The Lithosphere – Asthenosphere System: Nature of the Tectonic Plates
(LAB 2015)

British Geophysical Association
New Advances in Geophysics 2015

The Geological Society, Burlington House, Piccadilly, London
5th & 6th February 2015

UNIVERSITY OF
Southampton
Schedule

Thursday 5th February 2015

09.30  Registration & Coffee
10.15  Introduction – Kate Rychert

Session 1: Chaired by Kate Rychert
10.30  Mid-lithospheric discontinuity below oceans from seismic surface waves – Jean-Paul Montagner
10.55  Olivine textural evolution constraints the nature of the lithosphere – asthenosphere boundary – Lars Hansen
11.20  Origin of the low velocity zone – Lars Stixrude
11.45  Seismic imaging of a mid-lithospheric discontinuity beneath Ontong Java Plateau – Saikiran Tharimena
12.05  Trans – Atlantic imaging of lithosphere – asthenosphere boundary using active source seismic methods – Satish Singh
12.25  Discussion
12.30  Lunch

Session 2: Chaired by Nicholas Harmon
13.30  Origin of geophysical characteristics of the asthenosphere – Shun-Ichiro Karato
13.55  Experimental constraints on seismic properties and rheology of the upper mantle: Effects of water and melt – Ulrich Faul
14.20  Models of lithosphere thickness and dynamic topography inferred from seismic tomography – Bernhard Steinberger
14.40  Oceanic boundary layer structure and dynamics from a comprehensive analysis of seismic anisotropy – Thorsten Becker
15.00  Implications of possible rapid core cooling for Earth’s atmosphere-mesosphere boundary and a plume-fed asthenosphere – Jason Morgan
15.25  Discussion
15.30  Break

Session 3: Chaired by Satish Singh
16.00  Synthetic seismic structure of oceanic lithosphere – asthenosphere and comparison with observations – Saskia Goes
16.20  Constraints on melt geometry and distribution in the crust and mantle from seismic anisotropy – James Hammond
16.40  Stability of the LAB during lithosphere extension and rifted margin formation: insights from forward numerical modelling – Ritske Huismans
17.05  Discussion
17.15  Poster Session and Wine Reception (Lower Library) – See the end of schedule for list of posters
**Friday 6th February 2015**

**Session 4: Chaired by Ulrich Faul**

10.00  A brief against the lithosphere – asthenosphere boundary hypothesis of plate tectonics – *Thomas Jordan*

10.20  Seismological constraints on the continental lithosphere – asthenosphere boundary – *Karen Fischer*

10.45  Break

**Session 5: Chaired by Karen Fischer**

11.20  LAB – transition between fossil and present-day flow-related velocity anisotropy – *Jaroslava Plomerova*

11.40  Deciphering the formation of the continental lithosphere – *Rainer Kind*

12.00  Mantle discontinuities and the origins of cratonic lithosphere in the northern U.S. – *Emily Hopper*

12.20  Lithospheric and upper mantle stratifications beneath Colombia: Using receiver functions from S waves – *Jose Faustino Blanco Chia*

12.40  Evidence for power-law flow in the Wharton basin asthenosphere – *Sylvain Barbot*

13.00  Lunch

**Session 6: Chaired by Saikiran Tharimena**

14.00  British Geophysical Association – *Mike Kendall / Jenny Collier*

14.20  Constraining the conditions required for the delamination of subducting crust – *Ben Maunder*

14.40  The role of small-scale convection on the formation of volcanic passive margins – *Jeroen van Hunen*

15.00  New constraints on the nature of the eastern Mediterranean crust – *Roi Granot*

15.20  Discussion

15.45  Conclusion – *Kate Rychert*

Instructions:

- Please report to the conference reception desk at the main entrance of the Geological Society situated on Piccadilly.
- Talk sessions will be held at the Janet Watson Lecture theatre.
- Poster and wine reception will be held in the lower library.

Contact:
Website : http://projects.noc.ac.uk/lab2015/
Email : lab2015@soton.ac.uk
Poster Presentation – 5th February 2015

1 Crustal imaging of Northern Scandinavian mountains from receiver function and ambient seismic noise analysis – Walid Ben Mansour

2 Slab driven mantle weakening and laterally variable plate – mantle decoupling – Margarete Jadamec

3 LIRHOS-CAPP: Exploring the lithosphere – asthenosphere system of northern Scandinavia applying ambient noise and surface wave tomography – Alexandra Gassner

4 The effect of strong heterogeneities in the upper mantle rheology on the dynamic topography, tectonic plate motion and the geoid – Anthony Osei Tutu

5 Bayesian inversion of broadband, surface-wave dispersion curves for shear-velocity structure and anisotropy of the lithosphere and asthenosphere – Matteo Ravenna

6 Slab dehydration and deep water recycling from present-day to the early Earth – Valentina Magni

7 Numerical modeling of slab breakoff and mantle flow patterns to assess the potential for generating post-collisional magmatism – Rebecca Hayes

8 Investigating the influence of viscoelastic post-seismic deformation at GPS site over the East Anatolian fault region – Fatih Sunbul

9 Lithospheric structure and LAB depth beneath the north Anatolian fault zone, Turkey – David Thompson

10 A seismic reflection image for the base of a tectonic plate – Tozer B.
Disclaimer

Abstracts from the British Geophysical Association – New Advances in Geophysics 2015 meeting held at the Geological Society of London on 5th & 6th February 2015 are provided herewith explicit permission from the presenting authors as listed in the schedule above. The British Geophysical Association or organizations that supported the meeting do not hold copyrights to any of the content presented in the following abstracts. Any individual who wants to reproduce any part of this material should consult the respective author(s).

Meeting Conveners:

Dr. Catherine Rychert, University of Southampton, UK (C.Rychert@soton.ac.uk)

Dr. Satish Singh, Institut de Physique du Globe, Paris, France (singh@ipgp.fr)

Organizer:

Saikiran Tharimena, University of Southampton, UK (S.Tharimena@noc.soton.ac.uk)
Mid-Lithospheric discontinuity below oceans from seismic surface waves

Jean-Paul Montagner, Institut de Physique du Globe, Paris, France

The nature of Lithosphere - Asthenosphere boundary (LAB) is controversial according to different types of observations. Using a massive dataset of surface wave dispersions in a broad frequency range (15300s), we have developed a 3D anisotropic tomographic model of the upper mantle at the global scale. It is used to derive maps of LAB from the resolved elastic parameters.

We investigate LAB distributions primarily below oceans according to three different proxies which correspond to the base of the lithosphere from the vertically polarized shear velocity variation at depth, the top of the radial anisotropy positive anomaly and from the changes in orientation of the fast axis of azimuthal anisotropy. The LAB depth determinations of the different proxies are basically consistent for each oceanic region. The estimates of the LAB depth based on the shear velocity proxy increase from thin (20 km) lithosphere in the ridges to thick (120-130 km) old ocean lithosphere. The radial anisotropy proxy presents a very fast increase of the LAB depth from the ridges, from 50 km to older ocean where it reaches a remarkable monotonic sub-horizontal profile (70-80km). LAB depths inferred from azimuthal anisotropy proxy show deeper values for the increasing oceanic lithosphere (130-140 km).

The results present two types of pattern of the age of oceanic lithosphere evolution with the LAB depth. The shear velocity and azimuthal anisotropy proxies show age-dependent profiles in agreement with thermal plate models while the LAB based on radial anisotropy is characterized by a shallower depth, defining a sub-horizontal interface with a very small age dependence for all three main oceans (Pacific, Atlantic and Indian). These different patterns raise questions about the nature of the LAB in the oceanic regions, of the formation of oceanic plates, and of the existence of a mid-lithospheric discontinuity within the oceanic lithosphere.

