IGA/CGA KEYNOTE ADDRESS

Friday 17th February 2012

The origin of animal ecosystems: integrating the Cambrian Explosion and Ordovician Radiation

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The Cambrian Explosion and the Great Ordovician Biodiversification Event (GOBE) marked two major turning points in the history of life. Although animals originated deep in the Neoproterozoic, some 13 animal phyla appeared for the first time during the early to mid Cambrian, many exceptionally preserved in Lagerstätten, for example Sirius Passet, and many representing some quite remarkable and bizarre body plans such as *Anomalocaris*, *Hallucigenia* and *Opabinia*. A modern-style marine ecosystem was already in place but that must wait some 30 million years before real biodiversity characterized community structures. During the GOBE, an interval of some 35 million years, accelerating inter-provincial (aided by dispersed continents), inter-community (migrations into deeper water) and intra-community (a narrowing of ecological niches) diversity generated a marked biodiversity spike in the later Ordovician. Traditionally both events have been viewed as discrete biotic radiations. New biodiversity trajectories for Late Precambrian - Palaeozoic biodiversity suggest that both can be placed in a sequence linking the soft-bodied ecosystems of the Neoproterozoic Ediacaran with the complex Devonian Nekton Revolution. Ecological factors, such as the escalation of predation, were major drivers of this biodiversity change.

SHELL SPONSORED KEYNOTE ADDRESS

Saturday 20th February 2012

On the link between climate and hominin evolution

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The influence of climate change on hominin evolution is widely acknowledged to be important, but possible forcing factors are still debated. DeMenocal (1995, 2004) was one of the pioneers who searched for causal relations between global climatic events and important junctions in hominin evolution. He found that marine paleoclimate records indicate a long-term trend of increasing aridity in Africa over the past 5 Myr, and proposed that shifts in climate around ~2.8, 1.7 and 1 Ma were associated with hominin speciation and extinction events. But how climate exactly influenced hominin evolution in Africa, and particularly where in Africa, remains a mystery. Here we develop a new model, the aridity refuge model, to clarify the influence of climate change on hominin evolution and their dispersal in Africa between 5 and 2.5 Ma. Central to this model is the idea that the longitudinal Indian Ocean coastal forest strip provided an isolated aridity refugium during recurrent long periodic (~400 ky) dry episodes in the period 5 to 2.5 Ma. Hominin evolution may have occurred in this area, and newly developed species would have dispersed far inland to rift basins via (re)established fluvial corridors during wet episodes in East Africa. Synthesising the fossil record, we hypothesize that after ~3 Ma, the Northern Hemisphere Glaciation caused latitudinal contraction of the Indian Ocean coastal forest strip, and break-up of the strip into three areas. As a consequence, *Australopithecus afarensis* populations became isolated, which led to the most important split in the hominin lineage.

TALKS: ABSTRACTS

The formation of breached relay zone geometries from splay propagation

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Faults commonly consist of arrays of en echelon segments. Displacement is transferred between adjacent segments by rotation of the intervening rock volume to form a relay ramp. Current models describe a progression of structure from an intact relay ramp to formation of a through-going fault when the relay ramp fails as displacement increases. This evolution has been proposed from extensive studies of relay geometries and is supported by much fewer studies of relay zone kinematics.

We present a detailed kinematic analysis of a segmented fault array from South East Asia which demonstrates a more complex evolution of segment boundaries than the conventional model suggests. Our analysis shows that a relay ramp may be breached at one structural level and simultaneously intact at another. The data also show that an initial through-going fault bend can develop a splay and a related zone of high strain. This geometry arises when a relay bounding fault propagates to structural levels at which a fault bend has already been established. In this case fault and bed geometries very similar to that of a breached relay ramp can result from an alternative mechanism i.e. the 'ramp' and splay forms after a fault bend is established.

Young faults in old rocks: a salutary lesson

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Phase 3 of a major behind-outcrop drilling project in the Upper Carboniferous Clare Basin, western Ireland, is currently underway. Earlier drilling targeted the upper and lower parts of the Ross deep-water system, with the current program aiming to characterise the central Ross and provide key insight into the wider stratigraphic development of the system. Borehole 12-CE-UCD-06 on the north side of Loop Head was meant to TD at 150m but unexpectedly encountered a splay fault with a well-developed gouge at 44m before entering and being conducted along near-vertical master fault zone below 70m. Significantly the faulting is not associated with the quartz veining that characterises the dominantly Variscan structures in the area. In hindsight the faults can be seen to be part of a NE-SW trending sinistral strike-slip fault zone that can be traced through a prominent cleft on Loop Head itself (accounting for Dermot and Gráinne's Rock) and it may even be imaged on INFOMAR sea floor bathymetry west of the Loop. The orientation, sense of displacement and late character of the fault indicate it may be related to Tertiary

conjugate strike-slip faults recognised elsewhere in Ireland. The latter may therefore occur even more widely than hitherto realised.

Strain analysis in areas of low-grade deformation

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The characterisation of strain in low strain regimes or in the early stages of rock deformation is problematic due to existing techniques of strain analysis lacking the sensitivity to accurately quantify such deformation. Additionally, the majority of these methods rely on the presence of direct strain markers whose original geometry is constrained, which are not always present and potentially have contrasting competencies to the rock matrix.

We present the application of two recently developed techniques to a range of rock types from the Munster Basin of southern Ireland and Rocky Mountain foreland of western Montana. The Mean Radial Length and the Delauney Triangulation Nearest Neighbour (DTNNM) methods do not require knowledge of the direct strain markers original geometry and in the case of the DTNNM is or has been shown to be particularly accurate for estimating bulk finite strain. The study will critically analyse the effectiveness of both techniques in a range of lithologies in such low strain settings. In addition an analysis of Anisotropy of Magnetic Susceptibility (AMS) properties will be compared to results from these techniques to help constrain and identify weak tectonic fabrics where present.

Larvikites of the Permian Oslo Province: A fresh appraisal

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Larvikite, Norway's 'National Rock' and global export, has its principal intrusive 'complex' (approx.55 x 35km) in the southern sector of the Oslo Graben. Despite much research, its status as a major layered intrusion, and larvikite as an accumulative (cumulate) rock have been somewhat under-emphasized. There is a virtually omnipresent igneous lamination and other, less common, cumulate structures such as cm-scale rhythmic layering. Even rarer are trough and 'cross bedding' structures and layering defined by alternating light/dark-coloured alkali feldspar.

The main cumulate structures dip inwards (45^{o} – 90^{o}), attitudes indicative of sidewall crystal accumulation in a convecting magma chamber. Syenitic magma, flowing downards at the walls, accounts for (i) a lineation of alkali feldspar long axes on the plane of igneous lamination perpendicular to its strike and (ii) the rare presence of 'oscillatory zoned' (convectively 'recycled'?) alkali feldspar primocrysts. The cumulate orientations (IGM) followed by detailed mapping of larvikite sub-types

(NGU) and aeromagnetic data all suggest a large, essentially oval, layered intrusive mass (not dissimilar in size to the Mt Kilimanjaro volcanic complex in E Africa).
A lack of major cryptic layering can be explained on an 'open system' model, involving eruptions from a Kilimanjaro-type volcanic edifice related to the arrival of syenitic pulses from the deep crust.

The Norwegian larvikites have been thoroughly researched geochemically and isotopically (excepting O, in progress at SUERC). Deep crustal fractional crystallisation of a.o.b. remains the favoured genetic mechanism.

U-Pb ion-microprobe zircon geochronology of a new lower crustal xenolith locality from the Iapetus Suture Zone in Ireland

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Deep crustal xenoliths transported by Lower Carboniferous volcanics occur at three localities in the Midlands and at a new locality in Co. Limerick, astride the Iapetus Suture Zone, which marks the oblique collision of Avalonia with Laurentia during the end-Silurian Caledonian Orogeny. Together, these xenoliths afford a unique opportunity to investigate an otherwise inaccessible part of the continental crust.

The Limerick xenoliths consist of granulite-facies, migmatised metasediments (qtz+Kfs±sil±grt+rt±ilm±zrn±mnz) and rare felsic orthogneisses (qtz±Kfs±pl±bt±ilm±rt±zrn). U-Pb ion-microprobe geochronology of two felsic orthogneisses indicates protolith ages of 395±2Ma and 388±2Ma. Oscillatory-zoned, magmatic zircons from the latter display unusual textures, tentatively interpreted as the result of deformation. They are overgrown by low Th/U rims that yield an age of 373±2Ma, thereby bracketing a deformation event between 388 and 373 Ma. In contrast, one of the metasediments yields a broader age range from 390Ma-360Ma, possibly indicating continuous zircon growth over 30Ma. In the same time interval, zircons from a granitic vein in a felsic orthogneiss suggest melting at 381±1Ma. A similar range of ages has been obtained from the Midlands xenolith suite.

Few ages recorded by the xenoliths correspond to tectonic events known at the surface indicating significant thermal decoupling of the upper and lower crust.

Micro-magnets measuring macro movements - The intrusion and subsequent deformation of the Carna Granite

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The late Caledonian Galway Granite Complex (~420-380Ma) comprises the Main Galway Granite Batholith and earlier intrusions including the Carna, Roundstone, Omey, Inis and Letterfrack Granites. A broad chronological sequence of intrusion has been established for this complex but little is understood about the structural controls, precise chronological succession and regional scale kinematics which dictated the siting and evolution of this hetrogeneous suite of intrusions.

Work presented here demonstrates how careful examination of rock magnetic data together with micro & macro scale structural analysis can reveal tight controls on the emplacement, cooling and deformation history of granites. These principles are applied to a study on the the Carna Granite where a concentric magmatic state fabric is overprinted by a structurally imposed, NW-SE striking, oblate fabric - believed to represent a continuation of the Clifden-Mace linement system. This structural overprint is reported throughout the earlier series of intrusions in the GGC but is not apparent in the Main Batholith.

It is proposed here that there are two discrete episodes and structures responsible for the creation of the Galway Granite Complex, the earlier intrusions being controlled by a major NW-SE structure (the Clifden Mace Line and its parallel sibling structures) and the later Main Batholith by movement along the E-W Skird Rocks Fault.

New fossil discoveries in the Trabane Member of the Bulls Head Formation, Lower Old Red Sandstone, Dingle Peninsula: age and palaeoenvironmental implications

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The Bulls Head Formation is the oldest red-bed sequence in the 2.8 km thick Dingle Group. The formation mainly comprises thinly bedded, fine purple-grey sandstone units interbedded with thin mudstone layers (Heterolithic Member) and is interpreted as a shallow lacustrine facies. The Formation also includes two lake margin sheetflood systems (the Boat Cove and Trabane Members) that are only developed on the northern lake limit. The Formation has previously been assigned a Silurian (late Ludlow-Pridoli) age, however, new fossil discoveries reported here from the Trabane Member indicate it is much younger in age. The new fossil material comes from a green-grey mudclast breccio-conglomerate dominated sequence in the upper part of the Trabane Member at Great Blasket Island and at Dunquin Harbour. Palynomorph assemblages recovered from the mudclast breccias and from the interbedded mudstones are composed of low diversity trilete and cryptospore taxa that are of early Devonian (Lochkovian) age. A disarticulated fish plate is reported from the matrix of a mudclast breccia and is assignable to the Heterostaci group of

jawless fish, which were common in the late Silurian and early Devonian. A palaeoenvironmental model of fluctuating lake levels, periodic fluvial sheetfloods with contemporaneous erosion and reworking is presented.

