct Primaries then Migrate

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Advanced methods of seismic data processing such as full-waveform inversion account for data that include multiply scattered waves, but such methods are prohibitively expensive across the seismic frequency range. Consequently, many standard processing steps including reverse-time migration (RTM) use the Born approximation: this approximation is to assume that waves have only scattered from heterogeneities in the medium once, thus requiring that data consist only of primaries (singly scattered energy).

A variety of methods are therefore usually deployed as pre-processing, to predict multiples (waves reflected several times) in recorded data; however, accurate removal of those predicted multiples from recorded data using adaptive subtraction techniques proves challenging, even in cases where they can be predicted with reasonable accuracy.

To overcome this problem, we propose an entirely new strategy: instead of synthesizing and removing multiples, we construct a parallel data set consisting of only primaries, which is calculated directly from recorded data. This approach thus obviates the need for both multiple prediction and removal, since no multiples exist.

We show how primaries can be constructed using convolutional interferometry to combine first arriving events of up-going and direct-wave down-going Green's functions to virtual receivers in the subsurface.

The required up-going wavefields at subsurface virtual receivers are constructed by Marchenko redatuming, a novel technique that estimates up- and down-going components of Green's functions between an arbitrary location inside a medium such as the Earth's subsurface, and the locations of real receivers (or sources) located at the Earth's surface. Crucially, this is possible without detailed models of the Earth's subsurface velocity structure: similarly to most migration techniques, the method only requires surface reflection data and estimates of direct (non-reflected) arrivals between virtual subsurface sources and the acquisition surface.

The method is demonstrated on a stratified synclinal model. It is shown both to be particularly robust against errors in the reference velocity model used, and to improve migrated images substantially.

Seismic Imaging in a low Q Environment

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Seismic imaging is an important geophysical tool for delineating and monitoring the earth's subsurface structure and its mineral and hydrocarbon resources. Owing to the earth's heterogeneity, such subsurface structures exist at different scales (sizes) with lateral and vertical variations in physical properties such as contrasts in bulk and shear moduli, densities, and attenuation coefficients. Seismic methods illuminate subsurface structures using compressional and shear waves. Recorded signal at surface and borehole seismic sensor locations arise from reflection, refraction, transmission, scattering and intrinsic attenuation of elastic waves at lithological contacts, structural boundaries and the earth's free surface, where abrupt and gradual changes in physical rock properties occur. The effects of scattering on seismic wave propagation can be described in terms of different propagation regimes and physical rock property contrasts: quasi-homogeneous for heterogeneities too small to be seen by seismic waves, Rayleigh scattering, Mie scattering and small-angle scattering. These scattering regimes cause characteristic amplitude, phase and travel time fluctuations, thus often limiting the resolving power of seismic imaging. Examples of reflections with strong contrasts in physical rock properties include the lower crustal reflection, the crust-mantle boundary, mafic sills and dikes as well as massive sulfide mineral deposits. In contrast, little attenuation has been paid to the role of intrinsic attenuation on hardrock seismic imaging. Both, intrinsic and scattering attenuation, will cause a reduction in signal to noise ratio and will pose a severe limitation to seismic exploration in hardrock environments.

Highly localized and extremely low Q were detected through multiple measurements from seismic datasets acquired in the Proterozoic (1700-1600 Ma) Athabasca Basin (Canada). The Athabasca Basin is known for its rich basement unconformity-related uranium deposits. Broadband VSP, offset VSP and 3D-3C surface seismic datasets reveal pronounced zones of high attenuation (low seismic quality factor Q). Q estimation methods used are time-domain amplitude decay, frequency-domain spectrum ratio and velocity dispersion. The results confirm that locally Q can be smaller than 10, The presence of low Q zones in the earth's crust provides an interesting challenge for a wide range of controlled source seismic imaging and passive source seismic monitoring studies.

Determining the location of the continent-ocean transition at rifted margins

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The continent-ocean transition is a key tectonic boundary with implications for the processes involved in lithospheric extension, for plate reconstructions, and for hydrocarbon maturation. The continental limit of the transition may be defined by the seaward limit of continental crust, by the location of the necking zone where the crust thins, or by the landward limit of crustal thinning. The oceanward limit of the transition may be defined as the first occurrence of full-thickness "normal" oceanic crust, by the oceanward limit of continental lithosphere, or indeed by the oceanward limit of thinned continental crust. In the light of modern observations, some of these definitions are becoming increasingly difficult to apply. The presence of linear seafloor-spreading magnetic anomalies has traditionally been used as evidence for the presence of oceanic crust, but in several locations clear linear anomalies have been identified over lithosphere that has not been formed by seafloor spreading, while elsewhere oceanic crust exhibits no linear anomalies because of formation during periods without magnetic field reversals. The necking zone has a distinctive gravity signature, but assigning crustal type based on gravity data is challenging. In seismic reflection profiles, the presence of tilted fault-blocks capped by sediments that predate fault activity has been interpreted as an indicator for the presence of continental crust, but such structural features can be observed where no continental crust is present beneath. Areas of exhumed mantle may be found adjacent to rifted margins, but also far from any continent. Using examples from both magmatic and magma-poor rifted margins, I will explore the seismic expression of continent-ocean transitions and discuss practical approaches to determining their location.

4D seismic through the life of the Harding and Gryphon Fields, Quad 9, UKCS.

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4D or time-lapse seismic involves acquiring repeated 3D seismic surveys over a producing field through its production life. A 'baseline' survey is acquired prior to the start of production and subsequent 'monitor' surveys acquired at appropriate times during later production. Since the field's geology remains unchanged differences between the monitor and baseline surveys generally show only production induced changes in the subsurface. In this manner, 4D seismic surveys can be used for field-wide surveillance supplementing information from production and reservoir engineering data. 4D seismic is often sensitive to fluid saturation changes in the reservoir, providing information on reservoir fluid movement such as water and gas sweep. It can also be sensitive to reservoir pressure changes and, in some cases, it can give indications of geomechanical changes induced by compacting reservoirs. This information can be critical for field development and production optimisation and can add significant value through increased hydrocarbon recovery and reduced cost. 4D seismic has seen a significant growth since the turn of the century and it is now regarded as a standard field development technology.

Whilst the benefits of 4D seismic are clear there is considerable complexity and uncertainty in acquiring, processing and interpreting the data. The magnitude of the 4D signals is largely controlled by the rock and fluid properties of the reservoir and the field development strategy. The detectability of 4D signals is dependent on the quality of the seismic data where a low noise environment and highly repeatable surveys are critical to 4D success. Interpretation of 4D data is often challenging and requires the close integration of geophysical, geological, reservoir engineering and production knowledge.

The Harding and Gryphon fields are located in Quad 9 of the Central North Sea (UKCS) approximately 320km (200 miles) northeast of Aberdeen. There are seven major producing fields in the area and a new development, Morrone, is due to produce its first oil early next year. The fields consist of late Palaeocene to early Eocene mass-flow sandstone reservoirs and have excellent reservoir properties. The rock and fluid properties are very conducive to 4D seismic and produce strong signals. Development of the fields has focussed on oil production to date but a large gas development project is planned that will produce the fields' gas caps as the oil production declines. 4D seismic data has been used throughout the oil development phase of the fields to guide development and infill drilling by monitoring water and gas sweep.

Regional geological and simulation models have been created to help plan for the gas development phase of the fields. They are intended to address key uncertainties in the range of in-place gas volumes and the connectivity between the fields. Typically, simulation modelling and history matching are used to evaluate and refine the subsurface models but in this case, the workflow was extended to use the 4D seismic data as an additional, independent and field-wide history match constraint. Simulation-to-seismic modelling was used to generate synthetic 4D seismic volumes from the models and was compared to the real 4D seismic data. Discrepancies were used to modify the reservoir sand distribution in the geological model and the inter-field connectivity in the simulation model. The combination of geological knowledge, production data history matching and 4D seismic data led to improved subsurface models and a more confident basis for subsequent planning.

Many challenges remain to further improve 4D seismic technology including better quality data, separation of pressure and saturation changes, geomechanics and seismic assisted history matching. 4D seismic will continue to be a key technology for maximising the recovery from our fields.

Lower crustal high-velocity bodies along North Atlantic passive margins, and their link to Caledonian suture zone eclogites and Early Cenozoic magmatism

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The structural grains and thrust sheets related to the Ordovician-Silurian collision between Baltica, Avalonia and Laurentia, which resulted in the Caledonian Orogeny, have controlled the subsequent geological development of the proto North Atlantic. During subduction of Baltica below Laurentia, the lower crust of the western margin of Baltica was buried to about 125 km depth, which resulted in metamorphism into eclogite facies. Remnants of these eclogites can at present be observed onshore in e.g. the Western Gneiss Region, Norway.

In this study we use crustal-scale Ocean Bottom Seismic models to infer the presence of two types of lower crustal bodies at North Atlantic passive margins; Type I, primarily interpreted as Early Eocene magmatic intrusions, and Type II, interpreted as Caledonian eclogites. We discuss how these eclogites might be related to the main Caledonian Suture Zone and other tectonic features in a conjugate North Atlantic setting. Based on the first-order approximation that P-wave velocities can be related to rock strength, the narrower continental margin at the southern (Møre) transect may be explained by stronger lower crust there, compared with the northern (Vøring) transect. This difference in strength, possibly resulting in a steeper dip in the subducting Baltica Plate south of the proto-Jan Mayen Lineament, may explain the asymmetry in extensional style observed across this lineament. Our interpretation locates the main suture off mid-Norway close to the Møre Trøndelag Fault Zone on the Møre Margin, along the western boundary of the Trøndelag Platform on the Vøring Margin, and further northwards beneath the Lofoten Ridge. The Lower Crustal Body Type I is about 60% thicker on the Greenland side, for both transects, and its thickness along the northern transect is more than twice that of the southern transect. These differences are consistent with sub-lithospheric interaction between the Icelandic hotspot and the continental rift / oceanic accretion system around the time of continental break-up.

High resolution 2D seismic reflection investigations in the Mora area of the Siljan impact crater, central Sweden

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The Siljan Ring impact structure is the largest known impact structure in Western Europe and of Late Devonian age. The present-day structure consists of a central dome that is about 20-30 km in diameter and that is surrounded by a ring-shaped depression. The Siljan Ring impact structure attracted the interest of the Swedish State Power Board (Vattenfall) in the early 1980s as a potential reservoir for abiogenic gas. In addition, Igrene AB (a small Swedish company) has drilled several boreholes in the southern half of the Siljan Ring for the purposes of gas exploration. In this study we focus on the southwestern part of the impact with the aim to map the Paleozoic sedimentary rocks and the subsurface structure the area. The Paleozoic successions are poorly exposed, but appear to be generally well preserved with a clear stratigraphy in some areas. Moreover, they are often influenced by impact tectonics.

High resolution seismic data were acquired in the Mora area over a period of five days during the summer of 2015 along four different profiles with a total length about 3 km. For the data acquisition a 3C MEMs-based land streamer system developed by Uppsala University was used in combination with wireless recording units. The land streamer system was designed for noisy environments and high-resolution imaging of the sub-surface. We used a Bobcat drop hammer as a seismic source. The shot spacing was 4 m with 5 hits being recorded at each shot position. After stacking the hits, conventional processing was applied to the data. Each profile was migrated and depth converted using a profile specific constant velocity for depth conversion.

The processed results show that clear reflections are present in the data, but the images are poorer where noise was present during acquisition or maximum source-receiver offset was too short. The seismic sections in the Mora area reveal a complex sub-surface geology and structure. Combined with borehole data, several potential faults with variable throw have been identified in the area. The faulting can be associated to the Caledonide orogeny to the west or to the impact itself. The thickness of the Paleozoic successions changes considerably along the profiles. Silurian rocks are thickest in the north at about 270 m and decrease to the south to be about 50 m thick. In contrast Ordovician rocks are thickest in the south and thin towards the north.

Joint geophysical characterisation of the CO2 storage site of Hontomín (Spain): magnetotelluric, seismic and well-log data.

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The first Technological Development Plant for geological storage of CO_2 in Spain is located in Hontomín (Burgos, north of Iberian Peninsula). The geophysical characterisation of the site included the acquisition of a 3D seismic reflection and a circumscribed 3D magnetotelluric (MT) survey. In this work, we combine the seismic and MT results and incorporate the available well-log data to produce a joint, integrated, interpretation of the subsurface. A complete structural model including its physical properties is constrained by the integration of the seismic reflection data and the geoelectrical model derived from the MT data. A major emphasis is dedicated to the determination of the 3D geometry of the fracture system and major faults. The combination/integration of both dataset places strong constraints on the structural and fluid flow characteristics of the existing faults, which is essential for ensuring a leak-less trap for CO_2 storage and to forecast the behaviour of the injected CO_2. The well-log data of the existing boreholes are used to derive resistivity-velocity relationships of the subsurface formations. These relationships enable a further combination of the velocity and resistivity models by computing a new 3D velocity model using the 3D resistivity model as a reference. The derived velocity model is compared to the logged and predicted velocity in the injection and monitoring wells to provide an overall assessment of the resistivity-velocity relationships. In the near surface, the derived velocity model is compared with the velocity model used for the static corrections in the seismic data. The results provide more complete information of the characteristics of the shallow subsurface, highlighting the presence of clays and water content variations. The good correlation of all the velocity models and well-logs data shows the great potential of the combined geophysical characterisation of the subsurface, in terms of its physical properties (velocity, resistivity) and structural/reservoir characteristics.

(Research supports: CGL2014-56548-P, 2009-SGR-1595, VATC: 20133830).

Mid-mantle reflectors within the oceanic lithosphere in the Pacific

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Recent seismological studies have detected seismic discontinuities within the lithosphere, which are often called mid-lithospheric discontinuity (MLD), particularly in the continental lithosphere (Rader et al., 2015). Investigation of physical property and distribution of MLD may help to understand evolution/alternation processes of the lithosphere. However, in the ocean area, there is little information about existence, distribution, depth or physical property of the discontinuities within the lithosphere.

In 2014 we conducted an active-source seismic refraction and reflection survey along an 1130-km-long line at southeast of the Shatsky Rise, Northwestern Pacific. The profile runs perpendicular to the magnetic anomalies, which indicate seafloor ages of 149 – 123 Ma (Nakanishi et al., 1992). Five ocean bottom seismometers (OBSs) were deployed and recovered by R/V Kairei of JAMSTEC. We used an airgun array with a total volume of 7,800 cubic inches, and fired it at every 200 m. Multi-channel seismic reflection (MCS) data were also collected with a 444-channel, 6,000-m-long streamer cable.

Remarkable observation in OBS records is wide-angle reflection phases (DR1) at large offsets (i.e., 150-500 km offsets). We applied the forward travel time modeling (Zelt and Smith, 1992) and the amplitude modeling (Larsen and Grieger, 1998) to determine distribution of reflectors which reflect DR1 phase. The results show that DR1 are reflection waves from thin low velocity patches which exist at the depths from 35 to 60 km from the seafloor. We interpreted that these patches correspond to the frozen melts within the oceanic lithosphere associated with ancient melts ponded around past lithosphere-asthenosphere boundary. We also observed even deeper reflection phase (DR2) at larger offsets (i.e., -870 km offsets). Travel time modeling of DR2 phase shows that depth of an interface which reflects DR2 is about 90 km deep from the seafloor, though it depends on the mantle velocity structure. This interface can be interpreted as the present lithosphere-asthenosphere boundary.

A new insight on the first Polish multi-channel seismic profiles in the Pacific Margin of Antarctic Peninsula, West Antarctica

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Extensive seismic crustal studies in West Antarctica have been made by the Polish Geophysical Expedition in the summer of 1979-1980. The expedition was organized by the Institute of Geophysics of the Polish Academy of Sciences. Whole experiment consisted of both deep seismic soundings and multi-channel seismic profiles conducted around the South Shetland Islands and the Bransfield Strait. Deep soundings results have been published numerous times during past 30 years, however MCS data were never fully processed nor published.

Collected data consisted of 10 linear seismic profiles recorded with 50 meters shot interval. Streamer was 1150 meters long with 24 channels, providing nominal fold of 12 traces per CDP. Two profiles went through South Shetland Trench(SST) while the rest of them were focused around the South Shetland Islands' shelf and the Bransfield Strait. Air gun array used was of about 34 litres capacity. The area of investigations was placed on the active edge of the Antarctic Plate: subduction zone of the South Shetland Trench, island arch of the South Shetlands and in the Bransfield Strait where few of the profiles crossed the young rift system.

Data have been processed with modern processing flow including various demultiple attempts and time migration although outdated acquisition scheme limitations could not be overcome. This expedition used one of the strongest airgun which provided more information of a deep structure of the subduction zone than similar expeditions from other countries.