Correspondence: jpm@ipgp.fr

Olivine textural evolution constraints the nature of the lithosphere-asthenosphere boundary

Lars Hansen, Department of Earth Sciences, University of Oxford
Chao Qi, Department of Earth Sciences, University of Minnesota
Kathryn Kumamoto, Department of Geological and Environmental Sciences, Stanford University
Jessica Warren, Department of Geological and Environmental Sciences, Stanford University
Richard Katz, Department of Earth Sciences, University of Oxford
David Kohlstedt, Department of Earth Sciences, University of Minnesota
The nature of the lithosphere-asthenosphere boundary (LAB) determines the mechanical and compositional coupling between rigid plates and underlying convecting mantle. Seismological studies reveal distinct reflectors (G discontinuity) in the uppermost oceanic mantle that are sometimes interpreted as the LAB. These reflectors roughly correlate with the location of discontinuities in radial seismic anisotropy but do not correlate with the location of discontinuities in azimuthal anisotropy. We test these recent interpretations against measurements of crystallographic textures in experimentally and naturally deformed peridotites. Key observations: 1) Experimental deformation of melt-free olivine aggregates reveals a systematic increase in texture strength and, therefore, in magnitude of elastic anisotropy with progressive deformation, eventually attaining a steady-state magnitude. 2) Systems with a moderate melt fraction (1–4%) attain a steady-state texture at very low strain (<~1) with reduced radial anisotropy relative to the melt-free case. 3) Samples from peridotite massifs exhibit cm- to m-scale compositional heterogeneity associated with melt production and extraction that serves to increase radial anisotropy. We use these textural observations to predict seismic anisotropy in the Pacific upper mantle. We implement a seismic structure characteristic of melt-free deformation and predict a discontinuity in azimuthal anisotropy in agreement with seismic observations. The predicted discontinuity coincides with the base of a high viscosity region, and therefore acts as a proxy for the rheological LAB. In addition, we implement a seismic structure characteristic of melt-rich deformation in a region defined by the dry peridotite solidus, yielding reduced radial anisotropy at shallow depths, also in agreement with observations. Alternatively, the observed discontinuity in radial anisotropy can be explained by the onset of melt-related compositional layering below the depth of the discontinuity. We conclude that, following a rheological definition of the lithosphere, the LAB is best defined by a discontinuity in azimuthal anisotropy that is coincident with a thermal boundary layer. The discontinuity in radial anisotropy appears related to melting near the ridge axis, which is consistent with the nature of the associated sharp reflectors (G discontinuity). We suggest that these reflectors and the discontinuity in radial anisotropy do not represent the LAB but instead represent intra-lithospheric structure that does not significantly modify the rheological behaviour of the lithosphere.

Correspondence: lars.hansen@earth.ox.ac.uk

Origin of the Low Velocity Zone

Lars Stixrude, Department of Earth Sciences, University College London
Carolina Lithgow-Bertelloni, Department of Earth Sciences, University College London

The origin of the low velocity zone is still not well understood, although the mechanisms responsible have important implications for the thermal evolution of the Earth and the origin of plate tectonics. The null hypothesis (a geotherm consisting of an adiabat and a conductive thermal boundary layer, and free of melt, water, and attenuation) accounts for many properties of the low velocity zone, including the depth at which the minimum velocity occurs and its variation with age, but the minimum velocity is not as low as seen by seismology (the velocity deficit). Attenuation, as found in global seismic attenuation
tomography, can explain much of the velocity deficit, but still leaves two features of the boundaries of the low velocity zone unexplained: 1) an apparently abrupt upper boundary to the low velocity, possibly associated with the G discontinuity, and 2) a high gradient zone beneath in which velocity increases with depth very rapidly. Here we show that by adding experimentally constrained attenuation to the null hypothesis, the entire velocity deficit is explained. Moreover, the upper boundary of the low velocity zone is remarkably abrupt, although possibly less sharp than receiver function analyses indicate. The high gradient zone can be explained by variations in the entropy with depth, i.e. cooling with increasing depth at depths beneath the low velocity zone, a property of the geotherm that is expected on the basis of mantle convection simulations.

Correspondence: l.stixrude@ucl.ac.uk

Seismic imaging of a mid-lithospheric discontinuity beneath Ontong Java Plateau

Saikiran Tharimena, Ocean and Earth Science, University of Southampton
Catherine Rychert, Ocean and Earth Science, University of Southampton
Nicholas Harmon, Ocean and Earth Science, University of Southampton

The interior of the continents, continental cratons, formed billions of years ago, and the events and conditions that produced these buoyant stable masses have been obscured by time. It is hypothesized that cratons were formed either by large mantle plume-related melting events that led to compositional depletion, stacking of young ocean lithosphere, island arc accretion with orogenic thickening at subduction zones, although no consensus has been reached. Recent seismic observations of mid-lithospheric discontinuities within the cratons have added additional detail and fueled debates over formation mechanism although the exact connection has not been established. Here we use SS precursors to image seismic discontinuities beneath Ontong Java Plateau (OJP), a massive anomalous oceanic lithosphere that is thought to be the result of melting events ~90 and ~120 Ma ago. OJP is a volcanic province in the Pacific that is currently resisting subduction, with size and buoyancy that lend itself to proto-craton comparisons. Discontinuities imaged at ~282 km and ~80 km depth suggest an anomalous structure beneath the plateau that has persisted despite traversing > 8000 km in the past 120 My since formation, implying a thick viscous root with frozen-in mid-lithospheric discontinuity. Therefore, the large melting event that formed OJP or a subsequent rejuvenation event likely created a viscous root with a frozen-in melt boundary. This suggests that melting events in the Archean initiated continent formation prior to the onset of subduction, leaving behind melt boundaries that are imaged today within the lithosphere.

Correspondence: S.Tharimena@noc.soton.ac.uk
Trans Atlantic LAB: Trans-Atlantic Imaging of Lithosphere-Asthenosphere boundary using active source seismic methods

Satish Singh, Institut de Physique du Globe de Paris, France

The nature of the oceanic lithosphere has been traditionally investigated using teleseismic surface waves, whose vertical resolution is on the scale of 20-40 km and lateral resolution of hundreds of kilometers. Recently, receiver function methods, which have vertical resolution of ~10 km, have provided the image of the lithosphere-asthenosphere boundary at a few locations, leading to debate about the nature this boundary. Active source seismic methods can provide both horizontal and vertical resolutions on the scale of hundreds of meters, but imaging down to 100 km depth is very challenging due the presence of multiples and low penetration of seismic energy. We propose to employ a newly developed technology from industry that can provide recording of four component low frequency seismic data on a very fine-scale, possibly allowing the imaging down to the base of the lithosphere at 100 km depth. In order to address debate about the LAB, we propose to acquire data starting from the Mid-Atlantic Ridge, where the base of the lithosphere lies at 3-4 km depth, up to African continental margin where the base of the lithosphere is likely to be at 100 km depth, providing a continuous seismic reflection profile. These data will be complemented by a coincident refraction profile. These new seismic data should also provide seismic images of melt lenses in the mantle beneath the spreading axis, if present, which should help up to develop a new model of melt generation and migration in the mantle. We should also be able to image deep penetrating faults that might have developed due to cooling of the lithosphere as it moves away from the ridge axis, allowing to generate model of hydration of oceanic lithosphere. This project is funded by the European Research Council Advanced Grant.

Correspondence: singh@ipgp.fr

Origin of geophysical characteristics of the asthenosphere

Shun-ichiro Karato, Department of Geology & Geophysics, Yale University

Partial melt origin of the asthenosphere has been a widely popular model for several decades. However, recent studies of partial melting and of the influence of partial melt on physical properties cast serious doubt as to this conventional model: In order to explain observed geophysical anomalies by partial melt, implausibly large amount of melt or implausibly large amount of volatiles in the mantle must be assumed (Karato, 21013; Dai and Karato, 2014).

An alternative is a sub-solidus model, but in this model, temperature effect alone cannot explain a sharp and large velocity drop as well as high and highly anisotropic electrical conductivity. A plausible sub-solidus model is to invoke a likely layering in water (hydrogen) content at the lithosphere-asthenosphere boundary (LAB). One of the models in this category was proposed to explain a sharp velocity drop (Karato, 1995; Karato and Jung,
1998), but it fails to explain a large velocity reduction. Recently, I proposed that anelastic relaxation involving elastically-accommodated grain-boundary sliding might explain a sharp and large velocity drop at LAB (and MLD: mid-lithosphere discontinuity) (Karato, 2012). After a brief discussion on this model, I will focus my talk on the recent studies on the role of hydrogen in electrical conductivity.

A challenge in explaining the observed high and highly anisotropic conductivity is that when one extrapolates earlier experimental studies to asthenosphere temperatures, not quite high conductivity is expected and conductivity is almost isotropic. These experimental studies also provided us with an interesting but challenging puzzle: the connection between conductivity and diffusion (the Nernst-Einstein relation) does not seem to work for hydrogen-assisted conductivity in olivine. I have developed a theoretical model of hydrogen in minerals based on our laboratory studies that explains the causes of this apparent failure of the Nernst-Einstein model. This model was tested by Dai and Karato (2014) who showed that conductivity mechanisms change with temperature, and at the asthenospherhic temperature, conductivity becomes high and highly anisotropic. Therefore anomalous electrical conductivity as well as a sharp and large velocity drop at the LAB can be attributed to the hydrogen-assisted changes in physical properties at the LAB.

Correspondence: shun-ichiro.karato@yale.edu

Experimental constraints on seismic properties and rheology of the upper mantle: Effects of water and melt

Ulrich Faul, Earth, Atmosphere and Planetary Sciences, Massachusetts Institute of Technology

Both melt and water can affect seismic velocities and attenuation, as well as the viscosity of the upper mantle. The effects however are not uniform for all conditions. Small amounts of melt have a substantial effect on the rheology in the diffusion creep regime, but probably much less in the dislocation creep regime. Water affects both diffusion and dislocation creep. Seismic properties are also significantly affected by melt. Until recently the effect of water on seismic properties had not been determined experimentally. First experiments show that water also has a substantial effect on seismic properties, as has been inferred on theoretical grounds.

