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Contents

1 Strategic Plan 2012-2016

In 2012 the Institute produced a new strategic plan covering the period 2012-2016[1]. As part of the development of this overarching Institutional strategy each school also produced its own strategic programme of activities. In the case of the School of Cosmic Physics this identified four broad 'pillars' that together support the school. The first and most important of these is the School's reputation for pioneering and excellent research, the others being its contributions to the third-level educational system, its involvement in shared research infrastructure and general public service and finally its work in public outreach. This report aims as far as possible to follow this structure.

2 Research Work

2.1 Star Formation

2.1.1 Submitted Proposals

SFI: A proposal by T.P. Ray to Science Foundation Ireland (Investigator Award Programme) on the development of Kinetic Inductance Detectors (KIDS) jointly with the Cavendish Laboratory in Cambridge, the Centre for Research and Adaptive Nanostructures and Nanodevices (CRANN) and the Department of Physics, NUI Maynooth was accepted by SFI to pass to Phase II. A decision on funding (Request 1.3 Million Euro) is expected is early 2013. ERC: An ERC Advanced Grant application has been submitted (in November 2012) to investigate the link between accretion and outflow in young stars using a combination of techniques: long-term monitoring of their spectral signatures (with Liverpool John Moores University), near-infrared interferometry (with the University of Grenoble), radio interferometry and Zeeman Doppler Imaging (with the University of Göttingen).

[1] http://www.dias.ie/images/stories/admin/Strategystatements/diasstrategic%20plan2012-2016.pdf

A. Scholz (Schrödinger Fellow) is currently preparing an ERC Consolidator Grant application.

Telescope Proposals Applications involving the Star Formation Group to use ESO's Very Large Telescope (VLT) and Atacama Large Millimetre Array (ALMA) in Chile and India's Giant Meter Radio Telescope (GMRT) near Mumbai were successful in being awarded time.

2.1.2 Accretion and Disk Properties of Young Stars

A systematic survey for eruptive young stellar objects using mid-infrared photometry *A. Scholz, D. Froebrich (Kent) and K. Wood (St. Andrews)*

Accretion in young stellar objects (YSOs) is at least partially episodic, i.e. periods with high accretion rates ('bursts') are interspersed by quiescent phases. These bursts manifest themselves as eruptive variability. Scholz et al. presented a systematic survey for eruptive YSOs aiming to constrain the frequency of accretion bursts. They compared mid-infrared photometry from Spitzer and WISE separated by approximately 5 years for two samples of YSOs, in nearby star-forming regions and in the Galactic Plane, each comprising about 4000 young sources. All objects for which the brightness at 3.6 and 4.5 μm is increased by at least 1 mag between the two epochs may be eruptive variables and burst candidates. For these objects, they carried out follow-up observations in the near-infrared. They discovered two new eruptive variables in the Galactic Plane which could be FU Ori-type objects, with K-band amplitudes of more than 1.5 mag. One object known to undergo an accretion burst, V2492 Cyg, is recovered by their search as well. In addition, the young star ISO-Oph-50, previously suspected to be an eruptive object, was found to be better explained by a disc with varying circumstellar obscuration. In total, the number of burst events in a sample of 4000 YSOs is 1-4. Assuming that all YSOs undergo episodic accretion, this constraint can be used to show that phases of strong accretion (>10^{-6} M_{sun} yr^{-1}) occur in intervals of about 10^4 years, most likely between 5,000 and 50,000 years. This is consistent with the dynamical time-scales for outflows, but not with the separations of emission knots in outflows, indicating that episodic accretion could either trigger or stop collimated large-scale outflows. These results will be published in Monthly Notices of the Royal Astronomical Society.

The frequency of large variations in the near-infrared fluxes of T Tauri stars *A. Scholz*

Variability is a characteristic feature of young stellar objects (YSOs) and could contribute to the large scatter observed in Hertzsprung-Russell (HR) diagrams for star-forming regions. For typical YSOs, however, the long-term effects of variability are poorly constrained. A. Scholz has used archived near-infrared photometry from the 2 Micron All Sky Survey (2MASS), UKIDSS and DENIS to investigate the long-term variability of high-confidence members of the four star-forming regions ρ-Oph, ONC, IC348 and NGC 1333. The total sample comprises more than 600 objects, from which approximately 320 are considered to have a disc. The data set covers time-scales up to 8 yr. About half of the YSOs are variable on a 2σ level, with median amplitudes of 5-20%. The fraction of highly variable objects with amplitudes > 0.5 mag in at least two near-infrared bands is very low: 2% for the entire sample and 3% for objects with discs. These sources with strong variability are mostly objects with discs and are prime targets for follow-up studies. A transition disc candidate in IC348 is found to have strong K-band variations, likely originating in the disc. The variability amplitudes are largest in NGC 1333, presumably because it is the youngest sample of YSOs. The frequency of highly variable objects also increases with the time window of the observations (from weeks to years). These results have three implications. (1) When deriving luminosities for YSOs from near-infrared magnitudes, the typical error introduced by variability is in the range of 5-20% and depends on disc fraction and possibly age. (2) Variability is a negligible contribution to the scatter in HR diagrams of star-forming regions (except for a small number of extreme objects), if luminosities are derived from near-infrared magnitudes. (3) Accretion outbursts with an increase in mass accretion rate by several orders of magnitudes, as required in scenarios for episodic accretion, occur with a duty cycle of > 2000-2500 years in the Class II phase. The results have been published in Monthly Notices of the Royal Astronomical Society.

LAMP: the long-term accretion monitoring programme of T Tauri stars in Chamaeleon I *G. Costigan, A. Scholz, B. Stelzer (Palmero), T.P. Ray, J. Vink (Armagh), S. Mohanty (Imperial College London)*

G. Costigan (DIAS PhD student) et al. have presented the results of a variability study of accreting young stellar objects in the Chameleon I star-forming region, based on approximately 300Å high-resolution optical spectra from the Fibre Large Area Multi-Element Spectrograph (FLAMES) at the Europeantheir Southern Observatory (ESO) Very Large Telescope (VLT). 25 objects with spectral types from G2-M5.75 were observed 12 times over the course of 15 months. Using the emission lines Hα (6562.81Å) and Ca II (8662.1Å) as accretion indicators, they found 10 accreting and 15 non-accreting objects. They derived accretion rates for all accretors in the sample using the Hα equivalent width, Hα 10 per cent width and Ca II (8662.1 Å) equivalent width. They found that the Hα equivalent widths of accretors varied by ≈ 7-100 Å over the 15-month period. This corresponds to a mean amplitude of variations in the derived accretion rate of ≈ 0.37 dex. The amplitudes of variations in the derived accretion rate from Ca II equivalent width were ≈ 0.83 dex and those from Hα 10 per cent width were ≈ 1.11 dex. Based on the large amplitudes of variations in accretion rate derived from the Hα 10 per cent width with respect to the other diagnostics, they do not consider it to be a reliable accretion rate estimator. Assuming the variations in Hα and Ca II equivalent width accretion rates to be closer to the true value, these suggest that the spread that was found around the accretion rate to stellar-mass relation is not due to the variability of individual objects on time-scales of weeks to around 1 year. From these variations, they can also infer that the accretion rates are stable within <0.37 dex over time-scales of less than 15 months. A major portion of the accretion variability was found to occur over periods shorter than the shortest time-scales in their observations, 8-25 days, which are comparable with the rotation periods of these young stellar objects. This could be an indication that what they are probing is spatial structure in the accretion flows and it also suggests that observations on time-scales of around a couple of weeks are sufficient to limit the total extent of accretion-rate variations in typical young stars. No episodic accretion was observed: all 10 accretors accreted continuously for the entire period of observations and, though they may have undetected low accretion rates, the non-accretors never showed any large changes in their emission that would imply a jump in accretion rate. The results were published in Monthly Notices of the Royal Astronomical Society.

POISSON project: A multi-wavelength spectroscopic and photometric survey of young protostars in L 1641 *A. Caratti o Garatti, R. Garcia Lopez (Bonn), S. Antoniucci (Florence). B. Nisini (Rome), T. Giannini (Rome), J. Eislöffel (Tautenburg), T.P. Ray, D. Lorenzetti (Rome), S. Cabrit (Paris)*

Characterising stellar and circumstellar properties of embedded young stellar objects (YSOs) is mandatory for understanding the early stages of stellar evolution. This task requires the combination of both spectroscopy and photometry, covering the widest possible wavelength range, to disentangle the various protostellar components and activities. As part of the POISSON project (Protostellar Optical-Infrared Spectral Survey On NTT), A. Caratti o Garatti, T.P. Ray et al. have presented a multi-wavelength spectroscopic and photometric investigation of embedded YSOs in L 1641, with the aim of deriving their stellar parameters and evolutionary stages and to infer their accretion properties. This multi-wavelength database included low-resolution optical-IR spectra from the NTT and Spitzer (0.6-40 μm) and photometric data covering a spectral range from 0.4 to 1100 μm, which allowed them to construct the YSOs spectral energy distributions (SEDs) and to infer the main stellar parameters. The NTT optical-NIR spectra are rich in emission lines, which are mostly associated with YSO accretion, ejection, and chromospheric activities. A few emission lines, prominent ice (H_2O and CO_2), and amorphous silicate absorption features have also been detected in the Spitzer spectra. The SED analysis allowed them to group their 27 YSOs into nine Class I, eleven Flat, and seven Class II objects. However, on the basis of the derived stellar properties, only six Class I YSOs have an age of approximately 10^5 years while the others are older (5×10^5-10^6 years), and, among the Flat sources, three out of eleven are more evolved objects (5×10^6-10^7 years), indicating that geometrical effects can significantly modify the SED shapes. Inferred mass accretion rates show a wide range of values (3.6×10^{-9} to 1.2×10^{-5} $M_{sun}\,yr^{-1}$), which reflects the age spread observed in their sample well. Average values of mass accretion rates, extinction, and spectral indices decrease with the YSO class. The youngest YSOs have the highest accretion rates, whereas the oldest YSOs do not show any detectable jet activity in either images and spectra. Apart from two objects, none of the YSOs are accretion-dominated. They also observe a clear correlation among the YSO accretion rates, M_{star}, and age. For YSOs with $t > 10^5$ yr and 0.4 $M_{sun} \leq M_{star} \leq 1.2\ M_{sun}$, a relationship between $\dot{M}_{acc}$ and t ($\dot{M}_{acc} \propto t^{-1.2}$) has been inferred, consistent with mass accretion evolution in viscous disc models and indicating that the mass accretion decay is slower than previously assumed. Finally, their results suggest that episodic outbursts are required for Class I YSOs to reach typical classical T Tauri stars stellar masses. These results have been published in Astronomy and Astrophysics.

Radio continuum observations of Class I protostellar discs in Taurus: constraining the greybody tail at centimetre wavelengths *A. Scaife, J. Buckle (Cambridge), R. Ainsworth (DIAS PhD student), T.P. Ray and the AMI Consortium*

A. Scaife, R. Ainsworth, T.P. Ray et al. have presented deep 1.8 cm (16 GHz) AMI radio continuum imaging of seven young stellar objects in the Taurus molecular cloud. These objects have previously been extensively studied in the submm to near-infrared range and their spectral energy distributions modelled to provide reliable physical and geometrical parameters. These new data were used to constrain the properties of the long-wavelength tail of the greybody spectrum, which is expected to be dominated by emission from large dust grains in the protostellar disc. They find spectra consistent with the opacity indices expected for such a population, with an average opacity index of $\beta = 0.26 \pm 0.22$ indicating grain growth within the discs. They used spectra fitted jointly to radio and submm data to separate the contributions from thermal dust and radio emission at 1.8 cm and derive disc masses directly from the cm-wave dust contribution. They find that disc masses derived from these flux densities under assumptions consistent with the literature are systematically higher than those calculated from submm data, and meet the criteria for giant planet formation in a number of cases. These results have been published in Monthly Notices of the Royal Astronomical Society.

2.1.3 The Formation of Brown Dwarfs and Planemos

New brown dwarf discs in Upper Scorpius observed with WISE *P. Dawson, A. Scholz, T.P. Ray, K.A. Marsh (Cardiff), K. Wood (St. Andrews), A. Natta, D. Padgett (NASA Goddard), M.E. Ressler (JPL)*

Dawson (DIAS PhD student) et al. presented a census of the disc population for United Kingdom Infrared Digital Sky Survey (UKIDSS) selected brown dwarfs in the 5-10 Myr old Upper Scorpius OB association. For 116 objects originally identified in UKIDSS, the majority of them not studied in previous publications, they obtained photometry from the Wide-Field Infrared Survey Explorer (WISE) data base. The resulting colour-magnitude and colour-colour plots clearly show two separate populations of objects, interpreted as brown dwarfs with discs (class II) and without discs (class III). They identified 27 class II brown dwarfs, 14 of them not previously known. This disc fraction (27 out of 116, or 23%) among brown dwarfs was found to be similar to results for K/M stars in Upper Scorpius, suggesting *the important result that the lifetimes of discs are independent of the mass of the central object* for low-mass stars and brown dwarfs. 5 out of 27 discs (19%) lacked excess at 3.4 and 4.6 μm and are potential transition discs (i.e. are in transition from class II to class III). The transition disc fraction is comparable to low-mass stars. They estimated that the time-scale for a typical transition from class II to class III is less than 0.4 Myr for brown dwarfs. These results suggest that the evolution of brown dwarf discs mirrors the behaviour of discs around low-mass stars, with disc lifetimes of the order of 5-10 Myr and a disc clearing time-scale significantly shorter than 1 Myr.

ALMA Observations of ρ-Oph 102: Grain Growth and Molecular Gas in the Disk around a Young Brown Dwarf *L. Ricci (CalTech), L. Testi (ESO), A. Natta, A. Scholz, I de Gregorio-Monsalvo (Santiago de Chile)*

A. Natta and A. Scholz as part of a consortium have presented Atacama Large Millimetre Array (ALMA) continuum and spectral line observations of the young brown dwarf ρ-Oph 102 at about 0.89 mm and 3.2 mm. They detected dust emission from the disk at these wavelengths and derived an upper limit on the radius of the dusty disk of around 40 au. The derived variation of the dust opacity with frequency in the millimetre (mm) provides evidence for the presence of mm-sized grains in the disk's outer regions. This result demonstrates that *mm-sized grains are found even in the low-density environments of brown dwarf disks and challenges our current understanding of dust evolution in disks.* The CO map at 345 GHz clearly reveals molecular gas emission at the location of the brown dwarf, indicating a gas-rich disk as typically found for disks surrounding young pre-main-sequence stars. They derived a disk mass of 0.3%-1% of the mass of the central brown dwarf, similar to the typical values found for disks around more massive young stars. The results were published in Astrophysical Journal and the European Southern Observatory have made a press release of this discovery including a video http://www.eso.org/public/news/eso1248/.

Substellar Objects in Nearby Young Clusters (SONYC): The Planetary-mass Domain of NGC 1333 *A. Scholz, R. Jayawardhana (Toronto), K. Muzic (Toronto), V. Geers, Vincent, M. Tamura (Tokyo), I. Tanaka (Hilo, Hawaii)*

A. Scholz and V. Geers have continued their work as part of the SONYC (Substellar Objects in Nearby Young Clusters) survey, and have investigated the frequency of free-floating planetary-mass objects (planemos) in the young cluster NGC 1333. Building upon their extensive previous work, they have presented spectra for 12 of the faintest candidates from their deep multi-band imaging, plus seven random objects in the same fields, using MOIRCS on the Japanes Subaru Telescope. They confirm seven new sources as young very low mass objects (VLMOs), with T_{eff} of 2400-3100 K and mid-M to early-L spectral types. These objects add to the growing census of VLMOs in NGC 1333, now totalling 58. Three confirmed objects (one found in this study) have masses below 15 Jupiter masses, according to evolutionary models, thus are likely planemos. They estimate the total planemo population with 5 to 15 Jupiter masses M in NGC 1333 is around 8. The mass spectrum in this cluster is well approximated by $dN/dM \propto M^{-\alpha}$, with a single value of $\alpha = 0.6 \pm 0.1$ for masses less than 0.6 solar masses, consistent with other nearby star-forming regions, and requires $\alpha \leq 0.6$ in the planemo domain. These results in NGC 1333, as well as findings in several other clusters by this group and others, confirm that the star formation process extends into the planetary-mass domain, at least down to 6 Jupiter masses. However, given that planemos are 20-50 times less numerous than stars, their contribution to the object number and mass budget in young clusters is negligible. These findings *disagree strongly* with the recent claim from a micro-lensing study that free-floating planetary-mass objects are twice as common as stars. If the micro-lensing result is confirmed, those isolated Jupiter-mass objects must have a different origin from brown dwarfs and planemos observed in young clusters. Results have been published in Astrophysical Journal.

2.1.4 Outflows and Jets

Outflows from Brown Dwarfs. *E. Whelan, T. Ray, F. Comeron (ESO), F. Bacciotti (Florence), P. Kavanagh (Tübingen)*

Studies of the 24 Jupiter mass brown dwarf 2MASSJ12073347-3932540 using ESO's VLT have imaged a jet from a brown dwarf for the first time. In addition to the jet close to the source, knots were also seen to the south-west along the known outflow axis. The feature furthest from the source is bow-shaped, suggesting it is a supersonic shock, with the apex pointing away from 2MASSJ12073347-3932540. This is a first, as brown dwarf optical outflows have to date only been detected using the specialist technique of spectro-astrometry pioneered by the DIAS Star Formation Group. This result also demonstrates for the first time that BD outflows are highly collimated, episodic and a small-scale version of those seen in low mass stars. These results have been published in the Astrophysical Journal.

Very Large Array Observations of DG Tau's Radio Jet *C. Lynch (Iowa and DIAS), R. Mutel (Iowa), M. Güdel (Vienna), T.P. Ray, S. Skinner (Boulder), P.C. Schneider (Hamburg), K. Gayley (Iowa)*

The active young protostar DG Tau has an extended jet that has been well studied at radio, optical, and X-ray wavelengths. Lynch (Iowa/DIAS), T.P. Ray et al. have reported sensitive new Very Large Array (VLA) full polarization observations of the core and jet between 5 GHz and 8 GHz. Their high angular resolution observation at 8 GHz clearly shows an unpolarized inner jet with a size of 42 au ($0\farcs35$) extending along a position angle similar to the optical-X ray outer jet. Using their nearly coeval 2012 VLA observations, they find a spectral index $\alpha = +0.46 \pm 0.05$, which combined with the lack of polarization is consistent with bremsstrahlung (free-free) emission, with no evidence for a non-thermal coronal component. By identifying the end of the radio jet as the optical depth unity surface, and calculating the resulting emission measure, they find that their radio results are in agreement with previous optical line studies of electron density and consequent mass-loss rate. They also detect a weak radio knot at 5 GHz located $7\farcs0$ from the base of the jet, coincident with the inner radio knot detected in 2009 but at lower surface brightness. They interpret this as due to expansion of post-shock ionized gas in the three years between observations. The results will be published in Astrophysical Journal.

Jet Rotation Investigated in the Near-ultraviolet with the Hubble Space Telescope Imaging Spectrograph *D. Coffey, E. Rigliaco (Florence), F. Bacciotti (Florence), T.P. Ray, J. Eislöffel (Tautenburg)*

D. Coffey, T.P. Ray et al. have presented results of the second phase of their near-ultraviolet investigation into protostellar jet rotation using the Hubble Space Telescope Imaging Spectrograph. They have obtained long-slit spectra at the base of five T Tauri jets to determine if there is a difference in radial velocity between the jet borders which may be interpreted as a rotation signature. These observations are extremely challenging and push the limits of current instrumentation, but have the potential to provide long-awaited observational support for the magneto-centrifugal mechanism of jet launching in which jets remove angular momentum from protostellar systems. They successfully detected all five jet targets (from RW Aur, HN Tau, DP Tau, and CW Tau) in several near-ultraviolet emission lines, including the strong Mg II doublet. However, only RW Aur's bipolar jet presents a sufficiently high signal-to-noise ratio to allow for analysis. The approaching jet lobe shows a difference of 10 $\mathrm{km\,s^{-1}}$ in a direction which agrees with the disk rotation sense, but is opposite to previously published optical measurements for the receding jet. The near-ultraviolet difference is not found six months later, nor is it found in the fainter receding jet. Overall, in the case of RW Aur, differences are not consistent with a simple jet rotation interpretation. Indeed, given the renowned complexity and variability of this system, it now seems likely that any rotation signature is confused by other influences, with the inevitable conclusion that RW Aur is not suited to a jet rotation study. These results have been published in the Astrophysical Journal.

AMI radio continuum observations of young stellar objects with known outflows *R. Ainsworth (DIAS PhD student), A. Scaife, T.P. Ray and the AMI Consortium*

R. Ainsworth, A. Scaife, T.P. Ray and the Arcminute Micro-kelvin Imager (AMI) Consortium have presented 16 GHz (1.9 cm) deep radio continuum observations made with AMI) of a sample of low-mass young stars driving jets. We combine these new data with archival information from an extensive literature search to examine spectral energy distributions (SEDs) for each source and calculate both the radio and sub-mm spectral indices in two different scenarios: (1) fixing the dust temperature (T_d) according to evolutionary class; and (2) allowing T_d to vary. We use the results of this analysis to place constraints on the physical mechanisms responsible for the radio emission. From AMI data alone, as well as from model fitting to the full SED in both scenarios, we find that 80 per cent of the objects in this sample have spectral indices consistent with free-free emission. We find an average spectral index in both T_d scenarios, consistent with free-free emission. We examine correlations of the radio luminosity with bolometric luminosity, envelope mass and outflow force, and find that these data are consistent with the strong correlation with envelope mass seen in lower luminosity samples. We examine the errors associated with determining the radio luminosity and find that the dominant source of error is the uncertainty on the opacity index, β.

AMI-LA radio continuum observations of Spitzer c2d small clouds and cores: Serpens region *A. Scaife and the AMI Consortium*

A. Scaife and the AMI Consortium have presented deep radio continuum observations of the cores identified as embedded young stellar objects in the Serpens molecular cloud by the Spitzer c2d programme at a wavelength of 1.8 cm with the Arcminute Microkelvin Imager Large Array (AMI-LA). These observations have a resolution of approximately 30.″0 and an average sensitivity of 19 μJy beam^{-1}. The targets are predominantly Class I sources, and they find the detection rate for Class I objects in this sample to be low (18%) compared to that of Class 0 objects (67%), consistent with previous works. For detected objects they have examined correlations of radio luminosity with bolometric luminosity and envelope mass and find that these data support correlations found by previous samples, but do not show any indication of the evolutionary divide hinted at by similar data from the Perseus molecular cloud when comparing radio luminosity with envelope mass. They conclude that envelope mass provides a better indicator for radio luminosity than bolometric luminosity, based on the distribution of deviations from the two correlations. Combining these new data with archival 3.6 cm flux densities they have also examined the spectral indices of these objects and find an average spectral index consistent *with the canonical value for a partially optically thick spherical or collimated stellar wind*. However, they caution that possible inter-epoch variability limits the usefulness of this value, and such variability is supported by their identification of a possible radio flare in Serpens SMM 1. These results have been published in Monthly Notices of the Royal Astronomical Society.

2.1.5 Comparing the Magnetic Topologies of of Main Sequence and Pre-Main Sequence Stars

Can We Predict the Global Magnetic Topology of a Pre-main-sequence Star from Its Position in the Hertzsprung-Russell Diagram? *S.G. Gregory (CalTech), S. G., J.F. Donati (Toulouse), J.A. Morin, G.A. Hussain (ESO), N.J. Mayne (Exeter), L.A. Hillenbrand (CalTech), M. Jardine (St. Andrews)*

Zeeman-Doppler imaging studies have shown that the magnetic fields of T Tauri stars can be significantly more complex than a simple dipole and can vary markedly between sources. J. Morin and his collaborators have collected and summarized the magnetic field topology information obtained to date and have presented Hertzsprung-Russell (H-R) diagrams for the stars in the sample. Intriguingly, the large-scale field topology of a given pre-main-sequence (PMS) star is strongly dependent upon the stellar internal structure, with the strength of the dipole component of its multipolar magnetic field decaying rapidly with the development of a radiative core. Using the observational data as a basis, this group have argued that the general characteristics of the global magnetic field of a PMS star can be determined from its position in the H-R diagram. Moving from hotter and more luminous to cooler and less luminous stars across the PMS of the H-R diagram, they present evidence for four distinct magnetic topology regimes. Stars with large radiative cores, empirically estimated to be those with a core mass in excess of around 40% of the stellar mass, host highly complex and dominantly non-axisymmetric magnetic fields, while those with smaller radiative cores host axisymmetric fields with field modes of higher order than the dipole dominant (typically, but not always, the octupole). Fully convective stars above 0.5 M_{sun} appear to host dominantly axisymmetric fields with strong (kilo-Gauss) dipole components. Based on similarities between the magnetic properties of PMS stars and main-sequence M-dwarfs with similar internal structures, they speculate that a bistable dynamo process operates for lower mass stars (less than 0.5 M_{sun} at an age of a few Myr) and that they will be found to host a variety of magnetic field topologies. If the magnetic topology trends across the H-R diagram are confirmed, they may provide a new method of constraining PMS stellar evolution models.

2.2 High-Energy Phenomena

2.2.1 Radiation Processes

Theory of magneto-bremsstrahlung in strong

magnetic fields revisited. *S. R. Kelner and F. A. Aharonian*

The character of radiation of relativistic charged particles in strong magnetic fields largely depends on the disposition of particle trajectories relative to the field lines. The motion of particles with trajectories close to the curved magnetic lines is usually referred to the so-called curvature radiation. The latter has been treated within the formalism of synchrotron radiation by replacing the particle Larmor radius with the curvature radius of the field lines. However, even at small pitch angles, the curvatures of the particle trajectory and the field line may differ significantly. Moreover, the trajectory curvature varies with time, i.e. the process has a stochastic character. Therefore for calculations of observable characteristics of radiation by an ensemble of particles, the radiation intensities should be averaged over time. In this paper, for determination of particle trajectories we use the Hamiltonian formalism, and show that that close to curved magnetic lines, for the given configuration of the magnetic field, the initial point and particle energy, always exist a smooth trajectory without fast oscillations of the curvature radius. This is the trajectory which is responsible for the curvature radiation. The result might have direct relation to the recent spectral measurements of gamma-radiation of pulsars. This work has been submitted to Phys Rev D [99].

Nuclear reactions in subrelativistic astrophysical plasmas *E. Kafexhiu, F. A. Aharonian, G. S. Vila, M. Barkov and R. A. Sunyaev*

The importance of nuclear reactions in low-density astrophysical plasmas with ion temperatures $T \geq 10^{10}$ K K has been recognized for almost thirty years ago (Aharonian and Sunyaev 1984). However, the lack of comprehensive data banks of relevant nuclear reactions and the limited computational power have not previously allowed detailed theoretical studies. Recent developments in these areas make it timely to conduct comprehensive studies on the nuclear properties of very hot plasmas formed around compact relativistic objects such as black holes and neutron stars. Such studies are of great interest in the context of scientific programs of future low-energy cosmic ?-ray spectrometry. In this work, using the publicly available code TALYS, we have built a large nuclear network relevant for temperatures exceeding 10^{10} K We have studied the evolution of the chemical composition and accompanying prompt gamma-ray emission of such high-temperature plasmas. We present the results on the abundances of light elements D, T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, and briefly discuss their implications on the astrophysical abundances of these elements. In the subsequent paper we have studied also the gamma-ray emissivity due to the capture of neutrons by protons, p-n bremsstrahlung, and gamma-rays from decays of neutral pions produced at pp interactions in different regimes of accretion flows [47].

Analytical expressions for inverse Compton radiation close to the cutoff energy. *E. Lefa, S. R. Kelner, F. A. Aharonian*

The spectral shape of radiation due to inverse Compton scattering is analyzed in the Thomson and the Klein-Nishina regime for distributions of relativistic electrons with exponential cutoff. Simple analytical expressions for the gamma-ray spectra spectrum close to the maximum cutoff region are derived. Planckian (black-body) radiation and the synchrotron photons as target photon fields. for inverse Compton scattering have been analyzed. These approximations provide a direct link between the distribution of parent electrons and the upscattered gamma-ray spectrum in the cutoff region [50].

2.2.2 Ultrarelativistic electron-positron pulsar winds

F. A. Aharonian, D. Khangulyan, S. I. Bogovalov, D. Malyshev and M. Ribo

Pulsars are thought to eject electron-positron winds that energize the surrounding environment, with the formation of a pulsar wind nebula. The pulsar wind originates close to the light cylinder, the surface at which the pulsar co-rotation velocity equals the speed of light, and carries away much of the rotational energy lost by the pulsar. Initially the wind is dominated by electromagnetic energy (Poynting flux) but later this is converted to the kinetic energy of bulk motion. It is unclear exactly where this takes place and to what speed the wind is accelerated. Although some preferred models imply a gradual acceleration over the entire distance from the magnetosphere to the point at which the wind terminates, a rapid acceleration close to the light cylinder cannot be excluded. Based on the recent observations of pulsed, very high-energy γ-ray emission from the Crab pulsar by the MAGIC and VERITAS collaborations, we have proposed that the latter can be best explained by the presence of a 'cold' ultrarelativistic wind dominated by kinetic energy. The conversion of the Poynting flux to kinetic energy should take place abruptly in the narrow cylindrical zone of radius between 20 and 50 light-cylinder radii centred on the axis of rotation of the pulsar, and should accelerate the wind to a Lorentz factor of $(0.5-1.0)\times 10^6$.

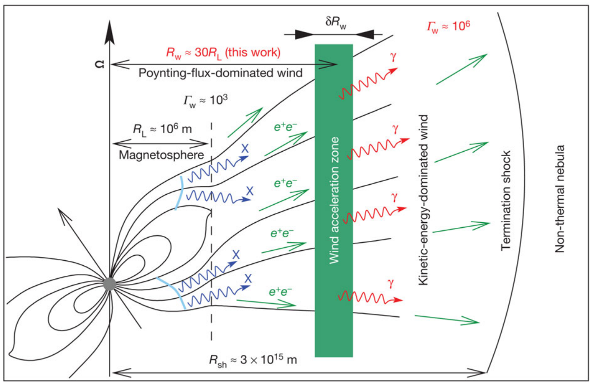

Figure 1:

The second evidence of a signal from the unshocked pulsar wind we found from the binary pulsar PSR B1259-63/LS2883. Namely, we claimed that the bright gamma-ray flare of this object detected by the *Fermi* telescope is due to the inverse Compton scattering of the unshocked electron-positron pulsar wind with a Lorentz factor $\Gamma_0 \approx 10^4$. The combination of two effects, both linked to the circumstellar disk (CD), is a key element in the proposed model. The first effect is related to the impact of the surrounding

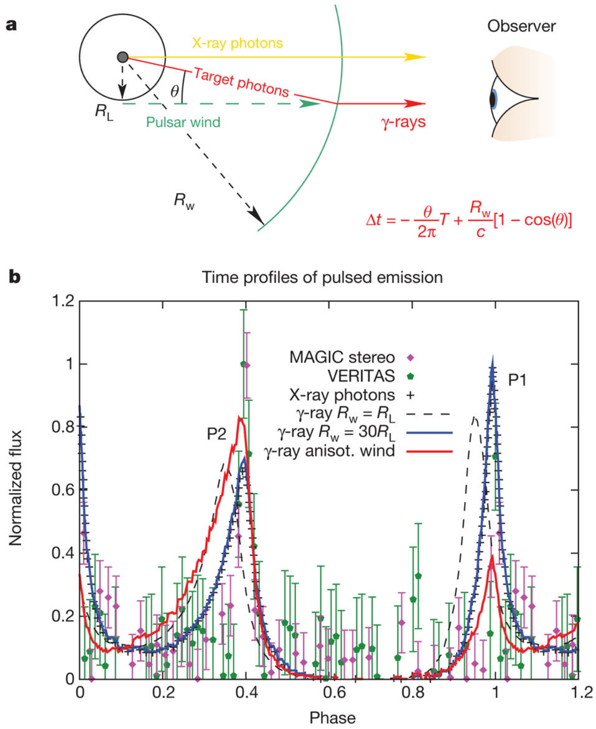

Figure 2:

medium on the termination of the pulsar wind. Inside the disk, the 'early' termination of the wind results in suppression of its gamma-ray luminosity. When the pulsar escapes the disk, the conditions for termination of the wind undergo significant changes. This could lead to a dramatic increase of the pulsar wind zone, and thus to the proportional increase of the gamma-ray flux. On the other hand, if the parts of the CD disturbed by the pulsar can supply infrared photons of density high enough for efficient Comptonization of the wind, almost the entire kinetic energy of the pulsar wind would be converted to radiation, thus the gamma-ray luminosity of the wind could approach the level of the pulsar's spin-down luminosity as reported by the Fermi Collaboration.