Microbial life in fluid inclusions: evidence from Permian to present day evaporite deposits

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We present evidence that living microbes exist in brine-filled fluid inclusions in modern evaporite deposits from Searles Lake, California, similar to those recorded by [1]Lowenstein *et al*., (2011) from halite deposits up to 150ka in age from Death Valley and Saline Valley in California. The Searles Lake halite-hosted fluid inclusions contain micro-ecosystems of motile microbes whose survival is dependent on the coexistence of nutrients within the enclosed brine (*e.g*., algal carbon from *Dunaliella sp.*). Comparisons are made between the unequivocal evidence for microbial life trapped in "young" fluid inclusions from California and fluid inclusion evidence from evaporites from the Irish Upper Permian (Kingscourt gypsum), the Spanish Triassic and Italian Miocene (Messinian ~5 to 7 Ma). Results of fluid inclusion petrography combined with UV microscopy and Raman spectroscopy indicates the presence of fossilized organic material within halite and gypsum hosted fluid inclusions from these deposits.

[1]*Lowenstein, T.K., Schubert, B.A. and Timofeeff, M.N. (2011) Microbial communities in fluid inclusions and long-term survival in halite. GSA Today, v.21,no1, 4-9.*

Pleistocene to Holocene stratigraphy of Azokh Cave, Lesser Caucasus

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Azokh Cave is located in the Lesser Caucasus and is hosted in thickly-bedded Mesozoic limestones. It comprises a series of (mainly) hypogenic karstic chambers

and passageways that interconnect to form a larger cave system. The largest of these entrance passages (named Azokh 1) contains c.11-12m of in-situ cave-filling sediments dating from at least Middle Pleistocene times towards the present. Much of these were removed during previous excavations; however, enough remains to allow subdivision of the succession into nine units (I-IX, in descending stratigraphic order). Very little remains of Units IX-VI in the lowermost part of the cave and these sediments appear to be largely unfossiliferous. Units V-I, above these, are rich in fossils and have produced many types of (macro- and micro-) mammal remains, along with evidence for human activity and occupation. Two other undisturbed entrance passages (Azokh 2 and 5) at the site also contain a sedimentary infill and details of their stratigraphy are being resolved.

The Azokh Cave site quite is significant for two reasons. Firstly, it is geographically located at an important migratory route-way between the African subcontinent and Eurasia and, secondly, middle-Pleistocene hominid remains were recovered from Azokh 1 during a previous phase of excavation work.

A method of modelling vertebrate skeletal taphonomy using the marine reptile *Serpianosaurus* (Reptilia; Sauropterygia)

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A taphonomic method developed to assess the fidelity of preservation of vertebrates is tested using two pachypleurosaurid genera from Monte San Giorgio, Switzerland. *Serpianosaurus* and *Neusticosaurus* are preserved in the Besano and Meride Limestone formations respectively, both comprising successions of alternating black shale and dolomite, representing normal background and episodic event bed deposition.

The method involves scoring nine anatomical units (the head, neck, dorsal, tail, ribs and four limbs) for two independent characters (articulation and completeness) to firstly determine the regions most affected as decay progresses. Secondly, how the characters are lost enables the taphonomic pathway to be inferred, and in turn, the environmental processes that acted on a carcass, either in the water column, and/or at the sediment surface. In *Serpianosaurus* and *Neusticosaurus* the character states indicate arrival of carcasses at the sediment surface shortly after death. Higher completeness in *Neusticosaurus* indicates subtle environmental differences between the two depositional settings, mainly a shorter length of time exposed on the sediment, due to more frequent event bed occurrence, and lesser impact of bottom currents, the main process responsible for removing small bones from carcasses. The origin of these taphonomic differences is not apparent from the lithologies.

Rapid response of Irish glacial climate to temperature variability recorded in Greenland ice cores – evidence from U-Series dated speleothems

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Dansgaard-Oeschger (D-O) and Heinrich events, during the last glacial have been well documented in the Greenland ice cores (e.g. NGRIP), but climatic records older than the Last Glacial Maximum are sparse at lower latitudes due to erosion. Speleothem deposition in shallow caves indicates the absence of permafrost or glaciation. In this study, intervals of speleothem deposition in Crag cave, South West Ireland determined by U-series-dating constrain the timing of ice- and permafrost-free conditions between the Holocene and the last interglacial. Ninety eight U-Th dates indicate phases of speleothem deposition, interrupted by visible hiatuses e.g. at 131.5 ±0.6; 104.8 ±0.2; 83.9 ±0.3; 47.1 ±0.1; 43.5 ±0.2; 38.0 ±0.1; 28.8 ±0.1; 23.3 ±0.1; 11.6 ±0.1 ka. These warm intervals show an overall synchronicity with D-O events recorded in NGRIP. Heinrich events 2, 3, 4, 5 and 6 are characterised by non-deposition. Measured $\delta^{18}O$ values from Marine Isotope Stage 5a are similar to the mean value for Holocene speleothems ($\delta^{18}O$ = -3.26 ‰ VPDB). A trend to higher $\delta^{18}O$ values during the glacial is interpreted to reflect changes in the ocean source region. $\delta^{13}C$ values down to -10 ‰ (VPDB) indicate the presence of C3 vegetation above the cave during the warm intervals. Correlations between $\delta^{18}O$ and $\delta^{13}C$ prior to depositional hiatuses are interpreted to reflect gradually decreasing drip rates.

Seasonal variability in soil CO_2 production; a case study from Ballynamintra Cave, Co. Waterford

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Cave air pCO_2 can be controlled by two distinct mechanisms (i) air advection processes (inflow and outflow events) and (ii) soil CO_2 production. It is important to identify these mechanisms in order to understand their role on the growth rates and carbon isotope systematics of speleothems. A small, shallow Irish cave (Ballynamintra, Co. Waterford) was monitored over a seasonal cycle using a Vaisala pCO_2 logger and four temperature loggers. Cave air temperature data from the loggers were used to distinguish between air advection and soil CO_2 production effects. Seasonal changes in soil CO_2 production, inferred from changes in cave air pCO_2, were investigated in detail using Arrhenius-type models that linked soil production to surface air temperatures. In winter time, when soil organic matter decomposition is not masked by active root respiration, CO_2 production can be explained by an Arrhenius-type model, but requires a high apparent activation energy (E_i). This high value reflects a greater soil respiration response for a given temperature change, when absolute temperature values are lower. Another

implication is that low cave air pCO_2 values during winter could result in significantly increased speleothem growth rates and seasonally biased palaeoclimate records.

The use of speleothems to reconstruct the North Atlantic Oscillation (NAO): a case study from N. Spain

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The North Atlantic Oscillation (NAO) is the most prominent mode of climate variability in the Northern hemisphere, especially during the boreal winter. The NAO alternates between two different modes: positive (negative) modes cause relatively warm/wet (cold/dry) winter conditions in Western Europe, while southern Europe becomes drier (wetter). Here we investigate the temporal and spatial stationarity of the NAO – climate relationship over Europe using a high-resolution global climate dataset and a published instrumental record of the NAO to select sites that exhibit a strong NAO-driven climate signal (temperature and precipitation amount). The observed NAO – climate correlations allow us to identify regions in Europe that are potentially suitable for NAO reconstruction. For example, $\square^{18}O$ in a speleothem from La Garma cave in N. Spain is significantly correlated with winter precipitation amount allowing NAO reconstruction. Preliminary data indicate that maxima in speleothem $\square^{18}O$ coincide with positive phases of the NAO.

Smoking chimneys: the newly discovered Moytirra hydrothermal vent, mid-Atlantic Ridge

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In August last year, an Irish-led scientific expedition (VENTuRE) aboard the national research vessel RV *Celtic Explorer* with the Holland 1 Remotely Operated Vehicle (ROV) discovered a previously uncharted field of hydrothermal vents along the Mid-Atlantic Ridge.

The discovery, at 3,000 metres water depth, is the first deep-sea vent field known on the Mid-Atlantic Ridge north of the Azores and biogeographically forms a significan extension toeh Azore vent faunal range.

In comparison with other vent fields, Moytirra is compact with a high flux of hydrothermal fluids forming a large buoyant plume in the water column. System is expressed on the seafloor by 15m tall metal sulfide chimneys in an unusual setting at

the bottom of a 200m fault scarp suggesting tectonic controls dominate the hydrothermal stockworks, an emerging pattern in ultra-slow spreading centres. The samples, of potential ore-grade, will give insights into the formation of ancient metal sulfide deposits that are a major geological context for the metal mining industry. High resolution multibeam maps of the area present further evidence of tectonic controls on sub-seabed fluid flow pathways.

Impact of sediment disturbance on the western mud belt of the Irish Sea as a Paleo-archive and its engineering significance

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The Mud Belt in the Western Half of the Irish Sea is located at the northern termination of a transport path which has its origins further south in St. Georges Channel (Belderson, 1964). As such the area is largely regarded as a depocentre consisting of predominately Holocene muds and silts overlying glacial tills deposited during the melting of the Devensian ice sheet which hold a high resolution record allowing for a detailed paleoenvironmental reconstruction of the area.

The area is economically important being extensively trawled for the commercial Dublin Bay prawn and is also earmarked for potential offshore windfarm development. However, anthropogenic activities such as trawling as well as bioturbation from various benthic fauna may affect the sedimentary record and geotechnical parameters of the sediment in the area, lowering the shear strength, hence making it more prone to scour which is a serious engineering consideration for such offshore installations. Therefore, the purpose of this study is to address the issues outlined above utilizing data acquired in order to characterise the geology of the Mud Belt. In doing so it is envisioned that it will provide a baseline study which will aid in any further management strategy of the area.

The bedrock geology of Dublin Bay

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The bedrock geology of Dublin Bay is poorly known because most previous research has focussed on the Quaternary cover. 22 offshore and two onshore boreholes along two trajectories running east-west across Dublin Bay were drilled in early 2011 on behalf of Dublin City Council. These boreholes were part of a site investigation for a wastewater final treated effluent outfall tunnel in deep bedrock which will extend from the Ringsend wastewater treatment works eastwards across the bay. The boreholes represent a unique scientific resource, as each wide-diameter drill core is typically about 80m long, and penetrates on average about 30m of unconsolidated sediments (recent sediment cover and Quaternary glacial deposits) and up to 75m of

bedrock. A three-month study was undertaken in summer 2011. It investigated eight of the boreholes, and revealed that much of the western portion of Dublin Bay is underlain by Viséan basinal limestone. In the east, Tournaisian limestone (Waulsortian mud-mound facies and Malahide Formation), Lower Palaeozoic greywackes and Lower Jurassic shales and limestones were encountered near the Burford Bank. The presence of Lower Jurassic rocks so close to the Burford Bank was unexpected and has implications for the structural geometry of the hydrocarbon-bearing Kish Bank basin immediately to the East.

Towards sediment mobility modelling of maërl: experimental work to determine the critical bed shear stress of maërl beds in Galway Bay

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Free-living coralline algae beds known as maërl or rhodolith beds are abundant in Galway Bay. These habitats are of great conservation significance with two species, *Lithothamnium coralloides* and *Phymatholithon calcareum*, found in Annex V of the EC Habitats Directive. While a link has been observed between species presence and areas with strong water currents; the role of hydrodynamic forcing factors on the mobility of maërl beds is still poorly understood. This research aims to gain a better understanding of the interactions between the hydrodynamics, sediment dynamics and ecology of maërl beds. The first step to understanding the influence of flow on the mobility of maërl is to determine the basic properties of this biogenic sediment.