Our deformation and seismic property measurements are performed with synthetic Fo90 olivine aggregates, ensuring that no melt is present at experimental conditions, unless deliberately added. This enables a clear separation of the effect of melt and water on the respective properties. The effect of water is investigated by doping the synthetic olivine with titanium and surrounding the samples in FeNi foils or Pt capsules. The different surrounding metals allow retention of variable amounts of water at water-undersaturated conditions at constant confining pressure. IR spectroscopy shows that the water is structurally incorporated in olivine, with absorption bands that are also found in the majority of natural olivine.
Deformation experiments indicate that the dry to wet transition occurs at water contents as low as about 5 ppm H/Si, i.e. less than 1 wt. ppm H2O. Coarse-grained (>20 micron) aggregates of olivine deform at higher stresses in a dislocation creep regime with a stress exponent of 3.5 and no indications of a grain size dependence. Both diffusion and dislocation creep regimes are adequately described by previously published flow laws for wet conditions. Aggregates with grain sizes of 10 micron or less deform at high stresses with an exponential (Peierls) flow law, seemingly both under wet and dry conditions. Ultramylonites in high stress shear zones will therefore be significantly weaker than more coarse grained aggregates under the same conditions.

Seismic property measurements on a Pt encapsulated sample with high water content shows substantially higher levels of attenuation and a correspondingly lower modulus compared to dry samples. The addition of water does not produce an enhanced peak due to elastically accommodated grain boundary sliding, but rather enhances the high temperature background due to diffusionally assisted sliding. This is consistent with the reduction in strength seen in the diffusion creep regime. If seismic properties scale with water content similar to rheological properties, even small amounts of water will affect seismic properties. This will make it difficult to distinguish between melt and water as the cause for observed velocity anomalies or discontinuities based on seismic properties alone.

For the viscosity of the upper mantle a distinction between water and melt is important, since water will reduce the viscosity in the dislocation creep regime, while small amounts of melt have much less of an effect. If the low velocities and high attenuation in the asthenosphere are due to water, a corresponding reduction in viscosity will occur. If the seismic asthenosphere is due to melt and a dislocation creep rheology applies the viscosity minimum may be much less pronounced and uncoupled from seismic properties.

Correspondence: hufaul@mit.edu

Models of lithosphere thickness and dynamic topography inferred from seismic tomography

**Bernhard Steinberger**, GFZ German Research Centre for Geosciences, Potsdam, Germany / Centre for Earth Evolution & Dynamics, University of Oslo, Norway
Thorsten W. Becker, University of Southern California, Los Angeles, USA

Dynamic topography is the vertical displacement of the lithosphere above the convecting mantle. Because many continental areas are close to sea level, it is important to understand how it changed through time causing continental inundations. Here a model is developed for the present-day, as starting point for future extensions back in time. A major challenge is that converting seismic velocity to density anomalies using a thermal scaling factor is not appropriate within the continental lithosphere, but density anomalies at lithospheric depth are most effective in causing topography. Therefore, first a lithosphere thickness model is derived: It is also based on tomography, and calibrated to match, on average, oceanic lithosphere thickness inferred from sea floor ages. On the continents, it features thick
lithosphere up to ~350 km for many cratons. We compare our lithosphere models in terms of correlation, ratio and spatial pattern with other approaches, including receiver functions, heat flow and elastic thickness. Notably, we find a good correlation with elastic thickness estimates, but larger values. Using an optimization to fit a number of constraints, a mantle viscosity structure is obtained, for which dynamic topography is compared to "residual" (i.e., actual minus isostatic) topography. Seafloor age-related topography, and an average difference across the ocean-continent boundary are also subtracted from both dynamic and residual topography. Various assumptions about lithospheric density anomalies are tested; best-fitting models feature a small positive density anomaly in the continental lithosphere - far less than inferred from thermal anomalies. Viscosity ~10^{20} Pas is inferred in the asthenosphere, and an increase to ~10^{23} Pas in the lower mantle. The resulting viscosity structure yields a good fit to the geoid. Using recent tomography models, computed rms amplitudes of dynamic topography are slightly (~30%) larger than residual topography, and correlation is ~0.6, whereby many smaller scale features can now also be matched much better than previously. In an alternative approach, above degree ~15 the geoid is converted to dynamic topography, as at these wavelength a high correlation between these, and with density anomalies above ~250 km is expected: This approach gives an even better agreement and higher correlation at short wavelengths.

Correspondence: bstein@gfz-potsdam.de

Oceanic boundary layer structure and dynamics from a comprehensive analysis of seismic anisotropy

Thorsten W. Becker, University of Southern California, Los Angeles, USA
Clinton P. Conrad, University of Hawai‘i at Manoa
Andrew Schaeffer, Dublin Institute for Advanced Studies
Sergei Lebedev, Dublin Institute for Advanced Studies
Ludwig Auer, Eidgenössische Technische Hochschule, Zürich
Lapo Boschi, UPMC, Paris

Seismic anisotropy in the Earth is strongest in the thermo-mechanical boundary layers of the mantle. There, observed variations in anisotropic patterns and strength should be straightforward to relate to mantle flow, particularly for the lithosphere asthenosphere domain. However, both frozen-in and active mantle convection scenarios have been invoked to explain observations, and no simple, global relationships have yet been identified. Here, we show that paleo-spreading orientations provide a good proxy for the shallowest, lithospheric azimuthal anisotropy patterns. This is presumably due to frozen-in lattice preferred orientation (LPO) of olivine assemblages, for which we find a spreading rate and seafloor age dependent correlation. Further down, LPO inferred from mantle flow models and full texture computations, in fact, produces a valid global background model for asthenospheric anisotropy patterns, and to some extent, within the oceanic lithosphere. The same is not true for most simplified (“ISA”) texture descriptions and absolute plate motion (APM) models, although a newly introduced, “ridge fixed reference” frame APM model provides a useful description. A ~200 km thick layer where flow model predicted LPO matches observations from tomography lies just below the ~1200 °C isotherm of half-space
cooling, indicating a strong temperature dependence of the processes controlling development of azimuthal anisotropy. We infer that the depth extent of shear, and hence the thickness of a relatively strong oceanic lithosphere, can be mapped in this manner. These findings for the background model, and ocean-basin specific deviations from the half-space cooling pattern, are found in all of the three recent surface wave models we considered. Further exploration of deviations from the background model may be useful for general studies of oceanic plate formation and dynamics, as well as regional-scale tectonic analyses. We discuss our findings in light of other evidence including that from existing and ongoing radial anisotropy and receiver function studies.

Correspondence: twb@usc.edu

Implications of Possible Rapid Core Cooling for Earth’s Asthenosphere-Mesosphere Boundary and a Plume-Fed Asthenosphere

Jason P. Morgan, Department of Earth Science, Royal Holloway, University of London

Much attention has recently been focused on the top of the asthenosphere — the lithosphere-asthenosphere boundary. However, it is also well-known that vertical seismic velocity gradients around the base of the asthenosphere (~250-400 km depths) are significantly steeper than in other regions of the mantle, and that there is even evidence for regional ‘mystery’ seismic reflectors within this depth interval in the sub-oceanic mantle. Two decades ago, colleagues and I proposed that Earth’s asthenosphere was plume-fed, hence had a potential temperature higher than underlying mesosphere, with implications for the structure of mantle convection. One issue raised against this hypothesis was the idea that plumes must form a weak part of mantle upwelling because the core provides little heat to the base of the mantle in comparison to the mantle’s internal radioactive heat and secular cooling. Here I revisit this issue, and find it possible that core cooling may be, at present, the largest single energy source driving mantle convection.