Geological structure visible on our data collaborate well with other profiles going through the SST and could help understand structure of the area. Previous interpretation (Maldonado *et al.* 1994) assumed high accretionary prism (up to 5 km of thickness). Our profiles revealed a distinct reflector below the continental slope. In our interpretation whole continental slope is covered in a glacial-marine sediments while the accretionary prism is restricted to the layer below the reflector. The authors discuss different possible scenarios for the formation of accretionary prism.

In the area of Bransfield Strait, very good sediment series of glaciations and deglaciations periods have been recorded. Near the Antarctic Peninsula expedition has registered series of glacial valleys, where one of them is cut through by a volcanic intrusion, leading to the assumption that recent volcanic activities is using post glacial valleys for easier penetration of intrusions.

Origin of subcrustal reflectivity in SW Iberia: Evidences from wide-angle seismic experiments

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From 2001, the IBERSEIS and ALCUDIA controlled source experiments have sampled the lithosphere of SW Spain. Apart from providing high resolution information of the crust of the Variscan South-Portuguese, Ossa Morena and Central Iberian Zones with two ~300 km long vertical incidence transects, these projects have also imaged the lithospheric mantle. A particularly conspicuous sub-crustal reflector was first identified on the IBERSEIS wide-angle reflection transect at offsets around 180 km. This interface, seemingly featuring a positive seismic impedance contrast, was modelled as a boundary at 62-71 km depth, with a Vp increase from 8.2 km/s to 8.3 km/s. The fact that this reflector was not identified in the coincident vertical incidence dataset led us interpret it as a gradient zone. A correlation with the 'Hales gradient zone', i.e. the mantle boundary featuring the phase transition between spinel and garnet peridotites was our preferred interpretation.

The ALCUDIA experiment, later acquired to the N of the IBERSEIS dataset, also shows prominent sub-crustal arrivals. Some of them coincide with those above described regarding amplitude, travel time and offsets (180 km) and have been modelled accordingly. In addition, these reflections may also appear locally in the vertical incidence dataset at 19 s TWT, further constraining the depth at which this feature is located and supporting a sub-horizontal boundary as its origin. Deeper mantle reflectivity also identified in the ALCUDIA wide angle transect (14-15 s reduced travel time, v_{red}=8km/s) also appears in most of the six shot gathers. The depth at which this reflectivity might originate coincides with that proposed for the lithosphere-astenosphere boundary in this area and it is tentatively related to this feature.

Integration of the information provided by the IBERSEIS and ALCUDIA datasets with older data from the ILIHA project, where mantle features were identified at similar depths, allows us to map a regional scale upper mantle discontinuity in southwest Iberia and probably the base of the lithosphere. The reason why mantle reflectivity in SW Iberia is so conspicuous might be related with the nature of the boundaries, the low signal/noise ratio of the datasets or to the surface geology providing a good coupling between the ground and the stations. (Research supports: CGL2014-56548-P, 2009-SGR-1595.

Constraints on the structure of the North Anatolian Fault in the lower crust and upper mantle from teleseismic tomography

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The deep structure of continental strike slip faults is poorly understood, with published models varying from narrow (~10 km) zones of localised deformation that cross-cut the entire lithosphere, to faults that exhibit broad zones (<100 km) of ductile deformation beneath the (upper) crust. Whilst strain is typically focussed within the seismogenic layer during the pre- and co-seismic stages of an earthquake, the lower crust and upper mantle play a more prominent role during the post- and inter-seismic phases of the seismic cycle. High-resolution images of fault structure in the lower crust and upper mantle are therefore key to resolving which of the fault models are applicable, but these are currently lacking. Moreover, lower resolution regional tomographic models of continental strike slip faults are not always in agreement with each other, precluding a consistent interpretation of deep fault structure.

The North Anatolian Fault (NAF) is a major active continental strike-slip fault with a length of 1500 km and a current slip rate of 25-30 mm/yr. Historical seismic records show that it is capable of producing high-magnitude events that activate different segments; currently a sequence of events is taking place along the NAF that started in 1939 with the Erzincan earthquake and followed a westward progression to the study region, where the devastating Izmit and Düzce events occurred in 1999. The NAF poses a seismic hazard to the city of Istanbul, which is situated close to one of the two strands in which the fault splays before reaching the Sea of Marmara.

An array of 70 temporary seismic stations (Dense Array for North Anatolia, DANA) with a nominal 7 km spacing was deployed for 18 months, starting in May 2012, as part of the multi-disciplinary Faultlab project. Coupled with data from three permanent broadband stations, a large number of local and teleseismic events were recorded. A high quality subset of the recorded events was selected for teleseismic tomography. Given the nature of the array, it is possible to achieve high resolution seismic imaging in 3-D, with a resolution comparable to the 7 km station spacing. We show a new velocity model that details the structure and characteristics of the fault zone throughout the crust and upper mantle in unprecedented detail, which improves our understanding of how strike slip faults accommodate strain below seismogenic depths (15-20 km). We use the results of this study to constrain the dimensions and structure of the North Anatolian Fault in the lower crust and upper mantle.

Deep crustal structure of the UAE-Oman mountain belt from wide-angle refraction and reflection profiles

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The UAE-Oman mountains constitute a 700 km long, 50 km wide compressional orogenic belt that developed during the Cenozoic on an underlying extensional Tethyan rifted margin. The mountains are associated with significant topographic relief, large-amplitude isostatic gravity anomalies and an unusually deep flanking foreland basin. Perhaps most significantly, this orogenic belt contains the world's largest and best-exposed thrust sheet of oceanic crust and upper mantle (Semail Ophiolite), which was obducted onto the Arabian rifted continental margin during the Late Cretaceous. Although the shallow structure of the UAE-Oman mountain belt is reasonably well known through the exploitation of a diverse range of techniques, information on deeper structure remains little. Moreover, the mechanisms by which dense oceanic crustal and mantle rocks are emplaced onto less dense and more buoyant continental crust are still controversial and remain a great challenge for the Earth Science community.

In an attempt to provide new constraints on the nature of continental and oceanic crust beneath both the Semail Ophiolite and underlying crust of the UAE-Oman orogenic belt, we have carried out the first integrated seismic reflection and refraction experiment in the UAE-Oman region in July 2014. The experiment combines passive and active seismic techniques, corroborated by potential field data.

The focus here is on an active-source seismic E-W transect extending from the UAE-mountain belt to the offshore. Seismic refraction data were acquired using the survey ship M/V Hawk Explorer, which was equipped with a large-volume airgun array (7060 cubic inches, 116 liters). About 400 air gun shots at 50-second time interval were recorded on land by eight broadband seismometers. In addition, reflection data were acquired at 20 seconds interval and recorded by a 5-km-long multichannel streamer. Results presented here include an approximately 85 km long (stretching about 35 km onshore and 50 km offshore) P-wave velocity crustal profile derived by a combination of forward modelling and inversion of both diving and reflected wave traveltimes using RAYINVR software. We find ophiolite seismic velocities of about 5.5 km/s, underlain by a thin layer of slower material (about 4.5 km/s). Furthermore, the velocity model reveals a Moho depth that rises from ca 35 km in the west to ca 25 km in the east.

A poststack depth-migrated profile (about 50 km long) coincident with the offshore part of the refraction profile shows a thick sequence (up to 6 km) of seaward dipping sediments that are offset by a number of listric (normal) faults, some of which intersect the seabed and so reflect recent tectonic activity.

Azimuthal anisotropy of Rayleigh wave phase velocity beneath southeast Australia

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The Phanerozoic Tasmanides of eastern Australia is the result of prolonged accretionary growth outboard of the Archean and Proterozoic core of central and western Australia that occurred from the Early Cambrian through to the Middle Jurassic. The southern end of the Tasmanides appears to be particularly complex and may include an exotic continental block, an amalgamation of multiple orogeny parallel accretion events, a large orocline and several arc complexes, which are largely covered by Mesozoic and Cainozoic sedimentary sequences. Tomographic studies performed during the last two decades or so have greatly contributed towards defining the 3-D extent of the building blocks characterizing the Tasmanides by assuming isotropic velocity variations. Even though other studies have examined azimuthal anisotropy velocity variations in eastern Australia, they do not include Tasmania or Bass Strait, which together form one of the most enigmatic parts of the orogenic system.

In this study, we use continuous ambient noise recordings to investigate the crust beneath mainland southeast Australia, Bass Strait and Tasmania and account for the apparent azimuthal dependence of measured Rayleigh phase velocities. Data stem from 582 stations of the high-density WOMBAT transportable seismic array (station spacing varying from 15 to 50 km in Tasmania and mainland Australia respectively), which has been operating in southeast Australia since 1998 and has been progressively moved 14 times. Dispersion measurements of the Rayleigh wave were extracted from the cross-correlations of the vertical component of all station pairs, which ultimately provide path-averaged phase velocities for periods ranging 2 to 20 sec. We then inverted and mapped the inherited lateral phase velocities variations for both isotropic and anisotropic wavefield components in the same period range. Final period-dependent maps of the two results show a fairly close agreement, particularly in mainland Australia and Tasmania. Notably, we observe a strong and consistent pattern of anisotropic fast directions that are compatible with the large scale tectonic trends of the Palaeozoic orogens, as interpreted from magnetic anomaly data. However, this juxtaposition vanishes when entering Bass Strait, where we observe a conspicuous transition in anisotropic fast directions defined by a clockwise rotation of the fast axes of about 80 degrees (5 to 20 sec period). Interestingly, although the agreement with magnetic anomalies is lost here, this orientation closely correlates with the Late Miocene (6-11 Ma) maximum horizontal stress trends, which are likely to reflect frozen stress-aligned cracks in the failed rift sedimentary basins that formed during the break-up between Australia and Antarctica.

Urban reflection seismics in Whakatane city, New Zealand - detection of concealed faults using a shear-wave system

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Concealed active faults pose a significant hazard to urban infrastructure and human life. The New Zealand active fault database suggests that active faults pass beneath or within many urban areas, including for instance Auckland, Blenheim, Christchurch, Hastings/ Napier, Taupo, Wellington, and Whakatane. Major, damaging events encompass as the Mw 7.1 Darfield earthquake in September 2010 and the Mw 6.3 Christchurch earthquake in February 2011. Statistical analysis of this database shows that many faults are still missing in this catalogue.

The main objective of our study was to extend the portfolio of methods assessing earthquake hazard due to concealed active faults. Therefore, we evaluated the applicability of high-resolution shear wave reflection seismic profiling using a small vibrator source and landstreamer to locate buried faults in urban areas of New Zealand. In February 2015, a shallow seismic survey was carried out in the city of Whakatane. As first step, measurements took place at the known surface trace of the Edgecumbe Fault 30 km west of Whakatane city. As a reference we studied the near surface expression in the seismic image of this active fault including the principle shear wave propagation characteristics in the sedimentary successions, consisting of effusive rocks of the Taupo volcanic zone mixed with marine transgression units. In the second step, a survey was performed in Whakatane with the aim to locate the trace of the Whakatane fault through the city.

In total, 11 profiles of 5.7 km length were acquired with high data quality, enhanced by night operation time slots to reduce the urban noise. The seismic sections evidence concealed rupture structures of obviously different age in the shallow sediments down to 100 m depth. Between 20-40 m depth we interpret normal faults with displacements of up to 15 m, while deeper rupture structures show stronger displacements of up to 20 m. In addition to these dip slip events, indications of strike-slip activities are visible. The evaluation of all profiles with respect to the spatial extent of the imaged structures suggests that the concealed ruptures are not aligned along supposed fault lineaments or main surface structures like the Whakatane river bed. Instead, morphological surface signatures on a historic map of 1867 and LIDAR imaging favour a correlation with small topographic variations.

Despite ongoing work and not yet available drillhole calibration, the shear wave reflection seismic system has proven good applicability in urban areas that allows a revised assessment of the hazard model for the region.

Resolution and uncertainty analyses of seismic refraction models: new constrains on the deep structure of the Porcupine Basin

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The Porcupine Basin is a tongue-shaped basin SW of Ireland formed during the opening of the North Atlantic Ocean. Its history of sedimentation reveals several rifting and subsidence phases during the Late Palaeozoic and Cenozoic, with a particular major rift phase occurring in Late Jurassic–Early Cretaceous times. Lithospheric stretching factors derived from subsidence analysis (β_s) suggest that extension increases dramatically southwards. However, previous works focused on seismic reflection and refraction profiles suggested that crustal stretching factors (β_c) along the basin axis can be significantly higher than previous β_s, implying major crustal faulting and uppermost mantle serpentinisation. Constraining β_c and the processes related to the opening of the basin, such as mantle serpentinisation, will enable to constrain the tectonic response to lithospheric extension, and the thermal evolution of the basin, providing, this way, new insights on rifted margins formation.

Here we characterize the deep structure of the Porcupine Basin from wide-angle seismic (WAS) and gravity data, with especial emphasis on the nature of the underlying mantle and the geometry of the crust-mantle boundary along the basin axis. We used a joint refraction and reflection travel time inversion method to model the data and obtain a P-wave velocity (Vp) model of the crust and uppermost mantle, together with the geometry of the main geological interfaces, as the Moho. The resolution of the tomography model is then assessed by means of a checkerboard test. The semblance between the starting and recovered anomaly of each checkerboard test is calculated and used to build a resolution map of the velocity model. A Monte Carlo-type analysis has been also performed to explore the uncertainty of the model parameter and to seek optimum values for certain inversion parameters (e.g. depth-kernel scaling factor). In this case, the statistical analysis has been applied following a layer stripping strategy to provide the velocity and geometry uncertainty of each layer of the model. The results of the resolution and uncertainty analyses enable us to present a robust interpretation of the nature of the uppermost mantle and geometry of the Moho beneath the Porcupine Basin, allowing us to constrain β_c along the basin axis. This project was funded by the Irish Petroleum Infrastructure Programme (www.pip.ie).

Seismic interferometry of railroad induced ground motions: Body and surface wave imaging

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Seismic interferometry applied to 120 hours of railroad traffic recorded by an array of vertical component seismographs along a railway within the Rio Grande rift has recovered surface and body waves characteristic of the geology beneath the railway. Linear and hyperbolic arrivals are retrieved that agree with surface (Rayleigh), direct and reflected P waves observed by nearby conventional seismic surveys. Train-generated Rayleigh waves span a range of frequencies significantly higher than those recovered from typical ambient noise interferometry studies. Direct P wave arrivals have apparent velocities appropriate for the shallow geology of the survey area. Significant reflected P wave energy is also present at relatively large offsets. A common midpoint stack produces a reflection image consistent nearby conventional reflection data. We suggest that for sources at the free surface (e.g. trains) increasing the aperture of the array to record wide angle reflections, in addition to longer recording intervals, might allow the recovery of deeper geologic structure from railroad traffic. Frequency-wavenumber analyses of these recordings indicate that the train source is symmetrical (i.e. approaching and receding) and that deeper refracted energy is present althought not evident in the time-offset domain.. These results confirm that train generated vibrations represent a practical source of high resolution subsurface information, with particular relevance to geotechnical and environmental applications.

On the use of sensitivity tests in seismic tomography

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Sensitivity analysis with synthetic models is widely used in seismic tomography as a means for assessing the spatial resolution of solutions produced by, in most cases, linear or iterative non-linear inversion schemes. The most common type of synthetic reconstruction test is the so-called checkerboard resolution test, in which the synthetic model comprises an alternating pattern of higher and lower wavespeed (or some other seismic property such as attenuation) in two or three dimensions. Although originally introduced for application to large inverse problems for which formal resolution and covariance could not be computed, these tests have achieved popularity, even when resolution and covariance can be computed, by virtue of being simple to implement and providing rapid and intuitive insight into the reliability of the recovered model. However, checkerboard tests have a number of potential drawbacks, including

(1) only providing indirect evidence of quantitative measures of reliability such as resolution and uncertainty;

(2) giving a potentially misleading impression of the range of scale-lengths that can be resolved; and

(3) not giving a true picture of the structural distortion or smearing that can be caused by the data coverage.

The widespread use of synthetic reconstruction tests in seismic tomography is likely to continue for some time yet, so it is important to implement best practice where possible. The goal of this paper is to develop the underlying theory and carry out a series of numerical experiments in order to establish best practice and identify some common pitfalls. Based on our findings, we recommend (1) the use of a discrete spike test involving a sparse distribution of spikes, rather than the use of the conventional tightly-spaced checkerboard; (2) using data coverage (e.g. ray path geometry) inherited from the model constrained by the observations (i.e. the same forward operator or matrix), rather than the data coverage obtained by solving the forward problem through the synthetic model; (3) carrying out multiple tests using structures of different scale length; (4) taking special care with regard to what can be inferred when using synthetic structures that closely mimic what has been recovered in the observation-based model; (5) investigating the range of structural wavelengths that can be recovered using realistic levels of imposed data noise; and (6) where feasible, assessing the influence of model parameterisation error, which arises from making a choice as to how structure is to be represented.