A series of experiments to determine the critical bed shear stress for initiation of motion of maërl sediments are taking place in the rotating annular flume of Delft University of Technology (TU Delft), Netherlands. The main advantage of such flumes is they avoid the entrance and exit conditions encountered in recirculating flumes, by effectively generating an infinite flow. Runs with maërl samples from different locations are made to assess how the critical bed shear stress varies across a subtidal bed (Aran Islands), intertidal bed (Muckinish) and beach sediments (Carraroe). Measurements of the three dimensional instantaneous velocities and turbulence are made using the Nortek Vectrino Acoustic Doppler Velocimeter (ADV). The bed shear stress is calculated using the Law of the Wall, Turbulent Kinetic Energy and Reynolds stress methodologies.

Other experiments to determine the grain size, settling velocity, density, grain shape of maërl are also taking place. This will help to determine whether maërl as a biogenic sediment behaves more like sand or more like gravel. Sediment mobility is defined as the percentage of time grains of a particular size are mobile in a tidal cycle or storm period and is considered to be an indicator of the disturbance of a habitat. This will be modelled by estimating the % of time the critical Shields parameter is exceeded. Specifically, the sediment mobility of maërl beds is being evaluated based on the results of the experimental work.

Could Early Cretaceous lignites have helped to source the giant Kinsale Head gas field, offshore Ireland?

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The giant Kinsale Head gas field is located in the North Celtic Sea Basin, c. 50 km offshore southern Ireland. The field is situated in water depths of c. 100m and was discovered by Marathon Oil in 1971 with the drilling of the 48/25-2 well. The main gas reservoirs are Early Cretaceous Albian shallow water marine sandstones (c. 1,000 m TVDSS) with secondary reservoirs developed in the underlying fluvial/alluvial Wealden section. Seals are provided for by intra-formational shales of the Lower Claystone and Gault Clay with the trap having developed during regional Alpine basin inversion. Geochemical analysis of the Kinsale Head gases indicates that they are isotopically very light (c. 99% methane). Previous interpretation of these data proposed hydrocarbon sourcing from a mixture of highly mature thermogenic marine shales together with a biogenic component. A number of wells drilled on the field encountered thick underlying lignite bearing units which yielded good gas shows when drilled. This paper will examine the potential for these lignites to have contributed to the charging of the field and what implications this sourcing model may have for future hydrocarbon exploration strategies in the basin.

Modelling sandstone connectivity in deep-water lobes

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Recent progress in understanding the internal architecture of deep-water lobes has benefited from high resolution seismic data and detailed outcrop studies, and has identified a 4-fold hierarchical geometrical arrangement involving beds, lobe elements, lobes and lobe complexes. Quantitative modelling of the hierarchy is important since understanding different scales of heterogeneity is one of the most critical factors influencing oil production from lobe reservoirs. A novel object-based numerical approach (vbFIFT) is developed aiming not only to reproduce the detailed architecture within lobe complexes, but also to investigate the connectivity of sandstones within and between different hierarchical components. Input parameters include the dimensions, shapes, and sedimentary properties (NTG, Amalgamation Ratios) at each hierarchical level, and are based on published datasets. The model successfully captures the 4-fold hierarchy and many of the characteristic features of deep-water lobes such-as the distal pitchout geometry, thickening-upward cycles and compensation stacking. The influence of unknown properties such as the

boundary transmissibility at each hierarchical level can be tested by varying the input parameters, and analysis of models can help refine the underlying sedimentary parameterisation. Future work will include analysing the connectivity and exploring what are the key depositional factors controlling reservoir performance.

New constraints on the development of the Ross deep-water system from behind-outcrop boreholes in the Clare Basin

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The 500m thick Upper Carboniferous Ross Formation in West Clare represents the deep-water sandy part of a major shallowing-upward succession. It preserves evidence in the form of multiple condensed sections or 'marine bands' (at least 9) for high-frequency ice-house forcing analogous to that seen on Miocene and younger margins. The overall progradational setting has been used to infer superposition of outer, mid and inner fan environments as the system advanced from the SW, and the apparent lack of fauna outside of marine bands has been taken by some to indicate intervals of brackish water.

Research boreholes on the Loop peninsula have now acquired an almost complete composite vertical section though the Ross, including the transition from the underlying Clare Shales. The borehole data reveal distinct phases of overall adjustment, initiation and fan growth that are inconsistent with simple progradation. A role for inherited slopes that promoted early bypass and out-of-equilibrium behaviour might explain unusual bed types in the early fill. The detail provided by the slabbed core shows that the interbedded mudstones were largely emplaced as event beds rather than 'background', and thin candidate hemipelagic mudstones preserve goniatites demonstrating that fully marine conditions were present outside of the condensed sections.

Late Holocene sedimentary provenance of the West Bengal Sundarbans: preliminary results and interpretations

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The Sundarbans comprise of one of the largest tidal halophytic mangrove forests in the world and are the primary habitat of many endangered charismatic mega-fauna species, including the Bengal Tiger. With a population of approximately four million inhabitants there are inherent challenges enforced on the sustainability of these

communities. The primary aim of this project is to discern the sources, processes responsible and rate of sedimentation taking place. A sedimentary facies analysis approach using the geochemical and sedimentological characteristics (powder x-ray diffraction and particle size analysis) of three cores from the lower-Sundarbans has shown quite distinctive mineralogical assemblages and grain size distributions. Particle size analysis has been able to elucidate some of the processes behind sedimentation, in particular the role of tidal ebb and flow factors. Radiocarbon (AMS ^{14}C) dating has been undertaken in order to constrain some record on the rate of sedimentation taking place. The consensus regarding sedimentation in the Sundarbans has been held that these areas are 'cut-off' from detrital, terrigenous sources of sedimentation. However, the preliminary results developed with this project appear to challenge this assertion and show that there are dynamic, in-situ processes taking place in this system.

On the trail of a blast from the past in NW Scotland

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In 2008 the enigmatic Stac Fada Member of the Mesoproterozoic Stoer Group, in north-west Scotland, was reinterpreted as an impact ejecta blanket based on the presence of shocked quartz and anomalous levels of Ir, Cr and Ni (Amor et al. 2008). This view is not universally accepted (e.g. Goodenough and Krabbendam 2011) while others maintain that, although of impact origin, it has been reworked by water and wind from its original situation (Osinski et al. 2011). New field observations along its 50km outcrop establish unequivocally that the Stac Fada Member is of impact rather than volcanic origin, has not been significantly reworked, and have established a sequence of events associated with the impact and its immediate aftermath. The nature of the impact-generated succession, and interpretation of various directional indicators, provide evidence for the nature of the pre-impact topography and for the scale and location of the impact crater.

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IRETHERM: Research and exploration challenges in assessing Ireland's deep low-enthalpy geothermal energy potential

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IRETHERM (www.iretherm.ie) is a new academic-government-industry research project funded by SFI, initiated in 2011, aiming to develop a holistic understanding of Ireland's (all-island) deep, low-enthalpy geothermal energy potential through integrated modelling of new and existing geophysical and geological data. The project's overarching objective is to establish those geological settings and localities with the greatest potential to provide hot geothermal waters in permeable aquifers or hot, dry rock in radiogenic granites that might support regional-scale space-heating and/or electricity generation.

Our paper discusses the strategies IRETHERM has adopted to meet the challenges of exploring for geothermal resources starting from a relatively low knowledge-base. Over a four-year period the project will:
(1) Model and understand upper-crustal temperature variations: (i) by building a 3-D model of crustal heat-production based on geochemical analysis of surface, borehole and mid- to lower-crustal xenolith samples and (ii) by modelling, using a self-consistent 3-D approach, observed surface heat-flow variation as a function of structural and thermal property variation in the crust and upper-mantle.
(2) Develop multi-parameter geophysical modelling and interpretation software tools that will enhance our ability to explore for and assess aquifers and granites. (3) Test a strategic set of eight "type" geothermal targets with a systematic program of electromagnetic surveys (MT, CSEM) across ten target areas.

The paper provides an introduction to the wide range of research of six new Ph.D. students and two new post-doctoral fellows, supported by IRETHERM's collaborators, focusing on eight geothermal target "types": (i) Permo-Triassic sandstones, (ii) granites, (iii) warm-spring lineaments, (iv) heat-flow/temperature anomalies, (v) deep penetrating fault zones, (vi) gravity anomalies of unknown origin, (vii) areas of natural seismicity and (viii) basal sediments of the Carboniferous and Devonian successions.

Development and application of a tool for extraction of sand dune morphometric parameters from digital terrain models: observations of characteristic distribution patterns of morphometric patterns within a large bedform field

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Code that runs within the GRASS GIS environment has been developed to automatically extract bedform length and height from bathymetric digital elevation models. The code utilises a raster scanning approach, analogous to taking a series of closely spaced cross-sections, therefore the technique is best suited to terrains

where the slope is perpendicular to the scanning direction. The processing pipeline may be summarised as follows: (1) rotation of bathymetric grid; (2) extraction of summitpoints; (3) extraction of a pair of troughpoints for each summitpoint; (4) calculation of dune parameters. The Steepest Descent algorithm is central to the extraction of the locations of the troughpoints where the latter are located with sub-pixel resolution. A plot of measured length against measured height demonstrates that smaller, peripherally located bedforms tend to be sediment starved, according to a globally observed dune length/height relationship; in contrast, larger, or more centrally located, bedforms reach or exceed their potential likely because of the finite width of well-defined sediment pathways. This research demonstrates the utility of GIS techniques to the detailed two-dimensional study of marine sediment transport processes.

Heterogeneity in microseismic noise generation, West of Ireland

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The mechanical coupling between the world's oceans and the Earth's crust produces low frequency seismic noise, which dominates the microseism spectrum. The relationship between the two leads to the possibility of obtaining information on the ocean wave field from seismic records. Microseisms are also used in passive seismic interferometry where it is assumed that when averaged over a sufficiently long time period the wave field is random. Optimization of both these applications requires an understanding of the degree of non-uniformity within the seismic source region, generated by ocean wave activity. The Atlantic region off the coast of Ireland is considered one of the major source regions for background seismic noise. A seismic network has been established along the west coast of Ireland. A preliminary analysis of the spatial and temporal variability of the wave field will be presented.

Towards a quantification of ocean wave heights from land based seismic data

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Ocean gravity waves are driven by atmospheric pressure systems and through their interactions with one another and reflection off coastlines, they generate pressure changes at the sea floor. These pressure fluctuations are the cause of continuous background seismic noise known as microseisms (Bromirski, 2009). Because microseisms are associated with ocean wave activity they are generally much stronger at coastal areas but they are recorded at seismic stations throughout the world. The levels of microseism activity vary as a function of the sea state and increase during periods of increased ocean wave activity. Since they were first noted in the early 20th century relatively little work has been undertaken to understand the characteristics of the ocean waves which drive these microseisms.

This project aims to determine the characteristics of the causative ocean gravity waves through calibration of microseism data with buoy data. With the development of a mathematical transfer function relating the two parameters, microseisms can then be used as a proxy for ocean wave height. The first ocean buoy offshore west of Ireland was deployed in 2000. As a consequence very little is known about the historical wave climate off the west coast. However the Valentia seismic station has been recording ground vibrations since 1963. A further aim of the project is to use our transfer function and apply it to the historical seismic data to reconstruct and thus extend Ireland's wave climate by more than 40 years.

Comparing the source mechanisms of long period (LP) volcano-seismic events recorded by temporary broadband seismic networks in 2009 and 2011 at Turrialba volcano, Costa Rica

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Shallow long-period (LP) seismic events have been recorded on Turrialba volcano, Costa Rica. This type of event has been recorded at many volcanoes across the world and, in some instances, swarms of LP events have signalled the onset of a volcanic eruption. However, the source mechanism of these events is still partly unknown.