Earth’s mantle and core are convecting planetary heat engines. The mantle convects to lose heat from slow cooling, internal radioactivity, and core heatflow across its base. Its convection generates plate tectonics, volcanism, and the loss of ~35 TW of mantle heat through Earth’s surface. The core convects to lose heat from slow cooling, small amounts of internal radioactivity, and the freezing-induced growth of a compositionally denser inner core. Core convection produces the geodynamo generating Earth’s geomagnetic field. A decade ago, the geodynamo was thought to be powered by ~4 TW of heatloss across the core-mantle boundary, a rate sustainable (cf. Gubbins et al., 2003; Nimmo, 2007)by freezing a compositionally denser inner core over the ~3 Ga that Earth is known to have had a strong geomagnetic field (cf. Tarduno, 2007). However, recent determinations of the outer core’s thermal conductivity (Pozzo et al., 2012; Gomi et al., 2013) indicate that >15 TW of power should conduct down its adiabat. Conducted power is unavailable to drive thermal convection, implying that the geodynamo needs a long-lived >17 TW power source. Core cooling was thought too weak for this, based on estimates for the Clapeyron Slope for high-pressure freezing of an idealized pure-iron core.
Here I show that the ~500-1000 kg m$^{-3}$ seismically-inferred jump in density between the liquid outer core and solid inner core allows us to directly infer the core-freezing Clapeyron Slope for the outer core’s actual composition which contains ~8±2% lighter elements (S, Si, O, Al, H,…) mixed into a Fe-Ni alloy. A PREM-like 600 kg m$^{-3}$-based Clapeyron Slope implies there has been ~774K of core cooling during the freezing and growth of the inner core, releasing ~24 TW of power during the past ~3 Ga. If so, core cooling can easily power Earth’s long-lived geodynamo. Another major implication of ~24 TW heatflow across the core-mantle boundary is that the present-day mantle is strongly ‘bottom-heated’, and diapiric mantle plumes should dominate deep mantle upwelling. The existence of strong core cooling is also hinted at by Bunge’s idealized plume models which imply that ~200°C of observed secular cooling of mantle plume melts is evidence of ~800°C of secular cooling at the core-mantle boundary over Earth history. I review this evidence, its implications for a plume-fed sub-oceanic asthenosphere, and other implications of this mode of mantle convection for time- and depth- variations in the temperature of the lithosphere-asthenosphere boundary beneath oceans and continents.

Correspondence: Jason.Morgan@rhul.ac.uk

Synthetic seismic structure of oceanic lithosphere-asthenosphere and comparison with observations

**Saskia Goes**, Department of Earth Science & Engineering, Imperial College London
John Armitage, Department of Earth Sciences, Royal Holloway, University of London
Caroline Eakin, Ocean and Earth Science, University of Southampton
Jeroen Ritsema, Department of Earth & Environmental Sciences, University of Michigan
Nicholas Harmon, Ocean and Earth Science, University of Southampton
James Hammond, Department of Earth Science & Engineering, Imperial College London
Catherine Rychert, Ocean and Earth Science, University of Southampton

To understand how lithosphere and asthenosphere differ in temperature, composition and melt content, it will be necessary to test plausible dynamic scenarios against a wide range of observables. Here we take a first step at comparing the seismic structure predicted for a simple oceanic lithosphere, formed by melt extraction and dehydration at the ridge and half-space cooling as it moves away from it, against seismic constraints. The lithospheric structure predicted by half-space cooling models is consistent with surface-wave velocity profiles as well as the age trend found in differential PP-P and SS-S travel times. However, the differential times require about a 50-100°C higher average potential mantle temperature below the Pacific than Indo-Atlantic oceans. Furthermore, they highlight large-scale regional deviations from the cooling trend, which may in part be related to plumes. The same style cooling model, now incorporating melt retention that may affect sub-ridge structure can explain the seismic structure below the East Pacific Rise as imaged by surface waves, including a double low velocity zone, with triangular anomaly above 50-60 km depth due to dry melting and low velocity layer between 60 and ~200km depth mainly resulting from solid-state anelasticity in hydrated mantle with only a minor contribution below the ridge of
hydrous melt. Depending on the sensitivity of attenuation to dehydration, this process can result in a sharp boundary for lithospheric ages, possibly up to 80 My. However, no aspect of the melt zone leads to a sufficiently sharp impedance contrast in isotropic velocity to explain receiver-function signals that have been attributed to the base of the dry melt zone. Alternative scenarios to explain discontinuity structure should also be able to satisfy the range of other constraints (including bathymetry, petrology and seismic attenuation) that simple cooling models already match.

Correspondence: s.goes@imperial.ac.uk

**Constraints on melt geometry and distribution in the crust and mantle from seismic anisotropy**

**James Hammond**, Department of Earth Science & Engineering, Imperial College London

Volcanism is driven by rocks melting in the upper mantle and the ascent of this melt to the surface. This process is the final stage in the Earth’s heat and chemical engines, allowing heat to escape from the interior and resulting in the formation of much of the Earth’s lithosphere. However, melt follows complex pathways to the surface, ponding at many depths before finally erupting at the surface; one of our most problematic natural hazards. Additionally, the presence of melt in the mantle can affect the strength of mantle rocks, thus affect mantle dynamics in tectonically active regions. If we are to understand the processes which form the crust, drive tectonic plates and give rise to volcanoes we must understand the mechanisms by which melt is stored and transported.

Techniques such as magnetotellurics or seismic tomography have provided invocative images of melt in the lithosphere. However, despite these breakthroughs it has remained difficult to estimate the details of melt storage; in particular the shape and amount of melt stored in the magmatic system. In most settings melt is likely to retain a preferential orientation, whether through being stored as dikes or sills in the crust, or through the formation of melt bands or preferentially oriented inclusions or channels in the mantle. This will cause significant seismic anisotropy, with the amount and symmetry of the anisotropy dictated by the nature of melt segregation. Thus, measurements of seismic anisotropy offer a richer dataset than simply measuring absolute velocities alone.

Here I will show the typical characteristics of melt induced anisotropy that may be observed in a variety of teleseismic techniques (shear-wave splitting, receiver functions, surface waves, Pn). I apply these observations to datasets from the East-African rift to show how melt is segregated in a region of continental breakup. These datasets offer the potential to better understand the storage characteristics of melt, especially when combined with other geophysical, geodetic and geological datasets such as magnetotellurics, GPS, InSAR and petrology.

Correspondence: j.hammond@imperial.ac.uk
Stability of the LAB during lithosphere extension and rifted margin formation: insights from forward numerical modeling.

Ritske S. Huismans, Department of Earth Science, University of Bergen, Norway

Contrasting end members of volcanic and non-volcanic passive margin formation show a large variability in basin shape and structure, subsidence history, and associated topographic evolution of the onshore rifted margins. The large range of structural style and associated topography of these systems imply a strong variability in the underlying thermo-mechanical conditions at the time of rifting. Whereas the structural style of the crust and its role during lithosphere extension are reasonably well known. The role of the mantle lithosphere during and after tectonic deformation, its potential mobility, potential interaction between the mantle lithosphere and the sublithospheric mantle, effects of melting, and the relative importance of compositional and thermal effects are, however, still poorly understood.

In some cases rifted margins appear to indicate non-uniform thinning of the crust and mantle lithosphere. A number of mechanisms including small-scale convective removal of the lower lithosphere, lithosphere counter-flow, and dynamic topography, have been invoked to explain anomalous lithosphere thinning and thickening in rifted margin settings. Here I use forward numerical models to illustrate contrasting mechanisms for mantle lithospheric mobility, which depend on rift mode, thermal state and composition and to evaluate their potential for explaining these apparent anomalous characteristics of the LAB beneath rifts and rifted margins.

Correspondence: Ritske.Huismans@geo.uib.no

A Brief Against the Lithosphere-Asthenosphere Boundary Hypothesis of Plate Tectonics

Thomas H. Jordan, Department of Earth Sciences, University of Southern California, Los Angeles, USA
Elizabeth Paulson, Department of Earth Sciences, University of Southern California, Los Angeles, USA

The lithosphere is the mechanically strong boundary layer, comprising crust and uppermost mantle that lies above a much weaker asthenosphere. A tenet of plate tectonics states that the lithosphere-asthenosphere boundary (LAB) marks the kinematic base of lithospheric plates, which slide over the deeper mantle by large-scale shearing concentrated in the upper part of the asthenosphere. Mantle structure is inconsistent with the LAB hypothesis. Beneath old ocean basins, the LAB is marked by a sharp Gutenberg (G) discontinuity at depths of 50-80 km; beneath stable continents, this transition is seismologically less distinct, but its depth is almost certainly less than 250 km. Vertical correlations of seismic velocities from ensembles of global and regional tomographic models indicate that, on the lateral scale of
plates, the asthenosphere translates coherently with lithosphere, beneath oceans to depths of at least 170 km over the lifetime of most oceanic lithosphere and beneath stable continents to depths of at least 350 km over much longer time spans. The vertical S-wave travel time through the oceanic upper mantle decays almost linearly with the square-root of crustal age out to 200 Ma, consistent with a half-space cooling model, although the apparent cooling rate is slower in the Pacific basin than other oceans, consistent with some vertical convective heat flux. We speculate that plate shear beneath stable continents, and perhaps elsewhere, may be concentrated in weak layer exhibiting low S velocities immediately above the 410-km discontinuity. In any case, the vertical scale of plate-coherent horizontal flow appears to exceed that assumed in most models of plate dynamics.