The energy spectrum of IC radiation of the unshocked pulsar wind strongly depends on the spectrum of the target photon field. If it dominates by a hot thermal radiation emitted, for example, from the surface of the neutron star, we should expect a sharp spectral feature formed in the deep Klein-Nishina regime with an energy $E = m_e c^2 \Gamma_0$. This scenario of formation of a line-like spectral feature above 100 GeV, has been invoked by us as an alternative source for the narrow gamma-ray line at 130 GeV reported recently from the direction of the Galactic Center. This explanation is alternative to the interpretation that refers the reported 130 GeV line to the annihilation of Dark Matter. In this paper we argue that cold ultrarelativistic pulsar winds can be alternative sources of very narrow gamma-ray lines. The confirmation of this exciting gamma-ray line emission by future independent measurements would be crucial for resolving the spatial structure of the reported hotspots, and thus for distinguishing between the dark matter and pulsar origins of this unusual spectral feature.

This work was published in Nature [6] as well as in [48, 7]

2.2.3 MHD simulations and implications for radiation of relativistic outflows

S. Bogovalov, D. Khangulyan, A. Koldoba, G. Ustyugova and F. A. Aharonian The high energy gamma-ray emission of relativistic outflows like pulsar winds or AGN jets has been one of the central research topics of our group. While in our previous studies we put an emphasis on the modeling of radiation processes, recently we started to pay more attention to the (magneto)hydrodynamics of the relativistic outflows interacting with surrounding medium. In particular,

(ii) Interaction of the pulsar and stellar winds in the binary system PSR B1259-63/SS2883. We studied the impact of the strength of magnetic field and the wind anisotropy on the character of interaction of the relativistic pulsar wind with the non-relativistic stella wind. We showed, in particular, that although both effects change the shape of the region occupied by the terminated pulsar wind, their impact appears to be small. In particular, for the magnetization of the pulsar wind below 0.1, the magnetic field pressure remains well below the plasma pressure in the post-shock region. This is opposite to the case of the pulsar wind nebulae where the magnetic field becomes dynamically important independent of the level of the wind magnetization [19].

(ii) Simulations of stellar/pulsar-wind interaction along one full orbit.

V. Bosch-Ramon, M. Barkov, D. Khangulyan, M. Perucho The winds from a non-accreting pulsar and a massive star in a binary system collide forming a bow-shaped shock structure. The Coriolis force induced by orbital motion deflects the shocked flows, strongly affecting their dynamics. Relativistic hydrodynamical simulations in two dimensions, performed with the code PLUTO and invoking the adaptive mesh refinement technique, have been used to model the interacting stellar and pulsar winds on scales 80 times the distance between the stars. In addition to the shock formed towards the star, the shocked and unshocked components of the pulsar wind flowing away from the star terminate by means of additional strong shocks produced by the orbital motion. Strong instabilities lead to the development of turbulence and an effective two-wind mixing in both the leading and trailing sides of the interaction structure, which starts to merge with itself after one orbit. Simulations show that shocks, instabilities, and mass-loading yield efficient mass, momentum, and energy exchanges between the pulsar and the stellar winds. This renders a rapid increase in the entropy of the shocked structure. Several sites of particle acceleration and low- and high-energy emission have been identified. Doppler boosting might have significant effect on radiation [22].

2.2.4 Clouds and red giants interacting with AGN jets.

Extragalactic jets are formed by supermassive black-holes located in the centers of galaxies. Large amounts of gas clouds and stars clustered in the galaxy nucleus interact with the jet with important impact on the dynamics of the jet and its mass-loading. These interactions have been studied in the innermost regions of an extragalactic jet using relativistic hydrodynamical simulations with axial symmetry carried out for homogeneous and inhomogeneous clumps inside the relativistic jet. These clumps may represent a medium inhomogeneity or a disrupted atmosphere of a red giant star. Once inside the jet, the clump expands and gets disrupted after few dynamical timescales. In the inhomogeneous case, a solid core can smoothen the process with the clump mass-loss dominated by a dense and narrow tail along the direction of the jet. In either case, matter of the clump is expected to be eventually incorporated to the jet. Particles, electrons and positrons, can be accelerated in the interaction region, and produce variable gamma-rays at interactions with the ambient plasma, magnetic and radiation fields. Very fast flare-like gamma-ray events, are expected due to these interactions. We demonstrated this interesting feature of the jet-star interaction scenario, and propose viable models for explanation of the rapid TeV variability of the blazar PKS 2155-304 on minute scales, as well as the gamma-ray lightcurve of the nucleus of the nearby radiogalaxy M 87 [21, 17, 16]

2.2.5 Propagation of protons and gamma-rays through intergalactic radiation and magnetic fields

A. Prosekin, W. Essey, A. Kusenko and F.A. Aharonian

Blazars are expected to produce both gamma rays and cosmic rays. Therefore, observed high-energy gamma rays from distant blazars may contain a significant contribution from secondary gamma rays produced along the line of sight by the interactions of cosmic-ray protons with background photons through the Bethe-Heitel pair production and photomeson processes. The electrons and gamma-rays produced in these interactions initiate electromagnetic cascades through the photon-photon pair production and the inverse Compton scattering. The cascade photons contribute to signals of point sources only if the intergalactic magnetic fields are very small, less than 10-15 G, and their detection can be used to set upper bounds on magnetic fields along the line of sight. Secondary gamma rays have distinct spectral and temporal features. We explored the temporal properties of such signals using a semi-analytical formalism and detailed numerical simulations, which account for all the relevant processes, including magnetic deflections. In the case of very small intergalactic magnetic field, the photon-electron cascades can contribute significantly to the gamma-ray emission of distant blazars. At very high energies, the gamma-ray horizon of the universe is limited to redshifts $z \ll 1$, and, therefore, any observation of TeV radiation from a source located beyond z=1 would call for a revision of the standard paradigm. While robust observational evidence for TeV sources at redshifts $z > 1$ is lacking at present, the growing number of TeV blazars with redshifts as large as $z \approx 0.5$ suggests the possibility that the standard blazar models may have to be reconsidered. We show that TeV gamma rays can be observed even from a source at $z > 1$, if the observed gamma rays are secondary photons produced in interactions of high-energy protons originating from the blazar jet and propagating over cosmological distances almost rectilinearly. This mechanism was initially proposed as a possible explanation for the TeV gamma rays observed from blazars with redshifts $z \approx 0.2$, for which some other explanations were possible. For TeV gamma-ray radiation detected from a blazar with $z > 1$, this model would provide the only viable interpretation consistent with conventional physics. It would also have far-reaching astronomical and cosmological ramifications. In particular, this interpretation would imply very weak extragalactic magnetic fields along the line of sight (in the range $0.01\,\mathrm{fG} < B < 1\,\mathrm{fG}$) and very effective acceleration of $E > 0.1\,\mathrm{EeV}$ protons in the jets of active galactic nuclei. [60, 94]

2.2.6 High Energy Processes in the Galactic Center

D. Jones, R. Crocker, W. Reich, J. Ott and F. A. Aharonian

Over the last several years, the central region of our Galaxy has been in the focus of interest of our group in general, and in the context of nonthermal processes, in particular. These processes proceed on different scales, from the compact regions near the central black hole Sag

A* to the 200 pc radius dense molecular zone, and giant gamma-ray structures, the so-called Fermi Bubbles - two enormous gamma-ray structures symmetrically extending to approximately 10 kpc above the Galactic plane. Recently we found a correspondence between giant, polarized microwave structures emerging north from the Galactic plane near the Galactic center and a number of GeV gamma-ray features, including the eastern edge of the recently discovered northern Fermi Bubble. The polarized microwave features also correspond to structures seen in the all-sky 408 MHz total intensity data, including the Galactic center Spur. The magnetic field structure revealed by the Wilkinson Microwave Anisotropy Probe polarization data at 23 GHz suggests that neither the emission coincident with the Bubble edge nor the Galactic center Spur are likely to be features of the local interstellar medium. On the basis of the observed morphological correspondences, similar inferred spectra, and the similar energetics of all sources, we proposed a direct connection between the Galactic center Spur and the northern Fermi Bubble. [46]

2.2.7 Light curves of soft X-ray transients in M31

N. Nooraee

Disc irradiation is thought to be capable of explaining the global behaviour of the light curves of soft X-ray transients (SXTs). Depending on the strength of the central X-ray emission in irradiating the disc, the light curve may exhibit an exponential or a linear decay. The model predicts that in brighter transients a transition from exponential decline to a linear one may be detectable. In this study, having excluded supersoft sources and hard X-ray transients, a sample of bright SXTs in M31 ($L_{\rm peak} > 10^{38}\,{\rm erg\,s^{-1}}$) has been studied. The expected change in the shape of the decay function is only observed in two of the light curves from the six light curves in the sample. Also, a systematic correlation between the shape of the light curve and the X-ray luminosity has not been seen.

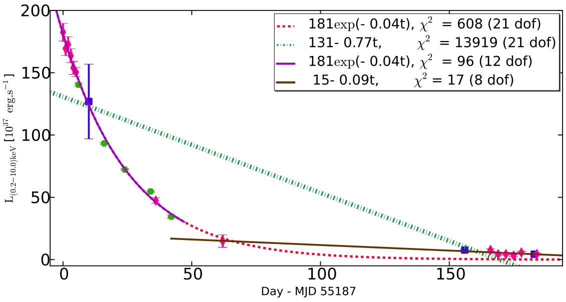

Figure 3: The X-ray light curve of CXOM31 J004253.1+411422 during its outburst based on data taken with three telescopes (Chandra/ACIS, the green hexagonal is XMM/EPIC-PN and the red diamond is Swift/XRT). Various combinations of exponential and linear fits to the data are also shown.

2.2.8 Superorbital modulation of X-ray emission from gamma-ray binary LSI +61 303

M. Chernyakova, A. Neronov, S. Molkov, A. Lutovinov, D. Malyshev and G. Pooley

We report the discovery of a systematic constant time lag between the X-ray and radio flares of the gamma-ray binary LSI +61 303, persistent over a long, multi-year timescale. Using the data from the monitoring of the system by RXTE we show that the orbital phase of X-ray flares from the source varies from ϕ_X 0.35 to ϕ_X 0.75 on the superorbital 4.6 yr timescale. Simultaneous radio observations show that periodic radio flares always lag the X-ray flare by $\delta\phi_{X-R}$ 0.2. We propose that the constant phase lag corresponds to the time of flight of the high-energy particle-filled plasma blobs from inside the binary to the radio emission region at the distance of 10 times the binary separation distance. We put forward a hypothesis that the X-ray bursts correspond to the moments of formation of plasma blobs inside the binary system.

2.2.9 Search for variable gamma-ray emission from the Galactic plane in the Fermi data

M. Chernyakova, A. Neronov, D. Malyshev, A. Lu-

tovinov and G. Pooley

High-energy gamma-ray emission from the Galactic plane above 100 MeV is composed of three main contributions: diffuse emission from cosmic ray interactions in the interstellar medium, emission from extended sources, such as supernova remnants and pulsar wind nebulae, and emission from isolated compact source populations. The diffuse emission and emission from the extended sources provide the dominant contribution to the flux almost everywhere in the inner Galaxy, preventing the detection of isolated compact sources. In spite of this difficulty, compact sources in the Galactic plane can be singled out based on the variability properties of their gamm-ray emission. Our aim is to find sources in the Fermi data that show long-term variability. We performed a systematic study of the emission variability from the Galactic plane, by constructing the variability maps. We found that emission from several directions along the Galactic plane is significantly variable on a time scale of months. These directions include, in addition to known variable Galactic sources and background blazars, the Galactic ridge region at positive Galactic longitudes and several regions containing young pulsars. We argue that variability on the time scale of months may be common to pulsars, originating from the inner parts of pulsar wind nebulae, similarly to what is observed in the Crab pulsar.

2.3 General Theory

2.3.1 Magnetic field amplification.

L. O'C. Drury and T. P. Downes

This is a current 'hot topic' in particle acceleration theory because it promises to resolve some of the major difficulties associated with the limitations on the maximum attainable energy. Most discussions have focused on a mechanism proposed by A Bell which is driven by the current of the accelerated particles[69]. There is an alternative mechanism driven simply by the pressure of the accelerated particles which offers some significant advantages, but which has not been explored in as much depth. In collaboration with Turlough Downes a simple toy computational model was developed and first numerical simulations carried out to confirm the potential of this process. [34]

2.3.2 Acceleration by Magnetic Reconnection.

L. O'C. Drury and V. Bosch-Ramon

There has been speculation that magnetic reconnection can drive a Fermi acceleration process analogues to diffusive shock acceleration. Some errors in the previous literature were pointed out and the limitations of this process discussed. [20, 32]

2.4 Invited talks and other conference activities

Felix Aharonian gave an invited talk on "X-ray emission of secondary electrons as a tool for probing hadronic sources" at the workshop 'Exploring nonthermal Universe with ASTRO-H', Hakone, Japan, 17-19 May , 2012;

gave an invited talk on 'High Energy Gamma Sources at the conference '100 years of cosmic rays', Bad Saarow, Germany, 5-8 Aug, 2012;

gave the summary talk on 'The origin of Galactic cosmic rays' at the workshop 'Searching for the sources of galactic cosmic rays', Paris, France, 12-14 Dec, 2012.

was the main organizer (Chair of SOC) of the 5th International Symposium on "High Energy Gamma-Ray Astronomy", 9-13 July, Heidelberg, Germany. This is the 5th of the largest regular (once per 4 years) meeting on gamma ray astronomy which he initiated in the mid 1990s;

participated, as a member of SOC, in the organization of the following scientific meetings: Positrons in Astrophysics (International Workshop; March 20-23, 2012, Mörren, Bernese, Oberland, Switzerland; Near Infrared Background and the Epoch of Reionization, May 14-15, Austin, Texas, USA; Science with the New Generation of High Energy Gamma-ray Experiments Lecce, Italy, June 20-22, 2012; 100 years of Cosmic Rays - Anniversary of their Discovery by Victor Hess, Bad Saarow, Germany, 5-8 Aug, 2012; CTA-LINK meeting, Buenos-Aires, Argentine, Nov 19-21; 26th Texas Symposium on Relativistic Astrophysics Sao Paulo, Brazil, December 15-20, 2012.

Luke Drury gave the opening invited talk at a conference in Poellau, Austria, to mark the centenary of Victor Hess's discovery of cosmic rays;

participated in the ESOF2012 event and introduced the key-note event commemorating Schroedinger's 'What is Life?' lectures as well as chairing a session on Black Holes;

gave a talk on Magnetic Field Amplification in SNR shocks' at the festconference to honour Felix Aharonian's 60th birthday held in Barcelona.

Valenti Bosch-Ramon gave invited talks on:

'High-energy process in gamma-ray binaries', 5th International Symposium on High-Energy Gamma-Ray Astronomy, July Heidelberg, Germany, 9-14 July, 2012;

'Gamma-ray emission from high-mass X-ray binaries', COSPAR 2012, Misore, India, 14-22 July, 2012;

'Gamma-Ray Binaries, Exploring the Non-thermal Universe with Gamma Rays', Barcelona, Spain, 6-9 November, 2012.

3 Contributions to Third-level Education

Felix Aharonian gave two lectures on 'Active galactic nuclei from radio to gamma-rays' as a part of the course of 'Astrophysical and Space Plasmas' at the International School of Space Science, L'Aquila (Italy), September 3-7, 2012;

gave three lectures on 'Gamma Rays from Active Galactic Nuclei' (1. Introduction, 2. Production sites, acceleration/radiation mechanisms, 3. Cosmological implications) at the at the School of the IRAP Ph.D. Erasmus Mundus Joint Doctorate Program (University of Nice), 3-21 September, 2012.

supervised 2 PhD students in DIAS, 4 PhD students in MPIK, Heidelberg, and 1 PhD student in the La Sapienza University of Rome (3 received their PhD in 2012)

Tom Ray gave a course of 9 lectures on introductory Astronomy and Astrophysics to Junior Freshman students and 14 lectures on Galactic Dynamics to Junior Sophister students in TCD Physics. He also gave lectures as part of the course of Astrophysical and Space Plasmas' at the International School of Space Science, L'Aquila (Italy), September 3-7, 2012; supervised 4 DIAS PhD students Paul Dawson, Rachael Ainsworth and Grainne Costigan and Donna Lee Rodgers (from Trinity College Dublin) from 1st December. Grainne Costigan (the Lindsay Scholar jointly with Armagh Observatory) is currently on a stipend funded by the European Southern Observatory at ESO Headquarters in Garching, Germany.

Luke Drury served as a member of the Search Committee for the next President of UCD which met on several occasion during the year.

Alex Scholz co-supervised DIAS the PhD students, Paul Dawson and Grainne Costigan.

Vincent Geers co-supervised Donna Rodgers Lee.

4 Contributions to research infrastructure and public service

4.1 Space Missions: JWST and EChO

The Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope. In early 2012 the MIRI Flight Model (FM) completed testing at the Rutherford Appleton Laboratories in Oxford before being shipped to NASA Goddard following acceptance by the NASA/ESA Delivery Review Board (DRB). At Goddard, it is currently (November 2012) being integrated into the Instrument Science Module (ISM) with the Fine Guidance Sensor (FGS) and Near-InfraRed Imaging Slitless Spectrograph (NIRISS) from Canada. DIAS personnel will attend a training session in NASA Goddard in December with the intention of supporting the first combined test of MIRI, the FGS and NIRISS in the Goodard cryo-chamber around March 2013. Two new people have been recruited to the MIRI project from December 2012 with funding for the next 3 years through ESA's PRODEX Office. They are Ruymán Azzollini (formerly INTA, Madrid) and Vincent Geers (formerly ETH, Zurich). Both will play a key role in the development of data analysis software for MIRI in collaboration with the Space Telescope Science Institute in Baltimore.

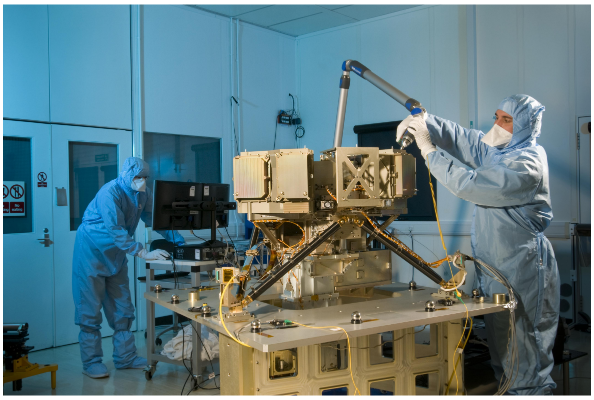

Figure 4: MIRI being aligned at the Rutherford Appleton Laboratory prior to its shipment to NASA Goddard. The emphasis at DIAS has now shifted to development of MIRI data analysis software and improved pipeline calibration.

Exoplanet Characterisation Observatory (EChO). DIAS has become a partner (T.P. Ray is a Co-PI) in the proposed Exoplanet Characterisation Observatory (EChO). This space observatory aims to analyse the atmospheres of planets around neighbouring stars and is currently being considered by ESA as an M-Class mission. EChO uses the principle that during a primary transit, when a planet crosses in front of its host star, the star's light passes through the edge of the planet's atmosphere, effectively providing an atmospheric transmission spectrum. In contrast the dip in its flux at infrared wavelengths reveals the emission, and at optical wavelengths, the reflection, spectrum of the planet during a secondary eclipse when the planet goes behind its star. Light-curves can thus be built up that map the temperature and composition of an exoplanet. It is envisaged, assuming the mission is accepted by ESA, that DIAS will provide beam splitters for the on board spectrometer and that it will also be involved, with Rutherford Appleton Laboratory, in establishing the infra-red detector characteristics and developing data analysis software for the detectors.

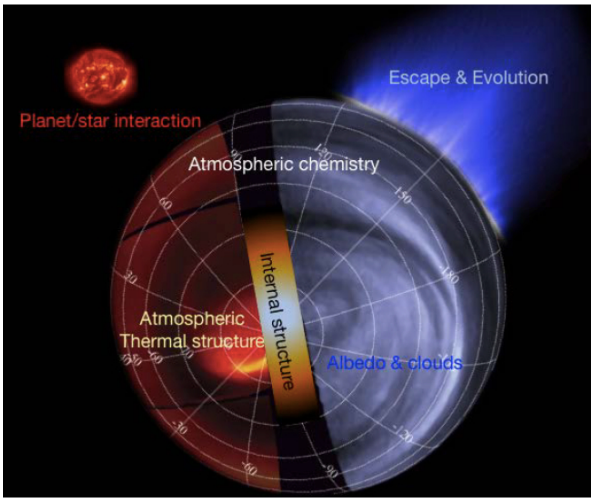

Figure 5: The Exoplanet Characterisation Observatory (EChO) is a medium sized mission currently being proposed to ESA. This figure illustrates its main objectives. T.P. Ray has joined the Consortium as Co-Principal Investigator. EChO will study the atmospheres of exoplanets using planetary transits.

4.2 HESS, Fermi, ASTRO-H, KM3NeT, CTA

The high-energy and astroparticle physics group in DIAS remains an active member of the HESS collaboration and participates in the production of high-impact papers of HESS. We also are involved in the data analysis, interpretation and publication of results based on the publicly available data banks of the the Fermi Large Array Telescope (LAT). We actively participate in the process of writing papers on the potential of the future gamma-ray (CTA) and neutrino (KM3NeT) telescopes. Finally, we play an important role in the preparation of scientific program of the future X-ray mission ASTRO-H.

4.3 e-Inis

The Institute-led e-INIS project to develop the shared national e-Infrastructure achieved further significant impact during 2012 before working toward project closure at year-end.

The National HPC Service operated by project partners ICHEC (Irish Centre for High End Computing) continues to fulfill a key enabling role across a broad and growing range of research disciplines in Ireland. In excess of 70 peer-reviewed publications were supported by access to ICHEC resources over the 2012 calendar year. Demand for the national HPC service continues to grow and this is no doubt partly attributable to the excellent user support and the development of the computational science community through ongoing training programmes. User support, training and improved access are key e-INIS funded activities within ICHEC.

In the early part of the year, the e-INIS project co-ordinator Keith Rochford was seconded to ICHEC to assist with the administration of the centre during a difficult period of transition. During that secondment, Keith played a significant role in the preparation of several funding proposals to sustain and enhance the Centre including a successful SFI recurrent award (M€1.4) and the Centre's response to the SFI equipment call to renew the compute infrastructure on which the national HPC service is operated (M€4.6).

It is regrettable that Grid-Ireland, Ireland's National Grid Initiative and partner in the EU EGEE and EGI projects, was forced to wind down operations in the latter part of the year and the Grid operation centre hosted at TCD closed officially on December 31st. As an active participant in the e-INIS collaborations, Grid-Ireland made significant contributions to the international Grid computing effort although a lack of domestic user-demand (and hence recognition of value) has led to a shortage of the recurrent funding required to maintain operations.

The users of the grid-connected computational resources are expected to migrate to the HPC systems operated by ICHEC and TCHPC and the Institute has worked with Grid-Ireland and HEAnet to migrate the essential Certificate Authority (CA) service to HEAnet, ensuring continuity of this service. The CA service is required for access to many of the shared e-infrastructure resources across Europe.

Ireland's capacity for data-driven and data-intensive research was further bolstered with the addition of a new node on the federated national data store. Following an full EU public procurement exercise led by the Institute, an additional 900 terabytes of storage capacity with associated storage interconnect and front-end service platform was installed in the UCD hosting centre adjacent to the home of the e-INIS HPC cluster, Stokes. This brings the total available storage capacity brought online during the project to 2039 TB. Recognising that the useful life of this infrastructure extends considerably beyond the life of the project, the e-INIS project executive agreed to the Institute's recommendation that the management of this latest resource be taken on by ICHEC and that it be operated in conjunction with the HPC service. We expect ICHEC to leverage the synergy achieved through the integration of data and HPC to foster further expertise in the areas of analytics and data-intensive computing.

The Institute has engaged with HEAnet and ICHEC to rationalise the design of the e-INIS high-performance network infrastructure deployed in 2008 to integrate the distributed shared

ICT resources across Ireland. The re-design aims to meet current demand from the research community while reducing the overall cost of network operations. In the absence of a budget for continued operation, a number of the links on the network have been decommissioned or downgraded. It is anticipated that growing demand from the user community will demand improved performance and justify further investment in the medium-term.

The e-INIS project has significantly advanced both the capability and capacity of the ICT infrastructure available to Irish researchers and their international collaborators. In light of the diminished available funding we have undertaken the rationalisation and consolidation of activities as required to sustain essential levels of service and to support the continued advancement and competitiveness of Irish research.

4.3.1 Individual Contributions

Felix Aharonian as the newly-elected vice president of the Division of the International Astronomical Union (IAU) 'High Energy Phenomena and Fundamental Physics' participated in the process of restructuring of the Divisions of IAU, creation of new Commissions and Working Groups, etc; as the ESA representative in the ASTRO-H project, during his 6weeks visit to ISAS/JAXA (Tokyo, Japan) in April-May 2012, has been leading work on the preparation of the scientific program of the ASTRO-H satellite related to the non-thermal aspects of observations with this X-ray mission; participated in the preparation of the document 'Pathway to the Square Kilometer Array (the German White paper)' ;served as an editor of the International Journal of Modern Physics.

Luke Drury served as a panel member evaluating ERC starter and consolidator proposals in January and March. In each case this involved several days in Brussels as well as considerable prior preparation; as President of the RIA, co-ordinated the production of a working paper on third-level governance at the request of the Minister for Education; helped tp organise the Dialogue Forum on Research Funding. http://www.ria.ie/ria/media/riamedialibrary/documents/about/policy%20documents/research-dialogue-report-16-novx.pdf; served as a member of advisory oversight board of the Irish Centre for High-End Computing (ICHEC).

Tom Ray became a member of the European Southern Observatory's Observing Programme Committee (OPC) and a Panel Chair (Interstellar Medium, Star Formation and Solar System) for the European Southern Observatory; he served in Brussels on the Marie Curie Fellowship Physics Panel; served on the Council of the Royal Irish Academy; served as Postgraduate Studies Advisor to the School, served on the Science and Technology Facilities Council (STFC) e-MERLIN Steering Committee; served on the RIA Astronomy and Space Science Committee; served on ESA's MIRI Steering Committee, served as a member of the irish Fulbright Panel.

Aleks Scholz became an advisor to the European Southern Observatory's OPC.

Malcolm Walmsley continued to serve as an editor of Astronomy and Astrophysics.

Antonella Natta served as a panel member evaluating ERC starter and consolidator proposals in January and March.

5 Public Outreach

The main, though not exclusive, focus of outreach work in the section is through Dunsink Observatory. In addition to the standard open-night events (see below) of which there were 12, including 4 family orientated evenings, and other special interest groups visiting there were three noteworthy developments. Firstly, we were able to run for the first time an event in cooperation with an industrial partner; DELL corporation organized a successful national HPC event in Dunsink and were delighted with the facilities available. Secondly, the Department of Education ran an in-house training event for primary teachers on astronomy in the curriculum using Dunsink. Thirdly, both a group from TCD and one from the NUI have made use of Dunsink as a location for an away-day period of strategic review. It is clear that the facility is addressing a real need and we may expect increased demand as word spreads.

Detailed List of Events Family Evening Events: 7th March, 23rd March, 10th April, and 25th October.

Normal Public Open Nights: 18th January, 1st February, 22nd February, 21st March, 28th March, 3rd October, 17th October 2012, and 7th November 2012.Special Day/Evening Events 2012: 8th February, UCD Group; 16th February, Failte Ireland; 6th March, DCU; 14th March, Marino College Group; 14th March, ESB; 28th March, Hamilton Festival; 26th March, SCP Board Meeting; 3rd April, Fingal County Council Meeting with DIAS; 20th April, Meeting with Fingal Planners; 21st June, TCD School of Physics Away Day; 23rd June, Solarfest; 2nd – 6th July, Teacher Training Week; 6th July, Italian Student Group; 20th July, Teagasc; 6th August , Zara Gifted Children Day; 22nd September, West of Ireland Astronomy Society; 21st September, Dublin City of Culture Evening; 16th October, Hamilton Walk; 18th October, Dell Day; 19th October, Poterstown Beavers Group; 24th October, Dunboyne Club; 25th October, Fingal Historial Society; 28th October, Russian Embassy Culture Day; 7th October, TCD Transition Year Group; 12th – 16th November, Science Week; 21st November, Trinity Biomedical Science Institute.

Dunsink Observatory was very busy during Science Week which ran from the 12th to the 16th November. There were day sessions for national schools from Wicklow, Kildare, Meath and Dublin and, in addition, evening sessions for secondary schools from Dublin City and its surroundings. In total 10 groups visited the observatory.The speakers, all who were from DIAS or with strong DIAS connections, who volunteered to gave talks in Dunsink Observatory during 2012, either for special events or the normal public open nights, included: Luke Drury, Tom Ray, Aleks Scholz, Andrew Taylor, Rachel Ainsworth, Iurii Babyk, Grainne Costigan, Paul Dawson, Turlough Downes, Emma Whelan, Nakisa Nooraee, Gareth Murphy, Lisa Fallon, Sean Delaney, Paul Dempsey, Masha Chernyakova, Valenti Bosch-Ramon, and Keith Rochford. In addition Peter Gallagher, Brian Espey and David Malone from TCD gave talks as did Brendan Boulter from Dell (Science Week) and Fergal Mullaly from NASA on the Kepler Mission on 27th June and 26th December.

Detailed organisation for many of the above events was carried out by Hilary O'Donnell. She was assisted by DIAS technical staff members, Eileen Flood and Anne Grace, on numerous occasions. Moreover, as in previous years volunteers from the Irish Astronomical Society and the Irish Astronomical Association helped out. In particular Terry Moseley, Michael O'Connell, John Flannery, Deirdre Kelleghan, Val Dunne and Robin Moore enthusiastically talked to the public about the beauty of the Night Sky.

Figure 6: Prof Clive Ruggles, Minister Joan Burton and Luke Drury at the launch of the Irish Astronomy Trail in Dunsink Observatory

In addition to this use as a meeting venue, the more conventional outreach aspect can only expect to grow after the launch of the Irish Astronomy trail and the great success of opening for the first time as part of Culture night.

6 Detailed Bibliography of Publications

Note that where possible hyperlinks have been provided to the journal article and preprint version.

6.1 Peer-reviewed Publications in 2012

[1] A. Abramowski et al. “Discovery of extended VHE γ-ray emission from the vicinity of the young massive stellar cluster Westerlund 1”. In: A&A 537, A114 (Jan. 2012), A114. DOI: 10.1051/0004-6361/201117928. arXiv:1111.2043 [astro-ph.HE].