Activity at Turrialba volcano has increased dramatically in recent years with high levels of seismic and fumerolic activity. Two field experiments were instigated with broadband seismometers deployed on the volcano in 2009 and 2011; a small phreatic eruption occurred in January 2010. The data from the field experiments have been analysed and over 5000 LP events identified. The frequency content and waveforms of the events are different for each dataset. During both experiments the LP events are located below the active (western) summit crater at shallow depth. These locations were then used to carry out full-waveform moment tensor inversion to constrain the source mechanism. The optimum source mechanism for the LP

events is a sub-horizontal tensile crack during both 2009 and 2011. Whilst the event locations and source mechanisms have been shown to be comparable between 2009 and 2011, the waveforms suggest subtle changes in the source process through time.

Investigating the source mechanisms of a family of long period (LP) events recorded on Piton de la Fournaise, La Réunion

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Volcano seismicity can be used to obtain an insight into a volcano's internal dynamics. Long Period (LP) events are of particular interest as they tend to precede or accompany volcanic eruptions, yet the mechanisms of these events are still not well understood.

Piton de la Fournaise, La Réunion, is one of the most active volcanoes in the world, however LP events on this volcano are rare. Since November 2009 the volcano has erupted five times, yet only 15 LP events were recorded in this period. Three of the eruptions were preceded by LP events, and several LPs were recorded during an intrusive phase. A family of similar LP events exists within these events.

In this work we attempt to address two important questions: why does such an active volcano have so few LP events, and what can we learn about the eruption process from these particular events? The family of LP events was located, using a double-difference method, within the summit crater at a very shallow depth. The source mechanism was determined using 3D-full-waveform simulations, and can best be described as a horizontal crack, whose orientation was corroborated using constrained moment tensor inversion.

Tellus Border Project – Project update and research opportunities

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Tellus Border is a £4.1M INTERREG IVA funded regional mapping project across the six RoI border counties following on from the award-winning Tellus project in NI. This is a partnership between the GSNI, GSI, Dundalk IT and QUB and runs to December 2013.

The geochemical survey entails collection of soils, stream sediments, stream waters and vegetation samples from c.3,500 sites. The airborne geophysics survey is a low-

level survey (58m), measuring magnetic field, radiometrics and electrical conductivity.

The aims of the project are to deliver a seamless cross-border dataset with Northern Ireland and to interpret the geological data across the twelve northern counties. The data will have important applications for geological, environmental and agricultural resource management as well as providing important baseline data on human health issues (e.g. Bioaccessibility of heavy metals, radon etc)

Raw and gridded data will be available online and free of charge at the end of the project, along with regional and thematic reports.

Three post-doctoral researchers, based at Dundalk IT and Queens University Belfast, are working on applied uses of the geophysical and geochemical data to investigate soil-carbon, wetlands hydro-ecology and groundwater pollution plumes.

Additional research opportunities will be outlined.

The structure and emplacement of the Newry Igneous complex from Tellus geophysical data and AMS

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The Newry Igneous Complex (NIC) comprises three predominantly granodioritic plutons. The recent Tellus survey of Northern Ireland has highlighted several geophysical anomalies within this area, including two previously unrecognised concentric aeromagnetic structures. Variations in U-Pb Zr ages suggest that these rings represent magma pulses intruded at different times. We link new structural and Tellus data with emplacement of the NIC.
The results of an anisotropy of magnetic susceptibilty (AMS) study reveal dominantly oblate fabrics, representing a concentric foliation that is steepest close to pluton edges. This suggests a forceful emplacement, whereby doming and vertical thickening occurred during intrusion. This is consistent with observed concentric aeromagnetic anomalies. AMS lineations are broadly NNE-SSW trending in the east and E-W trending in the west of the complex. Lineations are also largely subhorizontal, although are locally steep at the SE and S edges of plutons.
We propose that these lineations were produced by lateral magma flow from a source located to the SE of the NIC. These lineations were then affected by doming as the central parts of respective plutons inflated. This emplacement model suggests there may be an underlying crustal structure to the SE of the NIC that controlled its ascent and emplacement.

Unravelling glacial sediment provenance in Northern Ireland using soil geochemistry

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Reconstructing palaeo-ice sheet dynamics provides important information on how ice sheet interact with the climate system over long time scales. Traditional approaches to reconstructing palaeo-ice sheets often rely heavily on geomorphological evidence as the basis for unraveling behavior such as palaeo flow directions. However, recent work on drumlins, which are the main ice flow indicators, has shown that using drumlin shape could be misleading. A novel approach is to use the geochemistry of glacial sediments to establish bedrock provenance from which former ice flow direction can be established. This study presents results from the first regional geochemical analysis of soils that have developed on glacial tills applying Principle Component Analysis (PCA) on the GSNI Tellus survey data. PCA is a variable reduction procedure that allows groups of elements to be identified which are used to infer till geochemistry. Till geochemistry is a function of parent materials and these PCA groupings can aid identification of bedrock sources and therefore sediment provenance. Initial results indicate that the majority of till deposits in Northern Ireland have been locally derived suggesting that till transport in this sector of the British-Irish Ice Sheet was low, with rapid comminution and low evacuation rates of entrained debris.

Soil carbon and peat depth assessment using airborne geophysical data

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It has become increasingly important to measure and model carbon stocks to facilitate the management of carbon changes over time. The Kyoto Agreement demands that all signatory countries have an inventory of their carbon stock, plus possible future changes to this store. This project utilizes existing airborne geophysical data generated by the Tellus Survey and newly acquired data collected as part of the EU-funded Tellus Border project in order to try and measure peat and organic-rich soil thicknesses. Selected peat bog sites will be used to ground truth and evaluate the use of airborne geophysical data and validate modelled estimates of soil carbon, peat volume and depth to bed rock. Field site investigation at selected sites will involve rainfall, carbon/methane data monitoring, laser scanning recording surface topography, depth probing and Ground Penetrating Radar (GPR) combined with a Differential Global Positioning System (DGPS). A 6km test line has been

selected near Bundoran, County Donegal, to ground truth airborne geophysical data along a flight line. The plane will fly every 4-6 weeks during the survey and will be flown at a series of different elevations allowing the data to be assessed temporally with different saturation levels. This will assist with data interpretation/evaluation.

Tellus Border is supported by the EU INTERREG IVA programme, which is managed by the Special EU Programmes Body

Remote sensing and GIS for landuse/landcover classification and water quality in the Northern Ireland

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This study presents landuse/landcover (LULC) classifications of Northern Ireland in order to quantify land-use types driving chemical loading in the surface water. The major LULC classes are agricultural land, bare land, forest, urban, and water. ENVISAT ASAR multi-look precision images and Landsat Enhanced Thematic Mapper (ETM) were used for classification. Accuracy assessment of supervised classifications shows that the best results were given by the winner and maximum likelihood classifications. ASTER digital elevation model was processed to extract the drainage systems and watersheds. Water quality was extracted from streams geochemical data of EU-funded Tellus Border project. GIS spatially distributed modelling generated maps showing the distribution of phosphorus, nitrate, dissolved organic carbon, and trace elements fluoride (F), calcium (Ca), aluminium (Al), iron (Fe), copper (Cu), lead (Pb), zinc (Zn), and arsenic (As). Based on the World Health Organization (WHO, 2011) water quality standards the concentration of P is high. NO_3 and DOC are normal in urban areas, moderate in agricultural lands, and high in the forest areas and bare lands. Ca, F and Fe are normal in all watersheds. Al, Cu, and As are high in the bare land. Pb and Zn are normal in the urban and agricultural land, and high in the bare land.

Investigating the use of Tellus Data to improve peat depth models for Northern Ireland

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Estimates of soil carbon stores are a key component of the required annual returns made by the United Kingdom to the Intergovernmental Panel on Climate Change. This research uses the Tellus radiometric data to improve peat depth models for Northern Ireland. Gamma radiation from rocks is attenuated by overlying peat, with terrestrial radiation levels varying with geology type. The geostatistical analysis of the preliminary case study site of Armoy peat bog in county Antrim indicates there is

some correlation between the Tellus radiometric data and peat depth. Laboratory experiments were performed to assess the influence of peat depth, moisture content and bulk density on terrestrial gamma radiation levels. The results of these experiments show a clear inverse exponential relationship between depth and radiation values. Field experiments at Armoy were also conducted to examine radiation attenuation by peat in relation to the surrounding soil. Recent work has involved using ground penetrating radar and portable gamma-ray spectrometry to analyse the relationship between radiation levels and peat depth on specific field sites. An improved peat depth model, produced through the integration and calibration of the Tellus data against known peat depths, could be used to improve carbon stock estimations.

Long term slip deficit modelling for the Sunda megathrust beneath the Mentawai Islands, Sumatra

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Shallow earthquakes are a response of crustal faults to stress. Faults are loaded by the slow, heterogeneous accumulation of tectonic stress and the almost instantaneous interaction with neighbouring earthquakes. These effects allow us to model the increase of stress on known active faults. In particular we can calculate changes in stress that can help identify regions of known active faults where secular loading is rapid, elapsed time since the last large event (normalised to the estimated recurrence time for large events) is long and interactions stresses due to recent events suggest that earthquake hazard is particularly high. Coral paleo-geodesy off western Sumatra has produced a multi-seismic-cycle geodetic record which provides physical constraints on the slip distributions of large and great earthquakes. Here we describe a new unifying description of the reconstruction of the evolution of slip deficit in which we include 330 years of heterogeneous loading of the Sunda megathrust and slip due to more than 30 historical and instrumentally recorded earthquakes. This complex slip deficit field is heterogeneous not only in the strain energy but also in the resolution and we introduce a new technique to clearly visualise both. We show that these results are consistent with the well published threat of a large tsunamigenic earthquake off western Sumatra and make some comments on constraining the threat.

Statistical quantification of time-dependence in the Coulomb model of earthquake triggering

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The Coulomb Failure Function ΔCFF describes the degree to which the stress change from an earthquake has brought a neighbouring fault either closer to or further from failure. We therefore expect that there will be more aftershocks in regions where ΔCFF>0 relative to areas which experience negative (or no) Coulomb stress change. The strong correspondence between the aftershock distribution of the 1992 M7.3 Landers earthquake and its CFF field seems to support the Coulomb triggering model. However, an analysis of the seismicity prior to Landers suggests that at least part of this strong result is due to background seismicity unrelated to the mainshock. A quantitative statistical analysis of the Landers aftershock distribution compared to the CFF is presented, including a quantification of the time-evolution of the correlation. We demonstrate the sensitivity of the statistics to assumptions made about background seismicity. While this suggests that Coulomb stress is not as strong a control on the aftershock distribution for Landers as it appears, it may help to explain why the model is less successful for other events. In addition, we demonstrate the decay of the correlation with time after the mainshock and the strong effect of secondary aftershock distributions on the results.

The strain rate on the Sunda megathrust, West Sumatra

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The Sumatra shoreline faces a subduction trench that is part of the border between the India-Australia and Eurasia plates. This region is historically known to produce destructive earthquakes capable of generating tsunamis as the ones that occurred recently in 2004, 2005 and 2007. The objective of better understanding the strain rate for the region makes part of the objectives of the seismic risk study we are making for the region. This study used, for now, GPS, earthquake data, and Holt & Haines (1995) numerical approach. A preliminary result is that the use of GPS or earthquake data in isolation has severe drawbacks, related, respectively, to the small number of GPS stations and the incompleteness of the earthquake catalogue. The combined solution avoids underestimation of the strain inherent to the Kostrov summation of seismic moments and provides details that cannot be reached by pure GPS modelling. Another preliminary result is that seismic strain rates for the Andaman-Nias region is greater than the GPS-earthquake combined strain rates. This seems to imply that the strain liberated by these earthquakes and aftershocks account for a period longer than the 50 years span of the catalogue and that was used for the Kostrov summation.