Seismic depth imaging for fresh groundwater simulations at the New Jersey shelf

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The occurrence of fresh groundwater in the New Jersey shelf area can be understood by means of hydrological modelling of the seaward groundwater discharge. For this purpose, we require an accurate geological model of the upper 1000 meters of the shelf to be populated with hydrological parameters. In this first part of the study, we therefore aim to image the predominant geologic horizons by processing marine reflection seismic data that were acquired prior to the IODP Expedition 313.

In order to obtain reliable depth positions of the geologic layers, we build a geologically consistent interval velocity model from the seismic data. For this purpose, we utilize and compare different methods ranging from one-dimensional velocity inversion up to layer-based and gridded reflection tomography techniques. We combine these with Kirchhoff pre-stack depth migration to obtain high-resolution reflection images of the shelf. To further enhance the quality of these images and to amplify the geologic horizons, we conclude our workflow with the application of two different focussing migration methods, which are the so-called coherency migration and the Fresnel volume migration.

The application of these methods significantly increases the signal-to-noise ratio and facilitates the geological interpretation of the seismic images. This lays the foundation for the construction of a realistic hydro-geological model of the shelf in the next stage of the project.

New solutions to long-standing problems in seismic data acquisition and imaging

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The seismic industry has undergone somewhat of a revolution over the last 10-15 years driven by the need to image increasingly complex targets and enabled by the continued growth of available computing power.

This revolution has been due to a combination of significant advances both in seismic imaging algorithms as well as seismic acquisition methods. On the one hand, full wave imaging and inversion methods have proven necessary to solve these imaging problems. On the other hand, the shortcomings in existing data have become increasingly clear. These shortcomings relate to three distinct areas:

1. The temporal bandwidth of the seismic data. Low frequencies are critical for penetration of seismic energy to the target and robust inversion. The bandwidth (both high and low frequencies) dictates the resolution in the seismic data. The temporal bandwidth is fundamentally limited by the signal to noise ratio in the recordings and the so-called sea-surface ghost problem.

2. Sub-surface illumination. Conventional 3D marine seismic acquisition geometries result in data that is only adequately sampled along a narrow range of azimuths. Complex sub-surface imaging requires data that is richly sampled in terms of both azimuth and take off angle (i.e., offset).

3. Spatial aliasing. Seismic data is often referred to as a 5D problem (two surface coordinates for each source and receiver location as well as the time axis). Some of these dimensions are heavily aliased as for example the receiver wavefield sampling in the cross-line streamer direction in marine seismic data.

In my presentation I will show how new fundamental insights into the sampling of wavefields have overturned “conventional wisdom” and changed the game for sub-surface seismic imaging by addressing these perceived shortcomings.

The RomUkrSeis wide-angle seismic profile: preliminary results

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RomUkrSeis was a controlled source wide-angle reflection and refraction (WARR) profile acquired in August 2014. It is 675 km long, running from the East European Craton in central Ukraine southwestwards into Romania where it crosses the Carpathian Mountains, the Transylvania Basin and terminates in the Apuseni Mountains. Some 350 single component seismic recorders were used in a single deployment (1.75-2 km spacing in Romania and 2-2.25 km in Ukraine) to record seismic waves from eleven shotpoints along the profile, eight in Romania and three in Ukraine. The seismic sources were eleven chemical shot points with charge sizes 800–1200 kg every 20–65 km.

The objectives of RomUkrSeis included mapping the two-dimensional regional architecture of the Carpathian Orogen, and its foreland basin, and the intramontane Transylvania Basin. A particular interest in this regard is crystalline basement affinity and Moho disposition along the profile, which crosses the boundary zone between the Archaean-Palaeoproterozoic cratonic lithosphere of the core of the European plate and lithospheric domains accreted to it during later Phanerozoic tectonic episodes (the Palaeozoic German-Polish Caledonian and Variscan orogenies overprinted by the Mesozoic Alpine-Carpathian orogeny). Processed shot gathers will be displayed along with a preliminary velocity model and its first-order interpretation.

RomUkrSeis was acquired by a consortium of organisations led by the University of Bucharest. Financial support came from Prospectiuni, Hunt Oil of Romania, Repsol (all of whom made grants to RomUkrSeis via the Romanian Geoscience Foundation; Prospectiuni also made “in kind” contributions during fieldwork), the Institute of Geophysics of the National Academy of Sciences of Ukraine (Kiev), the Institute of Geophysics of the Polish Academy of Sciences (Warsaw) and the University of Aberdeen. Some of the seismic recording equipment was provided by the Helmholz Centre of GFZ Potsdam, Germany. The many individuals who helped in the field, mainly students and others from the University of Bucharest, but also from Prospectiuni as well as from the Kyiv and Warszawa institutes, are gratefully acknowledged.

SS Precursor Imaging of Upper Mantle Discontinuity Structure beneath the Pacific

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The depth and nature of the oceanic lithosphere-asthenosphere boundary are central to our understanding of the definition of the tectonic plates and lithospheric evolution. Although it is well established that oceanic lithosphere cools, thickens, and subsides as it ages according to conductive cooling models, this relatively simple realization of the tectonic plates is not completely understood. Old (>70 Ma) ocean depths are shallower than predicted. Furthermore, precise imaging of the lower boundary of the oceanic lithosphere has proven challenging. Here we use SS precursors to image the discontinuity structure across the Pacific using 24 years of teleseismic data. We image a sharp discontinuity (3-15% drop in shear velocity over < 20 km) in the depth range of 35 – 81 km that increase in depth with age from the ridge to 60 – 70 My according to conductive cooling along the 1100 °C isotherm. The discontinuity is imaged at 50 – 81 km depth at older ages, with no apparent age dependence. We image a relatively sharp (4% drop in shear velocity over <11 km) deeper discontinuity in the depth range of 80 – 120 km (average depth of ~100 km) with no apparent age dependence. The shallower discontinuity at 35 - 81 km depth is laterally continuous across most of the Pacific. We do not detect variation in the amplitude of the phase with back-azimuth suggesting that it is not caused by azimuthal anisotropy alone. In addition, variations in radial anisotropy from olivine lattice preferred orientation are not sufficient to explain the magnitude of the drop. Therefore, the discontinuity is likely related to a variation in hydration and/or melt. Its lateral extent and strength may suggest a relationship with the lithosphere–asthenosphere boundary. Imaging of the deeper discontinuity near 100 km is sparse, and suggests mantle heterogeneity perhaps related to complicated flow.

Ambient seismic noise and the North Sea: Can we image what lies beneath?

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The recent development of ambient seismic noise imaging offers the potential for obtaining detailed models of the crust. The resolution is largely controlled by the configuration of the seismometer network rather than by a distribution of earthquakes, which has been a limitation of traditional passive seismic imaging methods. In this approach, each station can be viewed as a "virtual source" of seismic energy that is recorded by every other station in the network. Cross-correlation of long-term recordings from station pairs reveals an empirical "Green's function" which is related to the impulse response of the medium between the two stations. Here, we present preliminary ambient noise imaging results from a recent broadband deployment on Faroe Islands, which are situated in the North Atlantic, approximately equidistant from Norway, Scotland and Iceland. The relatively small number of stations (12) means that the dataset is ideal for developing and testing the methodology that we will apply to a much larger North Sea dataset (>50 stations) in the future. In order to obtain cross-correlations with high signal-to-noise ratios, we apply phase weighted stacking, which is shown to be a significant improvement over convectional linear stacking. For example, coherent noise concentrated near the zero time lag of the linearly stacked cross correlations appears to have an influence on the dispersion characteristics beyond 10 s period, but we have managed to minimize these effects with phase weighted stacking. Furthermore, we use phase-match filtering to optimise the extraction of travel time information from surface wave dispersion analysis. We obtain group velocity maps from 0.5s to 20s period by inverting inter-station travel times using an iterative non-linear inversion scheme. These preliminary results reveal the presence of significant lateral heterogeneity in the mid-upper crust, with group velocity variations as large as 10%. Furthermore, there is some evidence of a low velocity zone in the upper crust, which may mark the base of the basalt layer. This is most clearly revealed by taking the average group velocity dispersion curve for all station pairs and inverting for 1-D shear wave velocity. The computation of phase velocity maps will hopefully verify and enhance these results, and will be followed by an inversion for 3-D shear wave speed. Subsequent application to the North Sea dataset will be challenging due to the highly attenuate nature of the crust in this region, which has previously been observed to dramatically reduce the signal-to-noise ratio of short period surface waves. However, preliminary indications are that, with the help of phase-weighted stacking, good quality empirical Green's functions can be retrieved for this large dataset.

Structure and evolution of backarc marginal rifts in Japanese island arcs

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The Japanese island arcs are marked by several deformed zones formed in late Cenozoic. They divided into two types, one is an arc-arc collision zone, such as the axial part of Hokkaido and Izu collision zone and the other is a reactivated deformation zone of back-arc marginal rift (BMR). A BMR is formed after a major opening of back-arc basin near a volcanic front away from the spreading center of a major backarc basin. BMR zones have been developed along the Sea of Japan coast of Honshu island, Japan. NE and SW Japan arcs experienced strong shortening after the Miocene backarc rifting. The amount of shortening shows its maximum along the BMR, forming a fold-and-thrust of thick post-rift sediments. The rift structure has been investigated by active source seismic investigation and earthquake tomography. The velocity structure beneath the rift basin demonstrates larger P-wave velocity in upper mantle and lower crust, suggesting a large amount of mafic intrusion and thinning of upper continental crust. Once rifting ended, thermal subsidence, and subsequently, mechanical subsidence related to the onset of the compressional regime, allowed deposition of up to 5 km of post-rift, deep marine to fluvial sedimentation. Continued compression produced fault-related folds in the post-rift sediments, characterized by thin-skin style of deformation. The syn-rift mafic intrusion in the crust forms convex shape and the boundary between pre-rift crust and mafic intrusive shows outward dipping surface. Due to the post rift compression, the boundary of rock units reactivated as reverse faults, commonly forming a large-scale wedge thrust and produced subsidence of rift basin under compressional stress regime. Large amount of convergence of overriding plate is accommodated along the BMR, suggesting that it is a weakest zone in whole arc-backarc system. The convergence between young (15 Ma) Shikoku basin and SW Japan arc produced intense shortening along the BMR along the Sea of Japan coast. After the onset of subduction along the Nankai trough (ca. 5 Ma), in the fold-and-thrust belt rate of shortening deformation of the marginal rift subsequently decreased. Due to the change in motion of the Philippine Sea plate at 2 Ma, the reverse faults in the BMR along the Sea of Japan coast of SW Japan, reactivated as strike-slip fault. The Izu-Bonin arc forms an arc-arc collision zone and forms asymmetric antiform with steep western frank. This asymmetric structure was produced by the strong deformation of the BMR of Izu-Bonin, showing another example of BMR as a weak zone.

New concepts for the plate tectonic reconstruction and the post-orogenic evolution of the North Atlantic

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Plate tectonic reconstructions of conjugate margins are dependent on many, often complicated, interpretations and assumptions about the crust and lithosphere. This includes, for example, their structure, thickness and affinity (oceanic or continental), the identification of rifted continental slivers and areas of exhumed upper mantle, and accordingly the identification of the ocean-continent transition.

We identify two geophysically and geometrically similar upper mantle structures in East Greenland and Scotland and suggest that these represent remnants of the same Caledonian collision event. We propose the concept of making plate-tectonic reconstructions in the North Atlantic by fitting these upper mantle structures together – a sub-crustal piercing point. This allows reconstructing passive margins, more independently from other, often difficult assumptions.

Specifically for the North Atlantic, this could improve the fit between the East Greenland, Norwegian and British margins. We identify a distinct sinistral offset between the two parts of the structure in Mesozoic palaeogeographic reconstructions. Removing this offset and lining up both conjugate portions, would remove extension from the Rockall Trough and tie Norway and East Greenland closer together.

Further, this sub-Moho structure may have imposed a fundamental control on major tectonic events of the North Atlantic post-orogenic evolution such as the occurrence of the Iceland Melt Anomaly and the separation of the Jan Mayen microcontinent. We suggest that this inherited orogenic structure played a major role in the control of North Atlantic tectonic processes.

Seismic spatial wavefield gradient and rotation measurements in land-seismic exploration

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Traditionally, land-seismic data acquisition is conducted using vertical-component (1C) sensors. A more complete representation of the seismic wavefield can be obtained by employing multicomponent (3C) sensors that record the full vector wavefield. If groups of closely-spaced multicomponent sensors are deployed in areal arrays , then spatial seismic wavefield gradients and rotational rates (from the curl of the particle velocity) can be estimated by differencing the outputs of the sensors. Seismic gradient and rotation data open up new possibilities to process land-seismic data. Potential benefits and applications of wavefield gradient data include local slowness estimation, improved arrival identification, wavefield separation at a local receiver group and effective noise suppression.

Using synthetic and field data, we explored the reliability and sensitivity of various multicomponent sensor layouts to estimate seismic wavefield gradients and rotations. Due to the wavelength as well as incidence and azimuth angle dependence of the sensor-group response as a function of the number of sensors, station spacing and layout, one has to counterbalance the impacts of truncation errors, random noise attenuation, and sensitivity to perturbations such as amplitude variations and positioning errors when searching for optimum receiver configurations. Field experiments with purpose-built rotation sensors were used to verify array-based rotation estimates.

Seismic wavefield gradient estimates and inferred wavefield attributes such as instantaneous slowness enable improved arrival identification (e.g., wave type and path). Under favorable conditions, seismic-wavefield gradient attributes can be extracted from even conventional vertical-component data and used to, for example, enhance the identification of shear waves. A further promising application of wavefield gradients is the removal of the free-surface effect on land-seismic recordings to obtain true amplitude and phase information of the desired upcoming wavefield (e.g., P wave) from the recorded superposition of the upcoming wave with the downgoing reflected P wave and mode converted reflected S wave.

Seismic structure of the Maranhão-Barreirinhas-Cearà margin, NW Brazil, from the MAGIC wide-angle seismic experiment

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The structure of the North-East equatorial Brazilian margin was investigated during the MAGIC (Margins of brAzil, Ghana and Ivory Coast) seismic experiment, a project conducted iby Ifremer (Institut Francais de Recherche pour l'Exploration de la Mer), UnB (University of Brasilia), FCUL (Faculdade de Ciências da Universidade de Lisboa) and Petrobras. This project focuses on the North-Western Brazilian margin and the Equatorial Atlantic Ocean bounded to the North by the São Paulo Double Fracture Zone and to the South by the Romanche Fracture Zone. It's main objective is to understand the fundamental processes which lead to the thinning and finally to the breakup of the continental crust in a specific context of a pull-apart system with two strike-slip borders.

The survey consists of 5 deep seismic profiles totaling 1900 km of marine multi-channel seismic reflection and wide angle acquisition with 143 deployments of short-period OBS's from the IFREMER pool. Three of the profiles were extended into land using land stations from the Brazilian pool at a total of 50 points. The experiment was devised to obtain the 2D structure along the profiles from tomography and forward modeling.

The analysis of the seismic dataset reveals from SW to NE 5 distinct domains oriented NW-SE that shows the evolution from unthinned continental crust to thin oceanic crust:

a) The unthinned continental crust thickness increases from 32 km in the Borborema-Ceará to 40 km in the Barreirinhas-Parnaiba province and the Ilha da Santana Platform;

b) The necking zone, where crustal thickness thins to about 10 km, is about 30 km wide at Borborema-Ceará , 50 km at Ilha da Santana, but considerably wider (>125 km) at the Barreirinhas margin at the corner of the pull-apart system, with two steps first in the upper crust then in middle/lower crust;

c) An intermediate domain, composed of the southern deep Basin II presenting 5-7 km thick sedimentary sequence (interleaved by a 0.5-1 km thick volcanic layer), and the shallower Northern basin III, extending into the São Paulo Double Fracture Zone and presenting 2.5-4.5 km thick marine sediments underlain by 2-3 km volcano-sedimentary to volcanic (lava flows) layers. The basement exhibits on all profiles a 5 km- thickness (with velocity ranging from 6.2 to 6.6 km/s). Bellow, a 2-3 km thick layer with very high velocity (7.4-7.6 km/s) and marked by reflections at the top and base is observed at Basin II. This layer is followed continuously towards the continent and joins the fourth continental layer imaged (only) beneath the Parnaiba-Barreirinhas province, but is absent bellow Basin III, and is interpreted as exhumed lower continental crust;

d) a 60 km-wide domain, bounded to the SW by a NW-SE volcanic line, that consists in a 5 km thick crust presenting 2 layers characterized by high acoustic velocity and interpreted as proto-oceanic crust and overlain by 5.5 km of sedimentary deposits;

e) a 5 km thick oceanic crust consisting of 2 layers and overlain by 5.5 km of sedimentary deposits, spanning between the two main fracture zones that fringe the Maranhão-Barreirinhas-Cearà segment.