[2] A. Abramowski et al. “Probing the extent of the non-thermal emission from the Vela X region at TeV energies with H.E.S.S.” In: A&A 548, A38 (Dec. 2012), A38. DOI: 10.1051/0004-6361/201219919. arXiv:1210.1359 [astro-ph.HE].

[3] A. Abramowski et al. “Search for Dark Matter Annihilation Signals from the Fornax Galaxy Cluster with H.E.S.S.” In: ApJ 750, 123 (May 2012), p. 123. DOI: 10.1088/0004-637X/750/2/123. arXiv:1202.5494 [astro-ph.HE].

[4] A. Abramowski et al. “Spectral Analysis and Interpretation of the γ-Ray Emission from the Starburst Galaxy NGC 253”. In: ApJ 757, 158 (Oct. 2012), p. 158. DOI: 10.1088/0004-637X/757/2/158. arXiv:1205.5485 [astro-ph.HE].

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[12] AMI Consortium et al. “Arcminute Microkelvin Imager observations of unmatched Planck ERCSC LFI sources at 15.75 GHz”. In: MNRAS 421 (Mar. 2012), pp. L6–L10. DOI: 10.1111/j.1745-3933.2011.01195.x. arXiv:1110.1454 [astro-ph.GA].

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2012 Research Report
School of Cosmic Physics: Geophysics Section

Contents

1 General

1.1 Research highlights

1.1.1 Water in olivine

Jones and colleagues' paper on "Water in cratonic lithosphere: Calibrating laboratory-determined models of electrical conductivity of mantle minerals using geophysical observations", published in *Geophysics, Geochemistry, Geosystems*, was highlighted by the American Geophysical Union (AGU) as one of the 6 featured Research Spotlight articles in all AGU journals for July, 2012. The paper featured in AGU's weekly newsletter EOS as one of three highlighted papers (EOS, vol. 93, number 32, page 316, 7 August 2012).

RESEARCH SPOTLIGHT Highlighting exciting new research from AGU journals

New model to estimate water in the Earth's mantle

The Earth's mantle could be holding as much water as the ocean and atmosphere combined—but in the form of defects in dry minerals, such as olivine, that make up a large fraction of the mantle. Water in mantle minerals weakens chemical bonds, affecting physical and chemical properties of the mantle, particularly viscosity and electrical conductivity.

Scientists continue to debate not just the amount of water but also its distribution in the mantle. Seismic velocity profiles, typically used to map the water content of the mantle, are, in fact, not sensitive to the amount of water. An increase of 1% by weight of water in mantle minerals, i.e., from "dry" to "very wet" conditions, reduces seismic velocities by at most 1%, which is often below the detection limit. On the other hand, an increase in water content by only 0.01%, from "dry" to "damp" conditions increases electrical conductivity in mantle minerals by an order of magnitude or more, making electrical conductivity a more sensitive tool to estimate the water content of mantle minerals.

Laboratory-derived models used to estimate electrical conductivity through the mantle not only fail to replicate geophysical and petrological observations but also have large disparities between models used by different laboratories. As a result, although electrical conductivity models are sensitive, many in the scientific community are skeptical of them.

Jones et al. calibrated laboratory-derived models of electrical conductivity of mantle minerals with well-constrained petrological observations of water content from two sites on the cratonic lithosphere in South Africa. However, unlike for previous models, these authors use a statistical approach, called Monte Carlo, to fit model parameters to field observations. Their findings show that two factors that critically affect estimates of water in minerals were not well defined in the previous models: one is the presence of excess charges (protons) that diffuse through the network of water molecules by a process called proton hopping, and the second is the amount by which water in mantle minerals reduces its total energy or enthalpy.

At present, the lack of petrological observations of the amount of water in mantle minerals at most sites in the world makes it difficult to constrain the above two factors. On the basis of their study, the authors propose more petrological studies and calibration of laboratory models with other geophysical and petrological field observations that may prove invaluable in understanding the behavior of the mantle. (*Geochemistry Geophysics Geosystems*, doi:10.1029/2012GC004055, 2012) —AB

1.1.2 Anisotropy beneath Southern Africa

Joanne Adam's paper on "Azimuthal anisotropy beneath southern Africa, from very-broadband, surface-wave dispersion measurements", with Sergei Lebedev, won one of three Student Author Awards of Geophysical Journal International for 2012. The award has been established to recognise and acknowledge the 'best papers' submitted to the journal from young scientists in the field and comes with a cash prise and a framed certificate. The awards are announced on the journal website and at the American Geophysical Union Fall Meeting in December 2012 and the European Geophysical Union General Assembly in 2013. Joanne's paper reveals the layering of seismic anisotropy beneath southern Africa. Reconciling long-debated previous observations, the results present important new evidence on the mechanisms of the assembly of ancient continents billions of years ago. Joanne's winning paper has been granted Free Access on the journal website.

1.1.3 IGRM best oral presentation award

Andrew Schaeffer, a Geophysics PhD student, won the best student oral presentation prize at the recent 2012 Irish Geological Research Meeting (IGRM) that took place at University College Cork on February 17-19. Andrew spoke on his research on global seismic tomography and was congratulated by the jury and by colleagues from across Ireland on an outstanding presentation. His talk — co-authored with Lebedev — was entitled "Anisotropic structure of the upper mantle, imaged using surface and S waveform tomography."

1.2 New external funding received in 2012

1.2.1 Jones: SFI IvP proposal: IRECSSEM – Evaluating Ireland's potential for onshore carbon sequestration and storage using electromagnetics

The world must transition from fossil-fuel energy supply to renewables energy supply. An absolutely necessary transitional technology is carbon capture, sequestration and long-term storage (CCS) if we are to minimise further harm to our planet's atmosphere from greenhouse gas emissions. Ireland was committed to having CCS by 2020 and the extant data point to offshore options, yet knowledge of onshore sedimentary basins for their potential to host car-bon dioxide (CO2) is inadequate. IRECCSEM, for *Evaluating Ireland's potential for onshore carbon sequestration and storage using electromagnetics*, will undertake an assessment, using electro-magnetic imaging, of the geometries and trapping structures beneath the two major onshore sedimentary basins, and develop appropriate electromagnetic monitoring tools.

The IRECCSEM project funding, provided by Science Foundation Ireland's 2012 Investigator Programme (IvP), will bring on a new Post-Doctoral Fellow and a new PhD student during 2013. Fieldwork will take place in 2014 and 2015.

1.2.2 Piana Agostinetti and Lebedev: SIM-CRUST

Dr. Nicola Piana Agostinetti was awarded one of Science Foundation Ireland's prestigious Starting Investigator Research Grants (SIRG). Dr. Nicola Piana Agostinetti is funded for 5 years, and the funding includes his salary, a PhD student, and field costs. The aim of the project is the passive seismic exploration of the Irish crust to better understand its geothermal potential.

Prof. Sergei Lebedev advised on the proposal from the DIAS side, and is the Starting Investigator's mentor and co-supervisor of the Ph.D. student.

1.2.3 Martinec: GOCE satellite data project

The ESA funded project "*Towards a better understanding of the Earth's interior and geophysical exploration research - GOCE-GDC*" on the GOCE satellite data processing and interpretations, in which DIAS (Martinec) is one of six cooperating partners, has been approved for financing.

1.2.4 Blake and Lebedev: CTBTO Research Award

A proposal, submitted to CTBTO, Vienna, for an award to support Emily Neenan for a 12-month M.Sc. research project, was successful. The CTBTO project is on high-resolution seismic imaging of Asia using novel, automated, surface-wave measurement techniques. It will be supervised by Lebedev and Blake and strengthen partnership and cooperation between CTBTO and DIAS.

2 Electromagnetic research activities

Group Leader: Senior Professor Alan G. Jones

2.1 IRETHERM

A.G. Jones, M. Muller

IRETHERM aims to develop a strategic and holistic understanding of Ireland's deep geothermal energy potential. In support of research efforts that will continue until mid-2015, the year 2012 saw tremendous progress made in acquiring the geophysical and geochemical data that are needed (i) to understand the origin and distribution of heat in Ireland's upper-crust and (ii) to define the subsurface characteristics of a range of different geological settings that offer potential for geothermal energy provision in different parts of Ireland. In addition, IRETHERM grew through new scientific collaborators that joined IRETHERM during 2012 that brought valuable expertise and research synergies to the team.

2.1.1 New IRETHERM collaborations

Dr. Mike Long (School of Civil, Structural and Environmental Engineering, UCD) will supervise our recently appointed M.Eng. student Tim Waters in systematically measuring the thermal conductivities of a representative suite of Irish rocks using UCD's newly built divided-bar apparatus.

Dr. Max Moorkamp (Department of Geology, University of Leicester) brings expertise in the field of geophysical joint-inversion methods that will enhance our ability to image deep geothermal resources in the crust.

Dr. Thomas Kalscheuer (ETH, Zurich) is working with our Ph.D. student Sarah Blake in imaging subsurface fluid conduit systems associated with several of Ireland's warm springs using Controlled Source Electromagnetic (CSEM) methods.

Dr. Tiernan Henry (Earth and Ocean Sciences, NUI Galway) will bring hydrological expertise to IRETHERM and supervise Sarah Blake's hydrochemistry work on Ireland's warm spring waters that aims to determine the source origin and depth of these waters.

Nick O'Neill and Gareth Jones (SLR Consulting), in taking over the IRETHERM baton from Roisin Goodman following her departure for Africa, bring a wealth of knowledge of geothermal energy in Ireland.

Dr. Nicola Piana Agostinetti and Prof. Sergei Lebedev (Dublin Institute for Advanced Studies) were awarded a significant Science Foundation Ireland grant in 2012 in support of Nicola's new "SIM-CRUST-geothermal" research project (Seismic Imaging and Monitoring of Ireland's Crust for geothermal resource assessment – in itself, worthy of independent reports in future editions of the GAI Newsletter!). Their collaboration provides the opportunity for synergistic imaging of Ireland's crust using a powerful combination of seismic and electromagnetic methods.

2.1.2 Research Focus 1: Heat production and heat distribution in Ireland's crust

One of the major sources of heat in the crust, in addition to heat transferred by conduction from the Earth's interior, is that produced by the decay of radioactive elements concentrated in the crust: uranium (U), thorium (Th) and potassium (K). One of the objectives of IRETHERM is to define the variation in radiogenic heat production across Ireland and with depth in the crust. Through the work of our two Ph.D. students at UCD, Nicola Willmot Noller and Tobias Fritschle, under the supervision of Prof. Stephen Daly, we have made significant progress with respect to this objective. Nicola initiated an extensive and on-going program to systematically measure the U, Th and K concentrations of many different rock types exposed at surface across Ireland using a newly purchased hand-held gamma-ray spectrometer. Tobi has geochemically analysed the radioactive element concentrations of borehole core samples from three of Ireland's buried granites (Drogheda and Kentstown granites, Co. Meath and Glenamaddy granite, Co. Galway) that will define the radiogenic heat production and the local/regional heating effect of these granites.

The contribution of conductive heat-flow from the Earth's interior to the total heat-flow observed at surface depends on the structure of the crust and the underlying lithospheric-mantle (primarily the thickness of the crust and lithosphere). Prof. Alan Jones and Dr. Javier Fullea have through 2012 been modelling Ireland's surface heat-flow as a function of crustal and lithospheric structure using a self-consistent approach (LitMod) that incorporates additional geophysical constraints provided by surface elevation, gravity and geoid anomaly and seismic data. Jones's work was undertaken whilst at Macquarie University in Sydney, funded by SFI's STTF programme, in collaboration with Juan-Carlos Afonso, the originator of LitMod and Fullea's PhD supervisor. What we have realised is that our ability to understand the variation in surface heat-flow across Ireland (and the geological controls on this variation) is compromised by the very small number of existing surface heat-flow measurements available – not more than two dozen measurements, unevenly distributed across the island. This lack of data is currently being addressed by our student Tim Waters (see above) who, in measuring the thermal conductivities of rocks from boreholes which have reliable down-hole temperature measurements as well, will allow new estimates of surface heat-flow to be made more widely across Ireland.

2.1.3 Research Focus 2: Geophysical assessment of "type" geothermal scenarios in Ireland

The primary geophysical tool we are using for imaging and assessing a range of different "type" geothermal settings, in the depth range surface to 6000 m, is magnetotellurics (MT). MT is a passive technique in which the naturally occurring time-variations in the Earth's magnetic and electric fields are measured at recording sites and used to derive the electrical conductivity structure of the subsurface, much like a X-ray of the body. Electrical conductivity provides an excellent "proxy" for subsurface geological variation in a geothermal context: hydrothermal aquifers are imaged as strong conductors and granitic bodies are imaged as strong resistors.

During two field campaigns in 2012 we acquired 220 MT and 24 CSEM recordings at six different localities around Ireland (**Figure 1**). A huge number of people participated in the fieldwork, all of whom whose efforts are gratefully acknowledged: from DIAS, IRETHERM Ph.D. students Sarah Blake, Robert Delhaye, Thomas Farrell and Chris Yeomans, Colin Hogg, Dr. Jan Vozar, Prof. Alan Jones, Duygu Kiyan, Florian le Pape, Dr. Mark Muller; from Indian Institute of Technology Roorkee, Summer intern Mohammad Shahrukh; from ETH Zurich, Dr. Thomas Kalscheuer and his M.Sc. student Frederic Wagner; from SLR Consulting, Charlie Carlisle and Aoife Ryan. We record here in the Annual Report a note of sincere thanks here to all farmers and local authorities who granted permission for access to land to install our instruments.

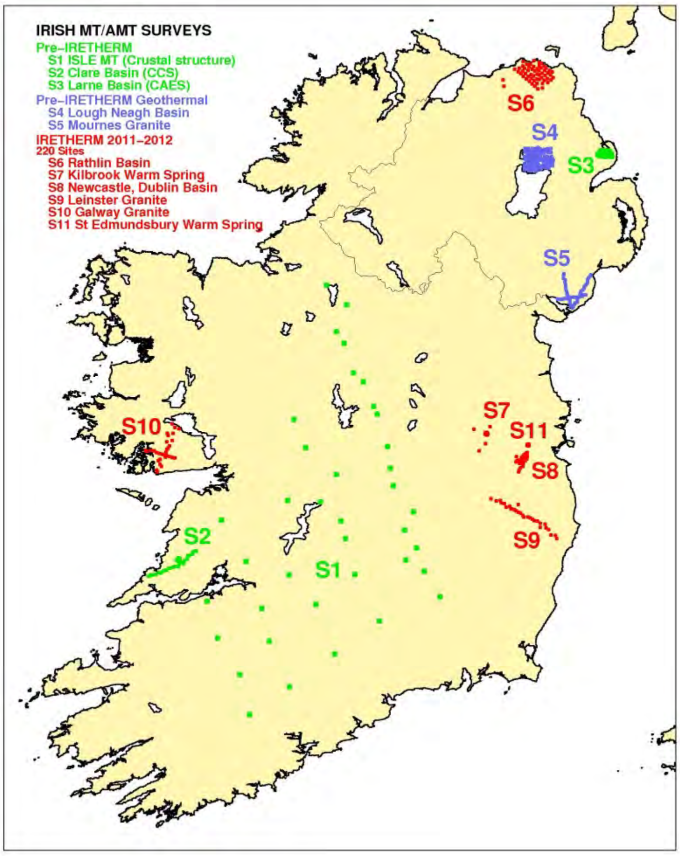


Figure 1. Distribution of MT sites in Ireland acquired by IRETHERM during 2012 (red points, surveys S6 to S11). MT data acquired pre-IRETHERM as part of earlier geothermal energy investigations are also shown (blue points, S4: Lough Neagh (GSNI), S5: Mourne Mountains (GSNI and DIAS)) as well as data acquired for a variety of other geological purposes (green points, surveys S1 to S3).

2.1.4 Geological/geothermal settings were investigated by our MT field surveys in 2012:

2.1.4.1 Rathlin Basin, Northern Ireland

The only sedimentary strata in Ireland known to provide reliable primary porosity, supporting deep hydrothermal aquifers, are found in the Triassic Sherwood Sandstone Group and in the upper-Permian, preserved in several basins or depocentres in Northern Ireland. Our survey over the Rathlin Basin (Survey S6, **Figure 1**), being worked on by Ph.D. student Robert Delhaye, aims to map the geometry of these strata at depth and assess their porosity and permeability characteristics – which are critical in the definition of their geothermal energy potential.

2.1.4.2 St. Edmundsbury and Kilbrook warm springs, north Leinster

In commencing our investigation of Ireland's warm spring occurrences, of which forty-two are known, two occurrences (Surveys S7 and S11, **Figure 1**) were selected initially for detailed geophysical investigation, based on their particularly interesting and distinct thermal and hydrochemical characteristics. Kilbrook warm spring is characterised by the warmest waters (24.8°C) and highest Total Dissolved Solids concentration in Ireland. St. Edmundsbury's waters are the closest to NaCl type in character, with more modest temperatures (16.9°C). Our high-resolution surveys over these occurrences, being worked on by Ph.D. student Sarah Blake and ETH-based M.Sc. student Frederic Wagner, aim to image the subsurface fluid conduit systems that bring these waters to surface.

2.1.4.3 Newcastle geothermal project, Co. Dublin

GT Energy's well-known borehole drilled at Newcastle encountered aquifer waters with particularly promising temperatures of about 46°C at a 1.4 km depth (with an average thermal gradient of ~33°C/km). In collaboration with GT Energy, Dr. Jan Vozar is working on MT data collected in the vicinity of the borehole (Survey S8, **Figure 1**) with the aim of better elucidating the geological context of this prospect. These data are very challenging, given the high contamination from cultural disturbances.

2.1.4.4 Leinster (Co. Wicklow) and Galway (Co. Galway) granites

Many of Ireland's exposed granites are associated with high radioactive element concentrations, high radiogenic heat production (HP) values and elevated surface heat-flow (SHF). Our initial MT surveys have focussed on two of these, the Leinster granite (Survey S9, Figure 1; SHF: 80 mWm-2, HP: 2–3 µWm-3) and the Galway granite (Survey S10; SHF: 65–77 mWm-2, HP: 4–7 µWm-3 in the Costello-Murvey unit). Ph.D. student Thomas Farrell is working on these data with the aim of defining the geometry, volume and local/regional heating effect of the granites and assessing their suitability for energy provision using Enhanced/Engineered Geothermal Systems (EGS). The output geophysical models will also be scrutinised for the possible presence of naturally occurring hydrothermal aquifers associated with either major faults that cross-cut the granites or the granite-country rock contacts.

2.1.5 Other geothermal related activities

Data from Sri Lanka were re-processed and analysed. These data pertain to possible fluid-related pathways for geothermal energy, so is directly relevant to IRETHERM activities.

Publication:

Hobbs, B.A., G.M. Fonseka, **A.G. Jones**, N. de Silva, N.Subasinghe, G. Dawes, N. Johnson, T. Cooray, D. Wijesundara, N. Suriyaarachchi, T. Nimalsisri, K. Premitallake, **D. Kiyan**, and **D. Khoza** (2013), In search of Geothermal Energy Potential in Sri Lanka: A preliminary magnetotelluric survey of the thermal springs. *Journal of the Geological Society of Sri Lanka*, accepted.

Invited Presentations:

Muller, M.R., **A.G. Jones, J. Fullea, C. Yeomans,** M. Loewer, L. Ayres, M. Desissa, and D. Reay (2012), Geophysics (mostly electromagnetic and thermal modelling) in (high- and low-enthalpy) geothermal energy investigations. Geophysical Association of Ireland Seminar on Environmental Geophysics, Dublin, 15 February.

Jones, A.G., **M.R. Muller,** N.H. Hunter Williams, J.S. Daly, A. Allen, R. Goodman, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2012), IRETHERM: A New Project to Develop a Strategic and Holistic Understanding of Ireland's Deep Geothermal Energy Potential. SEEP 2012, 5th International Conference on

Sustainable Energy & Environmental Protection, Dublin City University, Ireland, 5-8 June.

Presentations:

Blake, S., **M.R. Muller, A.G. Jones,** and the IRETHERM team (2012), IRETHERM: Multi-disciplinary investigation of Irish warm springs and their potential for geothermal energy provision. IGRM 2012, UCC, Cork, Ireland, 17-19 February.

Blake, S., **M.R. Muller, A.G. Jones,** and the IRETHERM Team (2012), IRETHERM: Multi-disciplinary investigation of Irish warm springs and their potential for geothermal energy provision. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

Delhaye, R., **M.R. Muller,** M. Loewer, **A.G. Jones,** D. Reay, and the IRETHERM Team (2012), The IRETHERM project: Assessment of Ireland's Permo-Triassic sedimentary basins as possible geothermal aquifers. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

Delhaye, R., **M.R. Muller,** M. Loewer, **A.G. Jones,** D. Reay, and the IRETHERM Team (2012), The IRETHERM project: Assessment of primary and secondary porosity media as possible geothermal aquifers. IGRM 2012, UCC, Cork, Ireland, 17-19 February.

Farrell, T., **A.G. Jones, M.R. Muller,** M. Feely, R. Goodman, and the IRETHERM Team (2012), The IRETHERM project: Assessing the geothermal energy potential of Irish Radiogenic Granites and enhancing Ireland's temperature database. IGRM 2012, UCC, Cork, Ireland, 17-19 February.

Farrell, T., **A.G. Jones, M.R. Muller,** M. Feely, and the IRETHERM Team (2012), The IRETHERM project: A magnetotelluric assessment of the geothermal energy potential of Irish radiogenic granites. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

Fullea, J., **M.R. Muller, A.G. Jones,** and the IRETHERM Team (2012), Exploring Geothermal Energy Potential in Ireland through 3-D Geophysical-Petrological Modelling of Surface Heat-Flow and Crustal and Upper-Mantle Structure. EGU Meeting, Vienna, Austria, 23-27 April.

Jones, A.G., **M.R. Muller, J. Fullea, J. Vozar, S. Blake, R. Delhaye, T. Farrell, C. Yeomans,** M. Loewer, D. Reay, and the IRETHERM Team (2012), IRETHERM: Research and Exploration Challenges in Assessing Ireland's Deep Low-Enthalpy Geothermal Energy Potential. 34th International Geological Congress, Brisbane, Australia, 5-10 August.

Jones, A.G., **M.R. Muller, J. Fullea, J. Vozar, S. Blake, R. Delhaye, T. Farrell, C. Yeomans,** M. Loewer, D. Reay, and the IRETHERM Team (2012), IRETHERM: Research and Exploration Challenges in Assessing Ireland's Deep Low-Enthalpy Geothermal Energy Potential. AGU Fall Meeting, San Francisco, USA, 3-7 December.

Jones, A.G., **M.R. Muller, J. Fullea, J. Vozar, S. Blake, R. Delhaye, T. Farrell, C. Yeomans,** M. Loewer, D. Reay, and the IRETHERM Team (2012), IRETHERM: Research and Exploration Challenges in Assessing Ireland's Deep Low-Enthalpy Geothermal Energy Potential. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

Muller, M.R., **A.G. Jones,** J.S. Daly, **J. Fullea,** A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2012),

IRETHERM: Research and Exploration Challenges in Assessing Ireland's Deep Low-Enthalpy Geothermal Energy Potential. IGRM 2012, UCC, Cork, Ireland, 17-19 February.

Muller, M.R., **A.G. Jones, J. Fullea C.M. Yeomans,** M. Loewer D. Reay, and the IRETHERM Team (2012), IRETHERM: Research and Exploration Challenges in Assessing Ireland's Deep Low-Enthalpy Geothermal Energy Potential. EGU Meeting, Vienna, Austria, 23-27 April.

Yeomans, C., **M.R. Muller,** J.S. Daly, **A.G. Jones,** and the IRETHERM Team (2012), Geothermal energy potential of the Greater Dublin area and the Mourne Mountains Granite Complex. IGRM 2012, UCC, Cork, Ireland, 17-19 February.

Yeomans, C., **M.R. Muller,** J.S. Daly, **A.G. Jones,** and the IRETHERM Team (2012), The IRETHERM Project: Geothermal energy potential of the Greater Dublin area and the Mourne Mountains Granite Complex. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

2.2 SAMTEX: Southern African Magnetotelluric Experiment

A.G. Jones, M. Muller, J. Fullea, D. Khoza, M. Miensopust, P.-E. Share, and colleagues from WHOI

2.2.1 Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton.

Previously published seismic, magnetotelluric and xenolith geochemistry models of the lithospheric-mantle structure of the Kaapvaal Craton, South Africa, provide apparently disparate views that appear, at first, difficult to reconcile with each other. In particular, in one recently published S-wave receiver function (SRF) study, an S-to-P conversion event at 160 km depth is used to infer a very thin (160 km thick) lithosphere that is inconsistent with the thicker lithosphere imaged in other geophysical studies. To help understand and resolve the apparent disparities, we use the LitMod software code to derive, thermodynamically consistently, a range of seismic velocity, density and electrical resistivity models from layered geochemical models of the lithosphere, based on mantle xenolith compositions, which simultaneously satisfy available geophysical observables: new surface-wave dispersion data, magnetotelluric responses, surface elevation and surface heat-flow.

The new surface wave dispersion data used as a constraint in our modelling work are available through collaboration with Joanne Adam and Sergei Lebedev. New collaboration with Nicola Piana Agostinetti provides the capacity for generating synthetic SRFs that allow comparison of the SRF responses of our lithospheric-mantle models with published SRFs.

Principle conclusions emerging from this work are:

1. All lithospheric-mantle models are characterised by a low-velocity zone (LVZ) with a minimum velocity at the depth of the chemical/thermal LAB. The top of the low-velocity zone does not define the LAB.
2. Models with a chemical/thermal LAB at 160 km depth fail to match all geophysical observables simultaneously.

3. The preferred model that satisfies all constraints places the chemical/thermal LAB at about 235 km depth.
4. We postulate, with support from synthetic SRFs, that a chemical transition at 160 km depth – from depleted harzburgite to (refertilised) high-T lherzolite – accounts for the observed SRF conversion event at this depth.

Publication:

Jones, A.G., S. Fishwick, R.L. Evans, **M.R. Muller**, and **J. Fullea** (2013), Velocity-conductivity relations for cratonic lithosphere and their application: Example of Southern Africa. *Geochemistry, Geophysics, Geosystems*, in press.

Presentations:

Muller, M.R., **J. Fullea, A.G. Jones, J. Adam,** and **S. Lebedev** (2012), Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa. 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

Muller, M.R., **J. Fullea, A.G. Jones, J. Adam,** and **S. Lebedev** (2012), Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa. 34th International Geological Congress, Brisbane, Australia, 5-10 August.

Muller, M.R., **J. Fullea, A.G. Jones, J. Adam, S. Lebedev,** and **N. Piana Agostinetti** (2012), Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa. AGU Fall Meeting, San Francisco, USA, 3-7 December.

Theses:

Khosa, D., 2012. Magnetotelluric studies across the Damara Orogen and southern Congo Craton. Ph.D. thesis, The University of the Witwatersrand, South Africa.

Share, P.-E., 2012. Prediction of DC current flow between the Otjiwarongo and Katima Mulilo regions, Namibia. M.Sc. thesis, The University of the Witwatersrand, South Africa.

2.3 INDEPTH

A.G. Jones, J. Vozar (PDF), F. Le Pape (PhD), with colleagues from China University of Geosciences Beijing, the University of Alberta, Cornell University, Stanford University, and INDEPTH collaborators

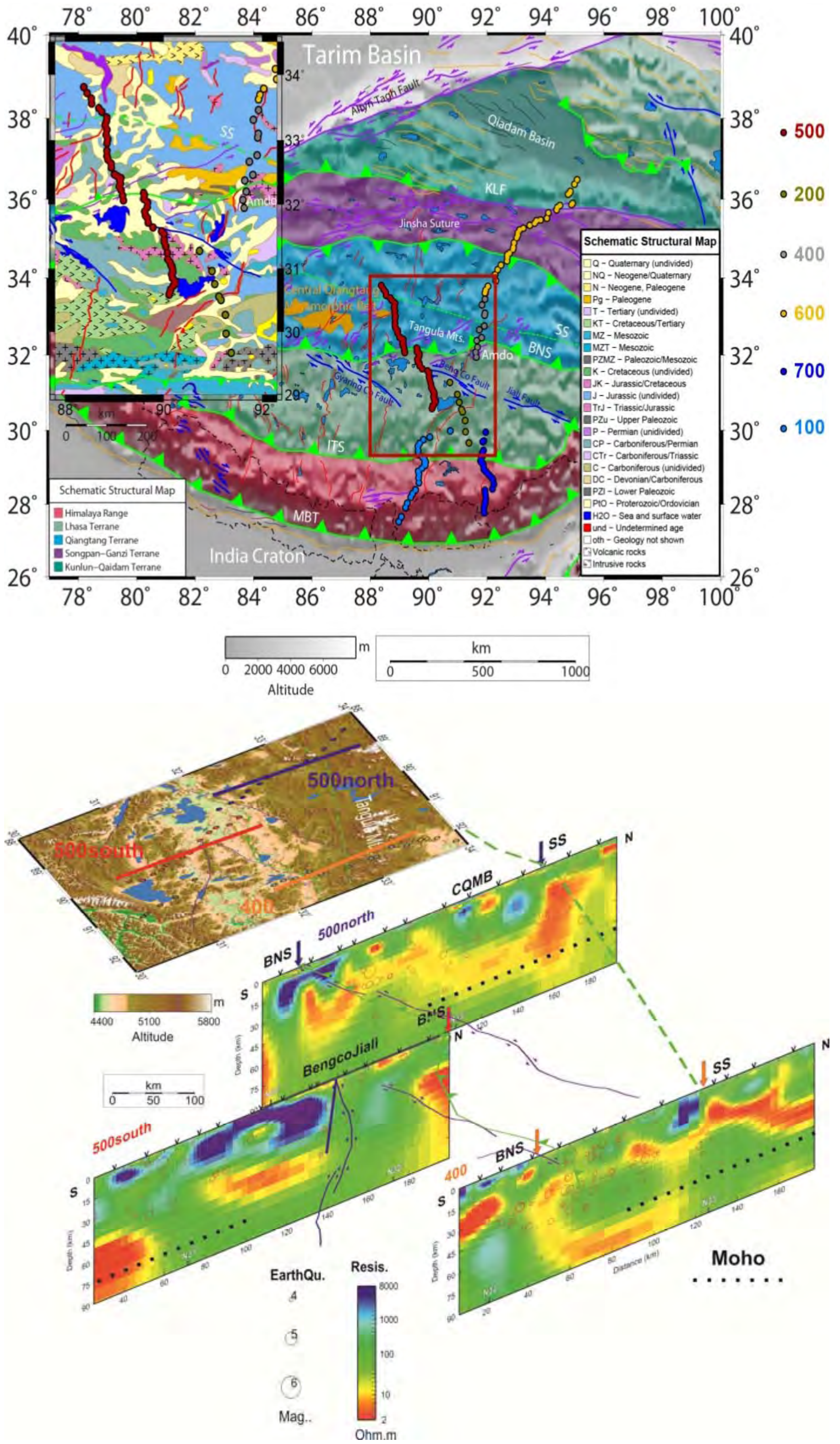
2.3.1 1D, 2D and 3D deep-probing electromagnetic studies and petro-physical modelling of the Tibetian Plateau

The research of Vozar focused on 1D, 2D and 3D deep-probing electromagnetic studies and petro-physical modelling of the Tibetan Plateau. In a frame of the SFI grant INDEPTH IV, the re-modelling of existing INDEPTH data was carried out, applying new inversion tools and new considerations such as anisotropy investigations and integrated modelling with seismic and petro-physical data.