Simulating seismicity induced by fluid injection

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Injection of fluid into the subsurface is a common technique and is used to optimise returns from hydrocarbon plays (e.g. enhanced oil recovery, hydrofacturing of shales) and geothermal sites as well as for the sequestering CO_2. While it is well understood that stress perturbations caused by fluid injections can induce/trigger earthquakes; the modelling of such hazard is still in its infancy. Our aim to create a model that will allow us to examine the role of operational and geological factors in seismogenesis around a sub-surface fluid injection.

By combining numerical fluid flow and seismicity simulations we have created a model for investigating induced seismicity over large time periods. Choice in how the stress/strain relationship evolves on our fault as well as in the methodology used for calculating fluid flow means that the model can accommodate the effects of complex geological structure.

As a case study we compare the effect that a injection scenario has on seismicity for faults placed above and adjacent to the injection reservoir. On comparing seismicity catalogues, we observe that it is the injection of fluid below the fault that produces the biggest change in seismicity, a feature that persists for more than 50 years after injection.

Using a genetic algorithm (GA) to accelerate a Monte Carlo Slip Estimation (MCSE) technique

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Examination of the temporal evolution of stress along a fault requires detailed models of heterogeneous slip that capture the spatial complexity of real earthquakes. Typically such reconstructions are limited to historical records or displacements measured from a small number of paleoseismic trenches. Along the Sunda trench the annual growth rings of coral microatolls store long term records of deformation sparsely covering large areas of an active megathrust fault offering the possibility of higher resolution reconstructions of slip in paleo-earthquakes.

Published coral data has been used to invert for several historical earthquakes, however these inversions are composed of unphysical, box-car slip functions. In Monte Carlo Slip Estimation (MCSE) discretised fractal slip models produce trial solutions whose predicted deformations can be compared to deformation observed in the coral record allowing the selection of possible distributions of slip in the paleo-events. Here we describe a Genetic Algorithm which increases the efficiency of the MSCE. Using evolution-based operators it produces data constrained models through the repeated evaluation and recombination of information, stored in a population of possible model solutions. Repeated iterations of the algorithm generate a set of models which can then be used to produce probabilistic maps of slip for

historical earthquake events. We investigate the data requirements for adequate solutions using synthetic data and test the method on Sumatran corals.

The systematic study of the stability of forecasts in the rate-and state-dependent model

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Dieterich's rate- and state-dependent model can be used to obtain a forecast of the observed aftershock rate for the space and time evolution of seismicity caused by stress changes applied to an infinite population of nucleating patches. The seismicity rate changes on this model depend on eight parameters. We use the 1992 Landers earthquake as a case study, using the Southern California Earthquake Data Centre (SCEDC) catalogue, to examine if Dieterich's rate- and state-dependent model can forecast the aftershock seismicity rate. We perform a systematic study on a range of values on all the parameters to test the forecasting ability of this model.

The Omori-Utsu law describes the aftershock rate as a power law in time following the main shock and depends on only three parameters, all of which can be estimated in the early part of the aftershock sequence and then extrapolated to give a long term rate forecast. We compare the Dieterich and the Omori-Utsu forecasts using the Akaike information criterion which appropriately penalizes each model for the number of free parameters used in the fit and explore the full spatial distribution of parameters, forecasts and forecast skill.

The shear velocity structure of the lithospheric mantle beneath Tibet

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The Tibetan Plateau formed as a result of continental collision between India and Eurasia. Although numerous seismic studies show images of India subducting beneath Tibet, fundamental questions, such as how far north and how deep India subducts, persist. In order to investigate the lithospheric mantle architecture beneath Tibet, we measure inter-station phase velocities of seismic surface waves. Within the high plateau, phase velocities at short periods are anomalously slow. At longer periods, as surface waves sample the lithospheric mantle, strong phase-velocity variations start to appear. The dispersion data is used to constrain radial anisotropic shear velocities at depth and to infer temperature estimates for deep, fast shear-speed lithospheric anomalies.

Our results show that West Lhasa (south west Tibet) is underlain by a fast (cold), cratonic-like lithospheric mantle whereas Central Lhasa is not. In central and northern Tibet the uppermost mantle has very low average velocities indicative of warmer temperatures. At greater depth beneath central Tibet, a high-velocity anomaly (>5%) lies below the slow (warm) uppermost mantle. Inferred temperature

estimates from the Vs anomalies show that the deep lithosphere is 300-820°C cooler. We demonstrate that these temperatures agree with a “deepened” Indian geotherm, suggesting India's subduction beneath Tibet.

Anisotropic structure of the upper mantle, imaged using surface and S waveform tomography

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The rapid recent expansion of global and regional seismic networks has paved the way for a new generation of tomographic models. We present a new global model of shear velocity and azimuthal anisotropy in the upper mantle, down to the base of the transition zone, constrained by an unprecedentedly large waveform dataset collected from over 2000 seismic stations. We applied the accurate and efficient automated-multimode-inversion of surface- and S-wave forms, which resulted in more than one million successful seismogram fits (~10-fold increase from only a few years ago), with structural information extracted from both the fundamental and higher modes.

Global isotropic V_S variations are compatible with previous models, though with greater sensitivity and reliability in well-sampled regions. However, the resolution of global azimuthal anisotropy has been improved significantly compared to earlier global tomography. In ocean basins, as observed previously, fast-propagation directions align with paleo-spreading orientations at lithospheric depths and modern plate motions within the asthenosphere. In continental domains, both lateral variations and radial layering of anisotropic fabrics are now resolvable at a smaller scale, for regional- and tectonic assemblage-scale domains. The implications of these new observations will be discussed, in comparison with past global estimates and correlations with other proxies for deformation, for example, global shear wave splitting.

Stratification of seismic anisotropy and deformation beneath South Africa, from the upper crust to the asthenosphere

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Southern Africa contains some of the oldest crust on Earth, with the ancient Kaapvaal craton bordered to the north by the Limpopo orogenic belt. 3-D distribution of azimuthal anisotropy beneath this region remains unclear. In order to fulfill this lack of resolution, we compute Rayleigh-wave dispersion curves between station pairs and merge them into four sub-regions with relatively homogeneous structures within them. We obtain accurate dispersion curves across a broad period range which resolves from the upper crust to the asthenosphere. Each subset is a

combination of curves that sample the region in different azimuths, in order to determine azimuthal anisotropy.

The azimuthal anisotropy in the upper crust of the Limpopo belt is significantly larger than in the Kaapvaal craton. The fast direction matches the collision direction between the Limpopo Belt and the Kaapvaal craton and is aligned with the average stress in these regions, suggesting that the anisotropy is associated with cracks. In the mantle lithosphere, anisotropy is small (<2%) and anisotropy in the Limpopo and northern Kaapvaal show fast directions parallel known Archean sutures. In the asthenosphere, anisotropy is present and shows fast directions parallel to the plate motion in the southern Kaapvaal craton.

POSTERS: ABSTRACTS

Chemical and isotopic study of sulfides from Conglomerate Group Ore, Navan, Ireland

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The Conglomerate Group Ore (CGO) sulfide of the Navan Zn-Pb deposit is hosted by a sequence of debrite and fault talus, which also contains significant syn-sedimentary iron sulfide. A representative suite of samples was analysed to evaluate textural, temporal and spatial variations in iron sulfide minor element geochemistry and sulfide mineral $\delta^{34}S$.

Microprobe analyses of pyrite and marcasite show deviation from ideal FeS_2, typically containing significant As, Zn, Pb, Ni, Mn and Cd. Post-ore, syn-sedimentary framboidal pyrite samples contain the lowest total abundances of minor elements, averaging 0.70 wt.%.

In-situ laser $\delta^{34}S$ analyses of CGO and syn-sedimentary sulfide minerals reveal a range from -40.3 ‰ to -12.7 ‰, suggesting that there was little to no hydrothermal sulfide contribution.

There is a correlation between timing, iron sulfide chemistry and $\delta^{34}S$ composition. Post-ore, sedimentary iron sulfides with the lowest minor element abundance, also have the lightest $\delta^{34}S$ values, whilst hydrothermal iron sulfides associated with Zn-Pb mineralization contain higher $\delta^{34}S$ and greater minor element concentrations. CGO sulfides typically have heavier $\delta^{34}S$ than -22 ‰, and never below -28 ‰, whereas post-ore, syn-sedimentary iron sulfide is always below -30 ‰.

IRETHERM: Multi-disciplinary investigation of Irish warm springs and their potential for geothermal energy provision

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Irish warm springs are one of several target types that will be assessed for their geothermal energy potential during the course of the four-year, SFI-funded IRETHERM project.

There are 42 recorded warm springs in Ireland, grouped into two distinct clusters in East Leinster and North Cork. Water temperatures of these springs (approximately 12-25°C) are elevated with respect to average Irish groundwater. This poster

presents our current assessment of existing and available hydrochemical and geophysical data that aims to identify the most promising localities for geothermal energy provision. It is surmised from existing evidence that the warm water source is a hydrothermal circulatory system extending to around 1500m depth with evidence of rapid upward movement of hot water through bedrock and dilution by cooler meteoric waters closer to the surface.

Future work will include detailed hydrochemical analysis of the springs to determine the source of the heated waters. An initial analysis of major ion and metal concentrations of all warm springs will be followed by more detailed analysis (including stable and radiogenic isotopes) of approximately six springs showing the most potential, carried out over a six-season sampling period. Geophysical methods (controlled source electromagnetics and magnetotellurics) will be used to help understand both the observed association of the springs with major structural lineaments (Iapetus Suture Zone and Variscan Front) and the conduit systems delivering the warm waters to the surface.

Quaternary sediment facies distribution in the Rockall trough, NE Atlantic

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The Rockall Trough is an elongate, NE-SW oriented, deep-water bathymetric depression lying west of Ireland and the UK. Deposition in this area has been controlled by the interplay between bottom currents and gravity flows. The main objective of this study is to document the sedimentary architecture and development of the Rockall Bank Mass Flow, one of the largest slope failures in the region, as well as other gravity flow deposits, through the analysis and correlation of piston cores. Core analyses include detailed lithological and sedimentary internal structure descriptions, multi-sensor core logging for physical properties, and ITRAX core logging for elemental composition.

Results so far indicate that our cores have sampled sediments at least as old as the previous interglacial period, and thus provide the Quaternary history of sedimentary deposition in the Rockall Trough. They generally comprise stiff grey mud and lighter beige to brown mud punctuated by laminated sandy and silty layers, with thicknesses from a few centimeters to 0.5m. Two main facies have been identified: (1) muds identified as hemipelagic sediments, and (2) graded sands and silts, interpreted as turbidites. Their thickness distributions, and internal structures as well as geochemical compositions, point towards different source contributions to the basin.

The IRETHERM project: Assessment of primary and secondary porosity media as possible geothermal aquifers

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IRETHERM is a collaborative, SFI-funded research project to identify and evaluate sites within Ireland possessing the greatest potential for deep, low-enthalpy geothermal energy provision. Geothermal aquifers, which might host such resources and that will be evaluated over the next four years, are found within relatively high primary or secondary porosity media, with viability depending largely on the permeability distribution which controls fluid flow and heat-exchange.

One known, promising primary-porosity target in Northern Ireland is the Triassic Sherwood Sandstone Formation (measured porosities and permeabilities of 8-24% and 2-1000 mD respectively), with temperature gradients in the range of 25-40^{o}C/km. Our poster presents the 2D modelling results of a recent magnetotelluric survey across the Permo-Triassic Lough Neagh Basin and considers the implications of the models for the basin's geothermal potential.