Seismic investigations in a geothermal area in mid-southern Tuscany

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Deep geothermal reservoirs are generally characterized by high temperatures and pressures, sometimes located in hard rock environments and even close to a super-critical state. For characterization of such a deep super-critical geothermal reservoir, the imaging of the subsurface at the highest possible resolution is required to reduce the uncertainties in exploration prior to the drilling phase.

Several seismic surveys were carried out for characterization of a possible drilling target horizon within a deep super-critical geothermal reservoir in Tuscany (project DESCRAMBLE). Seismic data were acquired with 2D and 3D seismic reflection surveys as well as Vertical Seismic Profiling (VSP). The seismic data from the VSP were acquired in November 2015 and comprise zero-offset as well as far-offset VSP shot locations using airgun and vibrators as active seismic sources. This survey was complemented by simultaneous recording of the source signals by a surface network of 340 one- and three-component geophones distributed over an area of approximately 6 km x 6 km around the drill site. The processing of the recorded seismic wavefields aims at the determination of seismic velocities by traveltime tomography. The results contribute to a migration velocity model required for precise imaging and depth estimation of the geologic structures. Moreover the target horizon of the super-critical reservoir was illuminated at different angles to improve the determination of the seismic parameter contrast.

The investigation area itself is characterized by a complex geology with strong velocity contrasts, near-surface inhomogeneities and fracture zones. The target horizon can be described as permeable layers embedded in a metamorphic environment. Moreover significant topography influences the recorded seismic data and presents a challenge for conventional seismic imaging methods.

The applied processing workflow comprises signal processing to suppress the significant noise content and to remove the influence of different source signatures. Furthermore the workflow tries to circumvent the issues regarding geological heterogeneity and topography by firstly performing first-arrival tomography to derive shallow P-wave velocity models followed by the application of three-dimensional focusing prestack depth migration methods, e.g. Fresnel-Volume migration. Such migration methods are based on Kirchhoff prestack depth migration and employ the restriction of the migration operator to focus the image to the part of the traveltime isochrone which contributes to the reflection. The results obtained from the different seismic surveys allow a first structural interpretation which will be directly integrated into geological modeling of the geothermal reservoir.

Controls on faulting, earthquakes and water cycling in the Alaska subduction zone

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Subduction zones worldwide exhibit remarkable variations in seismic activity and slip behavior along strike and down dip, and many factors have been invoked to explain this variability. Here we will review new constraints on plate boundary properties and the incoming oceanic plate off the Alaska Peninsula from marine seismic reflection/refraction data and their relationship to pronounced variations in earthquake behavior in this subduction zone. We observe remarkable along-strike changes in incoming sediment thickness and plate structure and along-strike and downdip variations in megathrust reflection character that correlate with changes in seismicity, locking and earthquake rupture history.

MCS reflection and wide-angle seismic data were collected off the Alaska Peninsula in July-August 2011 on the R/V *Langseth* during the Alaska Langseth Experiment to Understand the megaThrust (ALEUT) program. This region encompasses the full spectrum of coupling: 1) the weakly coupled Shumagin Gap; 2) the Semidi segment, which last ruptured in the 1938 M8.2 event, appears to be locked at present, and 3) the Kodiak asperity, the western part of the 1964 M9.2 rupture. It also exhibits substantial variations in seismicity.

Remarkable variations in bend faulting and hydration of the subducting oceanic plate are observed along strike, which may be controlled by the relationship between the orientations of pre-existing structures in the incoming oceanic plate and the subduction zone. Significantly more bending faulting is observed in MCS profiles and bathymetry data from the Shumagin Gap, where pre-existing structures are favorably aligned, than the Semidi segment where they are oblique to the trench. Abundant bending fault enables hydration of the crust and upper mantle based on a reduction in P-wave velocity from seismic refraction data.

The thickness of sediment on the incoming plate also changes along strike. Up to 1.5 km of sediment are observed on the incoming oceanic plate in the Semidi segment, and a relatively thick and continuous layer interpreted as subducted sediment can be imaged at the plate boundary here up to ~50 km from the trench; this layer is relatively continuous, faults in the accretionary prism sole into it, and it is characterized by reduced velocities. In the Shumagin Gap, where the incoming sediment section is only 0.5 km thick and more pervasively faulted at the outer rise, a thin, discontinuous sediment layer is observed near the trench, but it does not appear to continue along the plate boundary beyond ~10 km from the trench.

These changes in bending faulting, hydration and sediment thickness correlate with variations in interplate and intermediate depth intraslab seismicity and changes in plate boundary properties at greater depths. Although the Semidi segment is locked and capable of producing great earthquakes, very little interplate and intermediate depth seismicity occurs here compared with the adjacent Shumagin Gap, which appears to be creeping and exhibits abundant seismicity. Downdip variations in the plate boundary character are also observed; a simple and bright reflection is observed at depths of ~12-25 km, ~40-100 km from the trench, within the center of the estimated locked zone. Where the megathrust appears to intersect the forearc mantle wedge, the character changes to a wide (~3-5 km thick), bright band of reflections, which we interpret to arise from a change in deformation style and/or distribution of fluids. Although the overall patterns in reflection characteristics are consistent between profiles across different segments, this transition in reflection characteristics occurs at larger distances from the trench within the Semidi segment than in the Shumagin Gap.

Extension and magmatism across the Suwanee Suture and South Georgia Basin from the SUGAR seismic refraction experiment

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The South Georgia Basin was at the center of the most recent sequence of continental collision and rifting events to shape eastern North America. It is the largest of the failed Mesozoic rift basins that formed during the breakup of Pangea, and it straddles the Suwannee Suture, which may represent the remnant of the Alleghenian suture that joined North America and Gondwana. The South Georgia Basin also lies at the center of the Central Atlantic Magmatic Province (CAMP). It is thus an excellent location to address important, unresolved questions in plate tectonics concerning the formation and rupture of continents. How does the accretion of terranes contribute to the construction of continental lithosphere, and what processes enable continental lithosphere to rupture?

Here we present new results from the SUwanee Suture and GA Rift basin (SUGAR) project, an NSF-EarthScope funded active-source seismic refraction project to image the crustal structure across these features. In March 2014, we acquired data along SUGAR Line 1, a ~325-km-long, NW-SE oriented profile that crossed the Suwanee Suture and western part of South Georgia Basin. The profile was densely instrumented with 1193 single-channel RekTek 125A seismographs ("Texans") spaced at ~250 m. The sources were 100 to 1800 lb shots spaced at ~20-50 km. In August 2015, we acquired data along SUGAR Lines 2 and 3. SUGAR Line 2 is a ~450-km-long profile spanning the eastern part of the South Georgia Basin and two possible locations for the Alleghenian suture. We deployed 1983 "Texans" spaced at 250 m and detonated fifteen 400 to 1600 lb shots spaced at ~16-50 km. SUGAR Line 3 targets the Brunswick magnetic anomaly; we instrumented this 100-km-long profile with 700 Texans spaced at 150 m and eleven 200 lb shots spaced at ~10 km. Over 68 students participated in field work for SUGAR during the two phases.

Shot gathers from all lines show clear refractions from the sediments, crust and upper mantle mantle, and wide-angle reflections from the base of the sediments, within the crust, and the base of the crust; all of these phases can be clearly correlated between shots. We have created a P-wave velocity model along SUGAR Line 1 with forward modeling and tomographic inversion of travel time picks. This model shows that the crust thins to ~33 km beneath the South Georgia Basin from ~47 km outside the basin based on receiver function results from the EarthScope SESAME project. Anomalously high lower crustal velocities (up to ~7.3 km/s) occur beneath the basin in the area of the greatest crustal thinning and may represent mafic intrusions from synrift magmatism or from CAMP. We favor the latter interpretation given that sills in this area are attributed to CAMP based on their ages. If this interpretation is correct, it suggests that much more crustal thinning has occurred beneath the South Georgia Basin than previously inferred from COCORP seismic reflection data. Although CAMP magmatism was distributed over a very large region and may have occurred after the main phase of extension in the South Georgia Basin, our interpretation suggests that magmatic intrusions in the crust were focused in regions of thinned crust and mantle lithosphere.

We will also present an initial velocity model of SUGAR Line 2, compare it with the results on Line 1, and discuss the implications for along-strike variations in the style of rifting, the volume and distribution of magmatism, and the location of the suture and its control on later tectonic and magmatic events.

New active-source seismic imaging of the Malawi (Nyasa) Rift from the SEGMeNT project

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Little is known about the controls on the initiation and development of magmatism and segmentation in young rift systems. The northern Lake Malawi (Nyasa) rift in the East African Rift System is an early stage rift exhibiting pronounced tectonic segmentation, which is defined in the upper crust by ~100-km-long border faults. Very little volcanism is associated with rifting; the only surface expression of magmatism occurs in an accommodation zone between segments to the north of the lake in the Rungwe Volcanic Province. The Study of Extension and maGmatism in Malawi aNd Tanzania (SEGMeNT) project is a multidisciplinary, multinational study that is acquiring a suite of geophysical, geological and geochemical data to characterize deformation and magmatism in the crust and mantle lithosphere along 2-3 segments of this rift.

As a part of the SEGMeNT project, we acquired a unique seismic reflection and refraction data in Lake Malawi (Nyasa) in March-April 2015. Over 2000 km of seismic reflection data were acquired with a 500 to 2580 cu in air gun array from GEUS/Aarhus and a 500- to 1500-m-long seismic streamer from Syracuse University over a grid of lines across and along the northern and central basins. Air gun shots from MCS profiles and 1000 km of additional shooting with large shot intervals were also recorded on 27 short-period and 6 broadband lake bottom seismometers from Scripps Oceanographic Institute as a part of the Ocean Bottom Seismic Instrument Pool (OBSIP) as well as the 55-station onshore seismic array. The OBS were deployed along one 270-km-long strike line and two ~40- to 50-km-long dip lines. This is the first “marine” deep penetration seismic reflection/refraction dataset acquired in any of the lakes in the East Africa Rift.

We will present preliminary data and results from seismic reflection and refraction data acquired in the lake and their implications for crustal deformation within and between rift segments. Seismic reflection data image structures up to ~5-6 km below the lake bottom, including syntectonic sediments, intrabasinal faults and other complex horsts. Some intrabasinal faults in both the northern and central basins offset the youngest sediments, indicating that they are active. These include faults in the area of the 2009 Karonga earthquakes. In the northern basin, intrabasinal faults are uniformly synthetic to the border fault, and fault spacing and fault throw decrease away from the border fault, as noted by previous studies. In the central basin, faulting patterns are significantly more complex. Velocity models created from seismic refraction data indicate significant variations in sediment thickness and velocity structure between and within the northern and central basins, as well as variations in crustal structure. We will discuss the implications of these new constraints on fault geometries and crustal structure for the distribution and style of extension in the Malawi (Nyasa) rift.

Active seismic profile in east-central Greenland. Seismic explosion sources on an ice cap.

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Controlled source seismic investigation of crustal structure below ice covers is an emerging technique. We have recently conducted an explosive refraction/wide-angle reflection seismic experiment on the ice cap in east-central Greenland. The data quality is high for all shot points and a full crustal model is modelled. A crucial challenge for applying the technique is to control the sources. Here, we present data that describe the efficiency of explosive sources in the ice cover. Analysis of the data shows, that the ice cap traps a significant amount of energy, which is observed as a strong ice wave. The ice cap leads to low transmission of energy into the crust such that charges need be larger than in conventional onshore experiments to obtain reliable seismic signals. The strong reflection coefficient at the base of the ice generates strong multiples which may mask for secondary phases. This effect may be crucial for acquisition of reflection seismic profiles on ice caps. Our experience shows that it is essential to use optimum depth for the charges and to seal the boreholes carefully.

We also present the crustal structure model in the continental part of Greenland along the profile based on the joint reflection/refraction tomographic inversion. The model shows strong lateral variations in the crustal thickness. The modeled Moho depth is changing from 39 to 47 km. The large volume of the lower most crust is observed in the central region of Greenland, while been absent in the costal region. The observed crustal structure corresponds to the transition from the younger terrane affected by the Caledonian orogeny to the stable cratonic region. Furthermore, the presence of the Icelandic plume ca. 60-40 Ma in the study area may also have a significant effect on the crustal evolution of the Greenland Caledonides and its transition to the Greenland Craton.

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Anisotropic velocity model building and imaging around the COSC-1 borehole, central Sweden

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The Scandinavian Caledonides provide a well preserved example of a Paleozoic continent-continent collision, where the surface geology in combination with geophysical data provide control of the geometry of parts of the Caledonian structure. The project COSC (Collisional Orogeny in the Scandinavian Caledonides) investigates the structure and physical characteristics of the thrust sheets and the underlying basement with two approximately 2.5 km deep fully cored boreholes in western Jämtland, central Sweden.

In 2014 the COSC-1 borehole was successfully drilled through the Seve Nappe Complex. This unit, mainly consisting of gneisses, has undergone (U)HP deformation and was ductilely transported during collisional orogeny.

A major seismic survey was conducted in and around the COSC-1 borehole to allow extrapolation of results from core analysis and downhole logging to the structures around the borehole. The survey comprised both seismic reflection and transmission experiments and consisted of three parts: 1) a high resolution zero-offset VSP, 2) a multi-azimuthal walkaway VSP in combination with three long offset surface lines, and 3) a limited 3D seismic survey.

The data from the multi-azimuthal walkaway VSP and the surface lines were used to derive a detailed velocity model around the COSC-1 borehole by inverting the first arrival travel times. The comparison of velocities from these tomography results with a velocity function calculated from the zero-offset VSP revealed clear differences in velocities for mainly horizontally and vertically traveling waves. Therefore, an anisotropic VTI model was constructed, using the P-wave velocity function from the zero-offset VSP and the Thomsen parameters ε and δ. The latter were partly calculated from ultrasonic laboratory measurements and partly obtained directly from the seismic data.

For the resulting VTI velocity model traveltimes were calculated with an anisotropic eikonal solver and served as the basis for the application of pre-stack depth migration techniques. The results of these anisotropic imaging approaches are compared to previous imaging results using only isotropic velocity models.

The overall results of the investigations are high-resolution images of the structures around the borehole. This information is vital not only for a reliable spatial extrapolation of the structural and petrophysical properties observed in the borehole away from it, but also for a improved understanding of the tectonic and geodynamic setting in the investigation area.

Ultra-deep marine seismic imaging: A voyage from BIRPS to Trans-AtlanticILAB

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British Institutions Reflection Profiling Syndicate, founded in 1981 by late Drum Matthews, pioneered the marine deep seismic imaging technique in the eighties and early nineties, and produced seismic reflection images of the continental lithosphere of unprecedented nature using industry technology. At that time, seismic industry was able to tow only a 3 km long streamer and ~3000 cubic inch source, but BIRPS was able to image structures down to 100 km depth. The BIRPS Group in Cambridge were very careful in designing the survey and towed air guns and streamer deeper, enhancing the lower frequencies, leading to deeper penetration, but that was not only the reason for their success. Most of the BIRPS surveys were in shallow water with flat seafloor and over the continental lithosphere. The shallow water environment produced multiples, but they were reverberatory in nature and could easily be eliminated using predictive deconvolution techniques. Secondly, the crystalline continental crust with very low attenuation provided excellent environment for deep seismic imaging. Other marine seismic groups working in deep water environment (e.g. ridge community) or with complex seafloor topography (e.g. subduction community), have to be content with seismic images from seafloor down to the first multiples as it was not possible to remove multiples using a 3 km long streamer. In order to remove deep water multiples, one would require a long streamer, and to penetrate deeper, one would require a large low frequency source.

As oil exploration moved in deep water in mid-nineties, industry realised the importance of using long streamers and started deploying 8-12 km long streamers. We took advantage of this development and worked with industry and were able to deploy a 15 km long streamer in 2009, the longest streamer ever deployed so far, and ~10 000 cubic inch source. In order to enhance low frequencies (down 4 Hz), we towed the streamer at 22.5 m depth and imaged structures down to 50-60 km depth after successfully removing the multiples. In order to decease the frequencies further, say down to 2 Hz, industry started developing multi-sensor streamers where pressure and displacement data could be recorded simultaneously, and also broadening the spectrum. In 2015, we deployed the Schlumberger's newest technology, IsoMetrix, containing four sensors at 0.76 m interval along a 12 km long streamer. The streamer was deployed at 30 m, and an array of 48 guns with a total volume of 10170 cubic inch was towed at 15 m. The objective of this experiment, called TransAtlanticILAB, was to image the lithosphere-asthenosphere boundary down 100 km. The data are still be being processed, but the initial on-board processing indicate the presence a reflection at 22 s, ~70 km below the seafloor.