Correspondence: tjordan@usc.edu

Seismological constraints on the continental lithosphere-asthenosphere boundary

Karen M. Fischer, Brown University, USA
Emily Hopper, Brown University, USA
Heather Ford, Yale University, USA
Ved Lekic, University of Maryland, USA

The seismological lithosphere-asthenosphere boundary (LAB), as defined by a gradient from high absolute velocities in the lithosphere to lower velocity asthenosphere, is present on a global basis. Scattered waves provide particular sensitivity to localized velocity gradients, such as the LAB, but require tomographic models for accurate interpretation. Beneath continental regions that have experienced significant tectonic activity in the Phanerozoic, strong LAB velocity gradients are widespread and typically localized in depth (< 30 km). In many cases the depths and amplitudes of these velocity gradients are consistent with the transition from a melt-poor lithosphere to a partially molten volatile-rich asthenosphere. LAB velocity gradients beneath most cratons are typically more gradual than those beneath oceans and younger continental regions, and, with a few exceptions, are consistent with purely thermal models, although gradual gradients in partial melt and volatile content cannot be ruled out.

The depths and amplitudes of LAB velocity gradients vary strongly across a number of plate boundary zones. For example, in the Salton Trough and Inner Borderlands of Southern California, transitions from thinner lithosphere beneath rifted regions to thicker lithosphere beneath unextended crust are laterally abrupt (LAB dips are more than 20°- 30°) and are well-correlated with the surface expressions of extension. Across the San Andreas Fault system, the LAB velocity gradient has a systematically lower amplitude on the western side of the plate boundary, indicating that the drop in shear velocity from lithosphere to asthenosphere is either smaller or is distributed over a larger depth range. In central California, the change in LAB velocity gradient occurs over a horizontal length scale of less than 50 km and lies directly beneath the San Andreas Fault. This result is best explained by the juxtaposition of mantle lithospheres with different properties across the fault, and it points to relative plate motion on a narrow shear zone (< 50 km in width) that extends
throughout the entire thickness of the lithosphere. Both of these examples are consistent with a rheologically strong mantle lithosphere in which strain can localize.

Correspondence: Karen_fischer@brown.edu

LAB – transition between fossil and present-day flow-related velocity anisotropy

Plomerová J., Institute of Geophysics, Academy of Sciences, Prague
Babuška V., Institute of Geophysics, Academy of Sciences, Prague
Vecsey L., Institute of Geophysics, Academy of Sciences, Prague

Fundamental difference in origin and orientation of seismic anisotropy in the mantle lithosphere and in the sub-lithospheric mantle has led to developing a new approach of LAB modelling. We define the LAB as a boundary between a fossil anisotropy in the lithospheric mantle and an underlying seismic anisotropy related to present-day flow in the asthenosphere. We present (1) a uniform updated model of the European LAB calculated from P-wave travel times collected during regional passive experiments, and (2) a global model calculated from depth-dependences of polarization and radial anisotropy of surface waves. In model (1) we transform lateral variations of static terms of relative residuals into a LAB relief according to an empirically derived residual-depth relation with a gradient of 9.4 km/0.1s The high velocity contrast across the LAB ($\delta v_P \sim 0.6$ km/s), resulting from the empirical gradient, can be explained by considering generally inclined high-velocity directions in the mantle lithosphere derived from 3D modelling of seismic anisotropy and sub-horizontal high-velocity directions in the asthenosphere.

Two lithosphere roots down to $\sim 220$ km (left) are mapped beneath the Western and Eastern Alps in model (1) (Babuška et al., 1990). The LAB is modelled at similar depths beneath central Fennoscandia and the East European Craton (Plomerová and Babuška, 2010). LAB depth changes at the Trans-European Suture Zone and is shallower beneath the Phanerozoic Europe with more distinct lateral changes than beneath its Precambrian part. A step-like LAB marks a base of individual mantle-lithosphere blocks with differently oriented anisotropy in the NW part of the TESZ bordering Fennoscandia (Babuška and Plomerová, 2004).

Our global model (Plomerová et al., 2002) based on approach (2) and data from (Montagner and Tanimoto, 1991) shows the LAB at depths of 200-250 km in Precambrian shields and platforms, around 100 km in Phanerozoic continental regions and between 40 and 70 km beneath oceans.

Applying 3D approaches that consider seismic anisotropy with general orientation of symmetry axes enable us to construct more realistic and self-consistent models of the LAB and large-scale structure of the lithosphere.

Correspondence: jpl@ig.cas.cz
Deciphering the formation of the continental lithosphere

Rainer Kind, GFZ German Research Centre for Geosciences, Potsdam, Germany

How the cratons were formed is still one of the great challenges in global tectonics. Two models types are suggested: Iceland-style plume subcretion or Tibet-style subduction accretion during plate collision. Improved images of the seismic discontinuities within the cratons could provide the answer. There are in several cratons numerous controlled source seismic observations of structures in the lithospheric mantle which have been interpreted as fossil subduction. Recent studies have shown that S receiver functions can resolve the larger scale structure of the cratonic roots with unprecedented resolution. We have imaged with US Array data the flat subducting Cretaceous Farallon slab below the western United States reaching to the Mid Continental Rift in the central US, which is far underneath the Archean and Proterozoic crust. Surprisingly we also found in a confined region the mid lithospheric discontinuity (MLD) of the Laurentia craton dipping to the west from 100 km depth at the Great Plains to near 200 km depth at the longitude of Yellowstone. East of the Great Lakes we identified the expected lithosphere asthenosphere boundary (LAB) near 200 km depth. In Scandinavia we also have identified layered structures in the mantle lithosphere. However, we have not been able to resolve the transition to Phanerozoic Europe due to the lack of seismic stations in Denmark and northern Germany. Tomography models show controversial results in this region. Our hypothesis is that lithospheric stacking is a significant part of craton formation.

Correspondence: kind@gfz-potsdam.de

Mantle discontinuities and the origins of cratonic lithosphere in the northern U.S.

Emily Hopper, Department of Earth, Environmental and Planetary Sciences, Brown University
Karen Fischer, Department of Earth, Environmental and Planetary Sciences, Brown University

This work examines how mantle lithosphere discontinuity structure varies beneath the cratonic terranes of the northern U.S.A. We use Sp phases recorded by permanent and temporary seismic networks to sample the Archean Wyoming, Medicine Hat and Superior cratons and the Proterozoic terranes that lie between them. Sp receiver functions for individual waveforms were obtained by extended time multi-taper deconvolution, and migrated into a 3D volume using common conversion point stacking, a spline representation of phase Fresnel zones, and 3D models for crust and mantle structure. The stack was bootstrapped. Unlike in the tectonically active western U.S., observations of a strong negative discontinuity (velocity decrease with depth) at the base of the tomographically-defined lithosphere in the cratonic regions are sparse; therefore, the transition to asthenospheric properties is gradual.
However, we do observe strong layering within the cratonic mantle lithosphere: typically a relatively continuous negative discontinuity in the 65-105 km depth range; and more discontinuous and intermittent negative mid-lithospheric discontinuities (MLDs) at greater depths (85-200 km).

We prefer a combination of mechanisms to explain these phases. We suggest that the lower dipping discontinuities are remnant formation structures, generated by imbricated lithosphere. They are most common around the craton margins, and are associated with the presence of eclogite xenoliths; furthermore, they can in some cases be tied to surface sutures. The upper negative discontinuity, which is very laterally extensive and of a more uniform depth, is consistent with a layer of frozen-in volatile-rich melts. Local xenolith studies show that phlogopite is present extensively throughout the region. An unusual earthquake in September, 2013 occurred within the high velocity mantle of the Wyoming craton at ~80 km depth, overlapping this negative MLD. This suggests that the negative MLD coincides with a zone of mechanical weakness, for example a hydrous layer.

Correspondence: Emily_hopper@brown.edu

Evidence for power-law flow in the Wharton Basin asthenosphere

Sylvain Barbot, Division of Earth Sciences, Earth Observatory of Singapore

Laboratory experiments indicate that the viscous deformation of olivine-rich mantle material is thermally activated and controlled by a power law, whereby the effective viscosity depends on stress. The rheology of olivine controls the depth to the asthenosphere, where ductile flow is weaker than the frictional strength of rocks. Geodetic evidence for nonlinear viscoelastic deformation has been found in the continental mantle, but never before in an oceanic plate. Here, we analyze the transient deformation following the 2012 Mw 8.6 Wharton Basin earthquake sequence under the Indian Ocean that was recorded by continuous geodetic stations along Sumatra to show evidence of power-law flow in the Wharton Basin asthenosphere. A combination of afterslip on the earthquake faults and viscoelastic relaxation in the asthenosphere can explain the geodetic time series, with rheological parameters compatible with a wet oceanic mantle. Whereas Newtonian viscoelastic relaxation and afterslip around the main shock predict widespread subsidence around Aceh, the models that include power-law flow successfully reproduce the regional postseismic uplift. These observations provide us with unprecedented insight about the mechanism of deep, time-dependent stress transfer between seismic events along the Sumatra subduction zone and may shed light on the processes behind the spatio-temporal clustering of great and giant earthquakes of the Sunda megathrust.