In addition to Ireland's Permo-Triassic basins, this component of IRETHERM also aims to assess primary or secondary porosity development in several other geological settings: (i) deeply penetrating shear zones - those with evidence of more recent displacement or reactivation offering the most potential, (ii) areas of enhanced natural seismicity that may correspond with active faulting, and (iii) basal sediments of the Devonian and Carboniferous successions. As bulk-rock electrical conductivity and fluid circulation are both dominated by the porosity-permeability distribution, magnetotelluric and controlled-source audiomagnetotelluric surveys will be strategically employed across Ireland to locate and assess potential porosity-controlled aquifers.

The Tellus Border Project: aeromagnetic mapping of six northern counties of ROI

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The high resolution Tellus airborne survey of 2005/6 covered all of Northern Ireland, an area of 15,872km^2. Magnetic, electrical conductivity and radiometric data were acquired along 2,209 flight-lines with a spacing of 200m and orientation 345º, a total line length of 80,757km. This has provided a wealth of new information about the geology, regional structure and mineral potential.

In the interests of environmental and earth sciences and relevant stakeholders this survey has been extended to the six border counties of Republic of Ireland. This new airborne geophysical survey commenced in October 2011 under the Tellus Border project. The contractor is Sander Geophysics Ltd. Tellus Border is financed by the INTERREG IVA program of the European Regional Development Fund. Survey specifications are the same as those of the original Tellus project. It is planned to cover 57,680 line km along 3562 survey lines and 201 tie lines.

The total magnetic intensity data so far collected by Tellus Border has delineated concealed dykes, lithological boundaries and intrusive bodies, generally commensurate with known geology. A combined provisional aeromagnetic map of the Tellus, Tellus Border and other existing aeromagnetic data indicates the continuity of the regional terrain boundaries and mega-dykes.

Ice sheet dynamics and the formation of subglacial bedforms

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Understanding how ice sheets flow is important because their discharge directly impacts on sea level and there is particular concern surrounding how climatic warming will impact on the stability of Greenland and Antarctica's ice sheets. Ice sheet motion is largely controlled at the bed which is extremely difficult to access. However, observations of palaeo-ice sheet beds (e.g. Dunlop and Clark, 2006) and beneath Antarctica (e.g. King et al., 2009) reveal that basal processes produce a suite of subglacial bedforms which indicates they are critical for understanding ice sheet motion. Subglacial beforms are longitudinal (e.g. drumlins) or transverse landforms (ribbed moraine) produced by ice flowing across unconsolidated sediments and drumlins are the most commonly produced landform. However, over 200 years of research consisting of >1400 papers has failed to reach a consensus on their formation. Recent work on ribbed moraines has demonstrated they can arise from an instability mechanism operating at the ice/bed interface (Dunlop et al., 2008) and it is hypothesised here that this may explain drumlin formation. This poster presents results from the largest morphometric data set on drumlins ever compiled (>50,000) which challenges existing paradigms on drumlin shape and is used to test numerical models of basal instability.

Dunlop, P and Clark, C.D (2006) The Morphological Characteristics of Ribbed Moraine*. Quaternary Science Reviews, 25. pp. 1668-1691.*
Dunlop, P, Clark, C.D. and Hindmarsh, R.C.A (2008) Bed Ribbing Instability Explanation: Testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment*. Journal of Geophysical Research - Earth Surface, 113 (F03005). pp. 1-15.*
King, E.C., Hindmarsh, R.C.A., Stokes, C.R (2009) Formation of Mega-scale glacial lineations observed beneath a West Antarctic ice stream. Nature Geoscience, 2, 585-588

Conodont biostratigraphy of the Clare Shale Formation at Paradise House, Ballynacally, Clare

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Knowledge of middle and late Carboniferous (Serpukhovian and Pennsylvanian) conodont faunas from Britain and Ireland is quite poor at present. This is largely a reflection of the widespread shift from carbonate to predominantly siliciclastic sedimentary deposition during this particular time interval. The latter (non-calcareous lithologies) are largely unsuitable for conodont processing, as they cannot be acid-etched to recover these phosphatic microfossils. A 56m stratigraphic section through dark organic-rich shales belonging to the Clare Shale Formation was examined and logged close to Paradise House, at Ballynacally on the banks of the Fergus Estuary in County Clare. The succession contains several discrete goniatite bearing marine bands, which indicated a H_{1a} to R_{1a} (Bashkirian; early Pennsylvanian) age to previous workers. The section also contains several calcareous nodules, interbedded with the shales, which have produced conodonts, including *Declinognathodus noduliferus*. Perhaps more significantly, several conodont forms have been recovered from the base of the sequence indicative of the late Serpukhovian. This suggests that the Paradise House Clare Shale section may actually straddle the Mid-Carboniferous boundary.

The IRETHERM project: Assessing the geothermal energy potential of Irish radiogenic granites and expanding Ireland's temperature database

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IRETHERM seeks to develop a strategic understanding of Ireland's deep geothermal energy potential through integrated modelling of new and existing geophysical and geological data. One aspect of IRETHERM's research focuses on Ireland's radiogenic granites, where increased concentrations of radioelements provide elevated heat-production (HP), heat-flow (HF) and subsurface temperatures.

In the 1980's, research conducted by the Applied Geophysics Unit, UCG, on Irish radiogenic granites thought to offer Enhanced Geothermal Systems (EGS) potential

yielded encouraging results in the Costelloe-Murvey granite, Galway (HP=7μWm^{-3} and HF=77mWm^{-2}), the Northern-Units of the Leinster granite (2-3μWm^{-3}, 80mWm^{-2}) and the Barnesmore granite, Donegal (4-6μWm^{-3}, 85mWm^{-2}). Preliminary gravity-modelling currently underway will help prioritise magnetotelluric fieldwork over prospective exposed and buried granites, culminating in a joint inversion of gravity and magnetotelluric data to produce a robust estimation of the volumetric extent of these granites, important in defining their EGS potential.

Ireland's temperature and heat-flow database (compiled in 2004) will be expanded by strategic temperature-logging in pre- and post-2004 boreholes, where possible. The objective is to derive additional heat-flow measurements, develop a 3D model of temperature variation in the Irish crust that accounts for variations in rock thermal conductivity, and accurately define areas associated with higher temperatures and geothermal energy prospectivity.

New Zealand earthquakes - Christchurch 2010-2011

D. Fay, Open University undergraduate student (resident and studying in Northern Ireland)

The poster will include the tectonic setting of the boundary of the Pacific and Australian plates running through New Zealand. It will describe the recent Christchurch earthquake sequence and the effects of these earthquakes and will cover some aspects of mitigation. The special characteristics of landforms and geology that contributed to the worst effects resulting from the earthquakes will be described. Some photographs of damage due to liquefaction, bolder falls and landslips will be shown. Various aspects of earthquake engineering will be considered. The poster will include an element of personal reminiscence.

Gondwana reconstructions and geology of the ice covered interior East Antarctica: constraints from the Pb isotope composition of feldspar

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The Gamburtsev Subglacial Mountains (GSM) of East Antarctica influenced the initiation, growth and boundary conditions of the East Antarctic Ice Sheet. Their geology and time of formation remain speculative because they are remote and ice-covered. Geophysical surveys suggest that, while the GSM comprise 1 Ga or older

rocks, their present topographic expression formed in the Mesozoic. Contrasting sedimentary provenance studies from sediment inferred to have been sourced from the GSM is younger (*c*. 0.5 Ga) in age, and more consistent with tectonic models for an Early Palaeozoic assembly of Antarctica within Gondwana.

We present feldspar Pb isotope data from 1) rocks exposed around Antarctica's periphery; and 2) individual detrital grains contained in material derived from the ice-covered interior. These data greatly assist with plate tectonic reconstructions of Antarctica and help constrain links with India and Africa. They also support the geophysical evidence (above) in that they reveal that parts of East Antarctica are at least Mesoproterozoic in age and have unique low μ feldspar Pb compositions. Furthermore, the results demonstrate that the sediment containing 0.5 Ga aged grains that was previously inferred to have been sourced from the GSM, were in fact derived from more proximal coastal regions.

Geothermal potential of the buried Drogheda and Kentstown granites, Co. Meath, Ireland

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The Drogheda and Kentstown granites are situated in the Iapetus Suture Zone in Co. Meath and are overlain unconformably by up to several hundred metres of Carboniferous sedimentary rocks. As buried granites, they are potential targets for geothermal exploitation and in this context, their geochemistry, the thermal insulating role of the overlying rocks and the structural setting of the Drogheda-Kentstown area is being evaluated.

Based on available geochemical analyses[1], the Drogheda and Kentstown granites have average heat production rates of 4.5 μW/m^3 and 2.5 μW/m^3, respectively. Besides their differences in heat production, mainly due to differences in their thorium contents, the geochemistry and petrography of the two granites generally appear distinct. The Drogheda granite is petrologically relatively 'primitive', displaying a high Mg# of ~58, SiO_2 concentrations around 64 $_{wt}$% and negligible alteration[1]. The Kentstown granite is more leucocratic and exhibits severe hydrothermal alteration.

The sedimentary sequence covering the granites consists predominantly of Carboniferous limestones, interlayered with thin shale and quartz-sandstone and may likely serve as a thermal insulator. However, the possibility that the cover rocks (particularly the shales) may also be significant radiogenic heat producers is also being investigated.

[1] McConnell & Kennan 2002: Irish Journal of Earth Sciences, 20, 53-60.

The spatial distribution of arsenic in gold bearing quartz veins, Croagh Patrick, Co Mayo

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Arsenopyrite, niccolite, pyrite and chalcopyrite are all reported from the Clew Bay area spatially related to the well-documented quartz vein-hosted gold mineralization occurring in the Ordovician/Silurian Cregganbaun and Killadangan Formations. Mineral exploration files show the spatial distribution of Au and As in stream sediment, soil, till and overburden. We present a series of elemental maps using an SEM (Hitachi model S-4700) linked to EDS (INCA® Oxford Instruments) to investigate the spatial distribution of arsenic in the quartz veins. These spatial elemental distribution maps show alteration of arsenopyrite and the channelling of released arsenic and iron into fractures. The hydrothermal alteration of the primary arsenic phase and fracture generation are considered to be synchronous. Results also indicate a spatial relationship between calcium and the alteration rims surrounding unaltered islands of arsenopyrite. The results here indicate that the microfractures containing arsenic and iron are the pathways through which groundwater remobilises these elements. Elevated levels of both elements are found in a number of local wells.

Twenty Years of the Cork Geological Association

B. Higgs and members of the CGA

The Cork Geological Association, founded in 2002, is celebrating its 20-year Anniversary. Archived material has been used to chart the origins and history of the Association. Members of the Association are mainly, but not exclusively, from the Munster region. Statistics on the number and nature of the fieldtrips and lectures over the past 20years have been collated and show a high level of interest in the Geosciences by members of the public.

The role of members of the Association in the production of geoscience resources is highlighted. In particular, the impact of the *Journal of the Cork Geological Association* is analysed. The challenges of keeping such an Association alive and well are discussed. Recommendations for the future sustainability of the Association are proposed.