In this talk, I will summarise my 25 years experience on ultra-deep seismic imaging starting from BIRPS up to TransAtlanticILB, and my interaction with industry during this voyage showing some important results.

A strategy for seismic full waveform of ultra-long streamer seismic data from offshore central Sumatra

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Seismic full waveform inversion (FWI) is a power full method to determine physical property of the subsurface from seismic data. The method was initially developed by Tarantola in eighties and is based on minimising the difference between observed data and synthetically calculated data, iteratively in a least-squares sense. Although Tarantola had a promising start, the results were not much better than prestack depth migration results. This was due to the fact that Tarantola was using near offset reflection data, the inversion of which is a linear problem, and the first iteration of FWI is migration. We realised this problem and started including wide-angle data (reflection and refraction both) that allowed us to invert intermediate wavelength structures, leading to a global solution to the inverse problem.

In parallel, Pratt and collaborators also realised the importance refraction arrivals, and inverted one frequency at a time, leading to an efficient implementation of FWI in the frequency domain providing velocity information for pre-stack migration. Industry identified the potential of this approach and extended it to 3D acoustic media. However, the application of the method was limited to first refraction events that arrive only at limited far offsets, and hence its application to academic problems also remained very limited. Secondly, the presence hard seafloor in oceanic environment, where S-wave velocity contrast could be very large, the acoustic approximation led to erroneous results.

To overcome the above problems, we developed a downward continuation (DC) algorithm that re-datum both sources and receivers to the seafloor, bringing out the first refraction arrivals close to zero offsets up to the maximum streamer length. Instead of acoustic, we used full elastic waveform inversion technique that can model S-wave velocity correctly in the subsurface.

We have applied this approach to data sets from the Sumatra subduction zone, which is one of the most seismically active zone on Earth. In the last one decade alone, it has hosted three Mw>8.4 great earthquakes (2004, 2005, 2007) along with 2010 tsunami earthquake. The data was acquired using a 15 km long streamer towed at 22.5 m water depth and a 9600 cubic inch air gun source, providing frequencies down to 2.5 Hz, extremely important for FWI. The water depth varied from 50 m to 5000 m, but the DC provided data refraction arrivals from 0 to 10-13 km. We performed FWI in four steps: (1) FWI of refraction DC data, (2) FWI of critical/post-critical reflection/refraction DC data, (3) FWI of pre-critical DC data and finally (4) FWI of pre-critical surface seismic data. This strategy allowed us to image velocity structures down to 8 km below the seafloor at 30-50 m resolution, providing information about active faults, fluid content along the faults, nature of the plate interface, and leading to important discoveries, such as the presence of gas released from the mantle wedge after 2007 great earthquake and a 50-m thick high velocity layer above the megathrust. In this talk, I will summarise our strategy for FWI and highlight some fundamental results obtained using the FWI.

The Parnaíba Basin WARR, Brazil

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The Parnaíba Basin is an intracontinental Palaeozoic sag basin, roughly circular in shape, occupying a 660,000 km2 area of northern Brazil. It is tectonic contact with the Amazon and São Luis cratons to the west and north respectively. It has an erosive contact to the east and south, overlying the Borborema and São Francisco Craton-Tocantins provinces respectively. The covered basement of the Parnaíba Basin, near its eastern border, is cut by the Transbrasiliano lineament. In order to detail the architecture of the Parnaíba Basin and its basement and to better understand the genesis of intracontinental basins, BP promoted a multidisciplinary research programme on the Parnaíba Basin called PABIP that involves partnerships between Brazilian and British universities and other organisations. The Parnaíba WARR (Wide Angle Reflection and Refraction) profile is one element of a number of geological, geochemical and geophysical studies comprising PABIP.

The WARR line is an E-W, 1,200 km long profile crossing the basin and its western and eastern limits, approximately following the path of the PABIP deep seismic reflection profile, which was acquired in 2013 and published in 2015. Thirty-six short-period three-component seismic stations were deployed along the refraction transect in August 2015, covering (mainly) the extremes of the line and the western and eastern limits of the basin. The objective was to complement the analysis of the WARR data with receiver function results. These stations worked in continuous mode until January 2016. Another six hundred one-component stations were installed along the profile in September-October 2015 and, during four nights, twenty-two shots, consisting of 1.5 tonnes of explosives each, were detonated.

The refraction data have been pre-processed and are of very good quality. The three-component stations have only recently been recovered and the data are under analysis. A preliminary model of the disposition of the Moho interface under the PABIP profile from the three-component station receiver functions and a preliminary image of crustal velocity distribution obtained by a tomographic inversion of first arrivals on the one-component stations will be presented and compared to the crustal model derived from the published deep seismic reflection profile.

Shear wave identification on vertical component seismic data by wavefield gradient analysis

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An extensive amount of data for land seismic exploration is still recorded with single-component geophones, measuring ground motion in the vertical direction only. Such recordings provide only incomplete information on the propagating wave field and make it difficult to identify and isolate shear (S-) wave modes, for which the wave polarization is expected to be mainly in the horizontal plane.

Here we propose a methodology that facilitates the identification of shear waves on vertical component seismic data recorded at the Earth's free surface. The method is based on the analysis of estimates of apparent horizontal phase velocities and rotational ground motions, both obtained from the spatial derivatives of the vertical component of the wavefield recorded at the free surface. The wavefield gradients are estimated by a finite-difference approximation using the recordings of adjacent geophones. Shear waves can be identified based on their lower apparent phase velocities and higher amount of generated rotational ground motion relative to the P-wave arrivals. Theoretically, the concept can be extended from the receiver-side to the source-side, yielding the possibility to create a virtual shear wave source from arrays of closely-spaced vertical impact sources at the Earth's surface. Such measurements could further facilitate the isolation of shear waves from vertical component data.

We illustrate the effectiveness of our methodology by showing how, for the first time, S-wave information could be extracted from the over 40-year-old active seismic data set collected on the lunar surface during the Apollo 17 mission. The resultant first near-surface S-wave velocity model aids in the geological interpretation of the shallow lunar crust and is of considerable importance for effective seismic imaging of the Moon's deep interior. We anticipate that, in a similar fashion, valuable S-wave information can be extracted from other vintage seismic data. In particular, we expect the methodology to be beneficial for shear-wave velocity model building and characterization of the complex near-surface zone.

The GEORIFT 2013 wide-angle seismic profile, preliminary results

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The GEORIFT 2013 deep seismic sounding (DSS) experiment was carried in August 2013 on territory of Belarus and Ukraine in wide international co-operation. The aim of the work is to study basin architecture and the deep structure of the Pripyat-Dnieper-Donets Basin (PDDB), which is the deepest and best studied Palaeozoic rift basin in Europe. The PDDB locates in the southern part of the East European Craton (EEC) and crosses in NW direction the Sarmatia, the southernmost of three major segments forming the EEC. The long PDDB was formed by Late Devonian rifting in the arch of the ancient Sarmatian shield. During the Late Devonian, rifting, associated with domal basement uplift and magmatism, was widespread in the EEC from the PDDB rift basin in the south to Eastern Barents Sea in the north.

The GEORIFT 2013 runs in NW direction along the PDDB and crosses the Pripyat Trough and Dnieper Graben separated by Bragin uplift of the basement. The total profile length was 675 km: 315 km on the Belarusian territory and 360 km in Ukraine. The field acquisition included 14 shot points (charge 600-1000 kg of TNT) every ~50 km (7 shot points in Belarus and 7 in Ukraine), and 309 recording stations every ~2.2 km. The data quality of the experiment was good, with visible first arrivals as far as up to 670 km (minimally up to 300 km). We present preliminary model of the structure to the depth of 60 km. Ray-tracing forward modelling (SEIS83 package) was used for the modelling of the seismic data. The thickness of the sedimentary layer ($V_p < 6.0$ km/s) changes along the profile from 1-4 km in the NW, through ~5 km in the central part, to 10-13 km, in the SE part of the profile. In ~350-450 km distance range, an updoming of the lower crust (with Vp of ~7.1 km/s) to ~25 km depth is observed. Large variations in the internal structure of the crust and the Moho topography were detected. The depth of the Moho varies from ~47 km in the northwestern part of the model, to 40 km in central part, and to ~38 km in the southeastern part of the profile. The sub-Moho velocities are ~8.25 km/s. Second, near-horizontal mantle discontinuity was found in the northwestern part of the profile at the depth of 50-47 km. It dips to the depth of ca. 60 km at distances of 320-370 km, similarly as on crossing EUROBRIDGE-97 profile (Thybo et al., 2003).

Seismic reflection profiling of the Baza sedimentary basin (Betics, Southern Spain)

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The Baza Basin is an intra-mountain evaporitic basin in Southern Spain. It is the largest of the Late Neogene continental basins of the Betic Cordillera. During the last 7 million years the basin alternately was flooded and fell dry. Therefore, up to 2.5 km thick lacustrine and ancillary continental deposits are found which provide an unique archive of climatic changes and paleo-climatic events.

Plans exist to analyze the sedimentary record with regard to the paleo-climate in the Mediterranean as well as on a global scale within a scientific drilling project. In preparation for such future drilling activities, controlled-source seismic measurements were used to investigate the structure of the Baza Basin and to find local zones of neo-tectonic deformation bounding the basin to the west (Baza fault).

In October 2013 a seismic reflection experiment was carried out in the center of the Baza Basin. A net of three 2D seismic profiles was arranged crossing the basin and the bounding fault system. A vibroseis source (two vibrators with 200 kN peak force each) was used with a source point spacing of 60 m along each of the 18 km long profiles. Eight sweeps with a frequency range of 8-100 Hz were conducted at each source point. The seismic wave field was recorded by a cable-free acquisition system of more than 330 continuously operating digital data recorders. The receivers were spread along the currently active profile with a spacing of 20 m. They were moved in a roll-along configuration to mainly cover the near-field offsets of the source points. The seismic data of the three profiles were conventionally processed so far. Tomographic inversion of the first arrivals (P-waves) provide additional information.

The seismic images show the asymmetric basin geometry. At least three seismic units are revealed which can be related to marine and continental (lacustrine) sediments. Several faults of the Baza fault system (bounding the basin to the West) can also be identified. Moreover, further faults are found in the center of the basin, however, only few of them reach the surface.

New crustal thickness estimates of the Australian continent using virtual deep seismic soundings

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Australia is a complex amalgamation of both Precambrian and Phanerozoic crustal terranes. Archean blocks in the west are separated by Proterozoic orogeny, and central Australia also exhibits accretion of a number of Proterozoic domains through EW-trending suture zones. A number of seismic initiatives have been instigated across the continent to better understand the detailed connection at depth between these contrasting geological regions. Here, we present new crustal thickness estimates using the virtual deep seismic sounding (VDSS) method for broadband station WRAB (Warramunga) and the NS-oriented BILBY network. The large data volume afforded by WRAB shows a high signal-to-noise ratio SsPmp phase across the 30°-50° epicentral distance range, along with other prominent direct and reverberated crustal phases. Crustal thickness estimated from the VDSS data are in the region of 43 km, in good agreement with previous estimates. Results from the 25 station BILBY transect also see distinct crustal thickness variations between adjacent terranes, varying from ~39 km within the Archean Gawler craton to ~52 km beneath the Proterozoic Musgrave block. Estimates correlate well with adjacent active source studies in several localities, but also deviate by as much as 8km in others.

Moho and magmatic underplating in continental lithosphere

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Underplating was originally proposed as the process of magma ponding at the base of the crust and was inferred from petrologic considerations. This process not only may add high density material to the deep crust, but also may contribute low density material to the upper parts of the crust by magma fractionation during cooling and solidification in the lower crust. Separation of the low density material from the high-density residue may be a main process of formation of continental crust with its characteristic low average density, also during the early evolution of the Earth. Despite the assumed importance of underplating processes and associated fractionation, the available geophysical images of underplated material remain relatively sparse and confined to specific tectonic environments. Direct ponding of magma at the Moho is only observed in very few locations, probably because magma usually interacts with the surrounding crustal rocks which leads to smearing of geophysical signals from the underplated material. In terms of processes, there is no direct discriminator between the traditional concept of underplated material and lower crustal magmatic intrusions in the form of batholiths and sill-like features, and in the current review we consider both these phenomena as underplating. In this broad sense, underplating is observed in a variety of tectonic settings, including island arcs,wide extensional continental areas, rift zones, continental margins and palaeo-suture zones in Precambrian crust. Wereview the structural styles of magma underplating as observed by seismic imaging and discuss these first order observations in relation to the Moho.

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Seismic structure of the crust in Eurasia

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We present a compilation of Moho topography and crustal structure in the area encompassing most of Europe, Greenland, Siberia, the North Atlantic Ocean and the Arctic shelves (EUNAseis and SibCrust models, Tectonophysics 2013). Our new, high resolution, continent-scale crustal model is based solely on seismic profiles and RF models published since 1960, which makes it applicable to potential field modelling. The database represents a major improvement in coverage and resolution with a sample interval of 50 km or less. It includes information on the depth to Moho, thickness and average P-wave velocity of five crustal layers (sediments, and upper, middle, lower, and lowermost crust) and Pn velocity. For each of the crustal parameters included in the compilation, we discuss uncertainties associated with theoretical limitations, regional data quality, and arising from interpolation.

We provide an extensive summary of the tectonic and geodynamic evolution of the region and discuss the origin of crustal heterogeneity and processes of crustal evolution in the Precambrian cratons of Europe and Siberia, and major Phanerozoic basins, orogens, and rift zones. We conclude that for all tectonic settings there are significant variations in depth to Moho and crustal structure, essentially controlled by the age of the last major tectono-thermal event. We demonstrate that generally-adopted global averages of crustal parameters are incorrect for any particular tectonic setting in Europe and in Siberia, and conclude that we cannot define a "typical cratonic" crust. We show that relative thickness of the upper-middle crystalline crust (Vp<6.8 km/s) and the lower (Vp>6.8 km/s) crust is indicative of the crustal origin, i.e. oceanic, transitional, platform, or extended crust. Continental rifting generally thins the upper-middle crust without changing the average Vp. Thinning of the lower crust during rifting is less significant and generally occurs without significant change in lower crustal average Vp, suggesting a complex interplay of magmatic underplating, gabbro-eclogite phase transition and delamination. The Barents Sea shelf differs from rifted continental crust in structure of the crystalline crust and average Vp velocities, indicating that processes other than rifting have also been involved in its evolution.

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Lithosphere structure and topography around the North Atlantic Ocean

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Major seismic data acquisition has recently taken place in several areas around the North Atlantic Ocean. Scandinavia has now been fully covered by broad-band seismology with a nominal station spacing of 60 km by the MAGNUS and ScanArray projects. Crustal scale controlled source seismic projects have covered southern Norway and the Polar region. Until recently, seismic surveys in Greenland were only carried out near the coasts, where the crustal structure is affected by oceanic break-up. New data acquisition has provided seismic data in central-eastern Greenland including the ice sheet. The data was acquired by 24 broadband (BB) onshore stations, partly on the ice cap, over a period of 3 years and as a refraction seismic profile on the ice cap by a team of six people during a two-month long experiment in summer of 2011.

We present models of the seismic structure of the upper mantle and crust based on the new data from Scandinavia and Greenland. The crust is approximately 35 km thick with two main layers and relatively low velocity (<6.7 km/s) in southern Norway, even in regions with high topography, whereas it is 45-50 km thick and includes a high-velocity lower crust (>6.9 km/s) in Sweden. Upper mantle velocities are low (~7.9 km/s) in S Norway and high (~8.2 km/s) in Sweden.

In Greenland our crustal model, constrained by seismic refraction and receiver functions, shows a decrease in crustal thickness from ~50 km below the centre of Greenland to ~40 km at the edge of the ice cap and ~20 km at the coast in the eastern part of the study area. High velocity lower crust (Vp 6.8 – 7.3 km/s) is only observed in Central Greenland. Receiver Function inversion indicates relatively low seismic velocities in the upper mantle for this cratonic area and a thin transition zone which indicates high temperatures throughout the lithosphere.

The origin of the pronounced circum-Atlantic mountain ranges in Norway and eastern Greenland, which have average elevation above 1500 m with peak elevations of more than 3.5 km near Scoresby Sund in Eastern Greenland, is unknown. The abrupt crustal thickening in Scandinavia is related to addition of a high-velocity (and high density) lower crust which is not the case in Greenland, where sharp eastward crustal thinning takes place around the highest mountains. We discuss the implications of these new observations for topography in relation to densities of the crust and uppermost mantle. Our new results on the crustal structure indicate that crustal isostasy alone cannot explain the topographic variation in the region, such that other phenomena, including possible dynamic processes must be active in the area.