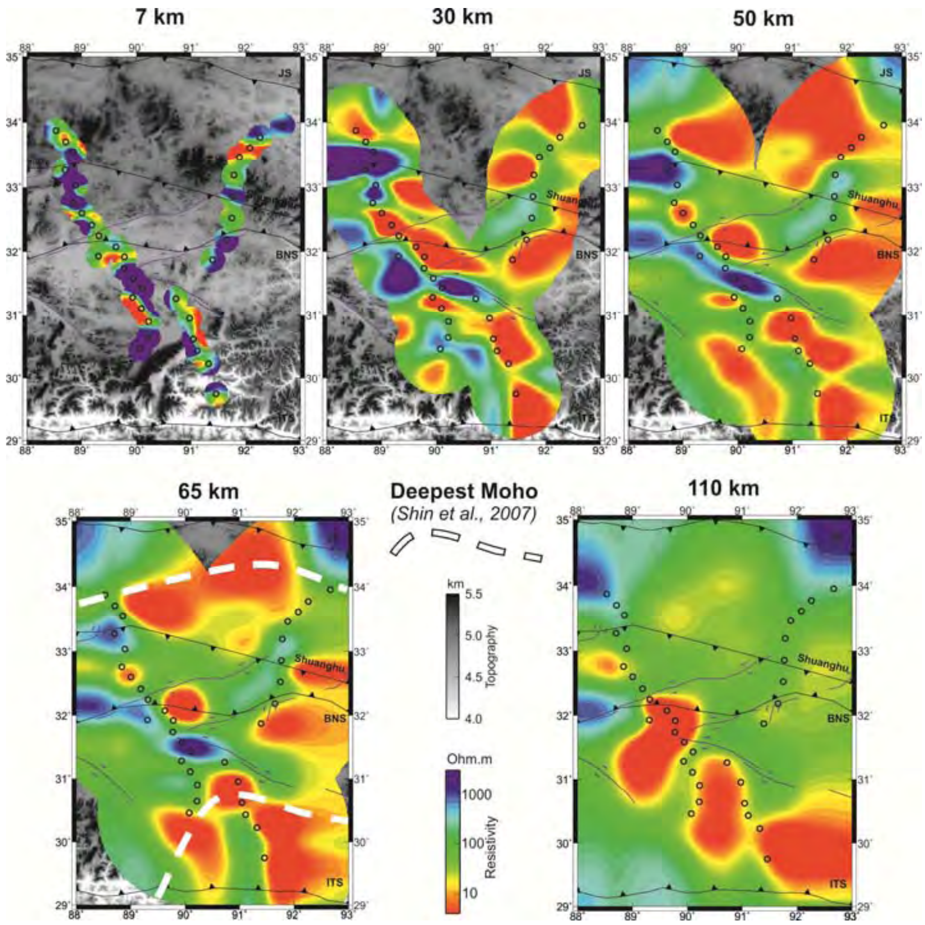
The modelling exhibits regional resistive and conductive structures correlated with ShuangHu Suture, Tanggula Mountains and strike-slip faults like BengCo-Jiali fault in the south. The BNS is not manifested in the geoelectrical models as a strong crustal regional structure. The strike direction azimuth of mid and lower crustal structures estimated from horizontal slices from 3D modelling (N110°E) is slightly different from one estimated by 2D strike analysis (N100°E). Orientation of crustal structures is perpendicular to convergence direction in this area. The deepest lower crustal conductors are correlated to areas with maximum Moho depth obtained from satellite gravity data.

The anisotropic 2D modelling reveals that lower crustal conductor in Lhasa Terrane is anisotropic. This anisotropy can be interpreted as a proof for crustal channel flow below Lhasa Terrane. But same Lhasa lower crust conductor from isotropic 3D modelling can be interpreted more likely as 3D lower Indian crust structure, located to the east from line 500, than geoelectrical anisotropic crustal flow.

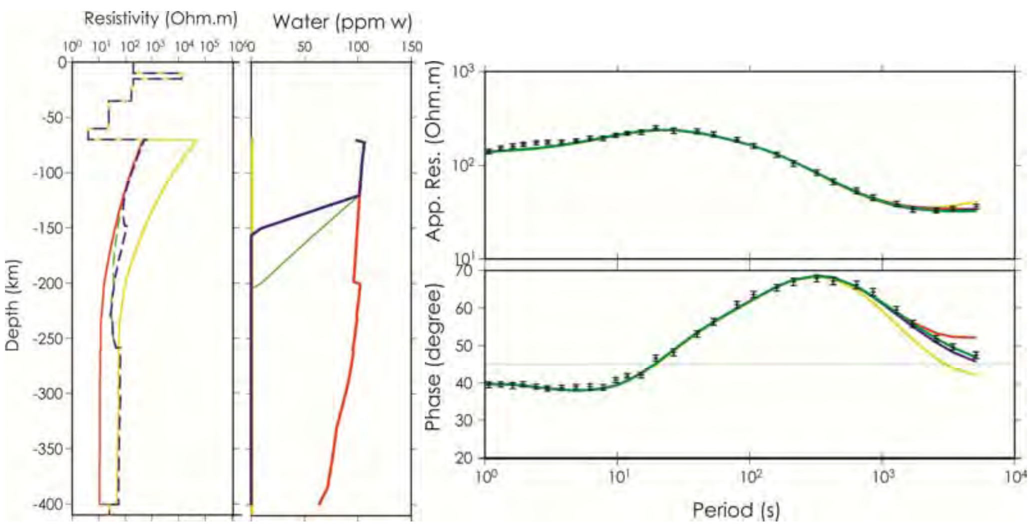
From deep electromagnetic sounding, supported by independent integrated petro-physical investigation, we can estimate the next upper-mantle conductive layer at depths from 200 km to 250 km below the Lhasa Terrane and less resistive Tibetan lithosphere below the Qiangtang Terrane with conductive upper-mantle in depths about 120 km



Across-strike and along-strike crustal study of central Tibet and BNS



Horizontal slices for selected final 3-D inversion model

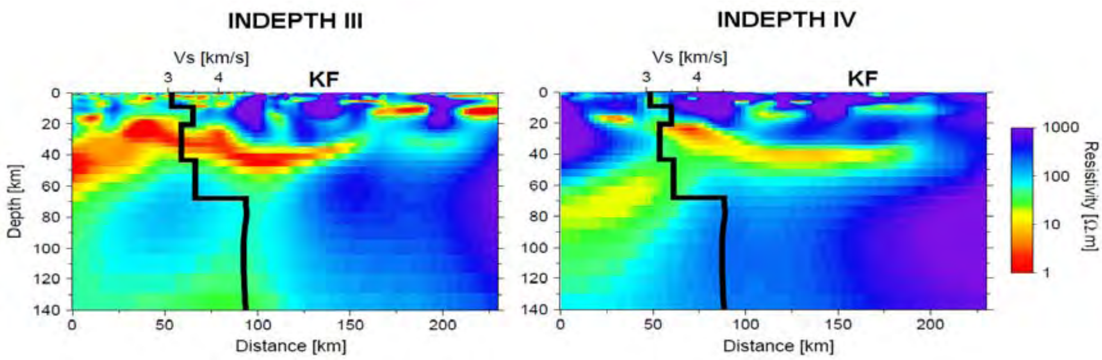


Calculated values: surface heat flow 82 mW/m^2, elevation 4850m. **Dry** lithospheric and sub-lithospheric mantle (for the LAB in depth 200 km) -> No fit for MT data. —

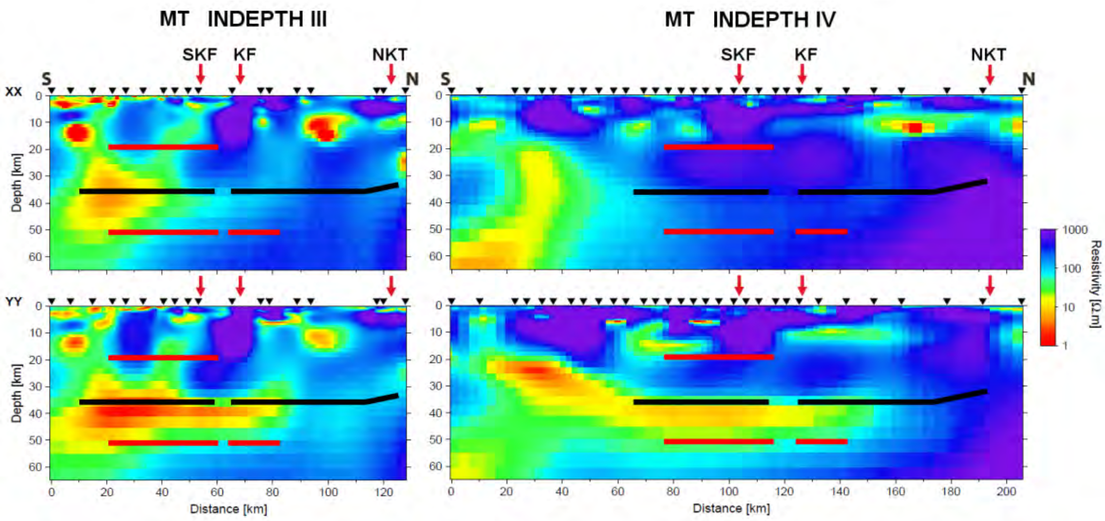
=> **Wet** lithospheric and sub-lithospheric mantle can fit both MT data and phase velocities. Different distribution of water content in mantle with linear decrease to: — 150 km, — 200 km, — 400km

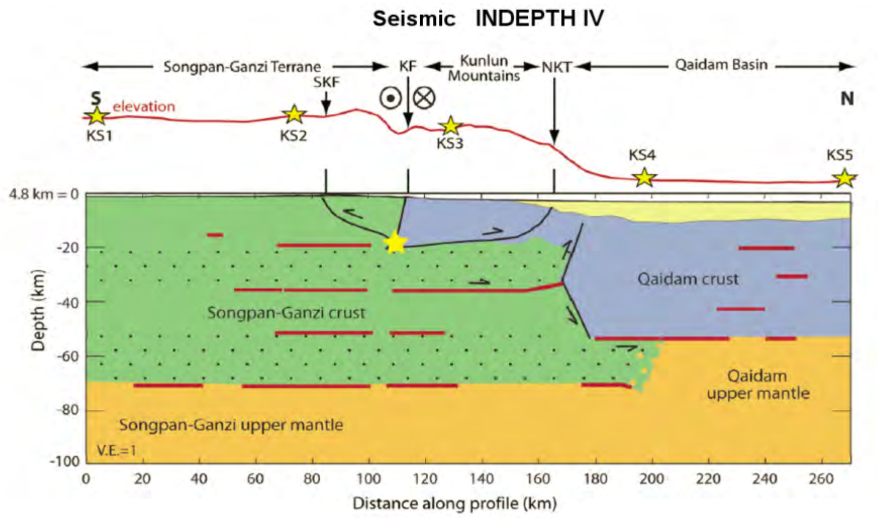
2.3.2 Tibetan Plateau's northern boundary

The Le Pape's research is focused on studies of discerning the transition between the particularly weak Tibetan plateau lithosphere and its surrounding rigid blocks, which is a key issue for complete understanding of the ongoing India-Eurasia collision. The overall goal of the last studies involved in the INDEPTH (International Deep Profiling of Tibet and Himalaya) project is to develop a better understanding of the structure and evolution of the northern margins of the Tibetan Plateau such as the Kunlun Fault. The fault is a major tectonic feature bounding the northern edge of the plateau and accommodating the plateau's current eastward extrusion. Both INDEPTH Phase III (600-line) and IV (6000-line) magnetotelluric (MT) data were investigated using 2D anisotropic inversions, as well as 3D modelling. In this study we highlight a new unequivocal evidence for electrical anisotropy at the northern edge of the Tibetan plateau. The anisotropic feature is identified as melt intrusion at the northern edge of the Tibetan plateau compromising the previous identification of the Kunlun Fault as a significant rheological boundary between weak, warm Tibetan crust and the rigid Eastern Kunlun-Qaidam block. The crustal melt penetration across the Kunlun fault system is likely to characterize the growth of the plateau to the north, as well as the accommodation of the north–south crustal shortening in Tibet.



Comparison of the Indepth III and IV MT yy models with a shear wave velocity 1D model from Agius and Lebedev [2010].





Indepth III and Indepth IV crustal models compared with the seismic reflectors and tectonic model taken from Karplus et al. [2011].

Thesis:

Le Pape, F., 2012. Characterization of a Crustal Transition Zone in Northern Tibet using Magnetotelluric Modelling. National University of Ireland, Galway.

Publications:

Le Pape, F., A.G. Jones, J. Vozar, and W. Wei (2012), Penetration of crustal melt beyond the Kunlun Fault into northern Tibet, *Nature Geoscience*, **5**, 330-335, doi: 10.1038/NGEO1449.

Zhao, G., M.J. Unsworth, Y. Zhan, L. Wang, X. Chen, **A.G. Jones**, J. Tang, Q. Xiao, J. Wang, J. Cai, T. Li, Y. Wang, and J. Zhang (2012), Crustal structure and rheology of the Longmenshan and Wenchuan Mw 7.9 earthquake epicentral area from magnetotelluric data. Geology, **40**, 1139–1142, doi:10.1130/G33703.1.

Presentations:

J. Vozar, **A.G. Jones,** and **F. Le Pape** (2012), Geoelectrical structures and their geometries in central Tibetan Plateau from INDEPTH magnetotelluric data, 21st EM Induction WorkshopDarwin, Australia, 25-31 July and IGC Brisbane.

J. Vozar, **J. Fullea, A.G. Jones, M. Agius,** and **S. Lebedev** (2012), Geophysical and petro-physical investigations of the lithosphere–asthenosphere boundary in central Tibet, 21st EM Induction WorkshopDarwin, Australia, 25-31 July and IGC Brisbane.

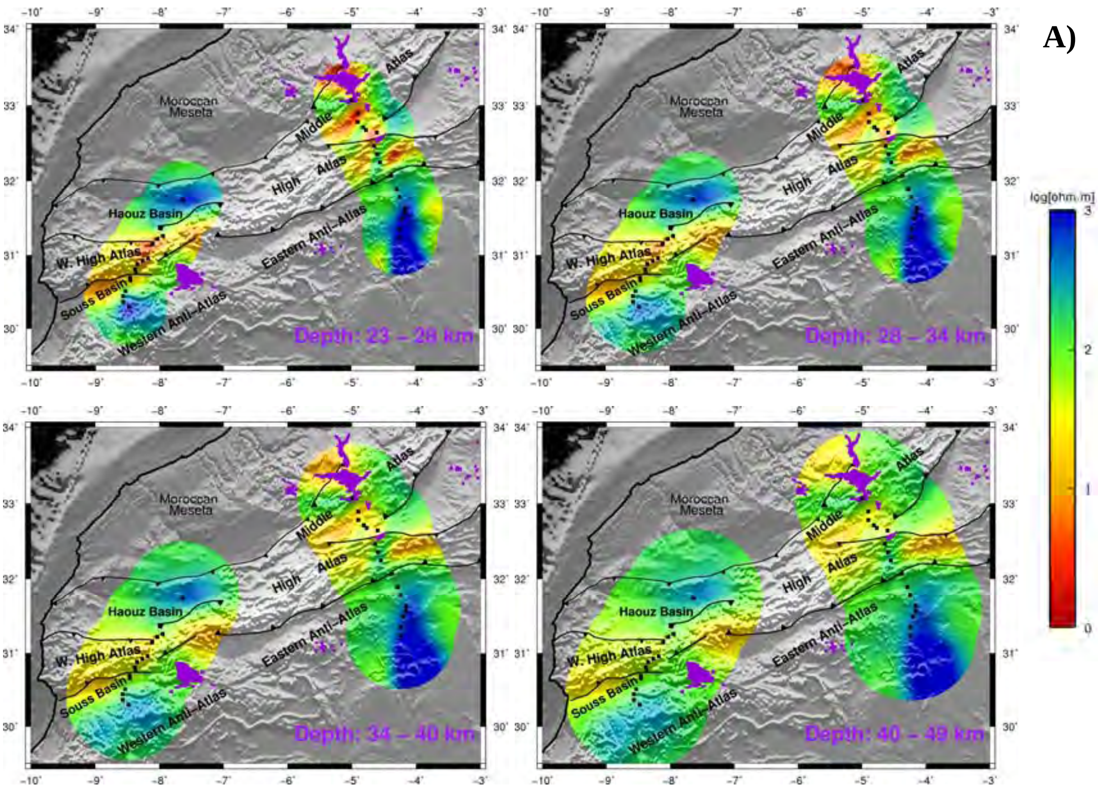
2.4 TopoMed: Plate re-organization in the western Mediterranean: Lithospheric causes and topographic consequences

The overarching objective of the project is to provide new electrical conductivity constraints on the crustal and lithospheric structures of the Atlas Mountains, and to test the hypotheses for explaining the observation of a “missing” mantle root inferred from surface heat flow, gravity and geoid anomalies, elevation and seismic data modelling (i.e. Zeyen et al., 2005; Teixell et al., 2005; Fullea et al., 2010). Overall, the project aims to understand the causes of vertical tectonics responsible for the Atlas

Mountains. The magnetotelluric (MT) survey across the Atlas Mountains region initiated in September, 2009 and ended in February, 2010. The survey comprises acquisition of broad-band (crustal probing) and long period (mantle probing) MT data along two profiles: a N-S oriented profile crossing the Middle Atlas through the Central High Atlas to the east (profile MEK) and a NE-SW oriented profile crossing the western High Atlas towards the Anti Atlas in the west (profile MAR) (**Figure 2B**). We have applied 3-D MT inversion scheme using non-linear conjugate gradients inversion code of Egbert & Kelbert (2012) to both profile data. In the 3-D models, whole Atlas Belt (except Anti-Atlas) is imaged as a conductive feature at middle and lower crustal scale (MEK and MAR profiles) and uppermost mantle scale (MEK profile) (**Figure 2A**).

MEK profile: The distinct conductivity difference between Middle-High Atlas and Anti Atlas correlates with the South Atlas Front fault, the depth extent of which appears to be limited to the uppermost mantle (approximately 55 km). Crustal seismic models from recently acquired seismic refraction profile (SIMA/PICASSO projects) also show low P wave velocities in the lower crust and upper mantle beneath Middle Atlas and High Mouloya plain (Ayarza et al., 2012). Without further knowledge, it can be concluded that melts can be responsible for the conductive anomaly (approximately 20 Ωm), as Cenozoic volcanism is present in the region. However, conductive anomaly is found at a depth shallower than the one where we would expect a significant amount of melt fraction provided that temperature (> 850 degrees) is high enough. The other candidate for explaining the observed high conductivity zone is exotic fluids enrich in volatiles which originated due to ancient rifting and associated magmatic activity at the transition from crust to the upper mantle (Schwarz et al., 1992). Another possible explanation, those fluids put down the solidus of crustal rock and induces partial melt.

In all inverse solutions, the crust and the upper mantle show resistive signature (750 Ωm - 1,000 Ωm) beneath the Anti Atlas which is the part of stable West African Craton.



A)

MAR profile: For the first time, the electrical resistivity distribution in the crust and in the upper mantle of Western High Atlas has been studied. The 3-D models show that conductive (1-20 Ωm) western High Atlas is confined by two resistive basins (>1,000 Ωm), Souss basin to the south and Houz basin to the north. At the southern boundary of the western High Atlas, the conductor is located at the shallower depth and it is deepening to the north. However, due to the presence of the strong upper crustal conductor beneath the southern boundary of High Atlas, the deeper structures in the upper mantle (>~35 km) could not be resolved.

B)

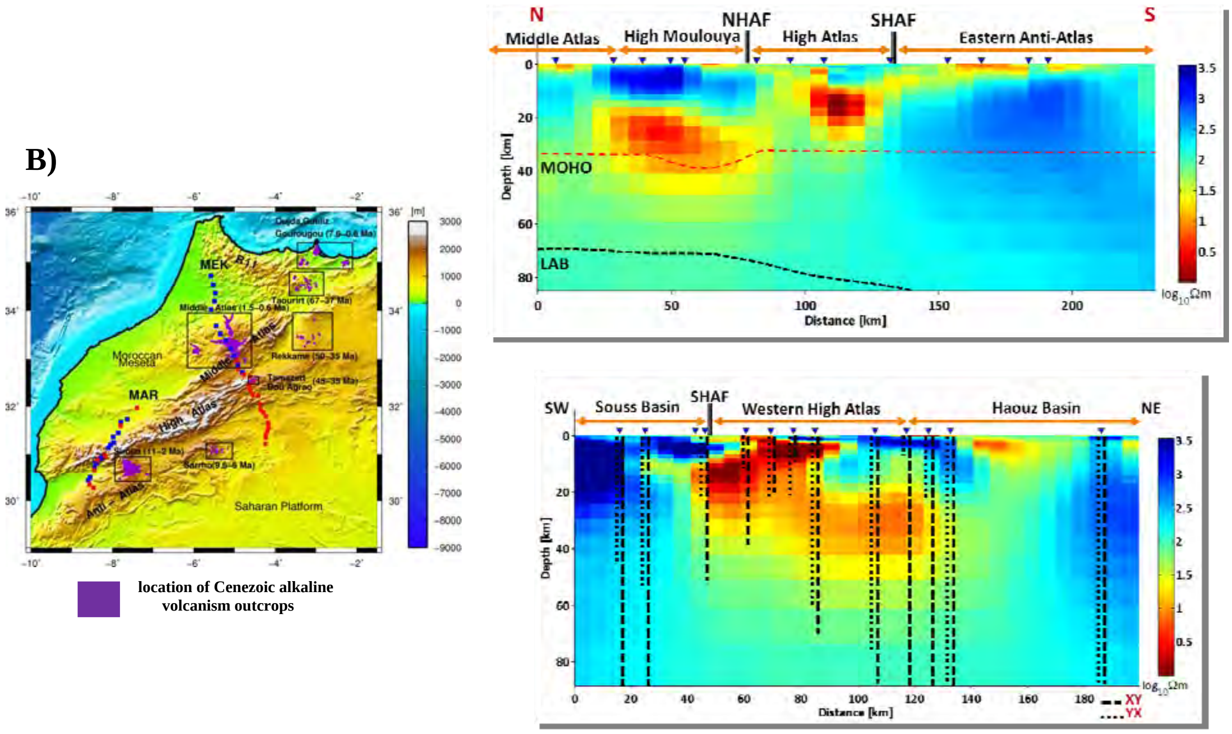


Figure 2: (A) Position of stations (black solid squares) and depth slices through preferred 3-D inversion model of full impedance tensor data for both profiles (MEK and MAR). **(B)** Cross sections from the preferred model along profile MEK (on top) and along profile MAR (on the bottom). The seismically defined Moho depth is highlighted by red dashed line. The black dashed-line represents the lithosphere-asthenosphere boundary (LAB) for the Atlas Belt based on integrated geophysical-petrological forward modelling (Fullea et al., 2010). The approximate Niblett-Bostick penetration depths of XY and YX mode are shown for MAR profile. North Atlas Front Fault, NHAF; South Atlas Front Fault, SHAF.

Working Group Meeting:

TopoMed Working Meeting held in Montpellier, 21-23 May, 2012.

Publication:

Jones, A.G., D. Kiyan, **J. Fullea**, J. Ledo, P. Queralt, A. Marcuello, A. Siniscalchi, and G. Romano (2012), Comment on "Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism" by Anahnah et al. (2011), *Tectonics*, **31**, TC5011, doi:10.1029/2011TC003051.

Presentations:

***Kiyan, D.,* A. G. Jones**, J. Fullea, J. Ledo, A. Siniscalchi, and G. Romano (2012), Crustal and uppermost mantle structures of the Atlas Mountains of Morocco inferred from electromagnetic imaging. AGU Fall Meeting 2012, San Francisco, 3-7 December.

***Kiyan, D.,* A. G. Jones**, J. Ledo, J. Fullea, A. Sinischalchi, G. Romano, J. Campanya, and the TopoMed MT Team (2012), 3D structures of the crust and upper mantle in the Atlas Mountains of Morocco from magnetotelluric data. EGU General Asesembly 2012, Vienna, Austria, 22-27 May.

***Kiyan, D.,* A.G. Jones,** J. Ledo, **J. Fullea**, A. Siniscalchi, G. Romano, and J. Campanya (2012), Crustal and lithospheric structures of the Atlas Mountains, Morocco: constraints from magnetotelluric data. IGC 2012, Brisbane, Australia, 5-10 August.

***Kiyan, D.,* A. G. Jones**, **J. Fullea,** and A. Pommier (2012), Crustal and lithospheric structures of the Atlas Mountains of Morocco: insights from magnetotelluric data. 21st EM Induction Workshop 2012, Darwin, Australia. 25-31 July.

Sinischalchi, A., G. Romano, **A.G. Jones**, J. Ledo, J. Campanyà, ***D. Kiyan*,** and the TopoMed MT Team (2012), Electrical signature of the Marrakech High Atlas: new insights from the TopoMed broad band magnetotelluric experiment. EGU General Assembly 2012, Vienna, Austria, 22-27 May.

2.5 Magnetotelluric theory

2.5.1 Electrical anisotropy

A computer program able to invert data relative to a bi-dimensional anisotropic domain has been developed and tested. Results from numerical tests relative to this code were presented in international conferences.

Publication:

Jones, A.G. (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth, *Geophysical Journal International*, **189**, 268-284, doi: 10.1111/j.1365-246X.2012.05362.x

Presentations:

Mandolesi, E., and **A.G. Jones** (2012), Magnetotelluric inversion in a 2D anisotropic environment. EGU, General Assembly, Vienna, 22-27 April.

Mandolesi, E., and **A.G. Jones** (2012), Magnetotelluric inversion in 2D anisotropic environment. 21st Workshop Darwin, Australia, July 25-31.

2.5.2 Distortion effects

Publications:

Jones, A.G. (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth, *Geophysical Journal International*, **189**, 268-284, doi: 10.1111/j.1365-246X.2012.05362.x

Jones, A.G. (2012), Distortion of magnetotelluric data: its identification and removal, In: *The Magnetotelluric Method*, edited by Alan D. Chave and Alan G. Jones, published by Cambridge University Press, Chapter 6, pp. 219-302, ISBN: 9780521819275.

2.6 Three-dimensional modelling and inversion

Workshop:

The second workshop in the Dublin-hosted series on *Three-dimensional Magnetotelluric Inversion* (MT3DINV2) was held in DIAS in March, 2012.

Publication:

Miensopust, M.P., P. Queralt, **A.G. Jones**, and the 3D MT modellers (2013), Magnetotelluric 3D inversion - a review of two successful workshops on forward and inversion code testing and comparison. *Geophysical Journal International*, in press, doi: 10.1093/gji/ggt066.

2.7 Joint Inversion

A.G. Jones, E. Mandolesi

A mutual-information based penalty function has been introduced as constraint in mono-dimensional and bi-dimensional magnetotelluric inverse problem. This penalty function has introduced as a suitable link between different geophysics parameters, providing a stable base for a possible joint inversion algorithm. Results relative to its performances have been presented at the AGU Fall Meeting 2012.

Presentations:

Mandolesi, E., and **Jones, A.G.** (2012), Anisotropic magnetotelluric inversion using mutual information constraint. AGU, Fall Meeting, San Francisco 3-7 December.

2.8 Other electromagnetic research

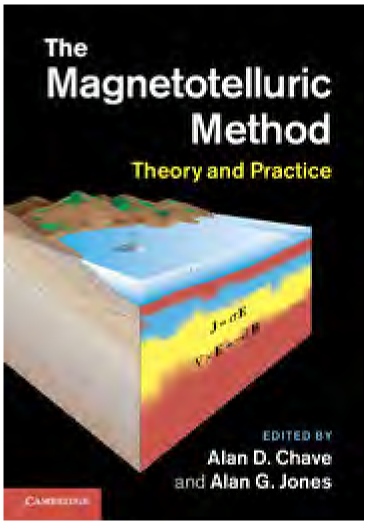
2.8.1 MaSca (Magnetotellurics in Scandes)

Presentation:

Smirnov, M. Yu, and the MASCA WG (M. Becken, M. Biolik, M. Cherevatova, J. Ebbing, S. Gradmann, M. Gurk, J. Huber, **A.G. Jones**, A. Junge, J. Kamm, T. Korja, C. Nittinger, L.B. Pedersen, A. Rodder, A. Savvaidis, and M. Yu. Smirnov) (2012), Magnetotellurics in Scandes (MASCA) project. Contributed paper at: 21st EM Induction Workshop, Darwin, Australia, 25-31 July.

2.8.2 Electrical Moho

Jones was invited to contribute to a special issue of *Tectonophysics* dedicated to the 100 year anniversary of Andrija Mohorovičić's 1910 paper that identified a seismic discontinuity that usefully defines the crust-mantle boundary from a seismological perspective. Calculations by Jones showed how difficult it is to detect a change in electrical conductivity unless special conditions are met.



Publication:

Jones, A.G. (2013), Imaging and observing the Electrical Moho, *Invited Review, Tectonophysics, "Moho" special issue,* doi: 10.1016/j.tecto.2013.02.025, in press.

2.8.3 MT book

Jones, together with Dr. Alan D. Chave (Woods Hole Oceanographic Institution), co-wrote and edited a book titled "The Magnetotelluric Method: Theory and Practise", published by Cambridge University Press (ISBN: 9780521819275).
Jones wrote one of the major chapters on Distortion of MT data, and co-authored two others.

2.8.4 Other contributions

Invited Presentations

Jones, A.G., 2012. Lighting up the lithosphere: Obtaining information about the Earth using very low frequency electromagnetic waves. Invited seminar, Macquarie University, 19 October.

Jones, A.G., 2012). MT - The answer to everything (What was the question?). Invited research seminar, Macquarie University, 8 November.

2.9 Main international collaborations

- U. Barcelona: Professors J. Ledo, P. Queralt, A. Marcuello, A. Mari
- U. Bari: Prof. A. Sinichalchi
- U. Leicester: Drs. S. Fishwick, M. Moorkamp, A. Avdeeva
- U. Montpellier: Profs. A. Tommasi, S. Demouchy
- U. Oulu: Prof. T. Korja, Dr. M. Smirnov
- China University of Geosciences Beijing: Profs. W. Wei, S. Jin, G. Ye
- Geological Survey of Canada: Mr. J. Craven, Dr. D. Snyder, Ms. J. Spratt
- WHOI: Drs. A.D. Chave, R.L. Evans
- Memorial University, St John's, Newfoundland: Professor Colin Farquharson
- Icelandic Geosurvey ISOR, Reykjavik, Iceland

3 Petrological-geophysical modelling

Group Leader: Senior Professor Alan G. Jones

3.1 Correlation of electromagnetic data with other geoscientific data

Joint modelling/inversion must begin from a standpoint of expecting a correlation between different physical or physio-chemical parameters. The relationship between velocity and conductivity has been explored over the last few years by Jones and colleagues, culminating in the paper in press in *Geochemistry, Geophysics, Geosystems*. Having this background in place, formal methods can now proceed.

Publication:

Jones, A.G., S. Fishwick, R.L. Evans, **M.R. Muller**, and **J. Fullea** (2013), Velocity-conductivity relations for cratonic lithosphere and their application: Example of Southern Africa. *Geochemistry, Geophysics, Geosystems*, in press.