Evolution and emplacement of the Northern Irish, Tyrone ophiolite during the Grampian-Taconic phase of the Caledonian-Appalachian orogen

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The Tyrone Plutonic Group (TPG) represents the upper portions of a tectonically dissected ophiolite accreted to the Laurentian Margin during the early Ordovician. Understanding its development and relationship to the Tyrone Central Inlier (TCI), a rare fragment of relatively high-grade peri-Laurentian continental crust, is fundamental for reconstructing the closure of the Iapetus Ocean. The TPG (c. 484-480 Ma) is composed of variably tectonised and metamorphosed, layered, isotropic and pegmatitic gabbros, dolerite dykes and rare pillow lavas. Lithologies are tholeiitic, LREE- and HFSE-depleted and of suprasubduction affinity, with primitive $\varepsilon Nd_{(t=480Ma)}$ values. S-type and peraluminous muscovite granite contains abundant inherited Proterozoic zircons, and was emplaced shortly after ophiolite emplacement (c. 470 Ma). A mélange exposed at the contact between the TPG and TCI comprises blocks of ophiolite derived amphibolite-facies gabbroic to doleritic material within banded and isoclinally folded syn-kinematic tonalitic to granitic melt, closely associated with Dalradian-affinity metasedimentary rocks. Syn-kinematic tonalitic melt within the contact suggests the TPG may have been emplaced relatively late within the orogen at c. 470-467 Ma synchronous with the Tyrone arc. Coeval accretion of a hot, c. 15km thick arc-ophiolite complex may explain how sillimanite-grade metamorphic conditions in the TCI were reached prior to c. 468 Ma.

New insights into the emplacement of the Seeconnell Complex within the Newry Igneous Complex, Northern Ireland

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This study focuses on an intermediate-ultramafic body, which we here refer to as the Seeconnell Complex (SC). It crops out at the northeastern margin of the Newry Igneous Complex (NIC), within the constituent Rathfriland pluton. Preliminary U-Pb radiometric dating indicates that the Newry Complex was intruded from c. 414 – 409 Ma in the Early Devonian, with the Seeconnell Body representing its oldest part.

Across the NIC flattened outward dipping fabrics indicate a forceful emplacement of the constituent plutons. Anisotropy of Magnetic Susceptibility (AMS) data can provide an insight into subtle fabrics which cannot be observed in the field. AMS fabrics from 30 orientated block samples from the SC show a dominantly shallow dipping foliation that although is parallel to strike with the foliation of the Rathfriland, is generally discordant to internal sheeting and the steeply dipping Rathfriland fabric. The foliation in the SC is also gently dipping in contrast with its steep contacts. This

provides evidence that the Rathfriland Pluton cross cuts the SC and may also have imprinted a post emplacement fabric.

Palynofacies Analysis of Santonian-Campanian Mudrocks in South-Central Montana

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Upper Cretaceous clastic deposits accumulated in the Western Interior Seaway, U.S.A, forming in response to compression, caused by the interaction of the Pacific and North American Plates. Delta development occurred as a result of erosion from crustal uplift of newly formed mountains, resulting in shoreline oscillations.

The Niobrara Formation and the Telegraph Creek Formation, dated Late Santonian, are conformably overlain by the Eagle Formation. The Ardmore Bentonite series dated at 81 Ma, marks the boundary between the Eagle Formation and the Claggett Formation. The formations are interbedded with bentonites, varying in thickness, from 2cm up to 0.6m throughout the formations. Complex clastic wedge- type geometry characterises the deposits of these formations. The size and range of the depositional centre, makes this an ideal study site for high resolution biostratigraphy.

To reconstruct the palaeoenvironmental conditions, palynological techniques will be implemented to establish the microflora and microfauna. Tyson Plot palynofacies analysis is utilised to determine the hydrocarbon source rock potential. AOM-phytoclast-palynomorph percentage particles are plotted to distinguish 11 different marine facies and kerogen types. This research can be utilised by other researchers in further studies of Santonian- Campanian microfossils, a subject of previous limited study.

Evaluating the shale gas prospectivity of the NW Carboniferous basin of Ireland

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This study evaluates the shale gas prospectivity of the Lower Carboniferous sediments in the NW Carboniferous Basin of Ireland. The methodology is to review all literature and subsurface data, and acquire new data from fieldwork, including detailed sedimentary logging and sample collection. The aim is to characterize the depositional environment and determine the mineralogical and microfacies variation to assess the scale of lateral and vertical heterogeneities across the basin. Regional sampling of outcrops is being undertaken to determine organic matter quality and quantity, and assess thermal maturity, to provide input data to build a burial history and produce a basin model using Petromod software.

The NW Carboniferous Basin has a history of extension that initiated during the Courceyan Stage, punctuated by a multiphase exhumation history during the Late Palaeozoic and Mesozoic, with several episodes of gas generation. Using published literature potential shale gas formations in the Dinantian and Namurian have been identified that include the Bundoran Shale, Benbulben Shale, Carraun Shale, Dergvone Shale and Gowlaun Shale. Average thicknesses of the shales range from 300m in the Bundoran and Benbulben Formation to 50m in the Gowlaun Formation. Published data suggests average TOC% range from 1 to 3.5%. Maturation levels are in the dry gas generation window (R_0 1.2-3.0). Initial review suggests good potential for shale gas, and the study will evaluate the optimum locations and stratigraphic intervals across the basin.

Sedimentary recycling in the Millstone Grit, Yorkshire

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Sedimentary rocks and modern sediments sample wide areas of the crust, which preserve units that vary greatly in age and composition. Determining the provenance of component minerals is complicated by the ability of some minerals to be recycled through multiple sedimentary cycles, so minerals from completely unrelated sources may end up in the same sedimentary basin. To untangle these multi-stage signals, two or more chemical signatures measured in minerals with different structural stability are required. For instance, feldspars can break down rapidly during sedimentary transport, while zircons can be much more resilient and survive repeated recycling.

One sedimentary succession suitable for testing this hypothesis is the Upper Carboniferous Millstone Grit Group, a fluvio-deltaic sequence of upward-coarsening mudstones, siltstones and sandstones deposited in the Pennine Basin of northern England. New data from throughout this sequence clearly indicate two main feldspar populations, consistent with previous work, but also a minor third group which may correlate with zircons previously thought to be multi-cycle. Since the suggested source region for these rocks is northwest Scotland and the Southern Uplands, which contain material from as far away as Greenland, these data have significant implications for transport distances of both labile and resistant minerals.

Ireland Array: New broadband seismic stations target the structure, evolution and seismicity of Ireland and surroundings

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Ireland Array is a new array of broadband seismic stations, now deployed across Ireland. The backbone component of the array is formed by 20 stations, equipped

with Trillium 120PA seismometers and distributed uniformly across Ireland. These 20 stations have been installed in 2010-2012 and will be deployed for 5 years. Deployments of additional 10 stations (each with a Guralp 40T seismometer) will be used to complement the backbone-component coverage and to target fine structure of the subsurface in specific target areas.

Ireland Array is a major new geophysical facility, producing abundant seismic data. It will reveal Ireland's deep structure and evolution in unprecedented detail. Ireland Array will also underpin geothermal energy research by illuminating in detail the physical structure of Ireland's crust and entire lithosphere. New insight into 3-D regional lithospheric structure and evolution will also benefit basin-evolution research, relevant for hydrocarbon exploration. Yet another target of Ireland Array will be Ireland's seismicity, modest but insufficiently understood at present.

Ireland Array is generating important new data for research on both regional and North-Atlantic scale problems and is aimed to benefit the entire Earth science community. Web: http://www.dias.ie/ireland_array

Robust shear-velocity profiles within oceanic lithosphere and asthenosphere: Implications for thermal and compositional structure

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The temperature contrast between the cold oceanic lithosphere and the hot asthenosphere beneath it is reflected in the pronounced drop in seismic velocities at the lithosphere asthenosphere boundary. In addition to the immediate effect of temperature, however, other factors may influence observed seismic velocities, including partial melting or elevated volatile content in the asthenosphere relative to the lithosphere. Because temperature changes, partial melting and volatile content all have a strong effect on viscosity, their characteristics and relative significance have important implications on models of dynamics of the oceanic plates.

We measure robust, accurate, dispersion curves in broad periods ranges using surface waves across central Pacific from pairs of permanent seismic stations and a combination of cross-correlation and multimode-waveform-inversion approaches. The dispersion curves are then inverted for isotropic-average shear velocity profiles and radial anisotropy. Regional-scale stratification of azimuthal anisotropy can also be constrained. The high accuracy and broad period ranges of the phase-velocity measurements and the small size and simplicity of the inverse problems that relate them to shear velocities enable us to determine particularly robust shear-velocity profiles. We discuss the implications of the detailed models of isotropic and anisotropic layering, and also lateral variations in lithospheric properties, including those between the Hawaiian and normal-ocean lithosphere.

Interference of forced folds generated by a complex saucer-shaped sill network in the South Rockall Trough

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We use 3D seismic reflection data to investigate how the geometry of a forced fold, generated by the intrusion of an underlying sill, may be controlled by the lateral propagation of the sill-complex. Forced folds that are magmatic in origin essentially form domes that accommodate the intrusion of some sub-horizontal sills. Continued flexure of the fold eventually produces tensional fractures in areas of extension, which may then be exploited by transgressive, inclined sill limbs, resulting in sills that have a saucer-shaped morphology. Saucer-shaped sills in the South Rockall Trough are commonly observed to form laterally continuous networks that step up to higher stratigraphic levels via inclined segments of older, deeper sills, which feed the central flat-bottoms of younger, shallower sills. The lateral and upwards migration of sills over time may also be reflected in the evolution of the forced folds. Implicitly, whilst forced folds may form attractive hydrocarbon traps, this may be comprised by fold growth interference.

Anisotropy of magnetic susceptibility data from the Rocky Mountains of Montana and initial comparisons to strain analysis techniques

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Anisotropy of Magnetic Susceptibility (AMS) is essentially a measure of the orientation of all minerals in a given rock sample. This technique is possibly one of the fastest and easiest methods of identifying strain fabrics in deformed rocks. This project aims to compare AMS fabrics to results from traditional strain analysis techniques from low tectonic strain settings.

It is envisaged that AMS will assist in the identification and constraint of weak tectonic fabrics. The study area is the forelands of the Rocky Mountains of Montana, an area characterised by large scale thrust faulting and brittle deformation centred around thrust zones, with very limited penetrative deformation or cleavage development.

A multidisciplinary approach to the interpretation of rock magnetic data; a case study from the Galway Granite Batholith

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Rock magnetics have long been used as a tool to investigate the internal architecture of igneous bodies and to evaluate their structural history. The high level of sensitivity and precision achievable when using Aniostropy of Magnetic Susceptability (AMS) data to evaluate an emplacement or deformation model makes this technique an extremely powerful tool. However, erroneous interpretations are likely if a full apprasial of the magnetic properties of the mineral assemblage is not made and, along with the host's micro-structural characteristics, taken into condsideration during interpretation.

We present data from a transbatholithic traverse (25 sites accross the Galway Granite Batholith). The traverse extends from the granite's interior, where a prolate magmatic state fabric is present, to the northern contact where an oblate pure shear solid state fabric has formed against Grampian host rocks. Microstructural analysis exhibits a continuous northward spectrum of down-temperature fabric development. AMS and other magnetic data, verified with CPO analysis, have been used to examine the distribution of fabric intensity on approach to the pure shear contact. It is found that, method dependent, characteristic degrees of aniostropy can be corrolated with a continuous succession of down temperature deformation.

A new U-Pb zircon age for the Bellewstown Terrane, eastern Ireland, constrains faunal correlations

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A recent quarry extension within the Ordovician Bellewstown Terrane sequence in the Iapetus suture zone of eastern Ireland (Hilltown Formation) reveals a new graptolite fauna in shale overlying a felsic tuff. Zircons extracted from sand-grade tuff are exclusively prismatic and primary in appearance. U-Pb dating of the zircons by LA-ICP-MS (n=75) gives a 'TuffZirc' age of 474.1 +1.1-2.5 Ma (Floian: Arenig). Previously, graptolites from the Hilltown Formation have been referred to the D. artus Biozone (Darriwilian: Llanvirn) and this age has been applied to an intra-Iapetus brachiopod fauna also present in the Hilltown Formation, even though equivalent brachiopod faunas in the Dunnage Zone of Newfoundland are older. The new age for the tuff appears to reconcile this previous faunal age discrepancy. Characterisation of the new graptolite fauna is ongoing and will be reported at the conference.