Seismic reflection and refraction imaging of the Parnaíba cratonic basin, North-East Brazil

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Cratonic sedimentary basins are characterized by their sub-circular shape, long-lived (>100 Myr) subsidence, shallow marine/terrestrial sediments that young towards the centre of the basin and exhibit little internal deformation, and thick seismic lithosphere. Despite the recognition of > 30 worldwide, the paucity of geological and geophysical data over these basins, means their origin remains enigmatic. In this study, we present results from crustal scale seismic imaging beneath the Parnaíba cratonic basin and its surrounding cratons, NE, Brazil. These data include a recently acquired 1400 km long seismic reflection profile recorded to 20 s TWTT and five wide-angle reflection/refraction receiver gathers located near the centre of the profile. These gathers contain reflection events as deep as 13 s TWTT at offsets of up to 100 km. Complementary to these data are gravity and magnetic field measurements, which were acquired at a spacing of 1 km along the regional profile and well log data from > 40 wells within the basin.

Across the regional profile, our reflection data reveals three distinct crustal blocks that are characterised by differing seismic facies and are separated by steep crustal-scale fault zones. From west-to-east these are the Amazonian/Araguaia, Parnaíba and Borborema blocks. In the west, within the Amazonian/Araguaia block, the Moho is imaged at 12.6–13.6 s TWTT, which, assuming a simple 1D velocity model for the crust and further constrained by gravity modelling, suggest depths of ~ 40.5—43.5 km. A package of upper crustal reflectivity appears folded and dips modestly eastward. This corresponds to ophiolitic metasedimentary rocks of the Araguaia group, emplaced above the Amazonian craton during the Brasiliano orogeny. These terminate against the crustal-scale Araguaia Fault Zone, east of which a ~ 300 km section of the Parnaíba block appears seismically opaque, until a prominent, 300 km long, mid-crustal reflection (MCR) appears near the centre of the basin. A potential Moho reflection is also visible beneath the MCR at 12.4–13.1 s TWTT (~ 40–42 km depth) similar to the depths resolved beneath the adjacent cratons. A low-fold stack of the wide-angle receiver gathers shows that the crust below the MCR is characterized by a ~ 4 s TWTT package of anastomosing reflections and gravity modelling suggests that the MCR represents the upper surface of a high-density (+140 kg m^{-3}) lower crustal body, that we believe may be of magmatic origin. This section terminates against the crustal-scale and steeply eastward dipping Transbrasiliano shear zone. This marks the juxtaposition of the Borborema block, which is characterised by extensive east dipping and subhorizontal events, interpreted as shear zones, that terminate at a strong Moho reflection that deepens from 12.0 to 13.8 s TWTT (~ 36 to 44 km depth) towards the basin.

Finally, we use our crustal structure interpretations as constraints for basin subsidence modelling and conclude that, although cooling of a thick (180 km) lithosphere following prolonged rifting (~ 65 Myr) can provide a good fit to the tectonic subsidence curves, the basin cannot be due to rifting alone as this does not account for the observed gravity anomaly and predicts too thin a crust (~ 34 km). Other processes must therefore be involved. The thicker than expected crust suggests warping due, for example, to far-field stresses or basal tractions. Another possibility, which is structurally compatible with our seismic interpretation, is a dense magmatic intrusion in the lower crust that has thermally loaded and flexed the crust in order to create accommodation space for the basin.

Local earthquake P-wave tomography at Mount St. Helens with the iMUSH broadband array

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We deployed 70 broadband seismometers in the summer of 2014 to image the seismic velocity structure beneath Mount St. Helens (MSH), Washington, as part of a collaborative project called imaging Magma Under St. Helens (iMUSH). Our goal is to illuminate the MSH magmatic system, using active- and passive-source seismology, magnetotellurics and petrology. Details of the velocity structure, coupled with other geophysical and geologic data, can help constrain the geometry and physical state of any bodies of melt beneath the volcano. The broadband array has a diameter of ~100 km centered on MSH with an average station spacing of 10 km, and will remain deployed through summer 2016. It is augmented by dozens of permanent stations in the area. We determine P-wave arrival times using Antelope software and incorporate permanent network picks for the region. There were more than 400 useable local events during the first year of iMUSH broadband recording, which to date have provided over 11,000 arrival times, with the number growing rapidly. The local events include 23 active shots that were set off in the summer of 2014 as part of the iMUSH experiment, which recorded with good signal-to-noise ratios across the entire array. Direct raypaths from local earthquakes and active shots reach 15-20 km depth beneath MSH. We use the program struct3DP to iteratively invert travel times to obtain a 3-D seismic velocity model and relocate hypocenters, computing travel times using a 3-D eikonal-equation solver. We intend to expand our analysis to include S-wave arrivals from active shots and local events, teleseismic arrivals to help constrain lower crustal seismic velocities, and potentially double-difference tomography methods. Our model interpretations will benefit from comparison and/or integration with other portions of the iMUSH experiment, such as active-source and ambient noise tomography, receiver functions, magnetotellurics, and petrology.

Structure and early evolution of the northern Gulf of Mexico: constraints from marine seismic refraction data

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Plate tectonic reconstructions of the Atlantic Ocean and surrounding continental masses indicate that the Gulf of Mexico opened in the Jurassic between Texas and the Yucatan block. Since the crystalline basement of the Gulf of Mexico lies deep beneath carbonate platforms, salt structures, and other sedimentary strata, we have few direct geological clues to the rifting history of this ocean basin. However, the gravity and magnetic data suggest that rifted continental crust along the northern and southern margins is flanked by ocean crust in the central Gulf.

The 2010 GUMBO study was carried out by the University of Texas Institute for Geophysics to investigate the nature of the northern continent-ocean boundary of the Gulf of Mexico. We used ocean-bottom seismic refraction data to construct an image of the seismic velocity structure along four profiles from the coast to the deep Gulf basin. The seismic transects in the west offshore Texas and Louisiana lie across the large and deep Louann salt basin. Seismic reflection data along two profiles in the eastern Gulf of Mexico offshore Alabama and Florida show much thinner salt layers, which is consistent with the idea that rifting was progressing from west to east as the evaporates were deposited.

The seismic velocity structure across the northwestern Gulf of Mexico margin offshore Texas shows strong lateral crustal heterogeneity beneath the shelf and slope. The thinned crust is consistent with large-scale extensional faulting and moderate amounts of syn-rift magmatism before continental breakup. In contrast, high compressional seismic velocities (> 7.2 km/s) are imaged in the thick lower crust of the northeastern Gulf of Mexico, which can be interpreted as extensive syn-rift magmatism and underplating, common features of volcanic rift margins. The Proterozoic, Laurentian continental lithosphere of central Texas may have been too thick at the onset of rifting (>100 km) to let magmatic diking control the extension in the northwest. In contrast, the continental lithosphere of the northeastern Gulf of Mexico may have been thinner, such that magma-assisted rifting formed a volcanic margin here later in the Jurassic.

Spatial gradient-based wavefield separation of multicomponent land seismic data

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The acquisition of multicomponent seismic array data on land not only provides recordings of the particle motion in three dimensions but also allows extracting the spatial gradients of the seismic wavefield across a rolling subaperture of closely spaced stations; this can be achieved by, for example, differencing the outputs of adjacent receivers. The full value of such estimates has hardly been realised and exploited to date in land seismic exploration and could potentially change the way multicomponent seismic data are acquired and processed. A promising application using wavefield gradient data is demonstrated here by up/downgoing wavefield separation of land seismic data.

Land seismic data acquired at the Earth's surface are superimposed recordings of the upgoing (incident) wave (P or S) and the two downgoing waves (the pure mode reflection and the mode-converted reflection). Hence, the composite ground motion differs in apparent direction and polarization to the incident wave. Linearly polarized upgoing S-waves at angles of incidence greater than, say, 30 degrees, can even have the resultant particle trajectory describing some three-dimensional figure. Mitigating the problem of wavefield interference at the free surface in order to retrieve true amplitude and phase information for subsurface characterisation is a longstanding problem in land seismic exploration. Traditionally, multicomponent seismic data interpretation is based on the assumption that P-waves appear on the vertical component, whereas S-waves appear on the horizontal component sensors. However, this only holds for vertical angles of incidence.

We propose an algorithm that removes the free surface effect for a wide range of incidence angles by up/down wavefield separation based on the elastodynamic representation theorem. The technique makes use of spatial wavefield gradient estimates from local receiver groups of densely spaced stations; this is in contrast to techniques (e.g. beam forming) requiring long baseline acquisition arrays. The derived filters to isolate the upgoing waves are based on first and third order horizontal derivatives of the recorded wavefield components, scaled by frequency and the local P- and S-wave velocities. Our method suppresses the downgoing reflected and downgoing mode-converted wavetypes from surface recordings and does not rely on a single arrival assumption. Synthetic data tests highlight that highly accurate amplitude and phase information of the upgoing wavefield can be recovered within the range of incidence angles accounted for by the filter expansions by incorporating the extra information contained in spatial wavefield gradients.

SH-wave reflection seismics as tool for investigating near-surface subrosion structures and faults

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Subrosion is a term for underground leaching of soluble rocks and is a global phenomenon. It involves dissolution of evaporites due to the presence of unsaturated water, fractures and faults. Fractures and faults are pathways for water to circulate and to generate subsurface cavities. Depending on the leached material and especially the dissolution rate, different kinds of subrosion structures evolve. The two end members are collapse and depression structures and they represent a dangerous geo-hazard if they occur in urban areas. Subrosion is a natural process, but it can be enhanced by anthropogenic manipulation of the aquifer system by extraction of saline water. To develop a comprehensive model of near-surface subrosion structures, reflection seismics is one of the methods further developed by the Leibniz Institute for Applied Geophysics.

The study areas are located in the cities of Bad Frankenhausen and Schmalkalden in Thuringia, Germany. Most of the geological underground of Thuringia is characterized by Permian deposits affected by leaching. Bad Frankenhausen is situated in northern Thuringia directly south of the Kyffhäuser mountain range at the Kyffhäuser Southern Margin Fault. This major fault is one of the main pathways for ground- and meteoric waters.

2014 and 2015 eight shear wave reflection seismic profiles were carried out in the urban area of Bad Frankenhausen, while three profiles were measured in the countrified surroundings. Altogether ca. 3.6 km were surveyed using a landstreamer with horizontal geophones as receivers and the hydraulic vibrator MHV 4S and the electro-dynamic micro-vibrator ELVIS as sources. The surveys measured in the densely built-up medieval center of Bad Frankenhausen required special equipment and configuration, e.g. a streamer with separate parts each containing 24 geophones for manual handling. The surveys carried out in the countrified surroundings are located parallel to previously measured P-wave profiles enabling the comparison of both seismic sections. Individual data processing was applied to each profile in order to improve the signal-to-noise ratio and the resolution by using e.g. a frequency-wavenumber filter and spectral balancing.

The analysis of the seismic sections revealed old covered and young near-surface subrosion structures which indicate that the leaching processes that started during the Tertiary are still ongoing. The reflection patterns indicate heterogeneous near-surface geology, with lateral and vertical variation of dis-/continuous reflectors, small-scale fractures and faults. The fractures and faults also serve as additional pathways for the circulating water and the deposits are partly subsiding along these features, resulting in the formation of depression and break-in structures in the near-surface. Diffractions in the unmigrated sections indicate voids in the subsurface that develop due to longtime subrosion processes. Variations of the traveltime, absorption and scattering of the seismic waves are also visible. The SH- and P-wave sections match very well, but for the analysis of shallow near-surface subrosion structures SH-waves have to be preferred due to the higher resolution.

In spring 2016, four additional profiles are scheduled at the filled-up sinkhole in Schmalkalden, southern Thuringia. A comparison of collapsed and uncollapsed sinkhole areas may provide further clues on seismic attributes or characteristics indicating subrosion.

The leaning church tower of Bad Frankenhausen, Germany – Characterization and detection of subrosion-controlled unstable zones and structures

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The underground leaching of soluble rocks, e.g. evaporates, is a global phenomenon. The contact with unsaturated water and the presence of fractures and faults which allow the water to circulate drive this natural process called subrosion. It can be enhanced by anthropogenic manipulation of the aquifer system and by extraction of saline water. Depending on the leached material and the parameters of the generation process two main types of subrosion structures evolve in the subsurface, collapse and depression structures. Due to rapid growth of urban areas towards zones affected by subrosion a detailed knowledge of these structures and the generation processes is important. In order to characterize and detect subrosion-controlled unstable zones and structures, near-surface lithological and structural parameters were determined by utilizing high-resolution shear-wave reflection seismics.

The study area is located in the city of Bad Frankenhausen in northern Thuringia, Germany at the Kyffhäuser Southern Margin Fault. Most of the geological underground of Thuringia is characterized by Permian deposits, and the major fault is one of the main pathways for the circulating ground- and meteoric waters that leach the Permian deposits. The most famous expression of the subrosion in the region is the leaning church tower in the medieval center of Bad Frankenhausen whose current inclination even exceeds the inclination of the leaning tower of Pisa.

2014 and 2015 eight shear wave reflection seismic profiles were carried out around the leaning tower and in the surrounding city area. The densely built-up area and the variable ground conditions e.g. unpaved soil, asphalt and a staircase required special equipment and configuration. Altogether ca. 1 km were surveyed using a horizontal micro-vibrator as source and horizontal geophones in SH-configuration attached to a landstreamer as receivers. The landstreamer was specially adapted for the limited space around the tower by separating it into three parts for manual handling. The described complex situation of the investigation area and varying survey conditions required individual data processing of each seismic data set as well. Two of the most important processing steps were a frequency-wavenumber filter in order to eliminate noisy frequencies and harmonic distortions and spectral balancing for an improved resolution.

The analysis of the seismic sections revealed structures associated with the continued subrosion of the Permian deposits. Lateral and vertical variations of the reflection patterns and the seismic velocities suggest very heterogeneous near-surface geology. Discontinuous reflectors and small-scale scarps and depression structures indicate a strongly fractured subsurface. Diffractions in the unmigrated sections are hinting at the presence of cavities proven by drillings. Other features are the increased scattering of the seismic waves and the reduced shear modulus. The last one is an indicator of the low near-surface underground stability. Additionally, a southward-dipping fault was found, located directly northward of the church. This is suggested as main pathway for the water that is leaching the Zechstein formations below the church.

Imaging the earth's interior with virtual sources and receivers

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Imaging of seismic reflection data is usually based on the assumption that the seismic response consists of primary reflections only. Multiple reflections, i.e. waves that have reflected more than once, are treated as primaries and are imaged at wrong positions. There are two classes of multiple reflections, which we will call surface-related multiples and internal multiples. Surface-related multiples are those multiples that contain at least one reflection at the earth's surface, whereas internal multiples consist of waves that have reflected only at subsurface interfaces. Surface-related multiples are the strongest, but also relatively easy to deal with because the reflecting boundary (the earth's surface) is known. Internal multiples constitute a much more difficult problem for seismic imaging, because the positions and properties of the reflecting interfaces are not known.

Imagine one could place seismic sources and receivers at any desired position inside the earth. Since the receivers would record the full wave field throughout the subsurface, this would give the required information about the structures and properties of the reflecting interfaces. Although in reality one cannot place sources and receivers anywhere inside the earth, it appears to be possible to create virtual sources and virtual receivers at any desired position. For this purpose we derived 3D Marchenko-type equations, which relate reflection data at the surface to Green's functions between virtual sources and virtual receivers anywhere in the subsurface. Based on these equations, we derived an iterative scheme by which these Green's functions can be retrieved from the reflection data at the surface and an estimate of the direct waves between the subsurface positions and the surface.

This methodology involves some major steps beyond standard seismic interferometry. With seismic interferometry, virtual sources can be created at the positions of physical receivers, assuming these receivers are illuminated isotropically. The 3D Marchenko method does not need physical receivers at the positions of the virtual sources. Moreover, it does not require isotropic illumination: to create omnidirectional virtual sources and receivers anywhere inside the earth, it suffices to record the reflection response with physical sources and receivers at the earth's surface only.

The retrieved virtual responses form an ideal starting point for accurate seismic imaging and monitoring, without artefacts caused by wrongly imaged multiple reflections. Other potential applications of the 3D Marchenko method are the prediction of the propagation of microseismic signals through an unknown complex subsurface,

- improved source imaging in time-reversal acoustics,
- improved 'classical' interferometric Green's function retrieval,
- prediction of primary reflection data from the full reflection response,
- etc.

Current research involves the extension of the 3D Marchenko methodology to vectorial elastodynamic and electromagnetic wavefields.

Deep structure of the Porcupine Basin using seismic refraction

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The Porcupine Basin is a narrow V-shaped failed rift basin of Permo-Triassic to Cenozoic age, with the main rifting phase in the Late Jurassic to Early Cretaceous. It is located offshore SW Ireland. As the basin is approximately only 150 to 200 km wide, it provides an ideal location for the study of hyper-extended crustal structures, from margin to margin, and the process of rifting.