Invited Presentations

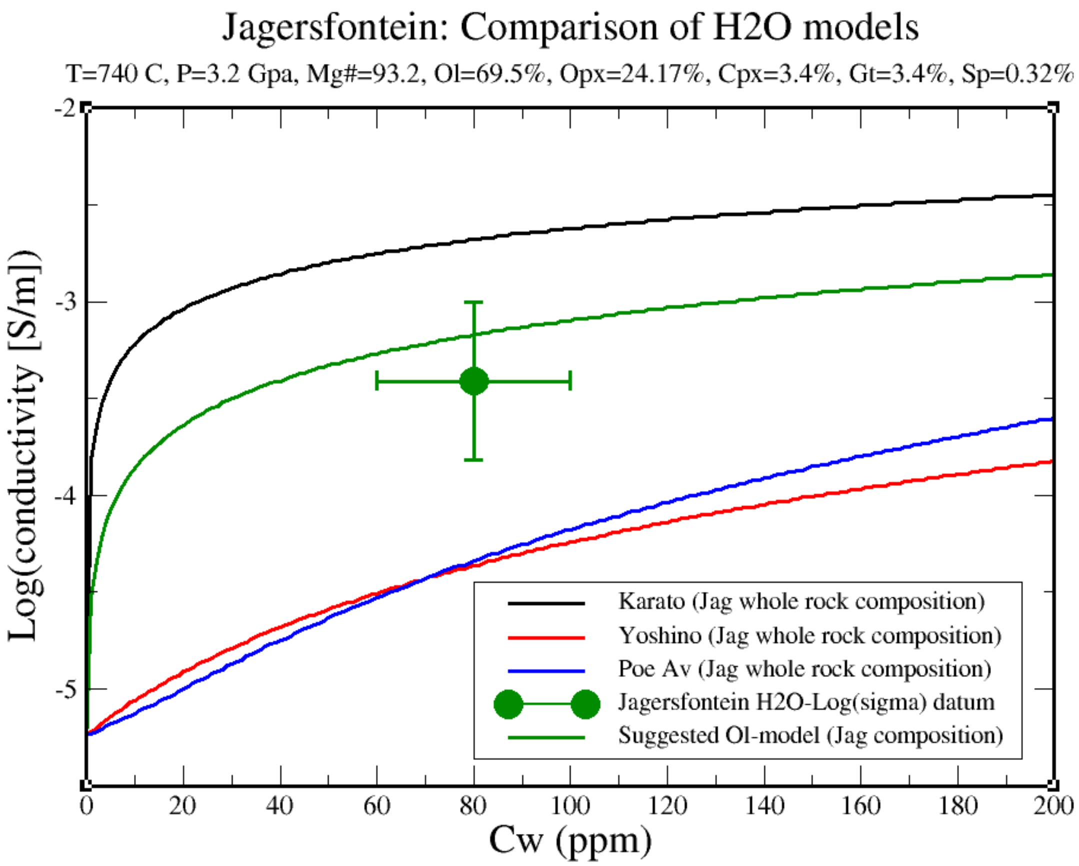
Jones, A.G., 2012. Illuminating lithospheric structures using electromagnetic waves and correlations with other geophysical, geological and petrological data. Invited presentation at: Lithosphere Workshop, University College Cork, Ireland, 17 February.

Jones, A.G., 2012. Lighting up the lithosphere using electromagnetic waves and correlations with other geophysical, geological, geochemical and petrological data. Invited seminar at: ETH Zurich, 24 February.

Jones, A.G., 2012. Velocity-conductivity relations for cratonic lithosphere and their application: Example of southern Africa. Invited keynote presentation at: 6th International Conference on Applied Geophysics, Kanchanaburi, Thailand, 15-17 November.

3.2 Water in olivine

The presence of bound water, more correctly hydroxyl, is the olivine matrix increases electrical conductivity by orders of magnitude. Laboratory measurements however are inconsistent on the quantitative effect. Jones and colleagues compared the results from the three main laboratories, and showed that all three are inconsistent with field observations where the water content, temperature, pressure and compositions are known from xenolith studies, and the electrical conductivity from careful SAMTEX data modelling.



Variation of conductivity at Jagersfontein parameters at 100 km depth of T = 740 °C, P = 3.2 GPa, for olivine water concentration varying from 0 – 200 ppm for the Karato (black lines), Yoshino (red lines) and Poe (blue lines) for the Jagersfontein composition assemblage (Mg# = 93.2, except for Gt where Mg# = 75.0) (solid lines). The abscissa annotates olivine water concentration, and that for the composition assemblage calculations, water concentrations for Opx, Cpx and Gt are taken as 2 Ol, 3 Ol and zero respectively. The observation datum (green point) is for a water content in Ol of 80 ±20 ppm (from xenoliths) and a log(conductivity) of 3.41 ±0.41 (from mapping of MT observations, with 2s error bounds). The solid green line represents the revised water model of Jones et al.

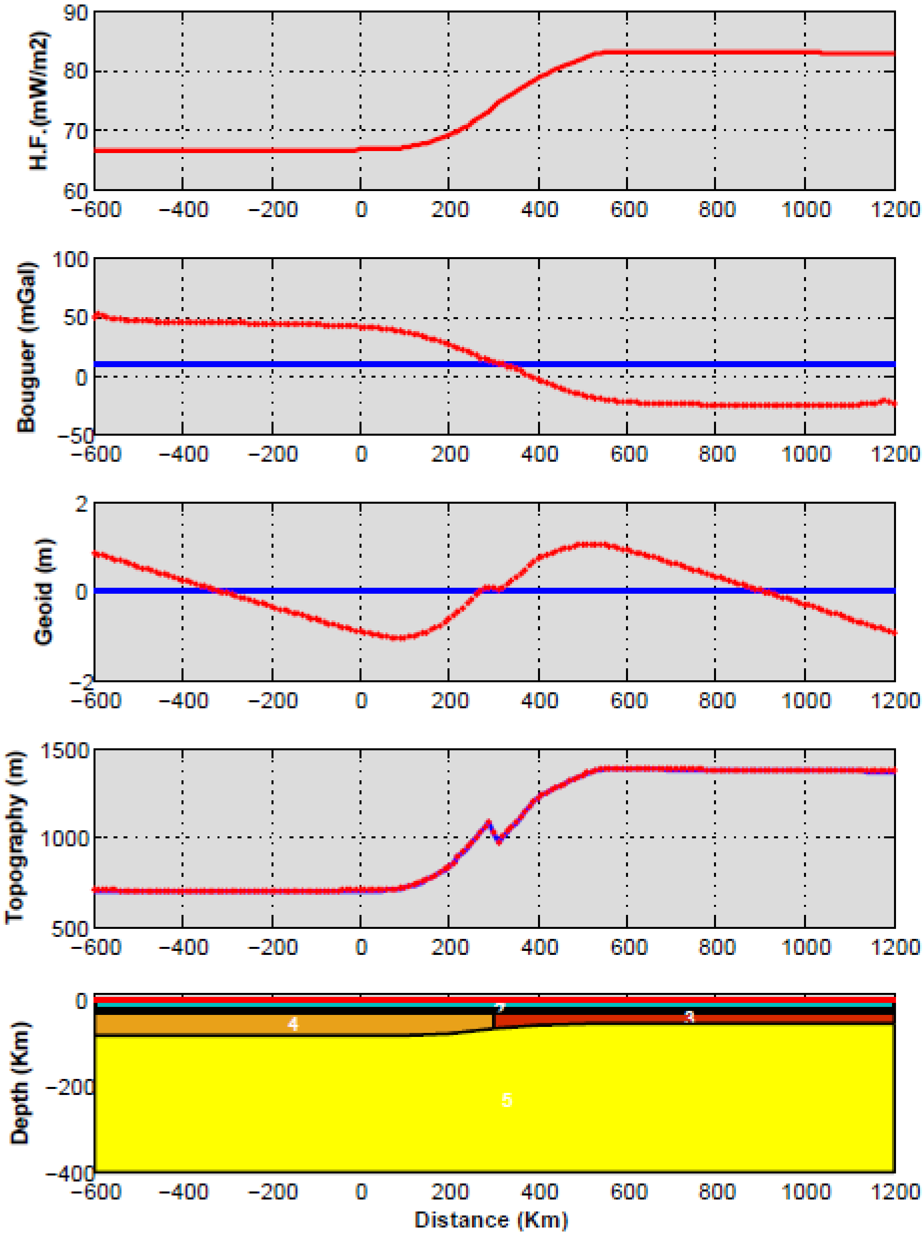
3.3 Modelling Ireland's lithosphere

3.3.1 In two-dimensions (2D)

Jones spent five weeks working with Dr. Juan Carlos Afonso at Macquarie University in October/November, 2012, funded by a Science Foundation Ireland Short Term Travel Fellowship (STTF), where he modelled the Irish lithosphere using Afonso's 2D LitMod code (Afonso et al., 2008). Jones also extended the LitMod2D approach by including calculations for electrical conductivity.

Jones demonstrated, from first-order arguments, that Ireland's lithosphere cannot be any thinner than around 90 km, and does not exhibit a strong 30 km thinning from south to north, as had been proposed by others (Landes et al., 2007). A thin lithosphere, of the order of 85 km in the south and 55 km in the north, would result in significant topographic uplift and north-south variation in topographic height, geoid height, Bouguer gravity anomaly and surface heat flow, none of which are observed.

A paper is in preparation for submission in 2013 on this work.



LitMod2D calculations for the Landes et al. (2007) lithospheric model with 30 km of thinning from 85 km to the south to 55 km to the north, and depleted lithospheric mantle to the south and fertile lithospheric mantle to the north. A flat Moho at 30 km with a vertical discontinuity between the two lithospheric domains is assumed.

3.3.2 *In three-dimensions*

Fullea undertook more detailed 3D modelling of Ireland. A paper is in preparation for submission in 2013 on this work.

3.4 Probabilistic Inversion

Working with Afonso and colleagues, the group has developed a probabilistic inversion approach that derives likely composition, temperature, pressure and water content from surface observables.

Publications:

Afonso, J.C., J. Fullea, W. L. Griffin, Y. Yang, **A.G. Jones**, J.A.D. Connolly, and S.Y. O'Reilly (2013), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: a priori petrological information and geophysical observables. Journal of Geophysical Research - Solid Earth, in press.

Afonso, J.C., J. Fullea, Y. Yang, J.A.D. Connolly, and **A.G. Jones** (2013), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. II: General methodology and resolution analysis. Journal of Geophysical Research - Solid Earth, in press.

Presentation:

Afonso, J.C., J. Fullea, Y. Yang, N. Rawlinson, **A.G. Jones**, and J.A. Connolly, 2012. Towards multi-observable thermochemical tomography of the lithosphere and sublithospheric upper mantle. Contributed paper at: Fall AGU, San Francisco, USA, 3-7 December.

3.5 Other petrological-geophysical modelling activities

Other petrological-geophysical modelling activities are described elsewhere in this Annual Report, including in South Africa (Section 2.2), Tibet (Section 2.3), Morocco (Section 2.4), and Mongolia (Section 5.10).

Invited presentations

Jones, A.G., 2012. Petrophysical information of the Earth's lithosphere from electromagnetic and seismic studies. Invited seminar, University of Adelaide, 31 October.

Jones, A.G., 2012. Petrophysical information of the Earth's lithosphere from electromagnetic and seismic studies. Invited seminar, University of Western Australia, 5 November.

Presentations

Jones, A.G., **J. Fullea**, **M.R. Muller**, and J.C. Afonso, 2012. LitMod: Modeling the lithosphere using geoid, topography, heat flow, gravity, seismic and electromagnetic data in a petrologically self-consistent manner. Contributed paper at: 6th International Conference on Applied Geophysics, Kanchanaburi, Thailand, 15-17 November.

4 Geodynamic research activities

Group Leader: Professor Zdenek Martinec

4.1 Toroidal magnetic field induced by tidal ocean circulation

We are dealing with the magnetic field induced by ocean circulation. The study is motivated by the fact that observations of the ocean-induced magnetic field by the CHAMP magnetic space mission, and most likely by the SWARM magnetic mission have the potential to be used as constraints on ocean dynamics. This has already initiated theoretical studies on the poloidal magnetic field induced by the horizontal ocean-circulation flow where the ocean layer is approximated by a single conductive sheet.

Publication:

Dostal, J., **Z. Martinec**, M. Thomas (2012), The modelling of the toroidal magnetic field induced by tidal ocean circulation, *Geophys. J. Int.*, **189**, 782-798, doi: 10.1111/j.1365-246X.2012.05407.x

Presentation:

Martinec, Z. (2012), Recent satellite missions on the Earth's gravity and magnetic fields. Institute of Geophysics & Tectonics, School of Earth & Environment, The University of Leeds, Leeds, 14 February.

4.2 Timing and origin of recent regional ice-mass loss in Greenland

Within the last decade, the Greenland ice sheet (GrIS) and its surroundings have experienced record high surface temperatures (Mote, 2007; Box et al., 2010), ice sheet melt extent (Fettweis et al., 2011) and record-low summer sea-ice extent (Nghiem et al., 2007). Using three independent data sets, we derive, for the first time, consistent ice-mass trends and temporal variations within seven majordrainage basins from gravity fields from the Gravity Recovery and Climate Experiment (GRACE; Tapley et al., 2004), surface-ice velocities from Inteferometric Synthetic Aperture Radar (InSAR; Rignot and Kanagaratnam, 2006) together with output of the regional atmospheric climate modelling (RACMO2/GR; Ettema et al., 2009), and surface-elevation changes from the Ice, cloud and land elevation satellite(ICESat; Sørensen et al., 2011). We show that changing ice discharge (D), surface melting and subsequent run-off (M/R) and precipitation (P) all contribute, in a complex and regionally variable interplay, to the increasingly negative mass balance of the GrIS observed within the last decade. Inter-annual variability in P along the northwest and west coasts of the GrIS largely explains the apparent regional mass loss increase during 2002–2010, and obscures increasing M/R and D since the 1990s. In winter 2002/2003 and 2008/2009, accumulation anomalies in the east and southeast temporarily outweighed the losses by M/R and D that prevailed during 2003–2008, and after summer 2010. Overall, for all basins of the GrIS, the decadal variability of anomalies in P, M/R and D between 1958 and 2010 (w.r.t. 1961–1990) was significantly exceeded by the regional trends observed during the GRACE period (2002–2011).

Publication:

Sasgen, I., M. Van Den Broeke, J.L. Bamber, E. Rignot, L.S. Srensen, B. Wouters, **Z. Martinec**, I. Velicogna, and S.B. Simonsen (2012), Timing and origin of recent regional ice-mass loss in Greenland, *Earth Planet. Sci. Lett.*, **333-334**, 293-303, doi: 10.1016/j.epsl.2012.03.033.

Presentations:

Sasgen I., M. Van Den Broeke, J.L. Bamber, E. Rignot, L. Sandberg Srensen, B. Wouters, **Z. Martinec**, I. Velicogna, and S.B. Simonsen (2012), Recent changes of the Greenland ice sheet: insights from GRACE, ICESat and InSAR/regional climate modeling. SLALOM 2012, Athens, 19-22 March.

Konrad, H., I. Sasgen, **Z. Martinec**, and E. Ivins (2012), Re-assessing Antarctic glacial isostatic-adjustment with GPS and GRACE observations. SLALOM 2012, Athens, 19-22 March.

Konrad, H., I. Sasgen, V. Klemann, E.R. Ivins, and **Z. Martinec** (2012), Re-assessing the influence of glacial-isostatic adjustment on Antarctic ice-mass balance estimated from GRACE. EGU General Assembly, Vienna, Austria, 22-27 April, (poster).

Martinec, Z. (2012), Forward and adjoint methods of glacial isostatic adjustment with non-vanishing surface horizontal traction, Joint GSTM/SPP1257 Symposium, GFZ Potsdam, 17-19 September, (poster).

4.3 Towards the inversion of GRACE gravity fields for present-day ice-mass changes and glacial-isostatic adjustment in North America and Greenland

We perform an inversion of gravity fields from the Gravity Recovery and Climate Experiment (GRACE) (August 2002 to August 2009) of four processing centres for glacial-isostatic adjustment (GIA) over North America and present-day ice-mass change in Alaska and Greenland. We apply a statistical filtering approach to reduce noise in the GRACE data by confining our investigations to GRACE coefficients containing a statistically significant linear trend. Selecting the subset of reliable coefficients in all GRACE time series (GFZ RL04, ITG 2010, JPL RL04 and CSR RL04) results in a non-isotropic smoothing of the GRACE gravity fields, which is effective in reducing the north-south oriented striping associated with correlated errors in GRACE coefficients. In a next step, forward models of GIA induced by the glacial history NAWI (Zweck and Huybrechts, 2005), as well as present-day ice mass changes in Greenland from ICESat (Sørensen et al., 2011) and Alaska from airborne laser altimetry (Arendt et al., 2002) are simultaneously adjusted in scale to minimize the misfit to the filtered GRACE trends. From the adjusted models, we derive the recent sea-level contributions for Greenland and Alaska (August 2002 to August 2009), and, interpret the residual misfit over the GIA-dominated region around the Hudson Bay, Canada, in terms of mantle viscosities beneath North America.

Publication:

Sasgen, I., V. Klemman, and **Z. Martinec** (2012), Towards the inversion of GRACE gravity fields for present-day ice-mass changes and glacial-isostatic adjustment in North America and Greenland. *J. Geodyn.*, **59-60**, 49-63, doi: 10.1016/j.jog.2012.03.004.

Presentations:

Sasgen, I., J.L. Bamber, M. van den Broeke, L. Sandberg Srensen, B. Wouters, **Z. Martinec**, M. Horwath, H. Konrad, E. Rignot, and I. Velicogna (2012), On regional ice sheet mass balance from GRACE, the mass budget method, and ICESat. EGU General Assembly, Vienna, Austria, 22-27 April.

Sasgen, I., H. Konrad, E.R. Ivins, M.R. van den Broeke, J.L. Bamber, **Z. Martinec**, and V. Klemann (2012), Regionally improved estimate of glacial-isostatic adjustment and its impact on Antarctic ice-mass trends from GRACE (project AGIA), Joint GSTM/SPP1257 Symposium, GFZ Potsdam, 17-19 September.

Martinec, Z. (2012), Forward and adjoint methods of glacial isostatic adjustment with non-vanishing surface horizontal traction, Joint GSTM/SPP1257 Symposium, GFZ Potsdam, 17-19 September, (poster).

Klemann, V., M. Tesauro, and **Z. Martinec** (2012), Featuring lithosphere rheology in studies of glacial isostatic adjustment, Joint GSTM/SPP1257 Symposium, GFZ Potsdam, 17-19 September, (poster).

4.4 Effects of uncertainties in the geothermal heat flux distribution on the Greenland Ice Sheet: An assessment of existing heat flow models

We analyze the uncertainties in the models of the Greenland Ice Sheet (GIS) that arise from ill-constrained geothermal heat flux (GHF) distribution. Within the context of dynamic GIS modeling, we consider the following questions: (i) What is the significance of the differences between the existing GHF models for the GIS modeling studies? (ii) How well does the modeled GIS controlled by the GHF models agree with the observational data? (iii) What are the relative contributions of uncertainties in GHF and climate forcing to the misfit between the observed and modeled present-day GIS?

The results of paleoclimatic simulations suggest that differences in the GHF models have a major effect on the history and resulting present-day state of the GIS. The ice sheet model controlled by any of these GHF forcings reproduces the observed GIS state to only a limited degree and fails to reproduce either the topography or the low basal temperatures measured in southern Greenland. By contrast, the simulation controlled by a simple spatially uniform GHF forcing results in a considerably better fit with the observations, raising questions about the use of the three GHF models within the framework of GIS modeling. Sensitivity tests reveal that the misfit between the modeled and measured temperatures in central Greenland is mostly due to inaccurate GHF and Wisconsin precipitation forcings. The failure of the ice sheet model in southern Greenland, however, is mainly caused by inaccuracies in the surface temperature forcing and the generally overestimated GHF values suggested by all GHF models.

Publication:

Rogozhina, I., **J.M. Hagedoorn**, **Z. Martinec**, K. Fleming, O. Soucek, O., Greve, and R., Thomas (2012), Effects of uncertainties in the geothermal heat flux distribution on the Greenland Ice Sheet: An assessment of existing heat flow models, *J. Geophys. Res*., **117**, F02025, doi:10.1029/2011JF002098.

Presentations:

Rogozhina, I., **J.M. Hagedoorn**, **Z. Martinec**, K. Fleming, O. Soucek, R. Greve, and M. Thomas (2012), The effects of the uncertainties in geothermal heat flux distribution on the present-day Greenland Ice Sheet. EGU General Assembly, Vienna, Austria, 22-27 April.

Rogozhina, I., **J.M. Hagedoorn**, **Z. Martinec**, K. Fleming, and K. Thomas (2012), Applicability and limitations of large-scale ice-sheet modeling for constraining subglacial geothermal heat flux. EGU General Assembly, Vienna, Austria, 22-27 April, (poster).

4.5 A benchmark study for glacial isostatic adjustment codes

The study of glacial isostatic adjustment (GIA) is gaining an increasingly important role within the geophysical community. Understanding the response of the Earth to loading is crucial in various contexts, ranging from the interpretation of modern satellite geodetic measurements (e.g. GRACE and GOCE) to the projections of future sea level trends in response to climate change. Modern modelling approaches to GIA are based on various techniques that range from purely analytical formulations to fully numerical methods. Despite various teams independently investigating GIA, we do not have a suitably large set of agreed numerical results through which the methods may be validated; a community benchmark data set would clearly be valuable. We present, for the first time, the results of a benchmark study of codes designed to model GIA. This has taken place within a collaboration facilitated through European Cooperation in Science and Technology (COST) Action ES0701.

The approaches benchmarked are based on significantly different codes and different techniques. The test computations are based on models with spherical symmetry and Maxwell rheology and include inputs from different methods and solution techniques: viscoelastic normal modes, spectral-finite elements and finite elements.

The tests involve the loading and tidal Love numbers and their relaxation spectra, the deformation and gravity variations driven by surface loads characterized by simple geometry and time history and the rotational fluctuations in response to glacial unloading. In spite of the significant differences in the numerical methods employed, the test computations show a satisfactory agreement between the results provided by the participants.

Presentations:

Spada, G., V. Barletta, V. Klemann, W. van der Wal, T.S. James, K. Simon, R.E.M. Riva, **Z. Martinec**, P. Gasperini, B. Lund, D. Wolf, L.L.A. Vermeersen, and M.A. King (2012), Benchmarking and testing the Sea Level Equation. The COST ES0701 experience. SLALOM.

Sasgen I., M. van den Broeke, J.L. Bamber, E. Rignot, L. Sandberg Srensen, B. Wouters, **Z. Martinec**, I. Velicogna, and S.B. Simonsen (2012), Recent changes of the Greenland ice sheet: insights from GRACE, ICESat and InSAR/regional climate modeling. SLALOM 2012, Athens, 19-22 March.

4.6 The adjoint sensitivity method of global electromagnetic induction for downward continuation of secular magnetic variations

Martinec (Geophys. J. Int., 136, 1999) developed a time-domain spectral-finite element approach for the forward modelling of vector electromagnetic induction data as measured on ground-based magnetic observatories or by the CHAMP satellite. We use the same time and space representations of magnetic induction vector and designed a new method of computing the sensitivity of the ground-based or CHAMP magnetic induction data to a magnetic field prescribed at the core-mantle boundary, which we term the adjoint sensitivity method. The forward and adjoint initial boundary-value problems, both solved in the time domain, are identical, except for the specification of prescribed boundary conditions. The respective boundary-value data on the ground or at the satellite's altitude are the X magnetic component measured by a vector magnetometer for the forward method and the difference between the measured and predicted Z magnetic component for the adjoint method. The squares of the differences in Z magnetic component summed up over the time of observation and all spatial positions of observations determine the misfit. Then the sensitivities of observed data, that is the partial derivatives of the misfit with respect to the parameters characterizing the magnetic field at the core-mantle boundary, are then obtained by the surface integral over the core-mantle boundary of the product of the adjoint solution multiplied by the time-dependent functions describing the time variability of magnetic field at the core-mantle boundary, and integrated over the time of observation.

Presentation:

Hagedoorn, J., and **Z. Martinec** (2012), Adjoint sensitivity method for the downward continuation of the Earth's geomagnetic field through an electrically conducting mantle. AGU 2012 Fall Meeeting, San Francisco, 3-7 December, (poster).

4.7 Interpretation of GOCE data over Congo basin

Work on interpreting the GOCE data over Congo basin has been continuing. The main aim focused on the refinement of the model of sedimentary rocks such that satellite gravity and gradiometry data are optimally adjusted. First, the 5-parameter Helmert's transformation is applied to transform the original Kadima et al. (2011) sedimentary model to a spatial position that resembles the gravity data over the basin. The transformation is defined by 2 translation, 1 rotation and 2 scale parameters that are searched by the method of steepest descent. The same procedure is applied to the Laske and Masters (1997) 1x1 degree sedimentary model for CONGO basin. The resulting transformed sedimentary models are only slightly changed with respect to the originals but they largely improve the fit of the gravity data over Congo sedimentary basin. However, there are still a few features of free-air gravity anomaly remaining unfitted by the sedimentary models. Secondly, the transformed sedimentary models are used to find the vertical density distribution of sediments. The free-air gravity anomaly can be optimally interpreted by a constant sedimentary density. Such a model does not, however, fit well the vertical gradient of gravity. Therefore, a density model is extended by including a linear increase in sedimentary density. The least-squares procedure is applied to find the parameters of density model by adjusting both gravity and vertical gradient of gravity.

Presentations:

Martinec, Z. (2012), Mass-density Greens functions for gradiometric data. GOCE Solid Earth workshop, University of Twente, Enschede, 16-17 October.

Fullea J. et al. (2012), 3D Geophysical-petrological modelling of the lithosphere: how can GOCE data help us assessing the geothermal potential of Ireland. GOCE Solid Earth workshop, University of Twente, Enschede, 16-17 October.

5 Seismology and geodynamics

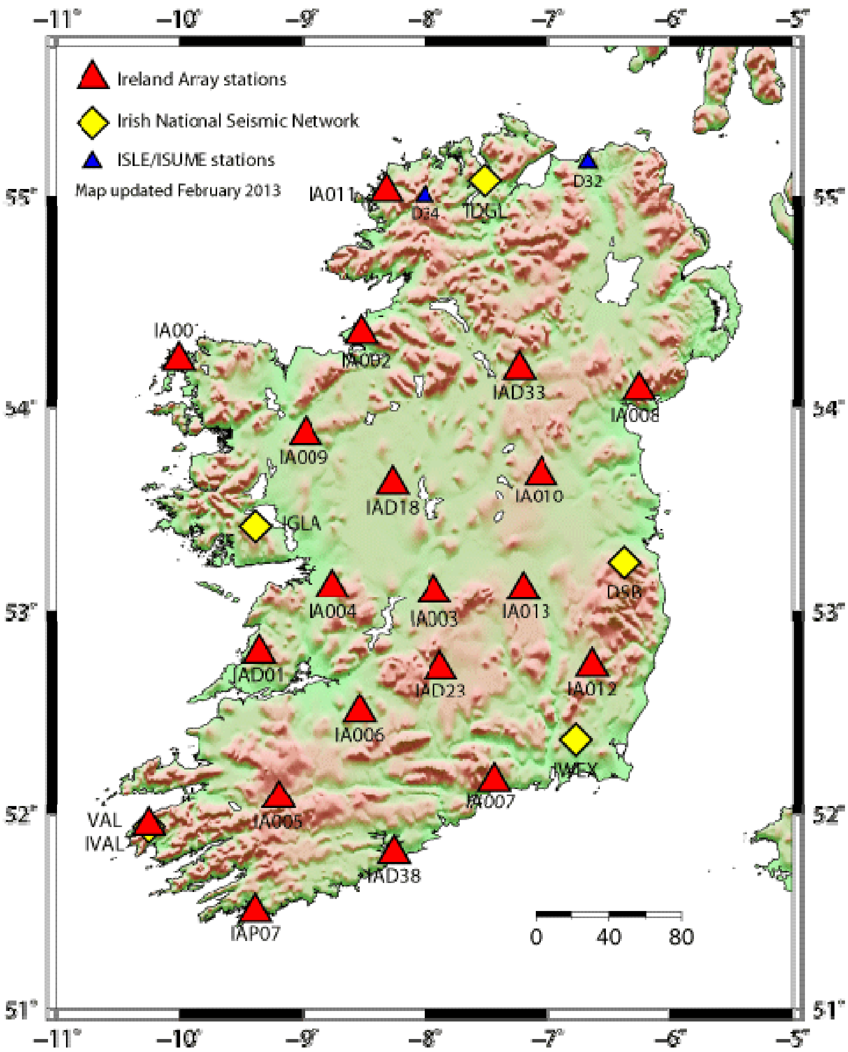
Group Leader: Assistant Professor Sergei Lebedev

The seismology and geodynamics group has achieved significant successes in its research, while working on a broad range of problems—from Ireland's subsurface, locally, to the Earth's crust and upper mantle, globally. The group's new global tomographic models are world-leading and offer unprecedented resolution of the Earth's upper-mantle structure. The successful deployment of Ireland Array, completed in 2012, will produce, for the first time, dense sampling of the entire country with broadband seismic data, offering new insight into the Caledonian evolution of Ireland's crust and its current structure and seismicity.

In a set of regional projects, the group targeted fundamental processes of Earth dynamics, from the formation and evolution of the first, Archean continental blocks (studies in southern Africa and Canada) to the dynamics of continental deformation active today (eastern Mediterranean, Tibet), and from the mechanisms of exhumation of high-pressure continental rocks to the evolution of oceanic tectonic plates. The quality of the work was recognised by prestigious awards to two seismology Ph.D. students.

5.1 Ireland Array

Sergei Lebedev, Clare Horan, Peter Readman, Louise Collins, Andrew Schaeffer, Nicola Piana Agostinetti, Andrea Licciardi, Matthew Agius, Franz Hauser, Joanne Adam, Brian O'Reilly, Tom Blake



On October 9, the 20th station of Ireland Array has been installed at Emo Court, Co Laois. This completed the deployment phase of the 20-station network. During the operation phase now, data collection and station maintenance will continue, producing a first of a kind broadband data set, sampling across Ireland. The dense coverage of the entire country with the stations of Ireland Array will enable detailed imaging Ireland's subsurface and monitoring of its seismicity, in both basic and applied studies. The imaging will reveal Ireland's deep structure and evolution in unprecedented detail. Ireland Array is also underpinning geothermal energy research by helping to reveal the structure of Ireland's crust – see SIM-CRUST below.

Presentations:

Lebedev, S., C. Horan, P.W. Readman, A.J. Schaeffer, M.R. Agius, L. Collins, F. Hauser, B.M. O'Reilly, and **T. Blake** (2012), Ireland Array: New broadband seismic stations target the structure, evolution and seismicity of Ireland and surroundings (Poster), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

Lebedev, S., C. Horan, P.W. Readman, A.J. Schaeffer, M.R. Agius, L. Collins, F. Hauser, B.M. O'Reilly, and **T. Blake** (2012), Ireland Array: A new broadband seismic network targets the structure, evolution and seismicity of Ireland and surroundings (3615, Talk), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

Lebedev, S., C. Horan, P.W. Readman, A.J. Schaeffer, M.R. Agius, J. Adam, L. Collins, F. Hauser, B.M. O Reilly, and **T. Blake** (2012), Ireland Array: A New Broadband Seismic Experiment Targets the Structure, Evolution and Seismicity of Ireland and the North Atlantic (DAP1+4: O5, Talk), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

5.2 Global seismic tomography, with surface- and body-wave waveforms

A. Schaeffer, S. Lebedev

Thanks to the rapid expansion of broadband seismic networks over the last decade, significantly improved resolution of global upper-mantle and crustal structure can now be achieved, provided that structural information is extracted effectively from both surface and body waves and that the effects of errors in the data are controlled and minimised.