Correspondence: sylbar.vainbot@gmail.com
Constraining the Conditions Required for the Delamination of Subducting Crust

Ben Mauder, Department of Earth Sciences, Durham University
Jeroen van Hunen, Department of Earth Sciences, Durham University
Valentina Magni, Department of Earth Sciences, Durham University
Pierre Bouilhol, Department of Earth Sciences, Durham University

It is commonly accepted that the building of the continental crust is linked to subduction zone processes, but the refining mechanism isolating the felsic product from its basaltic counterpart, leading to a stratified crust, remains poorly understood. Delamination of subducting material, its subsequent melting and segregation, with the felsic part being underplated and added to the crust from below has been suggested to be a viable scenario.

In this study we use thermos-mechanical numerical models of subduction to explore the possibility of delamination of the igneous slab crust and determine the conditions that are required by varying key parameters, such as subduction speed and angle, slab age, crustal thickness and density, overriding plate thickness, mantle temperature, depth of eclogitisation and the rheological properties for crustal and mantle material. We also quantify the extent of the resultant crustal melting, and its composition.

Our preliminary models demonstrate that, for present day mantle potential temperatures and average slab crustal thickness, only the uppermost 23km of mafic slab crust may delaminate and only for extreme rheologies (i.e. very weak crust) or very slow subduction (~2cm/yr convergence), making slab mafic crust delamination unlikely. Contrastingly, in an early earth setting (High mantle temperature potential and thicker mafic slab crust) we find that delamination of the subducting mafic crust is a dynamically viable mechanism for a reasonable rheology under a wider range of subduction conditions and that when it does occur, it can be much more extensive, in some cases with the entire crust delaminating from the slab. After only ~5 My from the onset of delamination, mafic crust would sit in the hot mantle wedge where it would likely cross its solidus. These melts would readily be segregated from the migmatitic mafic source and contribute to the formation of felsic crust with little interaction with the mantle wedge, explaining part of the geochemical spectrum of the earliest continental crust.

Correspondence: Benjamin.maunder@dur.ac.uk

The role of small-scale convection on the formation of volcanic passive margins

Jeroen van Hunen, Department of Earth Sciences, Durham University
Jordan J. J. Phethean, Department of Earth Sciences, Durham University

Several models have been presented in the literature to explain volcanic passive margins (VPMs), including variation in rifting speed or history, enhanced melting from mantle plumes, and enhanced flow through the melting zone by small-scale convection (SSC) driven by lithospheric detachments. Understanding the mechanism is important to constrain
the paleo-heat flow and petroleum potential of VPM. Using 2D and 3D numerical models, we investigate the influence of SSC on the rate of crust production during continental rifting. Conceptually, SSC results in up/downwellings with a typical spacing of a few-100 km, and may lead to enhanced decompression melting. Subsequent mantle depletion changes buoyancy (from latent heat consumption and compositional changes), and affects mantle dynamics under the MOR and potentially any further melting.

Decompression melting leads to a colder, thermally denser residue (from consumption of latent heat of melting), but also a compositionally more buoyant one. A parameter sensitivity study of the effects of mantle viscosity, spreading rate, mantle temperature, and a range of material parameters indicates that competition between thermal and compositional buoyancy determines the mantle dynamics. For mantle viscosities $\eta_m > \sim 10^{22}$ Pa s, no SSC occurs, and a uniform 7-8 km-thick oceanic crust forms. For $\eta_m < \sim 10^{21}$ Pa s, SSC is vigorous and can form VPMs with $> 10-20$ km crust. If thermal density effects dominate, a vigorous (inverted) convection may drive significant decompression melting, and create VPMs. Such dynamics could also explain the continent-dipping normal faults that are commonly observed at VPMs. After the initial rifting phase, the crustal thickness reduces significantly, but not always to a uniformly thick 7-8 km, as would be appropriate for mature oceanic basins. Transverse convection rolls may result in margin-parallel crustal thickness variation, possibly related to observations such as the East-Coast Magnetic Anomaly.

Correspondence: jeroen.van-hunen@durham.ac.uk

New constraints on the Nature of the Eastern Mediterranean Crust

Roi Granot, Department of Geological and Environmental Sciences, Ben Gurion University of the Negev

Some of the fundamental tectonic problems of the Eastern Mediterranean remain unresolved due to the extremely thick sedimentary cover (~15 km) and the lack of accurate magnetic anomaly data. We conducted a magnetic survey of the Herodotus and Levant Basins (Eastern Mediterranean) to study the nature and age of the underlying igneous crust. The towed magnetometer array consisted of two Overhauser sensors recording the total magnetic field in a longitudinal gradiometer mode, and a marine vector magnetometer. Accurate navigation together with the gradiometer data allows the separation of the magnetic signature of the lithosphere from the contributions of the external magnetic field and the geomagnetic field. Total field data in the Herodotus Basin reveal a sequence of long-wavelength NE-SW lineated anomalies suggesting a deep (~18 km) 2D magnetic source layer. The lineated anomalies form two segments offset by some ~50 km that unravel the configuration of the southern part of the NeoTethyan mid-ocean ridge system. The full vector data indicate that an abrupt transition from a 2D to 3D magnetic crustal sources occur east of the Herodotus Basin, along where a N-S gravity scar is found. The continuous northward motion of the African Plate during the Paleozoic and Mesozoic result in predictable anomaly skewness patterns for the different time periods. Forward magnetic modeling best fit the observed anomalies when using Early Permian remanence directions.
Altogether, these results demonstrate that a NeoTethyan Permian (~280 Ma) oceanic crust underlies the Herodotus Basin.

Correspondence: rgranot@bgu.ac.il

**Crustal imaging of Northern Scandinavian Mountains from receiver functions and ambient seismic noise analysis**

**Walid Ben Mansour**, Department of Geology, University of Leicester, UK
Richard W. England, Department of Geology, University of Leicester, UK
Max Moorkamp, Department of Geology, University of Leicester, UK
Andreas Kohler, Department of Geosciences, University of Oslo, Norway

Vertical surface motions are often the result of interaction between the lithosphere and the asthenosphere, particularly in the case of epirogenesis. On the Eastern North Atlantic passive margin, the Scandinavian mountains are a perfect example of epirogenesis with peaks above 1 km, consequence of uplift during the Neogene. The underlying crust consists of FennoScandian cratonic basement overthrust by an ancient continental margin sequence during the Caledonian orogen (400 Ma).

Supported by geophysical and geochemistry data, several mechanisms (isostatic adjustment in response to erosion, magmatic underplating, mantle-plume, mantle convection) suggested for explain this Neogene uplift. In order to bring new constraints on these models and the structure of the cratonic basement in this region, we have conducted a seismic study across the Northern Scandinavian Mountains and the craton.

Two passive seismic arrays (SCANLIPS2 and SCANLIPS3D) were deployed for 18 months between 2007-2009 and 2013-2014. Here we will show the results from P receiver functions (PRFs) using these two networks and first results from a seismic ambient noise study. The first results show that there is not relationship between the topography and the Moho depth (average crustal thickness of 44+/3 km and Vp/Vs ratio 1.83+/0.03). The variation and distribution of density could explain the presence of this topography on the passive margin. The first Rayleigh and Love dispersion curves show little variation with azimuth across the Scandinavian mountains and could be used in a surface wave tomography imaging of the lithosphere.

Correspondence: wbm2@le.ac.uk

**Slab driven mantle weakening and laterally variable plate-mantle decoupling**

**Margarete Jadamec**, Department of Earth and Atmospheric Science, University of Houston, USA

Continued research into the processes governing subduction has expanded the classical view of two-dimensional corner flow, to a slab driven flow that can be quite complex. More
recently, geographically referenced 3D geodynamic models using an experimentally derived composite non-linear viscosity formulation were able to fit a range of observables, suggesting the strain-rate dependence as an alternate mechanism to increased temperature, water, or melt fraction for reducing the viscosity in the mantle wedge (Jadamec and Billen, 2010; 2012). However, these models were 3D and complex, so it is useful to examine the key parameters in a simplified 2D subduction setting. Therefore, high-resolution, 2D numerical models of subduction are presented that investigate the relative role of a Newtonian versus composite viscosity, maximum yield stress, and the initial slab dip on the slab driven mantle weakening and (de)coupling along the base of the lithospheric plates.