A previous study using basin subsidence analysis shows increasing stretching factors from less than 1.5 to the north to more than 6 to the south. A ridge feature, the Porcupine Median Ridge (PMR), has been identified in the middle of the southernmost part of the basin. During the last three decades, this ridge has been successively interpreted as a volcanic structure, a diapir of partially serpentinised mantle, or a block of continental crust. Its nature still remains debated today. The interpretation of the nature of the PMR is critical for both (1) academic research: to understand the final stages of the rifting of the basin; and (2) oil and gas industry: to improve the understanding of the thermal evolution of the basin for potential resources.

In this study we use seismic refraction profiles acquired across the northern and southern Porcupine Basin to derive P-wave velocity models using tomography modelling, following a layer-stripping strategy. We use coincident seismic reflection profiles and gravity modelling to help interpret the seismic velocities. Thus, we image the deep structure of the basin, the geometry of the continental crust thinning, and the PMR.

We show (1) an asymmetric crustal thinning, implying some simple shear during the extension, (2) a wider zone of ultra-thin crust in the South (~ 90 km) than in the North (~ 30 km), with thinning factors up to 6 in the North and up to 10 in the South, (3) a low velocity mantle, with velocities < 7.5 km/s, together with ultra-thinned crust, implying up to 20% upper-mantle serpentinisation, and (4) velocities of 5-5.7 km/s in the PMR, associated with a high velocity zone in the sedimentary sequence. This observation argues in favour of an igneous nature of this ridge and associated features.

The project is funded by Petroleum Infrastructure Programme (PIP).

Resolving the crustal velocity structure across the Orphan Basin, offshore Newfoundland, Canada, using a combination of vintage and new refraction/wide-angle reflection data

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The SIGNAL (Seismic Investigations off Greenland, Newfoundland and Labrador) 2009 cruise was undertaken by the Geological Survey of Canada (GSC) and the Geological Survey of Denmark and Greenland (GEUS), with scientific contributions from Dalhousie University, to collect refraction/wide-angle reflection (RWAR) profiles as part of each country's continental shelf program under UNCLOS (United Nations Convention on the Law of the Sea) Article 76. Of the five profiles collected, Line 1 extended from the Bonavista Platform off Newfoundland, across the Orphan Basin, to Orphan Knoll and beyond into oceanic crust. The line followed the same track as an earlier seismic refraction line from the GSC (line 84-3) from which a velocity model for Orphan Basin had been produced. The ocean-bottom seismometer (OBS) locations along the SIGNAL line were chosen to complement the earlier GSC line and to extend the line further toward land and seaward, as well as to improve the station coverage. By combining the results from both surveys, a total of 38 OBS were used for the velocity modelling, improving the resolution of the final model.

The final crustal velocity model across Orphan Basin shows thinned continental crust (15 to 20 km thick) beneath most of the basin with thinner crust (10 km thick) immediately outboard of the Bonavista Platform. Such a thinning had previously been suggested based on gravity modelling that was used to extend the velocity model for GSC 84-3 landward. This thinning was interpreted as a failed rift zone and the results from the SIGNAL cruise are consistent with that interpretation. Seaward of the failed rift, the velocity structure of the thinned continental crust is generally uniform over 250 km toward Orphan Knoll. Immediately outboard of Orphan Knoll, the crust thins to 8 km and exhibits a velocity structure consistent with oceanic crust. Velocities resolved for the uppermost mantle are typical for unaltered mantle and range between 7.8 and 8 km/s, confirming that serpentinized mantle does not appear to be present beneath this part of the Orphan Basin.

The absence of serpentinized mantle beneath the Orphan Basin, in contrast with what has been observed for the basins on the conjugate Irish margin, has rheological implications for the tectonic evolution of the basin and of the underlying lithosphere. Serpentinization of the upper mantle requires crustal-scale faults along which seawater can come into contact with the mantle. A broadly distributed zone of crustal extension beneath the Orphan Basin may have prevented the development of deep fractures reaching beyond the lower crust, although the mechanisms by which this can be achieved in the presence of hyperextended continental crust remain to be explained.

Regional implications of a continuous 55-million year record of transient mantle convective activity beneath North Atlantic Ocean

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In the North Atlantic Ocean, a mid-ocean ridge bisects the Icelandic mantle plume and provides a window into its temporal evolution. V-shaped ridges of thick oceanic crust observed south of Iceland are thought to record pulses of upwelling within this plume. Specifically, excess crust is thought to form during the quasi-periodic generation of hot solitary waves triggered by thermal instabilities in the mantle. Here we use regional seismic reflection profiles to show that V-shaped ridges have formed over the past 55 million years providing the longest record of plume periodicity of its kind. Two of these profiles were acquired along flowlines that traverse the entire oceanic basin. The sedimentary pile together with the sediment-basement interface are imaged. We find evidence for minor, but systematic, asymmetric formation of crust, due to migration of the mid-ocean ridge with respect to the underlying plume. We also find changes in periodicity: from 55 to 35 million years ago, the V-shaped ridges form every 3 million years or so and reflect small fluctuations in plume temperature of about 5-10 degrees C; from 35 million years ago, the periodicity changes to about 8 million years and reflects changes in mantle temperature of 25–30 degrees C. At present, a V-shaped ridge is migrating southwards along the Reykjanes Ridge. At the spreading axis, this ridge demonstrably influences earthquake activity, normal fault geometry and trace elemental geochemistry. We suggest that long-term changes in periodicity are probably caused by perturbations in the thermal state at the plume source, either at the mantle-transition zone or core–mantle boundary. The planform of the Icelandic plume, the geometry of the V-shaped ridges, and the interaction of the mid-oceanic ridge with plume flow all imply that this plume is the largest on Earth with a buoyancy flux of ~20 Mg/s. Our results have significant implications for the oceanographic, sedimentary and epeirogenic evolution of the North Atlantic region. First, plume-related vertical motion of the Greenland-Iceland-Scotland oceanic gateway appear to have controlled overflow of Northern Component Water, the ancient precursor of North Atlantic Deep Water. Secondly, this gateway control can be shown to have moderated deposition of the Bjorn, Gardar and Eirik contourite drift deposits. Thirdly, distal plume activity has played an important role in the regional uplift of Scotland and western Norway which sit on top of anomalously hot asthenospheric channels emanating from the centre of the plume on Iceland.

Lower crustal intrusion on North Atlantic rifts from seismic refraction, seismic reflection and passive microseismics

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Lower crustal intrusion of basaltic melts during rifting have played a pivotal role in the structure of the North Atlantic continental margins because melting was enhanced by the presence of an underlying mantle plume. This continues to be the case under Iceland, where the mid-Atlantic Ridge is elevated above sea level by the Iceland mantle plume and enhanced melting creates up to 35 km of crust on the rift.

We first show how the percentage of magmatic intrusion on the rifted continental margins can be constrained from the seismic velocity structure deduced from seismic refraction experiments using dense arrays of ocean bottom seismometers. The intrusions create a high-velocity lower crustal layer. The composition and hence the seismic velocity of the intrusive igneous rocks are controlled by the temperature of the underlying mantle from which they were generated: hotter mantle creates higher velocity igneous rocks. We show that when interpreting the temperature of the parent mantle from the lower crustal velocities it is crucial to recognise that the high-velocity lower crustal layer is a mixture of pre-existing country rock (with generally lower seismic velocities) and new intruded igneous rock rather than an underplated layer with 100% new igneous rock.

We next show seismic reflection images across the Faroes continental margin that show both surface basaltic flows as seaward dipping reflectors and lower crustal intrusive sills that cut across the dipping fabric of the country rock into which they intrude.

Lastly, we show how we have caught lower crustal intrusion in the act beneath the northern volcanic zone of Iceland. Swarms of earthquakes occur 20 km below the surface in the normally ductile crust in the vicinity of Askja volcano, on the rift in north-east Iceland. The earthquakes are inferred to be the result of melt being injected into the crust as it moves from one sill to another. Moment tensor solutions show that most of the earthquakes are opening cracks accompanied by volumetric increases. This is consistent with the failure causing the earthquakes being by melt injection opening new tensile cracks. Faults at the tips of sills act to focus melt transport between sills and so must be an important method of transporting melt through the lower crust towards the surface.

Evolution of young oceanic crust formed at the Costa Rica Rift in the Panama Basin, an overview of the OSCAR project

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We are exploring the interaction between the young oceanic crust and the overlying ocean in the Panama Basin using geophysical, geological and oceanography data. Our geophysical dataset provides critical information for building a comprehensive model of young oceanic crust from zero-age at the Costa Rica Ridge axis to 6 Ma at ODP borehole 504B. Seismic data were collected in several configurations. 3D seismic data were collected over two 35 x 35 km^2 areas, one centred at the ridge axis and the other at borehole 504B; 2D profiles, using a 4.5 km long multichannel streamer oriented in the spreading direction connect the two 3D grids. To the west of the ridge segment, a 2D profile was collected across the Ecuador fracture zone. Additionally, 75 ocean-bottom seismographs (OBS), and 12 magnetotelluric (MT) instruments were deployed. Closely spaced heat flow transects were measured along several profiles and we collected a suite of oceanographic data throughout the survey area. Underway geophysical data consists of swath bathymetry, gravity and magnetic data.

We present seismic reflection data from profiles both parallel to and perpendicular to the spreading direction. These images reveal changes in magmatic accretion and faulting over the last 6 Ma, possibly indicating fluctuations in magma supply; variable sediment deposition and deformation. In the spreading direction these images can be used to infer stress conditions. These data also reveal the complex structure of the adjacent Ecuador fracture zone, with its associated pull-apart basins.

A 2D velocity-depth model along the primary 330 km north-south profile, from ridge-axis to 6 Ma crust was created from forward and inverse traveltime modelling of phases identified on OBS data. By incorporating wide-angle multichannel streamer data from our two-ship, synthetic aperture acquisition together with traditional wide-angle ocean-bottom seismograph data we are able to constrain the structure of the upper oceanic crust. Our results show a long-wavelength trend of increasing seismic velocity and density with age, and a correlation between velocity structure and basement roughness. Increased basement roughness leads to a non-uniform distribution of sediments, which we hypothesise influences the pattern of hydrothermal circulation and ultimately the secondary alteration of the upper crust.

A combination of the complementary wide-angle and normal incidence seismic datasets and their individual models act as a starting point for joint inversion of seismic, gravity and MT data. The joint inversion produces a fully integrated model, enabling us to better understand how the oceanic crust evolves as a result of hydrothermal fluid circulation and cooling, as it ages from zero-age at the ridge-axis to 6 Ma at borehole 504B.

This research is part of a major, interdisciplinary NERC-funded research collaboration entitled: Oceanographic and Seismic Characterisation of heat dissipation and alteration by hydrothermal fluids at an Axial Ridge (OSCAR). Collaborating institutes: Durham University, Newcastle University, National Oceanography Centre, UCL, University of Oxford, GEOMAR, Virginia Tech, Oregon State University, Universidad Nacional de Colombia, Woods Hole, Universidad de Costa Rica, Instituto Oceanografico de la Armada – Ecuador.

Seismic structure of the crust in Eurasia

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We present a new digital seismic crustal structure model of the Neoarchean North China Craton and surrounding orogeny belts. All available seismic profiles, complemented by receiver function interpretations of crustal thickness, were used to establish the four layered (sedimentary cover, upper crust, middle crust and lower crust) model. This model, defined on a 0.25° × 0.25° grid, estimates Moho depth, internal structure of the crust (thickness of four layers and average P wave velocity of crystalline crust) and the Pn velocity of study area. The crust is thin in the east (30 km), much thinner than the global average for cratonic crust of 40-42 km, which may be caused by reworking of the crust during the Paleozoic and late Cenozoic. The average Moho depth of the western part is 42-44 km which is in consistent with previous models and global average. The sediments cover is 2-5km in thick and typical thicknesses of the upper, middle, and lower crust are 16-24 km, 10-22 km, and 0-6 km, respectively. The crystalline crust have average P-wave velocity ranges from 6.28 km/s in the northeastern part as well as the southern of the central North China Craton to 6.42 km/s in the western thicker crust, which still includes a lower crustal layer. The velocity in the uppermost mantle is very heterogeneous with Pn values ranging from 7.8 km/s to 8.3 km/s. The extremely low Pn velocities may be caused by the Phanerozoic reworking of the Archean lithosphere around Tanlu Fault Zone and the emplacement of late Mesozoic and Cenozoic basalts at the northern and central part of the Trans North China Orogen. With low heat flow and thick crust, high Pn-velocity appears at the Ordos basin. The Moho depth of the Sulu-Dabie-Qiling-Qilian orogenic belt ranges from 31km to 51km and show strong correlation with the thickness of three layers in the crystalline crust.

Seismic evidence of the Tan-Lu fault zone in Bohai Sea of eastern China from P-wave tomography

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The Tan-Lu fault zone is a huge tectonic belt in eastern China. It extends over 3000 km long and passes through the Bohai Sea from the Shandong peninsula in the south to the Liaodong peninsula in the north. Originating from the collision of the North China block with the South China block in Indosinian period, the fault zone had experienced strike-slipping, extensional, compressional deformation and magma intrusions since Mesozoic Era. It is thought to be a continental-scale fault zone that penetrates the crust into the upper mantle. The Bohai Sea links the northern and southern segments of the Tan-Lu fault zone. Its shallow crust is covered by Cenozoic basins and bounded by a series of basement faults. Some faults may be connected to the Tan-Lu fault zone in the deep crust. Geophysically, the Tan-Lu fault zone is a Bouguer gravity boundary that separates negative anomalies in the east and positive anomalies in the west. On the magnetic map, the northern Bohai Sea is characterized by a NNE-trending positive anomaly zone. This magnetic zone becomes scattered in the southern Bohai Sea, with approximately NWW-trending anomalies parallel to the Zhangjiakou-Penglai fault zone. Seismically, most earthquakes are distributed in the southern Bohai Sea, including the Ms7.4 event in 1969; very few of them took place in the northern Bohai Sea.

To determine the relationship between the deep structure of the Tan-Lu fault zone and local tectonic activity, we used seismic tomography to construct a three-dimensional P-wave velocity model for the crust and upper mantle of the Bohai Sea. The data were collected from existing seismic stations around the marine area. Compared to previous tomographic studies, the crust and uppermost mantle of the Bohai Sea are well imaged with good resolution. A strong heterogeneity is observed in the crustal structure of the Bohai Sea, which shows P-wave velocity variations correlated to tectonic activity on the Tan-Lu fault zone and the Zhangjiakou-Penglai fault zone. A low-velocity sediment layer in the shallow crust and high-velocity layers in the deep crust, with no low-velocity zones in the lower crust, characterize the structure of the northern and central Bohai Sea. These features suggest a stable structure that corresponds to low earthquake activity in the northern Bohai Sea. At the same time, the Tan-Lu fault zone is truncated in the southern Bohai Sea by the NNW-trending Zhangjiakou-Penglai fault zone. Tectonic activity since the Holocene Epoch has made the crustal structure in this area very complicated and is a primary cause of frequent seismic activity. Additionally, low average velocities are observed in the deep crust and upper mantle of the Bohai Sea, which are likely to be related to mantle upwelling beneath the North China Craton. We suggest that hot material from the upper mantle intrudes into the lower crust through the Tan-Lu fault zone to form a high-velocity layer after cooling. This high-velocity layer may strengthen the crust-mantle boundary and lessen seismic activity on the fault zone.

Tectonic history of Median Tectonic Line in Japan from its birth to present activity suggested by seismic profiling

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Median Tectonic Line (MTL) in Southwest (SW) Japan is one of the largest and most significant faults in Japanese Islands. It separates the Inner and Outer Zones of SW Japan, which are characterized by presence and absence of Cretaceous igneous activities, respectively. It was originated as a part of a great left-lateral strike-slip fault system along the eastern margin of Paleo-Asian Continent in Cretaceous Period, associated with Kurosegawa Fault Zone in SW Japan, Tanakura and Hatagawa-Futaba Faults in Northeast Japan and Central Sikhote-Aln and Partizansk Faults in Far-east Russia (Yamakita and Otoh, 2000). It is now active as a right-lateral strike-slip fault with some normal or reverse dip-slip component in a new plate configuration after the middle Miocene opening of Japan Sea. We review and summarize its tectonic history suggested by seismic profiling.