We have constructed a new global, vertically-polarized-shear-speed model that yields considerable improvements in resolution, compared to previous ones, for a variety of features in the upper mantle and crust. The model, SL2013sv, is constrained by an unprecedentedly large set of waveform fits (~3/4 of a million broadband seismograms), computed in seismogram-dependent frequency bands, up to a maximum period range of 11—450 s. Automated Multimode Inversion of surface- and S-wave forms was used to extract a set of linear equations with uncorrelated uncertainties from each seismogram. The equations described perturbations in elastic structure within approximate sensitivity volumes between sources and receivers.

Going beyond ray theory, we calculated the phase of every mode at every frequency and its derivative with respect to S- and P-velocity perturbations by integration over a sensitivity area in a three-dimensional (3D) reference model; the (normally, small) perturbations of the 3D model required to fit the waveforms were then linearised using these accurate derivatives. The equations yielded by the waveform inversion of all the seismograms were simultaneously inverted for a 3D model of shear and compressional speeds and azimuthal anisotropy within the crust and upper mantle. Elaborate outlier analysis was used to control the propagation of errors in the data (source parameters, timing at the stations, etc.). The selection of only the most mutually consistent equations exploited the data redundancy provided by our dataset and strongly reduced the effect of the errors, increasing the resolution of the imaging.

Our new shear-speed model is parametrised on a triangular grid with a ~280 km spacing. In well-sampled continental domains, lateral resolution approaches or exceeds that of regional-scale studies. The close match of known surface expressions of deep structure with the distribution of anomalies in the model provides a useful benchmark. In oceanic regions, spreading ridges are very well resolved, with narrow anomalies in the shallow mantle closely confined near the ridge axis, and those deeper, down to 100–120 km, showing variability in their width and location with respect to the ridge. Major subduction zones world-wide are well captured, extending from shallow depths down to the transition zone.

The large size of our waveform fit dataset also provides a strong statistical foundation to re-examine the validity field of the JWKB approximation and surface-wave ray-theory. Our analysis shows that the approximations are likely to be valid within certain time-frequency portions of most seismograms with high signal-to-noise ratios, and these portions can be identified using a set of consistent criteria that we apply in the course of waveform fitting.

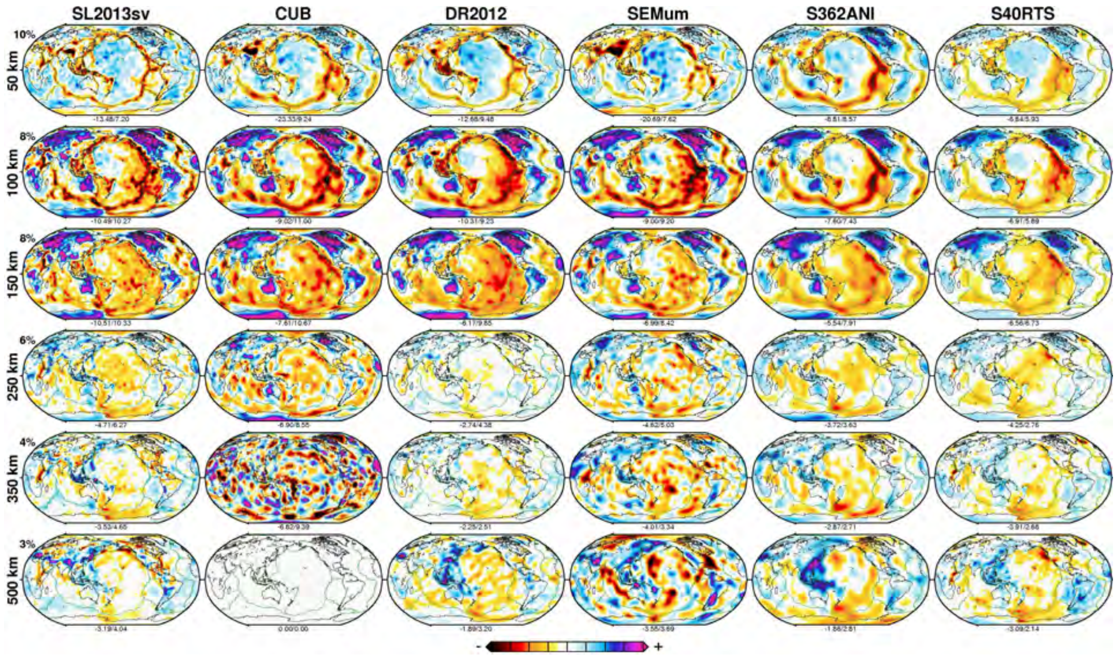


Figure. Comparison of SL2013sv with five recent global tomographic models: CUB (Shapiro & Ritzwoller 2002), DR2012 (Debayle & Ricard 2012), SEMum (Lekic & Romanowicz 2011), S362ANI (Kustowski et al. 2008a), and S40RTS (Ritsema et al. 2011). At each of five depths in the upper mantle, perturbations are in percent with respect to the mean value for that model. The minimum and maximum values are indicated underneath each map, and the same linear colour scale spans from negative to positive saturation values indicated for each depth (at left). Models are ordered left-to-right by decreasing peak-to-peak variations at the 100 and 150 km depths. Our new model, SL2013sv, offers an unprecedented, substantially improved resolution for a variety of features in the upper mantle and crust.

<u>Presentations:</u>

Schaeffer, A.J., and **S. Lebedev** (2012), Anisotropic structure of the upper mantle, imaged using surface and *S* waveform tomography (Talk, BEST STUDENT TALK PRIZE WINNER), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

Schaeffer, A.J., and **S. Lebedev** (2012), Isotropic and Anisotropic Structure of the Upper Mantle, Imaged with Surface and *S* waveform Tomography (Talk). 3rd QUEST workshop, Tatranska Lomnica, Slovakia, 20 - 25 May.

Schaeffer, A.J., and **S. Lebedev** (2012), Global Waveform Tomography: Imaging the Earth's Upper Mantle With Millions of Surface- and S-Wave Forms (ES1: O6, Talk), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

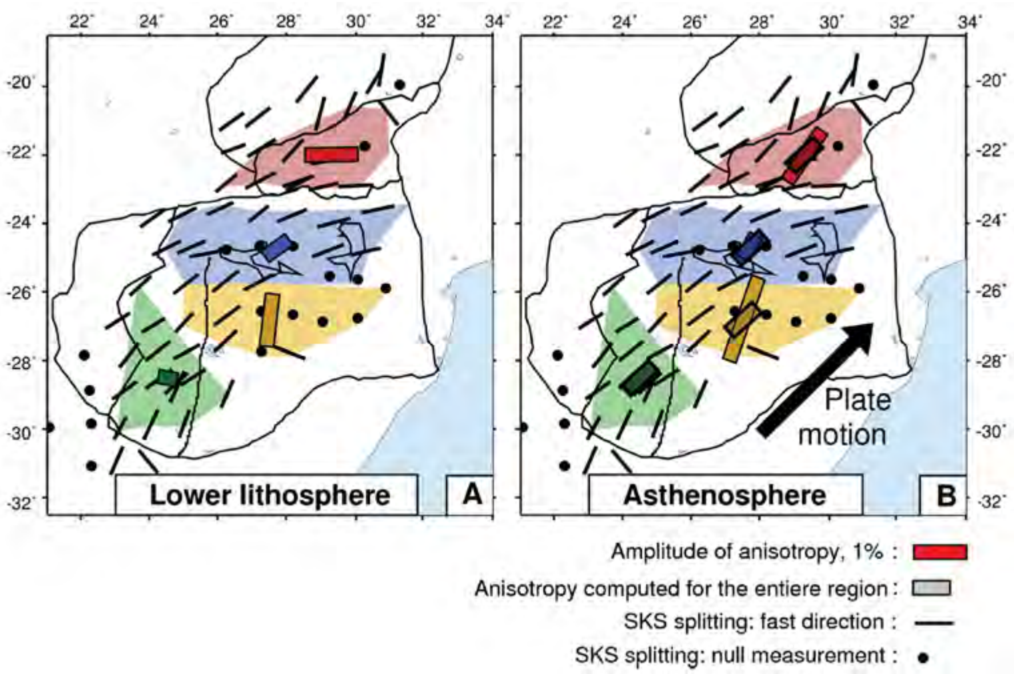
Schaeffer, A.J., and **S. Lebedev** (2012), Shear speed structure of the Earth's upper mantle and transition zone, imaged using surface and *S* waveform tomography (Talk). AGU Fall Meeting, San Francisco, 3-7 December.

5.3 Seismic anisotropy and deformation of southern Africa's cratons

J. Adam, S. Lebedev

Surface wave anisotropy indicates the distribution of azimuthal anisotropy and past and present deformation with depth. For four cratonic subregions in southern Africa (the northern, central and southwestern Kaapvaal Craton and the Limpopo Belt), we measured robust, Rayleigh- and Love-wave, region-average dispersion curves in a very broad period range: from 5 to 250–400 s (Rayleigh) and from 5 to 100–250 s (Love), depending on the region. Our azimuthal coverage was sufficient to determine Rayleigh-wave anisotropy within each region at periods from 5 to 150–200 s, resolving anisotropy from the upper crust down to the asthenosphere. We used the jackknife method to estimate uncertainties and the F-test to determine whether or not anisotropy was required by the data. The F-test results confirmed that 2ϕ phase-velocity anisotropy was required between 5 and 17 s and at periods greater than 35 s.

Strong anisotropy measured in the Limpopo Belt at short periods (5–10 s, decreasing with period) is probably due to aligned microcracks. The regional E–W extensional stress, associated with the South-ward propagation of the East African Rift, is evident from earthquake source mechanisms and is likely to have opened N–S-oriented cracks. This matches the N–S fast Rayleigh-wave propagation directions that we detect both in the Limpopo Belt and, with a smaller amplitude, in the central and western Kaapvaal Craton. Our results show that it is possible to estimate regional stress from surface-wave anisotropy, measured using broad-band array recordings of short-period surface waves.



Fabric within the deep mantle lithosphere of the Limpopo Belt and northern Kaapvaal Craton is aligned E–W to ENE–WSW, parallel to the Archean–Palaeoproterozoic sutures where these blocks got attached to the core of the craton and to each other. Our results confirm the earlier inferences from their SKS-splitting measurements: (i) that the entire lithosphere of these blocks underwent pervasive deformation with suture-parallel flow during the ancient continental collisions, and (ii) that the fabric created by the Archean–Palaeoproterozoic deformation is preserved within the lithosphere to this day. Suture-parallel fabric is absent in the deep lithosphere of the western Kaapvaal Craton (Kimberly block). It was not, therefore, reworked in the collision with the central Kaapvaal Craton, unlike the blocks that accreted in the north. This may have been either due to its mechanical strength or because the collision mechanism was different from those that operated in the north. The depth resolution of the surface wave data also provides a solution to the debate over the interpretation of SKS-splitting measurements: asthenospheric versus lithospheric dominant anisotropy. The distribution of anisotropy beneath southern Africa comprises elements of both models. Anisotropy in the asthenosphere is present and shows fast directions parallel to the plate motion. Anisotropy in the Limpopo and northern Kaapvaal Craton lithosphere shows fast directions parallel to the Archean–Palaeoproterozoic sutures. The depth intervals where the SKS splitting originates can be determined by comparing the depth distributions of anisotropy and the fast directions given by the splitting measurements. Beneath the Limpopo Belt and northern Kaapvaal Craton, SKS splitting reflects the E–W- and ENE–WSW-oriented fabric in the lithosphere. Beneath the western Kaapvaal Craton, in contrast, SKS splitting reflects the fabric in the asthenosphere, oriented parallel to the SW–NE plate motion.

Publication:

Adam, J. M.-C., and **S. Lebedev** (2012), Azimuthal anisotropy beneath southern Africa, from very-broadband, surface-wave dispersion measurements. *Geophys. J. Int.,* **191**, 155-174. [WINNER, GJI Student Author Award for best paper, 2012 (J. Adam).]

Presentations:

Adam, J., and **S. Lebedev** (2012), Stratification of seismic anisotropy and deformation beneath South Africa, from the upper crust to the asthenosphere (Talk), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

Adam, J., and **S. Lebedev** (2012), Inversion of surface wave dispersion curves for anisotropy and exploration of parameters trade-offs. 3rd QUEST workshop, Slovakia, 20-25 May.

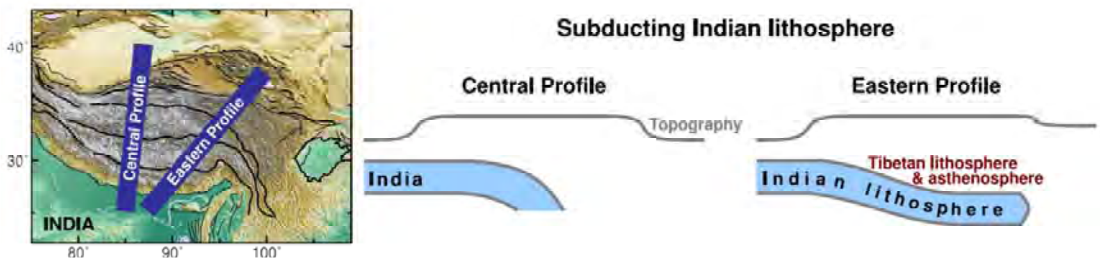
Adam, J., and **S. Lebedev** (2012), Broad-band measurement of inter-station phase velocities and their inversion for shear-velocity azimuthal anisotropy (poster, extended abstract published), Noise and Diffuse Wavefields workshop, Neustadt, Germany, 11-14 November.

5.4 Seismic study of the structure and dynamics of Tibet

M. Agius, S. Lebedev

Seismic deployments over the last two decades have produced dense broadband data coverage across the Tibetan Plateau. Yet, the lithospheric dynamics of Tibet remains enigmatic, with even its basic features debated and with very different end-member models still advocated today. Most body-wave tomographic models do not resolve any high-velocity anomalies in the upper mantle beneath central and northern Tibet, which motivated the inference that the Indian lithosphere may sink into deep mantle beneath the Himalayas in the south, with parts of it possibly extruded laterally eastward. In contrast, surface-wave tomographic models all show pronounced high-velocity anomalies beneath much of Tibet at depths around 200 km. Uncertainties over the shapes and amplitudes of the anomalies, however, contribute to the uncertainty of their interpretations, ranging from the subduction of India or Asia to the extreme viscous thickening of the Tibetan lithosphere. Within the lithosphere itself, a low-viscosity layer in the mid-lower crust is evidenced by many observations. It is still unclear, however, whether this layer accommodates a large-scale channel flow (which may have uplifted eastern Tibet, according to one model) or if, instead, deformation within it is similar to that observed at the surface.

Broad-band surface waves provide resolving power from the upper crust down to the asthenosphere, for both the isotropic-average shear-wave speeds (characterising the composition and thermal state of the lithosphere) and the radial and azimuthal shear-wave anisotropy (indicative, in an actively deforming region, of the current and recent flow). We measured highly accurate Love- and Rayleigh-wave phase-velocity curves in broad period ranges (up to 5-200 s) for a few tens of pairs and groups of stations across Tibet, combining, in each case, hundreds to thousands of inter-station measurements made with cross-correlation and waveform-inversion methods. Robust shear-velocity profiles were then determined by extensive series of non-linear inversions, designed to constrain the depth-dependent ranges of isotropic-average shear speeds and radial anisotropy consistent with the data. Temperature anomalies in the upper mantle were estimated from shear-velocity ones using pre-computed petro-physical relationships. Azimuthal anisotropy in the crust and upper mantle was determined by surface-wave tomography and, also, by sub-array analysis targeting the anisotropy amplitude.



Our results show that the prominent high-velocity anomalies in the upper mantle are most consistent with the presence of subducted Indian lithosphere beneath much of Tibet. The large estimated thermal anomalies within the high-velocity features match those to be expected within subducted India. The morphology of India's subduction beneath Tibet is complex and shows pronounced west-east variations. Beneath eastern and northeastern Tibet, in particular, the subducted Indian lithosphere appears to have subducted, at a shallow angle, hundreds of km NNE-wards.

Azimuthal anisotropy beneath Tibet is distributed in multiple layers with different fast-propagations directions, which accounts for the complexity of published shear-wave splitting observations. The fast directions within the mid-lower crust are parallel to the extensional components of the current strain rate field at the surface, consistent with similar deformation through the entire crust, rather than channel flow. Anisotropy within the asthenosphere beneath northeastern Tibet (sandwiched between the Tibetan lithosphere above and the subducted Indian lithosphere below) indicates SSW-NNE flow, parallel to the direction of motion of the Indian Plate, including its subducted leading edge.

Thesis:

Agius, M.R., The structure and dynamics of the lithosphere beneath Tibet from seismic surface-wave analysis. Trinity College Dublin, 2012. Submitted October 31, defended November 28, 2012.

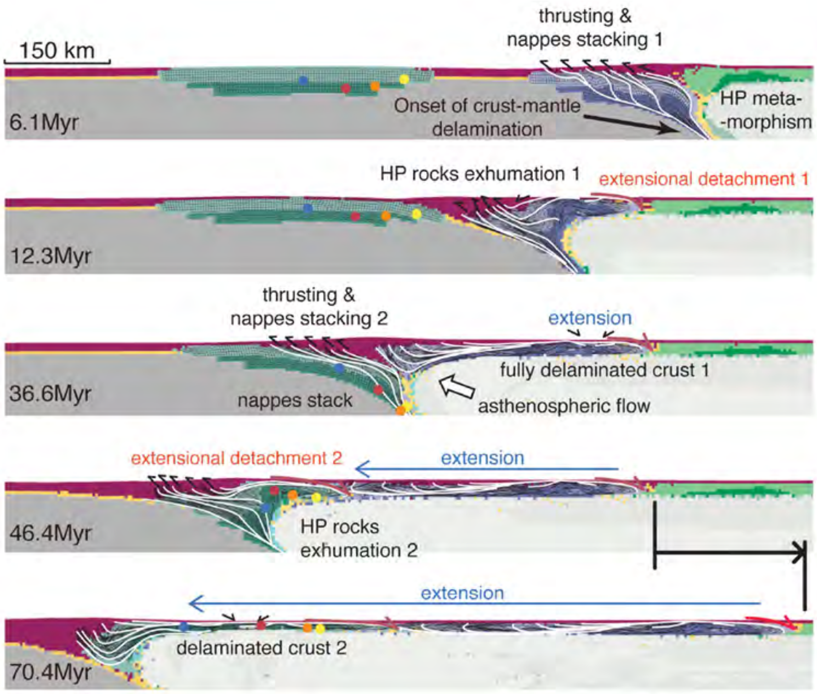
Presentation:

Agius, M.R., and **S. Lebedev** (2012), The shear velocity structure of the lithospheric mantle beneath Tibet (Talk), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

5.5 Geodynamic modelling of continental deformation

C. Tirel, S. Lebedev, in collaboration with J.-P. Brun (Rennes), E. Burov (Paris VI)

The scars of continental collisions that shaped today's continents are often marked by very peculiar rocks, once brought to tens-to-hundreds-km depths by subducting lithospheric plates, metamorphosed under high pressure there, and then rapidly exhumed to the surface, without being strongly deformed. Although these rocks are important markers of continental assembly, the mechanism of their exhumation remains a puzzle. The exhumation of high-pressure (HP) rocks is a big unsolved problem of Earth science. Of the solutions proposed, erosion is too slow, and subduction-channel viscous circulation cannot explain the HP rock units' commonly observed lithological-stratigraphical continuity (lack of strong deformation).



Our numerical simulations have revealed a surprisingly simple solution: when a subducted micro-continent's buoyant crust detaches from the lithospheric slab that dragged it down, the dense slab starts sinking faster, the subduction zone retreats, and the metamorphosed rocks ascend into the space that opens. Reproducing complete subduction-accretion-exhumation cycles in detail, our numerical modelling elucidates the basic HP-exhumation mechanism that can fully account for geological and geophysical observations.

Publication:

Tirel, C., J.-P. Brun, E. Burov, M.J.R. Wortel, and **S. Lebedev** (2012), A plate tectonics oddity: Caterpillar-walk exhumation of subducted continental crust. *Geology*, in press.

Presentation:

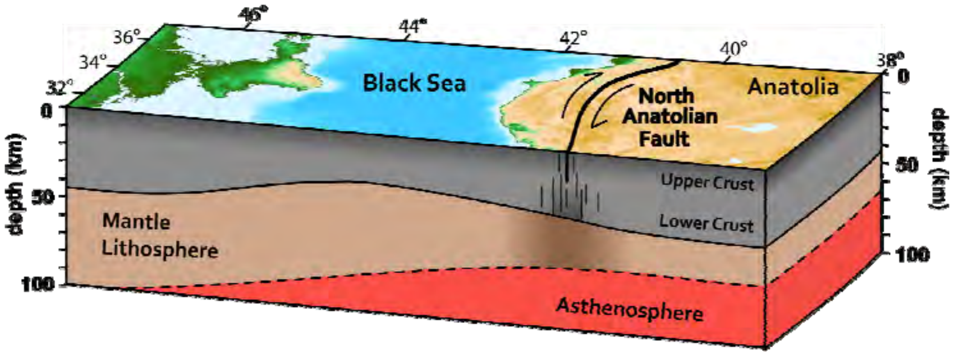
Brun, J.-P., **C. Tirel**, M. Philippon, E. Burov, C. Faccenna, F. Gueydan, and **S. Lebedev** (2012), On the role of horizontal displacements in the exhumation of high pressure metamorphic rocks (Solicited Talk), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

5.6 Structure and Deformation of the Eastern Mediterranean

E. Neenan, M. Agius, A. Schaeffer, C. Tirel, S. Lebedev

Active lithospheric deformation in eastern Mediterranean shows complex lateral and vertical variations. The distribution of diffuse and localised deformation is governed by three-dimensional variations in the rheological properties of the rock within the lithosphere. Because the crustal and mantle deformation is generally three-dimensional, with strain patterns depth-dependent, it is difficult to determine the deformation mechanisms from surface observations alone. Anisotropic fabrics within and beneath the lithosphere present a record of deformation at depth. Such fabrics can be determined from anisotropy of seismic surface waves.

We measured phase velocities of surface waves using seismic stations in eastern Mediterranean and inferred depth-dependent orientations of anisotropic fabrics in the crust and mantle. We also used the measurements to determine isotropic-average shear-velocity profiles, indicative of temperature within the lithosphere and, therefore, of its mechanical strength.



The shear associated with the westward motion of Anatolia is localised at and near the North Anatolian Fault (NAF). The lithosphere gets warmer and thinner from the Black Sea (north of NAF) to central Anatolia (south of NAF), so that the fault is localised near the transition between the mechanically strong and weak lithospheric blocks. The ductile lower crust and mantle lithosphere beneath NAF show E-W, fault-parallel, distributed flow within an at least 100 km wide zone. The underlying asthenosphere flows in a different, NE-SW direction, towards the retreating Hellenic Subduction Zone.

Although the movements of both the lithosphere and asthenosphere are probably driven by the same processes (primarily, the trench retreat), the motion of lithospheric blocks is different from that of the asthenosphere; it is influenced by boundary conditions and lateral variations in the mechanical strength of the lithosphere.

Presentations:

Lebedev, S., E. Neenan, B. Knapmeyer-Endrun, T. Meier, **M.R. Agius, A.J. Schaeffer**, C. Tirel, and W. Friederich (2012), Lithospheric dynamics in eastern Mediterranean: Insights from seismic structure and anisotropy (6626, Talk), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

Neenan, E., M.R. Agius, A.J. Schaeffer, and **S. Lebedev** (2012), The North Anatolian Fault and lithospheric dynamics in eastern Mediterranean: A seismic surface-wave study (Poster), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

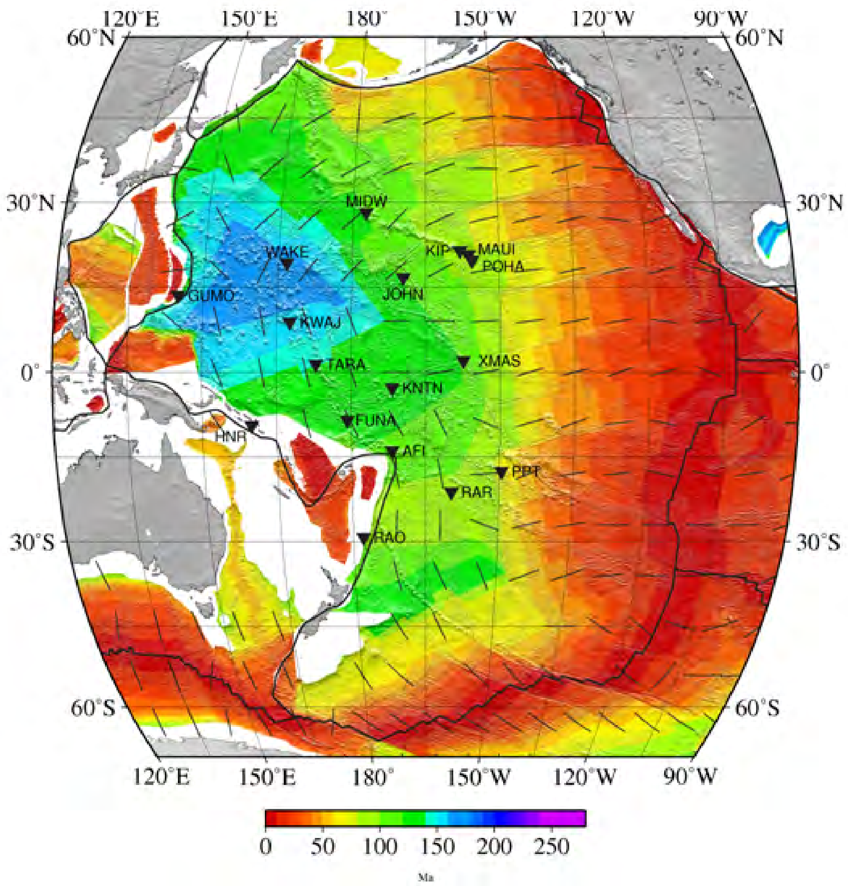
Neenan, E., A.J. Schaeffer, M.R. Agius, and **S. Lebedev** (2012), The North Anatolian Fault and lithospheric deformation in eastern Mediterranean: A seismic surface-wave study (6650, Poster), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

Neenan, E., A.J. Schaeffer, M.R. Agius, and **S. Lebedev** (2012), The North Anatolian Fault and lithospheric dynamics of eastern Mediterranean: A seismic surface-wave study (ES4: P091, Poster), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

5.7 Structure and thermal evolution of the Pacific lithosphere

P. Lynch, A. Schaeffer, M. Agius, S. Lebedev

Seismic velocities within the lithosphere and asthenosphere beneath oceans reflect the increase of temperature with depth and its variations laterally, as well as, at least in places, partial melting and higher volatile content in the asthenosphere relative to the lithosphere. Seismic anisotropy preserves a record of flow in the mantle rock and provides important constraints on the dynamics of the lithosphere-asthenosphere system.



We measured phase velocities of surface waves across central and western Pacific using pairs of permanent seismic stations and a combination of cross-correlation and multimode waveform inversion approaches. Robust, accurate Rayleigh- and Love-wave dispersion curves in broad period ranges were averaged from tens to hundreds of one-event measurements. The dispersion curves were then inverted for isotropic-average shear-velocity profiles and radial anisotropy. Regional-scale stratification of azimuthal anisotropy was also constrained.

We found that azimuthal anisotropy is stratified between the lithosphere and asthenosphere, with fast directions matching the paleo-spreading directions in the former and the current plate motion in the latter. Shear-velocity azimuthal anisotropy is 2-3 % within the lithosphere.

Near Hawaii, the lithosphere is heated by the Hawaii Hotspot and then cooles as it moves away from it. Phase velocities and V_S profiles show the thickening of the lithosphere with time as it cools. Very slow cooling rates at distance contrast with the very high rate immediately following the thermal rejuvenation. An observable signature of rejuvenation of the lithosphere, however, persists for tens of million years.

Love- and Rayleigh-wave dispersion measurements show the north-central Pacific to be faster (cooler) than the south-central Pacific, in spite of the similar lithospheric age in both regions. This probably reflects rejuvenation of south-central Pacific lithosphere by the hotspots that are currently situated to the east of it.

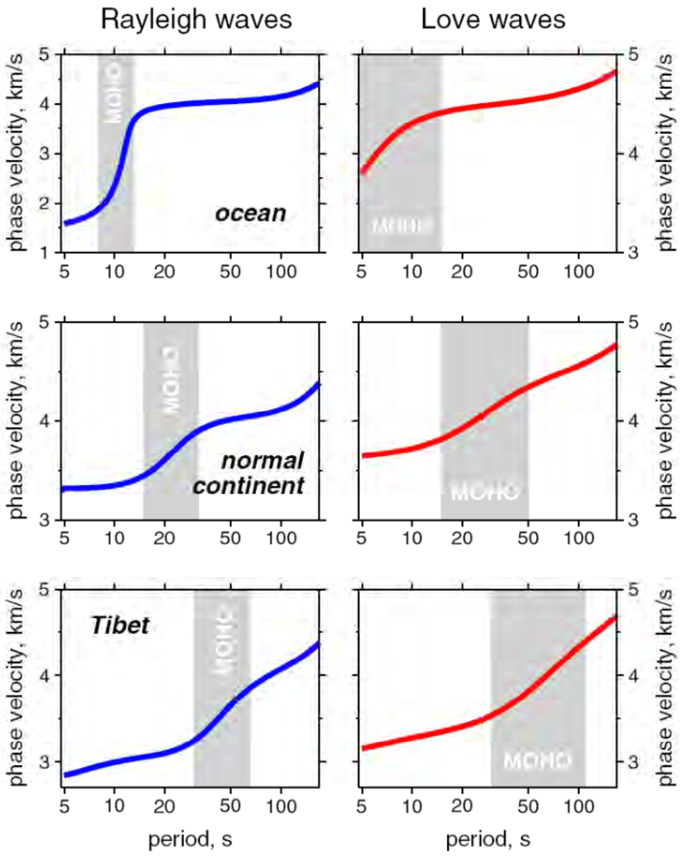
Presentation:

Lynch, P., A.J. Schaeffer, M.R. Agius, and **S. Lebedev** (2012), Robust Shear-Velocity Profiles Within Oceanic Lithosphere and Asthenosphere: Implications for Thermal and Compositional Structure (Poster), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

5.8 Mapping the Moho with seismic surface waves

S. Lebedev, J. Adam

The strong sensitivity of seismic surface waves to the Moho is evident from a mere visual inspection of their dispersion curves or waveforms. Rayleigh and Love waves have been used to study the Earth's crust since the early days of modern seismology. Yet, strong trade-offs between the Moho depth and crustal and mantle structure in surface-wave inversions prompted doubts regarding their capacity to resolve the Moho. We reviewed surface-wave studies of the Moho and, then, used model-space mapping to establish the waves' sensitivity to the Moho depth and the resolution of their inversion for it. If seismic wavespeeds within the crust and upper mantle are known, then Moho-depth variations of a few kilometres produce large (>1%) perturbations in phase velocities. However, in inversions of surface-wave data with no a priori information (wavespeeds not known), strong Moho-depth/shear-speed trade-offs will mask ~90% of the Moho-depth signal, with remaining phase-velocity perturbations ~0.1% only. In order to resolve the Moho with surface waves alone, errors in the data must thus be small (up to ~0.2% for resolving continental Moho).



With larger errors, Moho-depth resolution is not warranted and depends on error distribution with period. An effective strategy for the inversion of surface-wave data alone for the Moho depth is to, first, constrain the crustal and upper-mantle structure by inversion in a broad period range and then determine the Moho depth in inversion in a narrow period range most sensitive to it, with the first-step results used as reference. Prior information on crustal and mantle structure reduces the trade-offs and thus enables resolving the Moho depth with noisier data; such information should be used whenever available. Joint analysis or inversion of surface-wave and other data (receiver functions, topography, gravity) can reduce uncertainties further and facilitate Moho mapping.