The results show that using the experimentally derived flow law to define the Newtonian viscosity (diffusion creep deformation mechanism) and the composite viscosity (both diffusion creep and dislocation creep deformation mechanisms) has a first order effect on the viscosity structure and flow velocity in the upper mantle. Models using the composite viscosity formulation produce a zone of subduction induced mantle weakening that results in reduced viscous support of the slab. The maximum yield stress, which places an upper bound on the slab strength, can also have a significant impact on the viscosity structure and flow rates induced in the upper mantle, with maximum mantle weakening and mantle flow rates occurring in models with a lower maximum yield stress and shallower slab dip. In all cases the magnitude of induced mantle flow is larger in the models using the composite viscosity formulation. The models suggest, therefore, that slab steepening is a natural part of the evolution of a subduction zone, and the slab strength as well as viscous support of the slab can play a large role in modulating the rate and extent of slab steepening and consequently the magnitude of induced mantle flow. The models show that using the composite viscosity formulation leads to a sharper definition of the rheological base of the lithosphere, which could be important in the interpretation of the lithosphere - asthenosphere boundary from seismic data. In addition, the slab driven zone of reduced mantle viscosity leads to lateral variability in the upper mantle viscosity.

This implies lateral variability of the coupling of the mantle to the base of the surface plates and lateral variability in the ability of the mantle to drive and resist tectonic plate motions.

Correspondence: mjadamec@central.uh.edu

LITHOS-CAPP: Exploring the Lithosphere-Asthenosphere System of northern Scandinavia applying Ambient Noise and Surface Wave Tomography

Alexandra Gassner, GFZ German Research Centre for Geosciences, Potsdam, Germany
Michael Grund, KIT Karlsruhe Institute of Technology, Karlsruhe, Germany
Christoph Sens-Schonfelder, GFZ German Research Centre for Geosciences, Potsdam, Germany
Joachim Ritter, KIT Karlsruhe Institute of Technology, Karlsruhe, Germany
Frederik Tilmann, GFZ German Research Centre for Geosciences, Potsdam, Germany

The LITHOspheric Structure of Caledonian, Archean and Proterozoic Provinces (LITHOS-
CAPP) project focuses on crustal and upper mantle structures of northern Scandinavia in terms of understanding their geodynamical evolution. This project is the German contribution (GFZ and KIT) to the SCANarray initiative implemented by a consortium including also NORSAR, NGU (both Norway) as well as Universities of Copenhagen, Oslo, Leicester, Uppsala, Bergen, Aarhus and Oulu. We aim at deeper in-sights into the development of high topographies at passive continental margins in the absence of recent compressional tectonic settings.

In the fall of 2014, in total 98 broadband stations have been deployed by the project partners covering central and northern Norway and Sweden and the western margin of Finland; 20 broadband seismic stations were provided by GFZ. Our project links to former studies which mainly covered the southern regions of Scandinavia (e.g. MAGNUS, SCANLIPS and Svekalapko). An unusually shallow crust and lithosphere-asthenosphere boundary (LAB) have been found beneath the high-topography Scandes mountain range of western Norway, where a clear crustal mountain root seems to be absent. The lower topography regions of eastern Norway and Sweden, however, reveal a thicker crust which is in contrast to the principles of Airy isostasy. Lower seismic velocities than expected for a tectonically stable region have been found for southern Norway with a sharp transition to higher VP and VS beneath Sweden.

To obtain a high-resolution (lithospheric) shear wave model, we will combine tomographic and waveform inversions of S- and surface waves with SKS splitting measurements. Here, the contribution of the GFZ comprises the analysis of surface waves and ambient noise and the subsequent production of 3D models, including both isotropic and anisotropic analyses. KIT will concentrate on body wave tomography using shear waves and SKS splitting examination. The focus is on the variation of crustal and lithospheric structure as well as seismic velocity across the Scandes mountain range and western (Phanerozoic) and eastern (Proterozoic) Scandinavia. The spatial variation of anisotropic structures can give us a hint at the tectonic formation since anisotropy may differ between the tectonic units or could be consistent over larger regions.

Correspondence: gassner@gfz-potsdam.de

The effect of strong heterogeneities in the upper mantle rheology on the dynamic topography, tectonic plate motion and the geoid

Anthony Osei Tutu, GFZ German Research Centre for Geosciences, Potsdam, Germany
Bernhard Steinberger, GFZ German Research Centre for Geosciences, Potsdam, Germany
Irina Rhogozina, GFZ German Research Centre for Geosciences, Potsdam, Germany
Stephen Sobolev, GFZ German Research Centre for Geosciences, Potsdam, Germany
Volker John, Department of Mathematics and Computer Science, FUB, Germany

The undulating nature of the earth surface (topography) on both continents and sea floor and the observed geoid anomaly are influenced by the convective processes within the Earth’s mantle driven by density anomalies. Hot, less dense material tends to rise and push
the overlying lithosphere upward, whereas cold, denser material tends to sink and pull the lithosphere downward (Steinberger, 2014). Evidence from ancient coastal areas currently submerged (Hartley et al. 2011) suggests significant changes in topography of several hundred meters relative to the present day Europe. The effect of such changes on the present-day relief and land area would drastically change the face of Europe.

The geoid is about 90% (Hager & Richards, 1989) determined by both the density anomalies driving the mantle flow and the dynamic topography (fig. 3), caused at the Earth surface and the core-mantle boundary. The remainder is largely due to strong heterogeneities in the lithospheric mantle and the crust, which also need to be taken into account. Surface topography caused by density anomalies both in the sub-lithospheric mantle and within the lithosphere depends on lithosphere rheology. Here we investigate these effects by assessing the differences between modeled dynamic topography and geoid from the spectral mantle flow code (Hager & O’Connell, 1981) and a fully coupled code of the lithosphere and mantle accounting for strong heterogeneities in the upper mantle rheology (Popov & Sobolev, 2008).

This study is the first step towards linking global mantle dynamics with lithosphere dynamics using the observed geoid as a major constraint and results from both codes will be presented and compared with the observed geoid and dynamic topography. By this method we are to evaluate the effect of plate rheology (strong plate interiors and weak plate margins) and stiff subducted lithosphere on these observables (i.e. geoid, topography, plate boundary stresses) as well as plate motion This effort will also serve as a benchmark of the two existing numerical codes developed for geodynamic modeling.

By considering the variabilities that exits in geodynamic predictions from the different seismic tomography models currently available, we look for models that correlate well with observations at both regional and global scales.

Correspondence: oseitutuanthony@yahoo.com

**Bayesian Inversion of Broadband, Surface-Wave Dispersion Curves for Shear-Velocity Structure and Anisotropy of the Lithosphere and Asthenosphere**

Matteo Ravenna, Dublin Institute for Advanced Studies
Sergei Lebedev, Dublin Institute for Advanced Studies

The increasing amount of broadband phase velocity dispersion measurements around the world is leading to significant improvements in shear velocity models on both regional and global scales. As the relation between surface-wave dispersion and the seismic velocity structure of the earth is nonlinear, a reliable way to perform the inversion is Monte Carlo sampling in a Bayesian framework. Considering the high sensitivity of surface waves to Vs in broad depth intervals and their low sensitivity to Vs in thin layers, there are strong trade-offs between shear speeds at neighboring depths resulting in non-uniqueness of solutions.
We develop a Markov Chain Monte Carlo method for joint inversion of Rayleigh- and Love-wave dispersion curves that is able to yield robust radially and azimuthally anisotropic shear velocity profiles, with resolution to depths down to the transition zone. The inversion is a one step process that doesn’t involve any linearization procedure or a priori bounds around a reference model. In a fixed dimensional Bayesian formulation, we chose to set the number of parameters relatively high, with a more dense parameterization in the uppermost mantle in order to have a good resolution of the Lithosphere - Asthenosphere Boundary region.

We impose a prior constraint consisting in a smoothing term that penalizes differences between velocities in neighboring layers, but doesn’t limit the ability of resolving strong gradient changes. We apply the MCMC algorithm to the inversion of surface-wave phase velocities accurately determined in broad period ranges in a few test regions, and present the resulting radially and azimuthally anisotropic shear velocity models.

Correspondence: mravenna@cp.dias.ie

Slab dehydration and deep water recycling from present day to the early Earth

Valentina Magni, Department of Earth Sciences, Durham University, UK
Pierre Bouilhol, Department of Earth Sciences, Durham University, UK
Jeroen van Hunen, Department of Earth Sciences, Durham University, UK

The fate of water in subduction zones is a key feature that influences the magmatism of the arcs, the rheology of the mantle, and the recycling of volatiles. We investigate the dehydration processes in subduction zones and their implications for the water cycle throughout Earth’s history. We use a numerical tool that combines thermo-mechanical models with a thermodynamic database to examine slab dehydration for present-day and early Earth settings and its consequences for the deep water recycling. We investigate the reactions responsible for releasing water from the crust and the hydrated lithospheric mantle and how they change with subduction velocity, slab age, and mantle potential temperature.