From the last decade of 20th century, some seismic profiling studies were carried out across MTL in western Kii Peninsular (Yoshikawa et al., 1992), Shikoku (Ito et al., 1996, 2009) and offshore eastern Kyushu (Yusa et al., 1992). These studies revealed that the fault plane of MTL is not vertical but dipping northward in middle angles in spite of its main strike-slip displacement. It may have originated from existing landward-dipping weak surfaces in accretionary complexes under condition of highly oblique subduction. This geologic structure well explains the Cretaceous tectonics around MTL, i.e. the uplift of high P/T Sambagawa Metamorphic rocks in the foot wall and the formation of the strike-slip sedimentary basin of the Izumi Group in the hanging wall, in combination with a hypothesis of arc-parallel stretching and thinning in a fore-arc region caused by passing of a subducting oceanic ridge along a trench.

In eastern terminal part of SW Japan, the structural trends, including the strike of MTL, largely bend from usual ENE-direction to NNE because of the collision against the Izu-Bonin arc in middle Miocene. Seismic profiling across Southern Japanese Alps showed that MTL in this part has a nearly vertical attitude and truncates the geologic structures of both sides at high angles (Ito et al., 2010), while it generally has middle-angle attitudes concordant with those, especially with that of the Outer Zone, in other part in SW Japan. MTL in this part is considered to be the northern extension of Akaishi Tectonic Line, which was newly formed by the collision and truncated the original MTL.

Many "active faults" were densely recognized as normal faults in the northern side of MTL in inland and offshore areas in eastern Kyushu by topographical and shallow seismic profiling studies. Recent reprocessing of old deep seismic profiling data and gravity analysis, however, demonstrated that these "active faults" do not cut the basement but do only surficial sediments. They are passive and secondary faults formed in an extensional regime in the hanging wall near a releasing bend of MTL, which is the true active fault with strike-slip movement.

Unraveling overtone interferences in Love-wave phase velocity measurements by radon transform

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Surface waves, including both Rayleigh and Love waves, contain fundamental mode and higher modes, which could interfere with each other. Different modes of surface waves have different sensitivities to the Earth's structures. If they are not properly separated, the inverted Earth structures using surface waves could be biased. The dispersion curve of fundamental-mode Rayleigh wave group velocity is separated from overtone dispersion curves. However, the group velocities of fundamental-mode and overtone Love waves are very close to each other, and fundamental-mode and overtone Love waves severely interfere with each other, especially for waves propagating through ocean basins.

In this study, we apply linear radon transform (LRT) to synthetic seismograms and real seismograms from the USArray to demonstrate the effectiveness of LRT in separating fundamental-mode Love waves from higher modes. Analysis on synthetic seismograms shows that two-station measurements on reconstructed data obtained after mode separation can completely retrieve the fundamental-mode Love-wave phase velocities. Results on USArray data show that higher mode contamination effects reach up to ~10 per cent for two-station measurements of Love waves, while two-station measurements on mode-separated data obtained by LRT are very close to the predicted values from a global dispersion model of GDM52, demonstrating that the contamination of overtones on fundamental-mode Love-wave phase velocity measurements is effectively mitigated by the LRT method and accurate fundamental-mode Love-wave phase velocities can be measured. In addition, LRT can be also applied to array-based measurements. Using US Array as an example, we divide the large array to a series of mini arrays with several hundred kilometer aperture, and then apply LRT to surface waves recorded at each mini array to separate the fundamental modes.

Dual-vergence structure from multiple migration of widely spaced OBSs

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The detailed structure of the Cascadia basin and frontal ridge region was obtained using data from several widely spaced ocean bottom seismometers (OBS). Mirror imaging was used in which the downgoing multiples (mirror signal) are migrated as they provide information about a much larger area than imaging with primary signal alone. Specifically, Kirchoff time migration was applied to hydrophone and vertical geophone data. Our results indicate remarkable structures that were not observed on the northern Cascadia margin in previous single-channel or low-fold multi-channel seismic (MCS) data. Results show that, in these water depths (2.0 - 2.5 km), an OBS can image up to 5 km on either side of its position on the seafloor and hence an OBS spacing of 5 km is sufficient to provide a two-fold migration stack. Results also show the top of the igneous oceanic crust at 5 - 6 km beneath the seafloor using only a small airgun source (120 cu. in.). Specifically, OBS migration results clearly show the continuity of reflectors which enabled the identification of frontal thrusts and a main thrust fault. These faults indicate the presence of a dual-vergence structure for the first time on this margin. These kinds of structures have so far been observed in < 0.5% of modern convergent margins and could be related to horizontal compression associated with subduction and low basal shear stress resulting from overpressure. Furthermore, fault geometry analyses indicate that the total amount of shortening accommodated due to faulting and folding is about 3 km, which suggest that thrusting would have started at least ~ 65 ky ago.

Traveltime and waveform tomography of shallow seismic data

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A new version of frequency-dependent traveltime tomography (FDTT) specifically designed for shallow seismic data is presented. It is a nonlinear, iterative approach with recalculated travel paths at each iteration, and the calculation of frequency-dependent total traveltimes, as opposed to delays times. The new approach involves two modifications to conventional traveltime tomography: (1) the calculation of frequency-dependent traveltimes using wavelength-dependent velocity smoothing (WDVS), and (2) the corresponding "fat" sensitivity kernels that arise from using WDVS. Results show that the former modification is essential to achieve significant benefits from FDTT, whereas the latter is optional in that similar results can be achieved using infinite-frequency kernels. The long seismic wavelengths relative to the total path lengths and the typical size of heterogeneities in the shallow subsurface mean the improvements over ray theory tomography are significant. The benefits of FDTT are demonstrated using conventional minimum-structure regularization techniques to address model nonuniqueness. For realistic synthetic data, the estimated FDTT models are more accurate than the corresponding infinite-frequency-derived models. For synthetic and real data, the FDTT models are better starting models for the highly nonlinear problem of waveform tomography (WT), implemented here using the existing 2-D frequency-domain method of Pratt (1999).

Both 2-D and 3-D applications of FDTT to real P- and SH-wave data from several shallow studies yield estimated minimum-structure models that contain more structure, consistent with prior information about the survey sites, than the corresponding infinite-frequency-derived models. The real data applications include the problem of detecting a known buried tunnel on Rice campus that is less than one wavelength in size, and imaging shallow sediments in 2-D and 3-D at two different groundwater contamination sites, one with over 100 wells for ground truthing, the other with only one well. The FDTT model of the tunnel is used as a starting model for WT of P- and SH-wave data. Applications of FDTT without regularization demonstrate the ability of the WDVS-derived sensitivity kernels to provide a natural smoothing of the velocity model and thereby allow the data alone to determine the final model structure.

Frequency-dependent traveltime tomography of dense 3-D seismic data from a shallow groundwater contamination site

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In 2012 Rice University carried out a shallow seismic survey in Rifle, Colorado, USA. The groundwater in the area was contaminated by vanadium and uranium ore-processing operations between 1924 and 1958. The purpose of the seismic survey is to provide constraints to improve hydrogeologic modelling. The 3-D P-wave survey covers an area ~96 m x 60 m. There were 2158 shots recorded by 384 channels yielding 828,672 traces. A propelled energy generator (PEG-40Kg) provided data with good signal-to-noise ratio (SNR), but a low dominant frequency of ~60 Hz. First arrival times were determined using a combination of manual picks and a cross-correlation scheme for intervening traces. Variable pick uncertainties were assigned based on SNR to upweight and downweight good and bad data, respectively. The overall good SNR allows for precise picking and an average uncertainty of 0.65 ms was assigned based on an analysis of all reciprocal time differences. Unreliable triggering (up to ~7 ms), but the desire for close data fitting, necessitated solving for shot time corrections during travelitme tomography, creating a mixed-parameter inverse problem; all final models provide an RMS misfit of 0.65 ms. Several steps in addition to conventional 3-D traveltime tomography were applied to exploit the dense data and precise picking to overcome the data's low frequency content, while avoiding the more demanding waveform and computational requirements of 3-D waveform inversion: (1) Stacking the arrival-time-corrected traces in offset bins for 1-D reflectivity modelling to constrain discontinuities; (2) reduced smoothing regularization based on the local angular distribution of raypaths; and (3) a frequency-dependent form of traveltime tomography in which wavelength-dependent velocity smoothing accounts for the data's frequency content. Model assessment methods include inversions of different data subsets and checkerboard tests with random shot errors. Results include an isovelocity surface that represents the major boundary in the study area: the top of the Wasatch formation.

A scan statistics approach to picking seismic wave arrival times using arbitrary-sized sliding windows

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Seismic wave arrival times are often used in seismic tomography to constrain the structure of the Earth's interior. Inaccurate identification of arrival times can seriously degrade the quality of recovered structure. Various automated and semi-automated methods have been applied to the problem of phase detection, including cross-correlation of seismic waveforms and the short and long term average ratio method. Scan statistics is an emerging field which can be applied to the problem of event detection. In this study, we will examine its application to the detection of teleseismic phases.

The objective of scan statistics is to detect whether a subset of data points (for example in a time series) deviates from the population in a way that is statistically significant. This is done with the use of arbitrary-sized sliding windows, which progressively analyses the dataset to locate regions with high statistical significance. It is observed that seismic wave arrivals are not easily seen in a raw seismogram, due to the presence of coda noise and the oscillatory nature of the seismogram.

A seismic wave arrival detection method is presented based on a scan statistics approach. In order to minimise the influence of the noise in a seismic wave arrival, we convert the time series into rank-space. In other words, every point in the time series is assigned a value from one (minimum amplitude) up to the total number of points in the time series (maximum amplitude). The time series is now independent of the underlying noise distribution since the noise is now distributed over the whole range of data and consequently, there is no need to model the noise. In this work it is shown that by computing the spectrogram and integrating over teleseismic frequencies, the scan statistics event detection approach can be used reliably on seismic wave arrivals. The approach for detecting the events, is based on examining the sum of the values inside a sliding window. First, a probability distribution is generated using a Monte Carlo approach in which we repeatedly select w (where w is the window length) unique integers in the range [1,N] (where N is the length of the time series) and compute their sum. The total number of times each sum occurs in the simulation divided by the total number of Monte Carlo samples yields the probability of each sum occurring. A probability distribution depends only on the number of values being added together and the length of the time series, so a new probability distribution needs to be computed for each distinct choice of w and N. A problem which arises from following this approach is that not all time series have the same length. This is addressed by splitting the time series into subintervals with equal length. To avoid losing events occurring at the boundaries an overlap between the subintervals is used. During implementation, as the sliding window moves across the time-series, the p-value is obtained by comparing the sum of values in the sliding window with the probability distribution; statistically significant events will have a low p-value. By following this method and plotting the probability surface (contour plot of probabilities for all starting point and window size pairs) some interesting results are revealed. The probability surface plot indicates clearly the event regions and they are suitable for further investigation using an optimisation method. Powell's optimisation method is used on the event regions to identify minima, which correspond to the occurrence of an event. In combination with this method, random restarts are also applied. Random restarts alleviate the dependence of the resulting minima on the original search vector of the local optimisation method. An agglomerative clustering algorithm is applied after random restarts to detect similar instances of the same solution and to find the best solution for the event region.

Using the aforementioned procedure P-wave arrival times were tested and reliably found with a low rate of false positives.

3-D crustal structure beneath the Costa Rica Rift from seismic refraction tomography

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Variability in the competing processes of magmatic accretion and tectonic extension at mid-ocean ridges shapes the varied structure of the oceanic crust. Despite rapidly increasing knowledge in this field in the past 30 years, the accretion and structure of oceanic crust is still poorly understood, especially the top 2-3 km or 'layer 2', which is often oversimplified. Using seismic refraction tomography, we determine the velocity structure of the oceanic crust at an intermediate spreading ridge axis and integrate our model with reflection, bathymetry and gravity data to understand the nature of crustal accretion.

The Costa Rica Rift is situated on the eastern arm of the Cocos-Nazca spreading centre, in the Panama Basin. It is a 140 km long ridge segment bounded by the Ecuador fracture zone to the west and the Panama fracture zone to the east. The Costa Rica Rift is spreading at an intermediate rate with slight asymmetry indicated by a half rate of 30 mm yr-1 to the north and 36 mm yr-1 to the south. We deployed 25 ocean-bottom seismographs (OBS) in a 5 x 5 grid covering an area 35 x 35 km2 over the ridge axis. A total of ~58,000 first-arrival refraction events were picked from the OBS records and used to invert for the P-wave velocity structure.

Here we present the 3D velocity-depth model from first-arrival seismic tomography (FAST) modelling. A low velocity region 30 x 10 km and extending up to 2 km below seafloor may indicate recent magmatic accretion. This region coincides with the section of the ridge axis that is expressed as a saddle-shaped dome rather than a valley. A P-wave velocity increase of ~1 km s-1 is observed between this on-axis region and a similar sized region immediately to the south. We hypothesise this abrupt increase in velocity to be a result of secondary off-axis volcanism and/or hydrothermal alteration. This 3D velocity-depth model can be compared with results obtained from a second 3D grid acquired 300 km to the south over ~6 Ma crust and to the 330 km 2D profile that links the two grids to understand the history of crustal accretion at the Costa Rica Rift.

This research is part of a major, interdisciplinary NERC-funded research collaboration entitled: Oceanographic and Seismic Characterisation of heat dissipation and alteration by hydrothermal fluids at an Axial Ridge (OSCAR). Collaborating institutes: Durham University, Newcastle University, National Oceanography Centre, UCL, University of Oxford, GEOMAR, Virginia Tech, Oregon State University, Universidad Nacional de Colombia, Woods Hole, Universidad de Costa Rica, Instituto Oceanografico de la Armada – Ecuador.

Reconstruction of the crust and lithosphere beneath southeast China from ambient noise tomography and receiver functions

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In southeastern continental margin of China the Southeast China and its adjacent (17°N-37°N, 100°E-125°E) is formed by Yangtze Craton and the Cathasyia block. Under the combined influence of the subductions of the Pacific plate and the Philippine plate, the shallow and deep structure is very complicated in Yangtze Craton, Gan-Xiang-Gui block, Jiangnan foldbelt. Here we reconstruct the main features of the structure of the crust and upper mantle from receiver functions and ambient noise tomography in the area in order to understand the block's boundary and it's modality of the convergence and collision process. Ambient seismic noise tomography, is becoming an increasingly well established method to estimate surface wave speeds. Compare with the traditional earthquake tomography, the method can be applied to regions with sparse, inhomogeneously distributed, or even non-existed seismicity, and produces reliable measurements. Receiver function method is an effective tool for imaging the crust and upper mantle structure in the continent. The image quality is strongly influenced by the spatial density of stations. Reconstructing and resampling seismic wavefields can improve the resolution and provide more accurate image using limit data from seismic network. We collect continuous seismograms, spanning the periods from 2009 to 2011 recorded by 580 permanent broadband stations. After making preprocess, we apply the cross correlation technique to ambient noise data. Using the automatic frequency-time analysis, Rayleigh wave group velocity dispersion curves are measured. A set of dispersion curves in the period range from 15 s to 40 s with SNR >10.0 are considered along 67999 paths. A 2-D surface-wave tomography estimates the average lateral resolution with about 100km and calculates lateral variation sets in group velocity distribution at the periods from 15 s to 40 s. At the short period of 15 s, the upper Yangtze Craton shows obvious high velocity anomalies (3 %— 6 %) while the low velocity anomalies (-6 %— -3 %) lies in Qinling-Dabie orogenic belt. In the 15 s and 20 s map, the low velocity anomalies (-5%— -3%) lie in Jiangnan orogenic belt between the Yangtze block and Cathasyia block. At long period of 40 s, the velocity is also high in Yangtze block. West to Yangtze block the Songpan-Ganze has low velocity anomaly. In Jiangnan orogenic belt and Cathasyia block the velocities are relatively low. Collecting seismic records from 375 permanent stations from 2010 to 2011, which 93 earthquakes exhibited magnitudes of over 5.5 and occurred at epicentral distances of 30-90°, we use P wave receiver functions and the H-k stacking scheme to obtain the crust and upper mantle structure. Then in the study we reconstruct the wavefields using the radial basis function (RBF) interpolation from a sparsely spaced seismic network. After calculating the receiver functions and H-k stacking we get high quality image of the deep structure in Southeast China. The crustal thicknesses are in the range from 25 km to 55 km. In the Yangtze Craton it is relatively thicker (40-55 km) than the southeastern coastal areas (about 25 km). In Guangdong, Guangxi and Fujian provinces the thickness of crust is less 35 km. Especially, the Moho discontinuity is obviously different beneath both sides of Tancheng-Lujiang fault. The accurate Vp / Vs ratios beneath virtual stations are also determined by searching for the Maximum energy in the stack. Beneath the Gan-Xiang-Gui block the ratio is relatively lower, about 1.60, than the upper Yangtze Craton. The study is supported by the National Natural Science Foundation of China (41274062).

SEISMIX 2016

seismology at the crossroads

17th International Seismix Symposium
Macdonald Aviemore Resort
Aviemore, Scotland
15-20 May