Publication:

Lebedev, S., J. M.-C. Adam, and T. Meier (2012), Mapping the Moho with seismic surface waves: A review, resolution analysis, and recommended inversion strategies. *Invited Review, Tectonophysics, "Moho" special issue*, 10.1016/j.tecto.2012.12.030, in press.

5.9 Seismic anisotropy in the Earth's crust and upper mantle

S. Lebedev, in collaboration with colleagues at DIAS and overseas

Seismic anisotropy provides valuable constraints on crustal and mantle dynamics and continental evolution. One particular question concerns the depth distribution and coherence of azimuthal anisotropy, which is a key for understanding strain-localization and the general character of force transmission between the lithosphere and asthenosphere.

On a global scale, shear-wave splitting and surface-wave tomography provide essential and complementary constraints on anisotropy, but significant differences between results from the two types of imaging have been reported, and it is uncertain to what extent they can be reconciled. The discrepancies may be due to differences in lateral averaging inherent to the methods or to approximations used in previous quantitative comparisons.

With colleagues in the US, we reevaluated the degree of coherence between the predicted shear wave splitting derived from tomographic models of azimuthal anisotropy and that from actual observations of splitting. Elaborate, full-waveform methods to estimate splitting from tomography yield generally similar results to the more common, simplified approaches. This validates previous comparisons and structural inversions. However, full waveform methods may be required for regional studies, and they allow exploiting the back-azimuthal variations in splitting that are expected from the complexities of depth-variable anisotropy. Applying our analysis to a global set of SKS splitting measurements and two recent models of upper-mantle azimuthal anisotropy, we show that the measures of anisotropy inferred from the two types of data are in substantial agreement. Provided that the splitting data is spatially averaged (so as to bring it to the scale of long-wavelength tomographic models and reduce spatial aliasing), observed and tomography-predicted delay times are significantly correlated, and global, angular misfits between predicted and actual splits are relatively low. Regional anisotropy complexity notwithstanding, our findings imply that splitting and tomography yield a consistent signal that can be used for geodynamic interpretation.

Surface-wave imaging of anisotropy beneath Hudson Bay, in a collaborative project with colleagues in Canada and Britain, has revealed a record of flow in the lower crust of an ancient orogen. These exciting results offer a glimpse into the crustal dynamics of billions of years ago and were reported on in a special piece "Tectonics: Ancient channel flow" in Nature Geoscience (5, 520, 2012).

Publications:

Pawlak, A., D.W. Eaton, F. Darbyshire, **S. Lebedev**, and I.D. Bastow (2012), Crustal anisotropy beneath Hudson Bay from ambient noise tomography: Evidence for post-orogenic lower-crustal flow? *J. Geophys. Res.*, **117**, B08301, doi:10.1029/2011JB009066, 2012. [Highlighted in "Tectonics: Ancient channel flow", *Nature Geoscience*, **5,** 520.]

Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly, and **F. Hauser** (2012), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen, *Geophys. Res. Lett.*, **39**, L04302, doi:10.1029/2012GL051014.

Becker, T.W., **S. Lebedev**, and M.D. Long (2012), On the relationship between azimuthal anisotropy from shear wave splitting and surface wave tomography, *J. Geophys. Res.*, **117,** B01306, doi:10.1029/2011JB008705.

Presentations:

Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly, and **F. Hauser** (2012), Implications for crustal accretion and evolution within the Caledonian Orogen: Results from anisotropic Rayleigh-wave tomography in Ireland (Poster), 55th Irish Geological Research Meeting, University College Cork, 17-19 February.

Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly, and **F. Hauser** (2012), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen (11162, Poster), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

5.10 Development and application of new methods for imaging the Earth's interior

S. Lebedev, in collaboration with colleagues at DIAS and overseas

With colleagues in Germany, we developed a new, S-velocity model of the European upper mantle, constrained by inversions of seismic waveforms from broadband stations in Europe and surrounding regions. We collected seismograms for 1990 to 2007 from all permanent stations for which data were available via the data centers of ORFEUS, GEOFON, ReNaSs and IRIS. In addition, we incorporated data from temporary experiments, including SVEKALAPKO, TOR, Eifel Plume, EGELADOS and other projects. Automated Multimode Inversion of surface and S-wave forms was applied to extract structural information from the seismograms, in the form of linear equations with uncorrelated uncertainties. Successful waveform fits for about 70,000 seismograms yielded over 300,000 independent linear equations that were solved together for the three-dimensional (3-D) tomographic model. Structure of the mantle and crust was constrained by waveform information from the fundamental-mode Rayleigh waves and from S and multiple S waves (higher modes). Both the non-linear waveform inversions and the 3-D tomographic inversion used a 3-D reference model with a realistic crust. Waveform information was related to shear- and compressional-velocity structure within approximate waveform sensitivity volumes.

We produced two versions of the model: one for the entire European upper mantle and another, with the highest resolution, focussed on the upper 200 km of the mantle beneath western and central Europe and the Circum Mediterranean. The mantle lithosphere and asthenosphere are well resolved by both models. The highest velocities in the mantle lithosphere of the East European Craton are found at about 150 km depth. There are no indications for a deep cratonic root below about 330 km depth. Lateral variations within the cratonic mantle lithosphere are resolved as well. The locations of kimberlites correlate with reduced S-wave velocities in the shallow cratonic mantle lithosphere. This anomaly is present in regions of both Proterozoic and Archean crust, pointing to an alteration of the mantle lithosphere after the formation of the craton. Strong lateral changes in S-wave velocity are found at the western margin of the East European Craton and hint to erosion of cratonic mantle lithosphere beneath the Scandes by hot asthenosphere. The mantle lithosphere beneath Western Europe and between the Tornquist-Teyissere Zone and the Elbe Line shows moderately high velocities and is of an intermediate character, between cratonic lithosphere and the thin lithosphere of central Europe. In central Europe, Caledonian and Variscian sutures are not associated with strong lateral changes in the lithosphere-asthenosphere system. Cenozoic anorogenic intraplate volcanism in central Europe and the Circum Mediterranean is found in regions of shallow asthenosphere and close to changes in depth of the lithosphere-asthenosphere boundary. Very low velocities at shallower upper mantle depths are present from eastern Turkey towards the Dead Sea transform fault system and Sinai, beneath locations of recent volcanism. Low-velocity anomalies extending vertically from shallow upper mantle down to the transition zone are found beneath the Massive Central, Sinai, Canary Islands and Iceland.

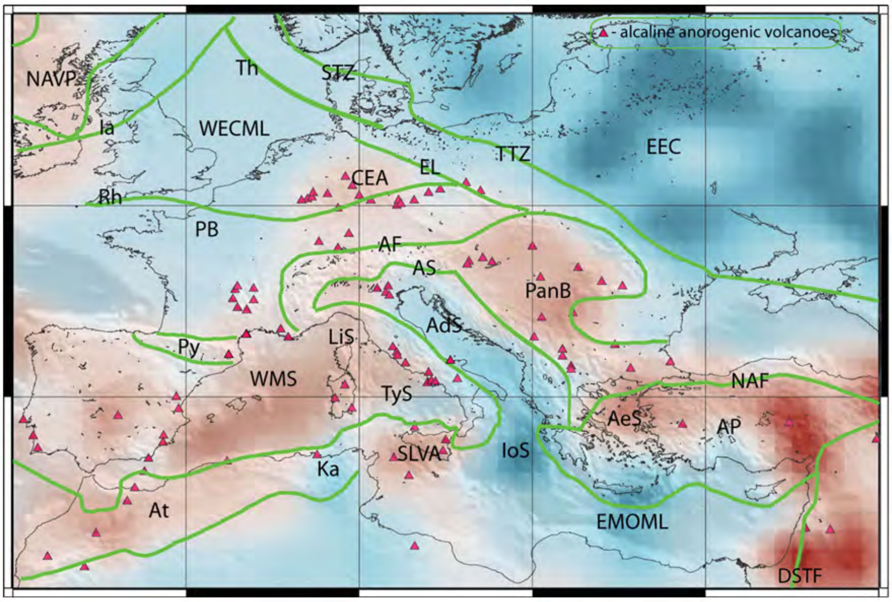


Figure 3. Seismic-velocity distribution at 100 km depth and structural interpretation for central Europe and the circum Mediterranean. Tectonic features: AdS, Adriatic Sea; AeS, Aegean Sea; AF, Alpine Front; AP, Anatolian Plateau; AS, Alpine Suture; At, Atlas Mountains; CEA, Central Europe Asthenosphere; DSTF, Dead Sea transform fault; EEC, East European Craton; EL, Elbe Line; EMOML, eastern Mediterranean oceanic mantle lithosphere; Ia, Iapetus Suture; IoS, Ionian Sea; Ka, Kabylies; LiS, Ligurian Sea; NAF, North Anatolian Fault; NAVP, North Atlantic Volcanic Province; PanB, Pannonian Basin; PB, Paris Basin; Py, Pyrenees; Rh, Rheic Suture; SLVA, Sicilian low-velocity anomaly, STZ, Sorgenfrei–Tornquist Zone; Th, Thor Suture; TyS, Tyrrhenian Sea; WECML, west European continental mantle lithosphere; WMS, western Mediteranean Sea. Alcaline anorogenic volcanoes are also indicated.

<u>Publications:</u>

Legendre, C., T. Meier, **S. Lebedev**, W. Friederich, and L. Viereck-Goette (2012), A shear-wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms. *Geophys. J. Int.*, **191**, 282-304.

Fullea, J., S. Lebedev, **M.R. Agius, A.G. Jones**, and J.C. Afonso (2012), Lithospheric structure in the Baikal–central Mongolia region from integrated geophysical-petrological inversion of surface-wave data and topographic elevation. *Geochem. Geophys. Geosyst.*, **13**, Q0AK09, doi:10.1029/2012GC004138.

<u>Presentations:</u>

Legendre, C., T. Meier, **S. Lebedev,** W. Friederich, and L. Viereck-Götte (2012), A shear-wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms (SO-1.003, Talk). Deutschen Geophysikalischen Gesellschaft (DGG), 5-8 March.

Soomro, R.A., C. Weidle, **S. Lebedev,** and T. Meier (2012), Automated inter station measurements of fundamental mode phase velocities – first tests (SO-P.008, Poster). Deutschen Geophysikalischen Gesellschaft (DGG), 5-8 March.

Legendre, C., T. Meier, **S. Lebedev,** W. Friederich, and L. Viereck-Götte (2012), A shear-wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms (8251, Talk), EGU General Assembly 2012, 22-27 April, Vienna, Austria.

Lebedev, S., and T. Meier (2012), Teleseismic interferometry: Measurement and model-space-map inversion of very-broadband dispersion of surface waves. 3rd QUEST workshop, Tatranska Lomnica, Slovakia, 20-25 May.

Meier, T., C. Legendre, **S. Lebedev,** W. Friederich, and L. Viereck-Goette (2012), A Shear-Wave Velocity Model of the European Upper Mantle from Automated Inversion of Seismic Shear and Surface Waveforms (ES4: O7, Talk), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

Soomro, R.A., C. Weidle, **S. Lebedev,** and T. Meier (2012), Automated Inter-Station Measurements of Fundamental Mode Phase Velocities – Examples and Tests (ES1: O17, Talk), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

Soomro, R.A., C. Weidle, **S. Lebedev,** L. Cristiano, and T. Meier (2012), Surface wave tomography of central to northern Europe – First tests using automated inter-station dispersion measurements (ES4: P086, Poster), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

Fullea, J., S. Lebedev, M.R. Agius, A.G. Jones, and J.C. Afonso (2012), Lithospheric structure in the Baikal-central Mongolia region from integrated geophysical-petrological inversion of surface-wave data and topographic elevation (ES4: P094, Poster), European Seismological Commission 33rd General Assembly, 19-24 August, Moscow, Russia.

Lebedev, S. (2012), Regional and global seismic tomography: Imaging the structure and dynamics of the Earth, Invited Seminar, University of Strasbourg, EOST, October 16.

5.11 Main collaborations

- University of Bergen, Norway (Profs. Henk Keers, Lars Ottemoller, Stephane Rondenay)
- University of British Columbia, Canada (Prof. Michael Bostock)
- University of Ottawa, Canada (Prof. Pascal Audet)
- University of Kiel, Germany (Prof. Thomas Meier, Dr. Christian Weidle)
- Ruhr University Bochum, Germany (Prof. Wolfgang Friederich)
- University College Dublin, Ireland (Prof. Chris Bean)
- Macquarie University, Australia (Drs. Juan Carlos Afonso and Yingjie Yang)
- University Paris VI, France (Prof. Evgeny Burov)
- University of Maryland, U.S. (Prof. Vedran Lekic)
- University of Southern California, U.S. (Prof. Thorsten Becker)
- Yale University, U.S. (Prof. Maureen Long)
- GNS (Geological and Nuclear Sciences), Wellington, New Zealand (Dr. Bill Fry)
- Utrecht University, the Netherlands (Profs. Jeannot Trampert, Rinus Wortel, Dr. Hanneke Paulssen)
- University of Potsdam, Germany (Dr. Brigitte Endrun)
- Université du Québec à Montréal, Canada (Prof. Fiona Darbyshire)

- Institute of Earth Sciences, Academia Sinica, Taiwan (Drs. Li Zhao, Frederic Deschamps, Cedric Legendre)

6 Seismological and potential field activities

Group Leader: Assistant Professor Brian O'Reilly

6.1 PIMS (Porcupine Irish Margin Seismics)

B. M. O'Reilly, P. W. Readman and F. Hauser

The study on the seismic structure of Ireland's crust and lithosphere was expanded to include northern England and Scotland to develop a general geological model for late Caledonian crustal development. This work attempts to bring together all available geological and seismological information.

These are used to build a model for the late Caledonian accretion history of the crust within this segment of the Caledonian Orogen, straddling the Iapetus Suture Zone beneath Ireland and Great Britain. Geological arguments are put forward, within the context of the main seismological results, including very recent surface wave observations (see ISUME). From these arguments a model is developed (**Figure 4**) that can explain the formation of the Earth's crust in this region and the development of geological features such as granites and volcanic rocks.

A paper on this work appeared in the Journal of the Geological Society, London in September. This paper presents these new, somewhat speculative, ideas regarding the late stage processes of continental crustal growth in Britain and Ireland that occurred about 400 million years ago. Related work on the structure and evolution in the Porcupine Basin was progressed during the year.

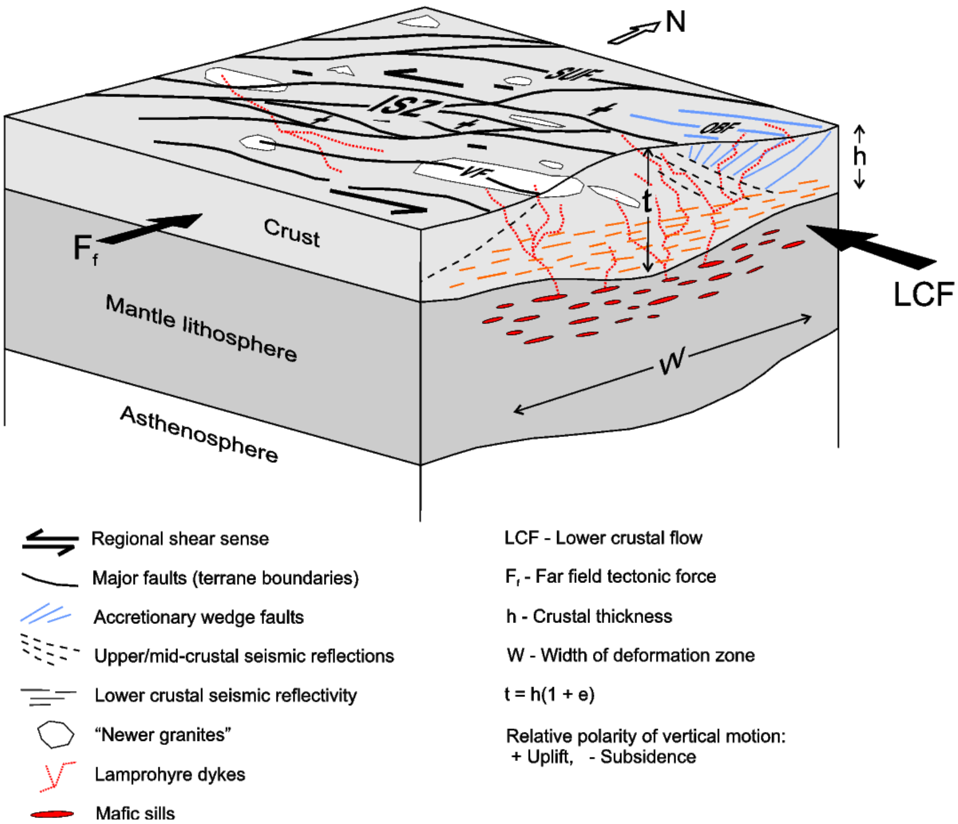


Figure 4. The “incipient delamination” for Ireland and Britain. Crust and mantle lithosphere have similarly orientated fabric at this stage in its history in the deformation history. A flow fabric is developed orientated parallel to the boundaries of the deformation zone. Structural fabrics at mid to lower crustal levels follow this flow-induced orientation and overprint earlier ones formed during the earlier subduction accretion history. Main crustal scale faults in Britain and Ireland: ISZ - Iapetus Suture Zone, OBF - Orlock Bridge Fault, SUF - Southern Uplands Fault, VF - Variscan Front.

Publication:

O’Reilly, B.M., F. Hauser, and **P.W. Readman** (2012), The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the “Newer Granites”. *Journal of the Geological Society*, London, **169**, 561-573.

6.2 TRIM (Tobi Rockall Irish Margins)

B. M. O’Reilly, and colleagues from University College Dublin, the University of Ulster and Durham

The evolution of the northwest European continental margin was strongly affected by Pleistocene glaciations, particularly where ice sheets extended onto the continental shelf and transferred glaciogenic sediment onto the slope, contributing to the formation of canyon systems, submarine fans and slides. Research conducted on the British- Irish Ice Sheet (BIIS) strongly indicates that its western margin extended offshore onto the continental shelf around Ireland and Britain.

However, until recently the study of submarine canyons and other slope and basin floor features have been limited by the low resolution of the available data. Recent advances in multibeam data processing and visualisation have yielded enhanced images. This study integrates high-resolution multibeam bathymetry and backscatter data with TOBI side-scan sonar data, resulting in a detailed geomorphological interpretation of the northwest Irish continental margin and an improved understanding of the effects of glacial forcing on the morphology and sediment architecture of the region. Correlation of the position and dimensions of glacial moraines on the continental shelf with the level of canyon evolution suggests that the sediment and meltwater delivered by the BIIS played a fundamental role in shaping the margin, including the upslope development of some of the canyon systems (**Figure 5**).

Glacial influence is also suggested by the variable extent of the sedimentary lobes associated with the canyons, which also provide an indirect measurement of the amount of glaciogenic sediment delivered by the ice sheet into the Rockall Trough during the last glacial maximum. The various slope styles observed on the Irish margin also represent snapshots of the progressive stages of slope development for a glacially influenced passive margin and may provide a predictive model for the evolution of other margins.

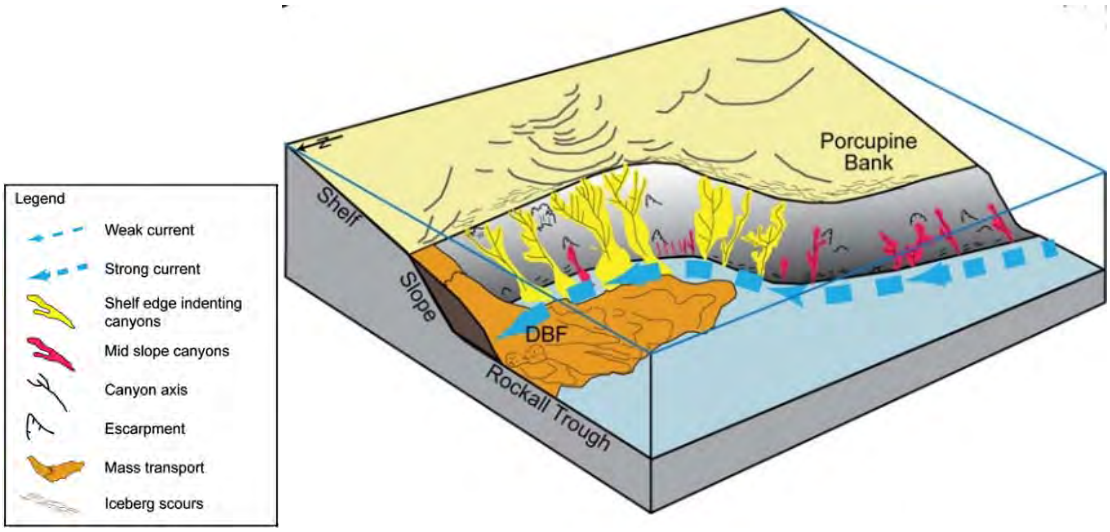


Figure 5. Slope evolution model of the eastern margin of the Rockall Trough in the late Pleistocene interglacials/Holocene. With the disappearance of the ice sheet from the shelf, canyons become sediment starved. Mass wasting only occurs in the upper reaches of canyons generating small turbidity currents and muddy debris flows keeping the canyons open. Strong bottom currents contribute to the redistribution of sediment within the Rockall Trough.

Publication:

Sacchetti, F., S. Benetti, A. Georgiopoulou, P.M. Shannon, **B.M. O'Reilly**, P. Dunlop, and R. Quinn (2012), C. Ó Cofaigh. Deep water geomorphology of the formerly glaciated Irish margin from high-resolution marine geophysical data. *Marine Geology*, **291-294,** 113-131.

6.3 ISUME (Irish Seismological Upper Mantle Experiment)

P. W. Readman, B. M. O'Reilly, S. Lebedev, F. Hauser and G. Polat

The servicing and deployment of instruments continued during the late summer and autumn of 2012. A paper entitled "Anisotropic Rayleigh-wave tomography of

Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen" appeared in Geophysical Research Letters. The results support the "incipient delamination model" for the late Caledonian development of Ireland's crust (see PIMS).

An analysis of Love wave dispersion data was begun during the year. Love wave dispersion curves have been used to construct dispersion maps, using regional to global earthquakes, which travel along similar great circle pathways (**Figure 6**). The results will be integrated with intermediate period Rayleigh wave phase velocity measurements obtaining previously during the project, to determine the amount of radial anisotropy for the crust in Ireland. They will provide further constraints on the seismic anisotropy properties, previously obtained from the Rayleigh wave dispersion studies and analysis of three-component controlled source seismic data.

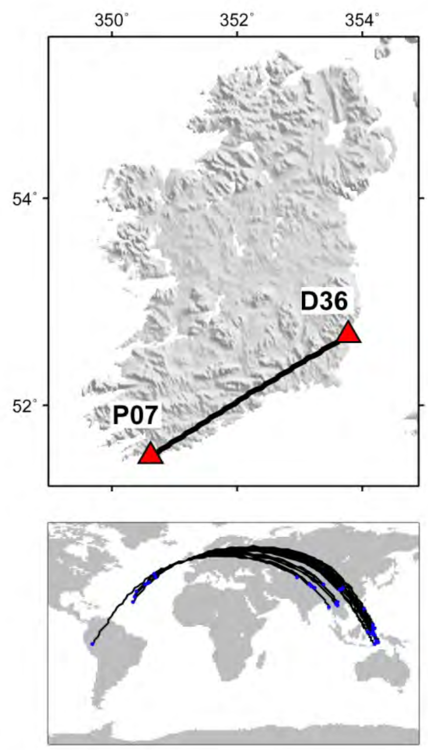


Figure 6. An example of an ISUME station pair used to measure surface wave dispersion curves across southern Ireland. Earthquakes in south-eastern Asia and the south American/central Atlantic region generate surface waves from opposite back-azimuths that travel along the same great circle pathway. This permits crustal phase velocities to be determined between the stations D07 and D36.

Publication:

Polat, G., S. Lebedev, P.W. Readman B.M. O'Reilly, and **F, Hauser** (2012), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen. *Geophysical Research Letters*, **39**, L04302, doi: 10.1029/2012GL051014.

Presentations:

Polat, G., S. Lebedev, **P.W. Readman**, **B.M. O'Reilly**, and **F. Hauser** (2012), Implications for crustal accretion and evolution within the Caledonian Orogen:

Results from anisotropic Rayleigh-wave tomography in Ireland. 55th Irish Geological Research Meeting, University College Cork, 17–19 February.

Polat, **G., S. Lebedev**, **P.W. Readman**, **B.M. O'Reilly**, and **F. Hauser** (2012), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen. European Geophysical Union General Assembly, Vienna, 22–27 April, 2012, Geopysical research Abstracts, **14.**

Blake, T.A., S. Lebedev, B.M. O'Reilly, N. Piana Agostinetti, M.R. Agius and **A.J. Schaeffer** (2012), An unusual occurence of a moderately sized earthquake (ML 4.2) on the Irish continental shelf and passive margin. AGU Fall Meeting, San Francisco, 3–7 December.

Lebedev, **S., C. Horan**, **P.W. Readman**, **A.J. Schaeffer**, **M.R. Agius**, **J. Adam**, **L. Collins**, **F. Hauser**, **B.M. O Reilly**, and **T. Blake** (2012), Ireland Array: A New Broadband Seismic Experiment Targets the Structure, Evolution and Seismicity of Ireland and the North Atlantic (DAP1+4: O5, Talk), European Seismological Commission 33rd General Assembly, Moscow, 19–24 August.

6.4 NAPSA (North Atlantic Petroleum Systems Assessment group)

B. M. O'Reilly, and colleagues from Memorial University, Newfoundland, University College Dublin, Memorial University, Newfoundland and Geotarctic Canada.

Work on a comparative study of the conjugate Irish and Canadian continental margins concentrated on a comparison of results from 3-D gravity inversion methods. Independently derived models for sedimentary basin structure were found to be compatible.

A recent regionally constrained 3-D gravity inversion study over the Irish Atlantic continental margin (Rockall, Porcupine and Goban Spur) showed excellent agreement between available seismic constraints of crustal structure and major structures resolved in the inverted 3-D density anomaly model for the margin. The resulting model allowed for crustal characteristics such as Moho structure and crustal thickness to be tracked and extrapolated across the margin into regions lacking deep seismic constraints. In the present study, equivalently constrained 3-D gravity inversion results have been computed for the Orphan Basin/Flemish Cap region using identical parameters to those used for the Irish study, allowing structures across the two margins to be compared (**Figure 7**).

One purpose of this study is to build upon previous tectono-stratigraphical and crustal work on both margins in order to reconcile their respective rifting histories and test hypothesized connections between linked basins and underlying pre-rift basement terranes. The process of continental break-up and sea-floor spreading did not begin until the early Eocene and had a major stratigraphic impact on the post-Mesozoic evolution of the Irish margins. Crustal thickness varies widely (~2 km to 32 km) with the thinnest crust occurring below the Orphan, Rockall and Porcupine basins, where exhumation of serpentinised cold mantle lithosphere sporadically occurs. Major magmatic underplating, associated with early Cenozoic volcanism, is confined to the outer fringes of the Hatton Continental Margin (Irish side). The results provide an improved understanding of the petroleum habitat of the region and in connecting exploration plays across the North Atlantic to their conjugate equivalents.

A paper on a preliminary plate reconstruction appeared in the Geological Society of London. Related work was presented at the "North and Central Conjugate Margins Conference 2012" that was held in Dublin in late August and also at. the Geological Association of Canada meeting, which was held in St. John's, Newfoundland, in the previous May.

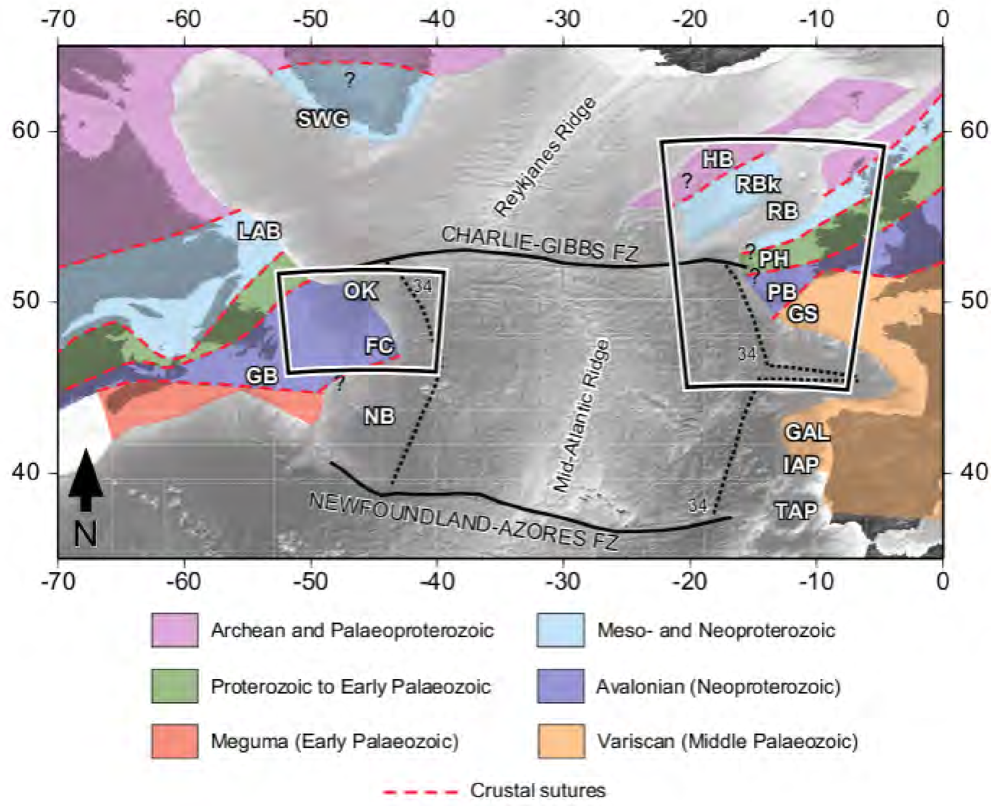


Figure 7. Bathymetric map of the North Atlantic region subdivided by inferred basement affinity of continental crust. Black boxes outline the regions over which constrained 3-D gravity inversions were performed. Abbreviations: main structural features i.e. GB - Grand Banks; FC - Flemish Cap; RB - Rockall Basin; PH - Porcupine High; PB - Porcupine Basin; FZ - fracture zone.

Publication:

Welford, K.J., P.M. Shannon, **B.M. O'Reilly**, and J. Hall (2012), Comparison of lithospheric density and Moho structure variations across the Orphan Basin/Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3-D gravity inversions, *Journal of the Geological Society*, London, **169,** 405-420.

Presentations:

O'Reilly, B.M, J. Kim Welford, and P. Shannon (2012), New wide-angle reflection seismic (WARRP) profiles across the conjugate margins of Ireland and Newfoundland. Third Central and North Atlantic Conjugate Margins Conference, Dublin, 21–24 August.

Welford, K.J., P.M. Shannon, **B.M. O'Reilly,** and J. Hall (2012), Comparison of lithosphere structure variations across the Orphan Basin/Flemish Cap and Irish

Atlantic conjugate continental margins from constrained 3-D gravity inversions. Third Central and North Atlantic Conjugate Margins Conference, Dublin, 21–24 August.

6.5 Collaborations

- UCD School of Geological Sciences: ISUME, TRIM, PIMS
- Applied Geophysics Unit, NUI Galway, ISUME
- University of Ulster (Colraine), TRIM
- Memorial University, St Johns, Newfoundland, NAPSA
- University of Liverpool, NAPSA
- University of Durham, TRIM

7 Seismic imaging of the Irish crust

N. Piana Agostinetti

7.1 Project overview

The project "Seismic imaging of the Irish crust" (SIM-CRUST) is funded by SFI under the "Starting Investigator Research Grant" programme (SIRG). Dr. Nicola Piana Agostinetti is funded for 5 years, and funding includes salary, a PhD student, and field costs.