Our results show that faster slabs dehydrate over a wide area: they start dehydrating shallower and they carry water deeper into the mantle. A hotter mantle (i.e., early Earth setting) drives the onset of crustal dehydration slightly shallower, but, mostly, dehydration reactions are very similar to those occurring in present-day setting. However, for very fast slabs and very hot mantle epidote is involved as a dehydrating crustal phase. Moreover, we provide a scaling law to estimate the amount of water that can be carried deep into the mantle. We generally observe that a 1) 100°C increase in the mantle temperature, or 2) ~15 Myr decrease of plate age, or 3) decrease in subduction velocity of ~2 cm/yr all have the same effect on the amount of water retained in the slab at depth, corresponding to a decrease of ~2.2x10^5 kg/m² of H2O. We estimate that for present-day conditions ~26% of the global influx water, or 7x10^8 Tg/Myr of H2O, is recycled into the mantle. Using a realistic distribution of subduction parameters, we illustrate that deep water recycling might still be possible in early Earth conditions, although its efficiency would generally decrease. Indeed,
0.5-3.7x10⁸ Tg/Myr of H₂O could still be recycled in the mantle at 2.8 Ga.

Correspondence: valentina.magni@durham.ac.uk

**Numerical modeling of slab breakoff and mantle flow patterns to assess the potential for generating post-collisional magmatism**

*Rebecca Hayes*, Department of Earth Sciences, Durham University, UK  
Jeroen van Hunen, Department of Earth Sciences, Durham University, UK  
Ben Maunder, Department of Earth Sciences, Durham University, UK  
Valentina Magni, Department of Earth Sciences, Durham University, UK  
Pierre Bouilhol, Department of Earth Sciences, Durham University, UK

Slab breakoff is often proposed as a mechanism for generating observed post-collisional magmatism in continental settings. Early numerical modeling results suggest this occurs at shallow depths, which would lead to partial melting through the decompression melting of upwelling asthenosphere through the slab window and the thermal perturbation of the overlying lithosphere. Interpretations of geochemical data which involve slab breakoff as a means of generating magmatism mostly assume these shallow depths. However recent modeling results suggest that deeper slab breakoff might occur deeper. Breakoff at depths greater than the overlying lithosphere is unlikely to result in magmatism through the previous mechanism, as the asthenospheric flow would not reach shallow enough depths to generate decompression melting nor come into contact with the overriding plate.

Here we test another possible mechanism that detached sinking slabs could trigger vigorous mantle return flows leading to asthenospheric upwelling to shallow depths, with lithospheric thinning of the overlying plate and associated decompression melting. 2-D numerical models are designed to investigate the dynamics of continental collision and resulting slab breakoff. We use these models to study whether partial melting can be induced from slab breakoff, potentially accompanied by vigorous mantle flow. To that end, the oceanic plate age, continental crustal thickness and crustal rheology are varied systematically. Results show that for breakoff occurring at depths greater than 150 km the return flow occurs too deep in the mantle to initiate partial melting. In that case slab breakoff is not a valid explanation for observed magmatism in collisional settings, and other mechanisms should be invoked, such as small scale convection at the base of the lithosphere, induced by the presence of fluids, back-arc extension, or slab delamination.

Correspondence: r.j.hayes@durham.ac.uk

**Investigating the Influence of Viscoelastic Post-seismic deformation due to Large Earthquakes in the East Anatolian Fault Region**

*Fatih Sunbul*, Environmental Sciences Research Institute, University of Ulster, UK  
Suleyman Nalbant, Environmental Sciences Research Institute, University of Ulster, UK
In this study, we investigate post-seismic viscoelastic relaxation of the lower crust and upper mantle following large earthquakes. We focus on the East Anatolian fault region GPS velocity field, assessing the effects of 15 large earthquakes (M>6.8) for three possible rheological models for the region. We find that the M7.9 1939 Erzincan earthquake has greatest contribution to the velocity field - up to 2.5 mm/yr over the observation period. This rate alone makes up about 50% of velocity rates measured at the neighbouring GPS sites. The earliest and second largest event in our computations, the M7.5 1822 Antakya earthquake, still contributes to the total velocity field and has more significant effect than the other recent earthquakes in the southern parts of the region. However, its effect is smaller than the error range of GPS measurements. Additionally, we estimate cumulative velocity fields of the earthquakes. Although individual contributions of most of the events are below the observed error range, the cumulative PS deformations are larger than the error ranges and mostly effecting GPS stations located in northern and middle parts of the region.

Correspondence: sunbul-f1@email.ulster.ac.uk

Lithospheric structure and LAB depth beneath the North Anatolian Fault Zone, Turkey

David Thompson1,2*, Sebastian Rost2, Greg Houseman2, David Cornwell1, Niyazi Türkelli3, Ügür Teoman3, Metin Kahraman3, Selda Altunç Poyraz3, Levent Gülen4, Murat Utkucu4, Andrew Frederiksen5, Stéphane Rondenay6, Joshua Williams2

1 School of Geoscience, University of Aberdeen, Aberdeen, UK
2 School of Earth and Environment, Institute of Geophysics and Tectonics, University of Leeds, Leeds, UK
3 Kandilli Observatory and Earthquake Research Institute, Boğaziçi Üniversitesi, Istanbul, Turkey
4 Department of Geophysical Engineering, Sakarya Üniversitesi, Sakarya, Turkey
5 Department of Geological Sciences, University of Manitoba, Winnipeg, Canada
6 Department of Earth Science, University of Bergen, Bergen, Norway

The North Anatolian Fault Zone (NAFZ) is a major continental strike-slip fault system, similar in size and scale to the San Andreas system that extends ~1200 km across Turkey. In 2012, a new multidisciplinary project (FaultLab) was instigated to better understand deformation throughout the entire crust in the NAFZ, in particular the expected transition from narrow zones of brittle deformation in the upper crust to possibly broader shear zones in the lower crust/upper mantle and how these features contribute to the earthquake loading cycle. Faults may also penetrate as narrow features all the way to the lithosphere – asthenosphere boundary (LAB), potentially providing pathways for fluids and magma to shallower levels. This contribution will discuss results from the seismic component of the FaultLab project, a 73 station network encompassing the northern and southern branches of the NAFZ in the Sakarya region. The Dense Array for North Anatolia (DANA) is arranged as a 6×11 grid with a nominal station spacing of 7 km, with a further 7 stations located outside of the main grid. With the excellent resolution afforded by the DANA network, we
will present images of crustal and lithospheric mantle structure using a variety of seismic imaging techniques (scattering methodologies, P- and S- receiver functions). Early results suggest significant amounts of anisotropy at depths of up to 60-70 km beneath the northern portion of the network which may indicate mechanical strength within the lithosphere to these depths. New results from S-to-P conversions will provide insights into any low velocities at deeper levels that are commonly ascribed to the LAB, and may provide information about any lateral variation in LAB depth associated with the deep penetration of this important strike-slip fault zone.

Correspondence: david.thompson@abdn.ac.uk

A seismic reflection image for the base of a tectonic plate

T.A. Stern, Institute of Geophysics, Victoria University, Wellington, New Zealand
S.A. Henrys, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand
D.A. Okayas, Department of Earth Sciences, University of Southern California, Los Angeles
J. Louie, Seismological Observatory, University of Nevada, Reno, USA
M.K. Savage, Institute of Geophysics, Victoria University, Wellington, New Zealand
S.H. Lamb, Institute of Geophysics, Victoria University, Wellington, New Zealand
H. Sato, Department of Earth Sciences, Tokyo University, Tokyo, Japan
R. Sutherland, Institute of Geophysics, Victoria University, Wellington, New Zealand /
Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand
T. Iwasaki, Department of Earth Sciences, Tokyo University, Tokyo, Japan
B. Tozer, Institute of Geophysics, Victoria University, Wellington, 6140, New Zealand /
Department of Earth Sciences, University of Oxford, UK

Plate tectonics successfully describes the surface of Earth as a mosaic of moving lithospheric plates. But it is not clear what happens at the base of the plates - the lithosphere-asthenosphere boundary (LAB). The LAB has been well imaged with converted teleseismic waves, where structural resolution is controlled by their 10-40 km wavelength. Here, we use explosion-generated seismic waves (~0.5 km wavelength) to form a higher-resolution image of the base of an oceanic plate that is subducting beneath North Island, New Zealand. Our 80 km-wide image is based on P-wave reflections and shows a ~15° dipping, abrupt, seismic wave-speed transition (~1 km thick) at a depth of ~100 km. The boundary is parallel to the top of the plate and seismic attributes indicate a P-wave speed (V_p) decrease of at least 8 ± 3% across it. A ~10 km deeper, and parallel, reflection event shows the decrease in V_p is confined to a channel at the base of the plate that we interpret as a sheared zone of ponded partial melts or volatiles. This is independent, high resolution, evidence for a low viscosity channel at the LAB that decouples plates from mantle flow beneath, and allows plate tectonics to work.

Correspondence: brookt@earth.ox.ac.uk