The aim of the project is the passive seismic exploration of the Irish crust to better understand its geothermal potential. Details of the seismic structure of the shallow crust (e.g. seismic anisotropy) are fundamental to assess key parameters for a geothermal site (e.g. rock porosity). To obtain such ambitious goal, different passive seismic techniques are used, from local earthquakes tomography to high-frequency receiver function, to ambient noise dispersion analysis. Local earthquakes tomography (LET) exploits the information brought to the surface by seismic waves generated by (natural) microseismicity and it has been mainly used to reconstruct 3D P-velocity models of the shallow crust. Receiver function (RF) analysis is based on the recording of P-to-s and S-to-p converted phases generated by teleseismic waves crossing a seismic discontinuity. Seismic anisotropy and sharp S-velocity discontinuity at depth are the main targets of RF analysis. Ambient noise is routinely used to compute the S-wave dispersion curve for different station pairs, from which S-velocity models can be retrieved.

The project is focused on two main target areas, the Lough Swilly area (Co. Donegal) and the Dublin basin, where two dense seismic arrays will be deployed for three years. Lough Swilly has been struck by a number of low-magnitude earthquakes in the last ten years and microseismicity should be relevant in the area. In the Dublin basin, a borehole for geothermal exploration has been drilled along the southern slope. Thus, complementary data are available and will be used to assess the resolution of our techniques. Both regions partially overlap with the area investigated by IRETHERM project and results from seismic and magneto-telluric studies will be compared. To extend the analysis to a broader area, seismic data recorded during temporary deployment in the last ten years (ISLE, ISUME, Ireland Array) will be analyzed.

7.2 Fieldwork

In the past six months, we installed the seismic array around Lough Swilly. Eight seismic stations equipped with Guralp CMG-40T seismometer have been deployed to cover an area about 30x30km wide. The array is completed by two stations deployed by ISLE project and one station of the INSN network (IDGL). Two more station will be deployed in the next few months. Thus, the array will be composed by 13 seismic stations. The array covers the epicentral area of the Jan 26th 2012 event, Mw=2.2. Preliminary analysis of the first months of recording confirmed that the array is properly working. A local event, un-felt by population, occurred on Sept 8th 2012 and it has been clearly recorded by all the stations working at the moment.

7.3 Preliminary results

The analysis of the data recorded in the last years is fundamental to extend our results to other part of Ireland and back in the past. We analyzed the data recorded during the sequence in Donegal (Jan-Feb 2012) and we found a number of aftershock which can be used to precisely locate the source area of the Mw=2.2 event. Also, focal mechanism for the largest event has been computed using both Irish and British stations.

7.4 Student, Conference, Collaborations

A PhD student has been selected for the project, Andrea Licciardi. He started working at DIAS on Sept 1st 2012. He is participating to fieldwork and working on data collected by IrelandArray. In late September Licciardi attended the 39th School of Geophysics "Understanding Geological Systems for Geothermal Energy" held in Erice (Italy), and a short course on S-wave receiver function held by Prof. Meghan Miller at Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome. Piana Agostinetti attended the Italian Geological Society meeting in Cosenza (Italy). NPA is associate researcher at INGV. Piana Agostinetti is actively collaborating with the seismology group at University of Southern California (USC) and Lamont-Doherty Earth Observatory (LDEO).

<u>Presentations:</u>

Miller, M.S., **N.P. Agostinetti,** P.D. Asimow, and L. Dunzhu (2012), Modeling high frequency waves in the slab beneath Italy, *Daoyuan Sun.* T33G-2753.

Agostinetti, N.P., and M.S. Miller (2012), What happens to the Juan de Fuca plate boundary beneath northern Cascadia? Insight into the methamorphism of the oceanic crust. T21C-2592.

Lebedev, S., M.R. Agius, A.J. Schaeffer, C. Horan, D. Piccinini, and **N.P. Agostinetti** (2012), Strike-Slip Tectonics in Northwestern Ireland? Evidence From the 2012 January Seismic Sequence in Co. Donegal, Ireland. S51B-241.

Steckler, M.S., H.S. Akhter, L. Seeber, R.G. Bilham, M.G. Kogan, F. Masson, T. Maurin, D. Mondal, **N.P. Agostinetti,** C. Rangin, and P. Saha (2012), GPS Velocities and Structure Across the Burma Accretionary Prism and Shillong Anticline in Bangladesh. T51F-2667.

Muller, M.R., J. Fullea, A.G. Jones, J. Adam, S. Lebedev, and **N.P. Agostinetti** (2012), Lithospheric-Mantle Structure of the Kaapvaal Craton, South Africa, Derived From Thermodynamically Self-Consistent Modelling of Seismic Surface-Wave and S-wave Receiver Function, Heat-flow, Elevation, Xenolith and Magnetotelluric Observations. V51D-05.

Blake, T.A., S. Lebedev, B. O'Reilly, N.P. Agostinetti, M.R. Agius, and **A.J. Schaeffer** (2012), An unusual occurrence of a moderately sized earthquake (Ml 4.2) on the Irish continental shelf and passive margin. S53A-2476.

8 Irish Geoscience Graduate Programme (IGGP)

The Second Year (2011-2012) of the Irish Geoscience Graduate Programme (IGGP) (www.iggp.ie), co-ordinated by The Dublin Institute for Advanced Studies (DIAS) has been very successful.

While there have been some courses withdrawn from the IGGP modules (mainly because it is only necessary to run them every two years) others have been added from DIAS. This year a much needed course in GIS from NUI, Maynooth has been added to the Programme, which is already fully booked. For 2013/14 there are 23 courses on offer, with over 100 participants registered to attend courses, so the number of applications received from students and Industry professionals has grown significantly. This number will increase further with active encouragement and participation from course providers and Heads of schools countrywide. For 2014-2015, the IGGP has been promised new courses from NUIG and UCC also which is very positive, and we continue trying to encourage the Northern Irish Universities to participate, though they have started encouraging students to attend IGGP courses (and some are) which is a very positive step. We have found that what also attracts the geoscience students attending is getting all their costs reimbursed, which is very helpful (eg. those travelling to attend at a host institution, from across the whole of the island of Ireland, not in their home city).

Between 2013-2015 our main objective is to provide quality Geoscience modules to further equip our Post graduates in the practical world and also to seek funding for its continuation beyond 2015 (if proven successful and there is sufficient interest within the Irish geoscience academics).

One key element of the success of the courses that was not envisioned at the outset is the inclusion of senior PhD students and Post-Doctoral Fellows as demonstrators, to aid the course presenter, or even primary course presenters themselves (e.g. DIAS 002 - Seismology for Non-Seismologists - presented by Dr. Mark Muller).

The Irish Geoscience Graduate Programme will continue to grow and flourish in the forthcoming years and welcomes new Graduates to all of its courses. DIAS and IGGP respectfully request all Academic Faculty in the Geoscience field and Professionals in Industry to actively offer courses and also to encourage participation from students at their own institutions.

All courses are available free of charge to any students registered at an Irish or Northern Irish Third or Fourth Level Academic Institution. The courses are also available to non-Irish students or to industry as Professional Development for a small fee.

Funding continues to be provided until 2015, by the Geological Survey of Ireland through an NDP- supported Griffith Award to Professor Alan G. Jones at the Dublin Institute for Advanced Studies (DIAS).

9 The Irish National Seismic Network (INSN)

T. Blake, C. Horan, L. Collins

The development and expansion of the INSN is continuing with the testing of a new location for the permanent seismic station in Co Louth (ILTH). This station will be a joint cooperation between GFZ Potsdam and DIAS. The station location has been changed, having failed to reach agreement with Coillte (national forestry agency) on contract terms. The new location is at Belurgan Estate north of Drogheda, Co Louth and noise tests carried out there to test the suitability of the site have been satisfactorily completed. The construction and laying on of communication and power services will go ahead in 2013. Substantial improvements were carried out at IDGL (Donegal) to ensure more secure watertight conditions in the seismic bunker. The other permanent seismic stations in the network have been running satisfactorily and providing significant seismic waveform data for both local, regional and teleseismic events to DIAS and the international data agencies. The most significant regional event was a Magnitude 4.0 earthquake off the west coast of Ireland, which was felt by a large number of people in the west of Ireland. This earthquake was the subject of a poster at AGU Fall Meeting, 2012 (see publications below). The largest teleseismic event registered last year was a Magnitude 8.6 event off the west coast of northern Sumatra, Indonesia.

Presentation:

"An unusual occurrence of a moderately sized earthquake (Ml 4.2) on the Irish continental shelf and passive margin." (Control ID 1475529) 2012 AGU Fall Meeting 3rd-7th December 2012, Moscone Convention Centre, San Francisco, California. Poster Session.

The ORFEUS Seismological Observatories Workshop held in Istanbul in Nov 2012, was attended by Blake.

9.1 North East Atlantic Mediterranean Tsunami Warning Group (NEAMTWG)

At a meeting of the Tsunami Technical Group, 10th December 2012, GSI the following people were present: Kieran Commins, Met Eireann; Guy Westbrook, Marine Institute; Tom Blake, DIAS; Brian McConnell, GSI. Brian McConnell reported on the NEAMWave12 exercise that took place on November 27th. One of four planned tsunami simulations (the other 3 in the Mediterranean), IPMA (Portugal) distributed a series of alert messages from a simulated earthquake and tsunami event in the Gulf of Cadiz, including arrival times at 6 Forecast Points around the Irish coast (submitted by GSI in advance). As with previous communications tests, GSI received emails directly and Met Eireann received messages by GTS which were automatically forwarded to the Technical Group. FAX messages were not received. There was a delay of about 3-4 minutes between arrival of the direct email and the GTS messages.

This is not serious given the travel time of 3h 20min to first Irish landfall. The exercise did not continue for long enough to include simulated arrival of the tsunami on the Irish coast, but calculated wave heights should be available from IPMA.

10 CTBTO - Comprehensive Nuclear-Test-Ban Treaty Organisation, National Data Centre (NDC).

T. Blake

Figure 8. Left-Right: Dr. Gerry Wrixon, Chairman of the Board, School of Cosmic Physics, DIAS; Mr. Eamon Gilmore, Tanaiste, Minister for Foreign Affairs and Trade; Dr. Lassina Zerbo, Director of International Monitoring Division, CTBTO, Vienna; Mr. Tom Blake, Head of National Data Centre (NDC), CTBTO, Ireland (DIAS)

Last year was a very significant year for DIAS and CTBTO. The original date set for the official opening of the National Data Centre for CTBTO in Ireland, was changed from June 1st, to June 22nd, due to a Government Referendum. The official opening was performed by An Tánaiste and Minister for Foreign Affairs and Trade, Mr Eamon Gilmore, TD and Dr Lassina Zerbo, Director, International Monitoring Centre, CTBTO, Vienna and attended by members of the School of Cosmic Physics Board and officials from the Disarmament and Non-proliferation Division of Dept Foreign Affairs as well as invited guests from other NDC's, the media and public officials. A poster display of their current research interests was mounted by the Schools' research staff.

Figure 9. Back Row (L-R), Dr. Alan Jones, Senior Professor and Head of Geophysics, Mr. Cecil Keaveney, Registrar of DIAS; Mr. Tom Blake, Head of National Data Centre (NDC), CTBTO, Ireland (DIAS); Dr. Sergei Lebedev, Mallet Assistant Professor of Seismology, DIAS, Front Row (L-R) Ambassador Tibor Toth, Executive Secretary, CTBTO, Vienna; Ms. Elizabeth Abele Hample, Director of Public Relations, CTBTO, Vienna

Later in the year, on September 16th, the Executive Secretary, CTBTO, Ambassador Tibor Toth, visited the National Data Centre, (NDC), while on a trip to Dublin to deliver the Schools of Cosmic Physics, Statutory Public Lecture at Trinity College.

Visitors to the NDC last year included Dr Marcus Walter from the German NDC in Hannover, Germany, Dr Yochai Ben-Horin, Head of the National Data Center, Tel Aviv, Israel and Dr Gert Jan van den Hazel, *ORFEUS* (Observatories and Research Facilities for European Seismology) Data Centre, Netherlands.

Currently waveform data is being streamed from selected Primary CTBTO seismic stations around the globe, in real-time from the International Data Centre in Vienna to the Irish NDC on a test basis.

Blake, as Head of the NDC participated in the CTBTO Simulation and Training exercises for On-Site Inspection (OSI) in Vienna in November as part of the training for the International Field Exercise IFE14 to be held in Jordan 2014.

Working Group B Technical Meetings held in Vienna in February and August were attended by Blake.

11 Collaboration with wider research community

11.1 Visitors

- Professor Fabrice Gaillard, CNRS Campus d'Orléans, France, 21-23 March, 2012.
- Dr. Max Moorkamp, University of Leicester, UK, 25-26 June, 2012.
- Professor David Eaton, University of Calgary, Canada, 22-27 November, 2012.

12 Public outreach: Seismology in Schools (Seismeolaíocht sa Scoil) Project

T. Blake, E. Neenan

Schools continue to receive earthquake updates from DIAS as they occur around the world which is then the focus of a geography lesson in class and an investigation of the seismic recording on the seismometer in the school. Teachers contact DIAS also for technical support for the seismometer and with any other seismological queries. The popularity and interest in the programme continues to grow but no new schools have joined in 2012. DIAS has had to cap the programme due to staffing and financial considerations.

Under the umbrella of the SIS programme started by DIAS as an outreach programme, there are now also 3 geo-parks incorporated in the project, Copper Coast, Co. Waterford, Cilffs of Moher, Co Clare and Marble Arch Caves, Co Fermanagh, in Northern Ireland. The Cliffs of Moher, a location that enjoys more than 700,000 visitors a year joined in February 2012. Following discussion at the European Geoparks conference at Arouca, Portugal, an FP7 proposal under activity 5.2.2.1, Science in society Call: Young People and Science, 'Supporting formal and informal science education in schools as well as through science centres and museums and other relevant means'. The topic is called 'Raising youth awareness to Responsible Research and Innovation through Inquiry Based Science Education'. The results of this initiative will be known early in 2013.

12.1 Electronic and print Media.

Following earthquakes at home in Donegal and Mayo and internationally, there was considerable media interest in the work both of the INSN and SIS programmes and Blake was interviewed by TV and radio on these occurrences.

<u>References</u>

"An unusual occurrence of a moderately sized earthquake (Ml 4.2) on the Irish continental shelf and passive margin." (Control ID 1475529) 2012 AGU Fall Meeting 3-7 December 2012, Moscone Convention Centre, San Francisco, California. Poster Session.

<u>Talks</u>

Blake, 'The development and growth of the DIAS Seismology in Schools Outreach Programme since 2008', ESC Assembly, Russian Academy of Sciences, Moscow 19-25th August, 2012

Blake, 'Seismology in Geoparks - An Irish Perspective', European Geoparks Meeting, Arouca, Portugal, September 18^{th}-21^{st}, 2012

Blake, Irish National Seismic Network and Seismology in Schools, Cork Geological Association at UCC on November 29^{th}, 2012

13 Short Courses, Workshops and Seminars

13.1 Short Courses

- Magnetotellurics, a 5-day Short Course presented by Professor Alan G. Jones as IGGP course DIAS 004 on 5-9 March, 2012 in Burlington Road.

13.2 Workshops

- The second workshop in the Dublin-hosted series on *Three-dimensional Magnetotelluric Inversion* (MT3DINV2) was held in DIAS in March, 2012.

13.3 Seminars

- **16 February** - Prof. Balz Kamber (Chair of Geology and Mineralogy at Trinity College Dublin): "The decay of radioactive heat production rates: expressions in the Precambrian rock record"
- **7 March -** Dr. Anna Avdeeva (University of Leicester): "3D Inversion of Distorted MT Data: Theory"
- **21 March -** Dr. Fabrice Gaillard (Institut des Sciences de la Terre d'Orleans): "Partial melting and electrical conductivity of the mantle"
- **22 March -** Ms. Leila Hashim (Institut des Sciences de la Terre d'Orleans): "Experimental evidence for crustal melting underneath the Himalayan belt"
- **29 March -** Professor Andrew Curtis (School of GeoSciences, University of Edinburgh): "The Extraordinary Theory of Seismic Interferometry"
- **12 June -** Dr. Steward Fishwick (University of Leicester): "Regional Scale tomography - Where to from here?"
- **19 June -** Daniel Bolte (DIAS and Charles University, Prague): "Ice Modelling: Why we need to know the past to understand the future!"
- **25 June -** Dr. Max Moorkamp (University of Leicester): "Using joint inversion to improve sub-basalt and sub-salt imaging"
- **29 June -** Louis Moresi (Monash University): "Whole of Basin modelling in the Australian context"
- **29 June -** Meghan S. Miller (University of Southern California): "Segmented slabs beneath the central Mediterranean"
- **6 July -** Prof. Qingsheng Liu (China University of Geosciences): "Magnetic structure of the continental lower crust"
- **18 September -** Prof. John Brodholt (UCL): "D" - Between a Rock and a Core"
- **26 September -** Dr. Marianne Karplus: "Crustal structure and tectonics of north Tibet from controlled-source and broadband seismology"

- **6 November -** Dr. Ondrej Soucek (Charles University in Prague, Mathematical Institute, Czech Republic)**:** “Melting of ice and liquid water transport in the ice shell of Europa”
- **23 November** - Prof. David Eaton (Department of Geoscience, University of Calgary, Alberta, Canada): “Isopycnicity, Thermal State and Secular Evolution of Cratonic Mantle Keels”

14 Exhibitions

14.1 BT Young Scientist Exhibition Jan 2012.

The public profile provided by the BT Young Scientists Exhibition is always welcome and the School participated again at the invitation of the Geological Survey of Ireland to provide an exhibit on earthquake motoring and Seismology in Schools (SIS) related material.

15 Miscellanea

T. Blake

Following earthquakes in Ireland (Donegal and Mayo) and internationally, there was considerable media interest in the work both of the INSN and SIS programmes and Blake was interviewed by TV and radio on these occurrences.

- RTE Radio 1 Drivetime with Mary Wilson, 26th January 2012.
- RTE Radio 1 Drivetime with Mary Wilson, 7th December 2012.

A.G. Jones

- Member, *Royal Irish Academy*
- Member, *Committee of Heads of Irish Geoscience Institutions*
- National Correspondent for Ireland, *International Association of Geomagnetism and Aeronomy*
- Member, *Royal Irish Academy’s Geosciences Committee*
- Member, *Geological Survey of Ireland’s Consultative Committee*
- Member, *Geo-Electromagnetism Committee, Chinese Geophysical Society*
- Science Officer, *Seismology Division, European Geosciences Union*
- International Editor, *Earth, Planets and Space*
- Topical Editor, *Geochemistry, Geophysics, Geosystems (G-cubed)* special theme on *Lithosphere-Asthenosphere Boundary*

S. Lebedev

- Associate Editor, *Geochemistry, Geophysics, Geosystems (G-cubed)*
- Institutional representative, *Incorporated Research Institutions for Seismology (IRIS)*
- National co-representative, *European Plate Observing System (EPOS)*
- Titular Member (member for Ireland), *European Seismological Commission (ESC)*
- An interview: *"How solid is the Earth's crust where tectonic plates collide?"* Broadcast on 10th Feb. 2011 on 103.2 Dublin City FM, on 'The Show with an Irish Spin on Science' with Seán Duke.

Z. Martinec

- Editor, *International Journal of Geophysics*.

M.R. Muller

- Committee Member of Geothermal Association of Ireland (co-opted as International Liaison Officer, 6 July, 2011).

16 Productivity

16.1 Publications in International Literature

1. **Adam, J. M.-C.**, and **S. Lebedev** (2012), Azimuthal anisotropy beneath southern Africa from very broad-band surface-wave dispersion measurements. *Geophysical Journal International*, **191**: 155–174. doi: 10.1111/j.1365-246X.2012.05583.x

2. Afonso, J.C., J. Fullea, W. L. Griffin, Y. Yang, **A.G. Jones**, J.A.D. Connolly, and S.Y. O'Reilly (2013). 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: a priori petrological information and geophysical observables. *Journal of Geophysical Research - Solid Earth*, in press.

3. Afonso, J.C., J. Fullea, Y. Yang, J.A.D. Connolly, and **A.G. Jones** (2013), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. II: General methodology and resolution analysis. *Journal of Geophysical Research - Solid Earth*, in press.

4. Becker, T.W., **S. Lebedev**, and M.D. Long (2012), On the relationship between azimuthal anisotropy from shear wave splitting and surface wave tomography, *Journal of Geophysical Research*, **117**, B01306, doi:10.1029/2011JB008705.

5. Chave, A.D., and **A.G. Jones** (2012), Introduction to the magnetotelluric method, In: *The Magnetotelluric Method*, edited by Alan D. Chave and Alan G. Jones, published by Cambridge University Press, Chapter 1, ISBN: 9780521819275.

6. Dostal, J., **Z. Martinec**, and M. Thomas (2012), The modelling of the toroidal magnetic field induced by tidal ocean circulation. *Geophysical Journal International*, **189**, 782-798, doi: 10.1111/j.1365-246X.2012.05407.x

7. Ferguson, I.J., **A.G. Jones**, and A.D. Chave (2012), Case histories and geological applications, In: *The Magnetotelluric Method*, edited by Alan D. Chave and Alan G. Jones, published by Cambridge University Press, Chapter 10, pp. 1-18, ISBN: 9780521819275.

8. **Fullea, J.**, **S. Lebedev**, **M.R. Agius**, **A.G. Jones**, and J.C. Afonso (2012), Lithospheric structure in the Baikal-central Mongolia region from integrated geophysical-petrological inversion of surface-wave data and topographic elevation. *Geochemistry, Geophysics, Geosystems*, **13**, Q0AK09, doi:10.1029/2012GC004138.

9. Hobbs, B.A., G.M. Fonseka, **A.G. Jones**, N. de Silva, N.Subasinghe, G. Dawes, N. Johnson, T. Cooray, D. Wijesundara, N. Suriyaarachchi, T. Nimalsisri, K.

Premitallake, **D. Kiyan**, and **D. Khoza** (2013), In search of Geothermal Energy Potential in Sri Lanka: A preliminary magnetotelluric survey of the thermal springs. *Journal of the Geological Society of Sri Lanka*, in press.

10. **Jones, A.G.** (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth. *Geophysical Journal International*, **189**, 268-284, doi: 10.1111/j.1365-246X.2012.05362.x

11. **Jones, A.G.** (2012), Distortion of magnetotelluric data: its identification and removal, In: *The Magnetotelluric Method*, edited by Alan D. Chave and Alan G. Jones, published by Cambridge University Press, Chapter 6, pp. 219-302, ISBN: 9780521819275.

12. **Jones, A.G.** (2013), Imaging and observing the Electrical Moho, *Invited Review, Tectonophysics, "Moho" special issue*, doi: 10.1016/j.tecto.2013.02.025, in press.

13. **Jones, A.G., D. Kiyan**, and the TopoMed MT team (2012), Comment on “Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism” by Anahnah et al. (2011). *Tectonics*, **31**, TC5011, doi:10.1029/2011TC003051.

14. **Jones, A.G., J. Fullea**, R.L. Evans, and **M.R. Muller** (2012), Calibrating laboratory-determined models of electrical conductivity of mantle minerals using geophysical and petrological observations. *Geochemistry, Geophysics, Geosystems*, **13**, Q06010, doi:10.1029/2012GC004055.

15. **Lebedev, S., J. M.-C. Adam**, and T. Meier (2012), Mapping the Moho with seismic surface waves: A review, resolution analysis, and recommended inversion strategies. *Invited Review, Tectonophysics, "Moho" special issue*, 10.1016/j.tecto.2012.12.030, in press.

16. Legendre, C., T. Meier, **S. Lebedev**, W. Friedrich, and L. Viereck-Goette (2012), A shear-wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms. *Geophysical Journal International*, **191**, 282-304.

17. **Le Pape, F., A.G. Jones, J. Vozar**, and W. Wei (2012), Penetration of crustal melt beyond the Kunlun Fault into northern Tibet. *Nature Geoscience*, **5**, 330-335, doi: 10.1038/NGEO1449.

18. **Miensopust, M.P.**, P. Queralt, **A.G. Jones**, and the 3D MT modellers (2013). Magnetotelluric 3D inversion - a review of two successful workshops on forward and inversion code testing and comparison. *Geophysical Journal International*, in press, doi: 10.1093/gji/ggt066.

19. **O’Reilly, B.M., F. Hauser,** and **P.W. Readman** (2012), The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the “Newer Granites”. *Journal of the Geological Society*, London, **169**, 561-573.

20. Pawlak, A., D.W. Eaton, F. Darbyshire, **S. Lebedev**, and I.D. Bastow (2012), Crustal anisotropy beneath Hudson Bay from ambient noise tomography: Evidence for post-orogenic lower-crustal flow? *Journal of Geophysical Research*, **117**, B08301, doi: 10.1029/2011JB009066.

21. **Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly,** and **F. Hauser** (2012), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen. *Geophysical Research Letters*, **39**, L04302, doi: 10.1029/2012GL051014.

22. Rogozhina, I., **J.M. Hagedoorn, Z. Martinec**, K. Fleming, O. Soucek, R. Greve, and Thomas (2012), Effects of uncertainties in the geothermal heat flux distribution on the Greenland Ice Sheet: An assessment of existing heat flow models. *Journal of Geophysical Research*, **117**, F02025, doi: 10.1029/2011JF002098.

23. Sacchetti, F., S. Benetti, A. Georgiopoulou, P.M. Shannon, **B.M. O'Reilly**, P. Dunlop, and R. Quinn (2012), C. Ó Cofaigh. Deep water geomorphology of the formerly glaciated Irish margin from high-resolution marine geophysical data. *Marine Geology*, **291-294,** 113-131.

24. Sasgen, I., V. Klemman, and **Z. Martinec** (2012), Towards the inversion of GRACE gravity fields for present-day ice-mass changes and glacial-isostatic adjustment in North America and Greenland. *J. Geodyn.*, **59-60**, 49-63, doi: 10.1016/j.jog.2012.03.004.

25. Sasgen, I., M. Van Den Broeke, J.L. Bamber, E. Rignot, L.S. Srensen, B. Wouters, **Z. Martinec**, I. Velicogna, and S.B. Simonsen (2012), Timing and origin of recent regional ice-mass loss in Greenland. *Earth Planet. Sci. Lett.*, **333-334**, 293-303, doi: 10.1016/j.epsl.2012.03.033.

26. **Tirel, C.**, J.-P. Brun, E. Burov, M.J.R. Wortel, and **S. Lebedev** (2012), A plate tectonics oddity: Caterpillar-walk exhumation of subducted continental crust. *Geology*, in press.

27. Welford, K.J., P.M. Shannon, **B.M. O'Reilly**, and J. Hall (2012), Comparison of lithospheric density and Moho structure variations across the Orphan Basin/Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3-D gravity inversions. *Journal of the Geological Society*, London, **169,** 405-420.

28. Zhao, G., M.J. Unsworth, Y. Zhan, L. Wang, X. Chen, **A.G. Jones**, J. Tang, Q. Xiao, J. Wang, J. Cai, T. Li, Y. Wang, and J. Zhang (2012), Crustal structure and rheology of the Longmenshan and Wenchuan Mw 7.9 earthquake epicentral area from magnetotelluric data. *Geology*, **40**, 1139–1142, doi:10.1130/G33703.1.

16.2 Publications in Proceedings Volumes

Adam, J., **S. Lebedev**, 2012. Broad-band measurement of inter-station phase velocities and their inversion for shear-velocity azimuthal anisotropy (poster, extended abstract published), Noise and Diffuse Wavefields workshop, Neustadt, Germany, 11 - 14 November.

16.3 Theses

Agius, M.R., 2012. The structure and dynamics of the lithosphere beneath Tibet from seismic surface-wave analysis. Trinity College Dublin. Submitted October 31, defended November 28, 2012.

Khosa, D., 2012. Magnetotelluric studies across the Damara Orogen and southern Congo Craton. Ph.D. thesis, The University of the Witwatersrand, South Africa.

Le Pape, F., 2012. Characterization of a Crustal Transition Zone in Northern Tibet using Magnetotelluric Modelling. National University of Ireland, Galway.

Share, P.-E., 2012. Prediction of DC current flow between the Otjiwarongo and Katima Mulilo regions, Namibia. M.Sc. thesis, The University of the Witwatersrand, South Africa.

16.4 Invited presentations

1. Afonso, J.C., **J. Fullea**, Y. Yang, **A.G. Jones**, W.L. Griffin, J.A.D. Connolly, S.Y. O'Reilly, and **S. Lebedev**, 2012. The compositional and thermal structure of the lithosphere from thermodynamically-constrained multi-observable probabilistic inversion. Invited paper at: EGU, Vienna, Austria, 22-27 May.
2. Brun, J.-P., C. Tirel, M. Philippon, E. Burov, C. Faccenna, F. Gueydan, and **S. Lebedev**, 2012. On the role of horizontal displacements in the exhumation of high pressure metamorphic rocks (Solicited Talk), EGU General Assembly 2012, 22-27 April, Vienna, Austria.
3. **Jones, A.G.**, 2012. Illuminating lithospheric structures using electromagnetic waves and correlations with other geophysical, geological and petrological data. Invited presentation at: Lithosphere Workshop, University College Cork, Ireland, 17 February.
4. **Jones, A.G.**, 2012. Lighting up the lithosphere using electromagnetic waves and correlations with other geophysical, geological, geochemical and petrological data. Invited seminar at: ETH Zurich, 24 February.
5. **Jones, A.G., M.R. Muller**, N.H. Hunter Williams, J.S. Daly, A. Allen, R. Goodman, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali, 2012. IRETHERM: A New Project to Develop a Strategic and Holistic Understanding of Ireland's Deep Geothermal Energy Potential. SEEP 2012, 5th International Conference on Sustainable Energy & Environmental Protection, Dublin City University, Ireland, 5-8 June.
6. **Jones, A.G**., 2012. Lighting up the lithosphere: Obtaining information about the Earth using very low frequency electromagnetic waves. Invited seminar, Macquarie University, 19 October.
7. **Jones, A.G.**, 2012. Petrophysical information of the Earth's lithosphere from electromagnetic and seismic studies. Invited seminar, University of Adelaide, 31 October.
8. **Jones, A.G.**, 2012. Petrophysical information of the Earth's lithosphere from electromagnetic and seismic studies. Invited seminar, University of Western Australia, 5 November.

9. **Jones, A.G.**, 2012. MT -The answer to everything (What was the question?). Invited research seminar, Macquarie University, 8 November.
10. **Jones, A.G.**, 2012. Velocity-conductivity relations for cratonic lithosphere and their application: Example of southern Africa. Invited keynote presentation at: 6th International Conference on Applied Geophysics, Kanchanaburi, Thailand, 15-17 November.
11. **Lebedev, S.,** 2012. Regional and global seismic tomography: Imaging the structure and dynamics of the Earth, Invited Seminar, University of Strasbourg, EOST, 16 October.
12. **Muller, M.R., A.G. Jones, J. Fullea, C. Yeomans, M. Loewer**, L. Ayres, M. Desissa, and D. Reay, 2012. Geophysics (mostly electromagnetic and thermal modelling) in (high- and low-enthalpy) geothermal energy investigations. Geophysical Association of Ireland Seminar on Environmental Geophysics, Dublin, 15 February.

16.5 Lecturing

Jones presented a 5-day MT Short Course to DIAS, Irish and international students.

Martinec presented a weekly seminar on potential field theory to DIAS and other students.