The European Plate Observing System; a research infrastructure project for the geosciences community

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EPOS, the European Plate Observing System, is a pan-European, multidisciplinary Research Infrastructure project approved by the European Strategy Forum on Research Infrastructures (ESFRI). The project is a long-term integration plan of national existing research infrastructures in the geosciences and aims to promote, and facilitate, innovative approaches for a better understanding of Earth's physical processes. It will integrate the diverse, infrastructures for solid Earth Science and will build on new e-science opportunities to monitor and understand the dynamic and complex solid-Earth System. The aim is to identify existing gaps and promote implementation plans within a range of geoscience disciplines to help solve some of the grand challenges.

The geosciences community in Ireland is formally represented within the EPOS consortium by the Geological Survey of Ireland. The GSI will also help coordinate a national group 'EPOS Ireland' which will ensure clear communication between EPOS and Irish researchers. This will provide an opportunity for the Irish geosciences community to directly engage with the wider European community, to build strong, intra- and interdisciplinary collaborations and to ensure sustainability for European research infrastructures. EPOS and the EU Infrastructure Programme may also provide wider, future opportunities to access geoscience resources within Europe.

The seismic signature of "hidden" faults at magma-poor rifted margins – investigation using synthetic seismic data

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The Porcupine Basin can be considered to be a magma-poor aulacogen and shares many similarities to magma-poor rifted margins (MPRMs) (e.g. W. Iberian Marin); extreme crustal attenuation ( ), serpentinised mantle, low volumes of syn-rift magmatism. An extension discrepancy is commonly observed at MPRMs, whereby the amount of stretching accommodated by seismically observable faults is much less than required to thin the entire crust to the extent that is observed on wide-angle seismic, and gravity models.

It has been suggested that whole crust stretching could be accommodated by unrecognised faulting at MPRMs. In order to facilitate high degrees of stretching (multiple fault generations are required. The complexity of both the geometries and associated seismic velocity profiles, produced by this progressive polyphase faulting (PPF) mechanism would serve to render the earliest fault generations difficult to image and identify on seismic data, causing any estimation of stretching accommodated by upper crustal faults to be grossly underestimated.

We present synthetic seismograms generated from both published and unpublished models of highly extended crust, demonstrating how the PPF mechanism can manifest on seismic data. We show that PPF is capable of accommodating the required stretching at MPRMs and that it is merely unrecognised on seismic data.

Celtic and Irish Sea sedimentary processes, Quaternary stratigraphy and offshore wind energy development

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Environmental and engineering knowledge on (sub-) seabed conditions and present day sediment transport is vital for offshore site development. This information will allow for wind farm development plans using various site-specific turbine designs, in turn, cutting the costs significantly in later development stages. This requires information of contemporary seabed dynamics and sub-surface sedimentary sequences.

Ireland's dynamic north-east and south coast provide unique study sites to investigate seabed scour around boulders and ship wrecks, model sediment plume dispersal, and model sediment transport.
The dynamics of the Irish Sea Ice Stream are poorly constrained due to the insufficiently detailed offshore Quaternary stratigraphy. Mapping the irregular bedrock and palaeo-valleys that have preserved glacial and probable interglacial sequences will help to develop a better understanding of the Irish Sea Glacier's movement.

This project addresses the marine geological knowledge gaps of the north and south coast of Ireland, where the expansion of grid connectivity is desirable and the potential for wind farm development is high.

Reconstructing the last Newfoundland ice sheet through the last glacial cycle (~28ka-10ka yr BP)

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Ice sheets are an integral part of the global climate system which respond to and drive climatic changes. Currently there is concern regarding the stability of earth's ice sheets in relation to climatic change and their potential impact on sea level. To address these concerns it is essential to establish how ice sheets respond to external forcing over long-time periods. An established methodology is to use the glacial landform record to reconstruct palaeo-ice sheet behaviour, which provides

critical information on how ice-sheets respond to external forcing through entire glacial cycles. The former Newfoundland Ice-sheet is of particular importance due to its position on the fringes of the North Atlantic and the much larger North American Laurentide Ice Sheet, analysing this record can provide new information on wider ice sheet-ocean-atmosphere interactions in this region. The aims of this project are to systematically map the glaciated landscape in Newfoundland using satellite remote sensing and use this data to reconstruct the dynamic history of the former Newfoundland ice sheet during the last glacial cycle. This poster presents the initial results from the mapping programme and shows the distribution of subglacial landforms in eastern Newfoundland which are used to reconstruct the former ice flow pathways.

Constraining crustal contribution to the isotopic composition of the Antrim Lava Group, NE Ireland

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Large Igneous Provinces represent episodic, catastrophic igneous events throughout Earth history. They are distinguished by high intensity bursts of principally mantle derived magma into the crust and onto the surface over geologically short timescales. Part of the Palaeogene North Atlantic Igneous Province, the Antrim Lava Group (ALG) in NE Ireland consists of mainly basaltic rocks and is split into two main formations – the Lower Basalt Formation (~60-62 Ma) and the Upper Basalt Formation (~59-57Ma) – which are separated by the Interbasaltic Formation, a time break in basalt effusion marked by a horizon of deep weathering punctuated by the eruption of intermediate to felsic lava flows.

Both Upper and Lower Basalt rocks show an overlapping range of initial $^{87}Sr/^{86}Sr$ (0.703088-0.704989) and $^{144}Nd/^{143}Nd$ (0.513107–0.512476), while the intermediate flows of the Interbasaltic Formation show elevated initial $^{87}Sr/^{86}Sr$ values (>0.708) and reduced $^{144}Nd/^{143}Nd$ (0.512235–0.51198), reflecting a significant crustal component. Pb isotopes define similar overlapping arrays sub-parallel to, but above, the NHRL. The consistent variation in both the Upper and Lower Basalt lavas suggest that they are related by a process of progressive contamination by material from a common source which has a time-integrated history of trace element enrichment (high Rb/Sr and low Sm/Nd).

The North Anatolian fault and lithospheric dynamics in eastern Mediterranean: A seismic surface-wave study

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Lithospheric deformation in eastern Mediterranean is complex and varies laterally. The shear associated with the westward motion of Anatolia is localised at and near the North Anatolian Fault (NAF). Because the crustal and mantle deformation is three-dimensional, with strain patterns depth-dependent, it is difficult to determine the deformation mechanisms from surface observations alone.

We measure phase velocities of seismic surface waves using seismic stations in eastern Mediterranean and infer depth-dependent orientations of anisotropic fabrics—a record of deformation in the crust and mantle. We also use the measurements to determine S-velocity profiles, indicative of temperature within the lithosphere and, therefore, its mechanical strength.

The lithosphere gets warmer and thinner from the Black Sea (north of NAF) to central Anatolia (south of NAF). The fault is thus localised near the transition between mechanically strong and weak lithospheric blocks. The lower crust and mantle lithosphere beneath NAF show E-W, fault-parallel, distributed flow within an about 100-km wide zone. The underlying asthenosphere flows NE-SW, towards the retreating Hellenic Trench. Although the motion of lithospheric blocks is driven by the same trench retreat, it is influenced by lateral variations in the lithosphere's mechanical strength and is very different from the flow in the asthenosphere.

Preliminary geoarchaeology of the Late Neolithic - Early Bronze Age Ballynoe Stone Circle, Northern Ireland: geological stone provenance and feedback into glacial flow paths

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Ballynoe, located 4km south of Downpatrick, County Down, is one of the finest stones circles in Ireland. With a diameter of 34m, it incorporates 107 stones up to 2m high, comprising an inner circle and mound, surrounded by a concentric outer circle plus entrance. The circle was built on drumlinised till underlain by Silurian sedimentary rock (greywackes).

Following fieldwork, the lithology and shape of all the stones was input into a GIS and attributed plots were examined.

Results show that: the inner circle is composed of smaller, well-rounded stones (27); the entrance is composed of large, well-rounded stones (14); and the outer circle is composed of a mixture of mainly large, angular and well-rounded stones (53). Lithologically the stones fall into two main groups: greywackes (76) and, unexpectedly, basic igneous (olivine gabbro and dolerite, 29). The latter are almost

exclusively well-rounded, whereas the greywackes are well-rounded to angular. All the stones, however, show evidence of glacial rounding and transport.

The greywackes have been glacially derived from the Ordovician-Silurian bedrock north of Ballynoe, whereas the gabbroic/doleritic rocks are most likely from the Palaeogene Scrabo sill complex, some 30km north near Newtownards. This study illustrates how geoarchaeological research can contribute to Quaternary studies in Ireland. However, the question remains as to where and how the stones were sourced by humans. If locally sourced from glacial deposits, we might expect to see a zone of depletion, of stones of Ballynoe proporations, in field boundaries around the site. Broad questions include whether Ballynoe, with its simiarities to the Swinside stone circle in Cumbria, was built by “Lake District settlers”.

Outcrop and thin section analysis of the Namurian Clare Shale Formation: A sedimentological perspective on the variability within shale gas reservoirs

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The focus of this study is the Namurian Clare Shales of the Carboniferous Shannon Basin. These deepwater, laminated, black, basinal marine mudstones have high total organic carbon values (TOC) ranging from 2-15% and high thermal maturity levels, averaging 5% Ro (vitrinite reflectance). This suggests they may have potential as a shale gas resource. However, little is understood on the importance of sedimentological factors on the variability within shale gas reservoirs.

This study will conduct a thorough analysis of the shale gas potential of the Clare Shale through: (i) detailed sedimentological logging and sampling to characterise the lithofacies and variability, (ii) thin section analysis of microfacies, focussing on organic matter distribution, (iii) TOC, RockEval and vitrinite reflectance analysis of these samples to better constrain the hydrocarbon potential. These datasets will be integrated to build a basin model, assess maturity and evaluate the optimum areas for exploration.

Preliminary field work has examined sections at Ballybunnion, Inishcorker, Lisdoonvarna, and Fisherstreet. The outcrops visited, which are gray-black in colour, contain marine fossils; terrestrial plant fossils; concretions; cementation variations; lamination grain size variabilities; upward-thickening and –coarsening packages. Preliminary results indicate a reasonable degree of sedimentological variability and thin section, petrographic and geochemical work is ongoing.

Investigation of groundwater flow pathways in a Karst Aquifer using static & towed Electrical ResistivityTomography (ERT) Data

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The Gort Lowlands in South Galway is a major karst region formed by extensive dissolution of the underlying Carboniferous limestones, resulting in an underground network of conduits and fissures that define the groundwater flow across the region. Caherglassaun Lough is located within this region, 5.5 km southeast of Kinvara, Co. Galway. Although technically a lake, Caherglassaun Lough behaves like a turlough. It is part of the regional drainage system and is fed and drains to groundwater. Water levels rise and fall seasonally as an expression of the groundwater regime.

The lough is fed by an subsurface network of conduits which drain westward from the Slieve Aughty uplands. Typical winter rainfall conditions result in the karst system becoming saturated. The gradient of groundwater flow is low and Caherglassaun Lough, in conjunction with numerous turloughs in the area, act as large reservoirs which provide temporary storage to enable the transmission of large volumes of water in the system to the sea.

The work presented here concerns a geophysical survey carried out between August and October 2010. Static ERT profiles were recorded around the lake to investigate the presence of conduits flowing in to and out of the lake. They were complemented by towed ERT profiles across the body of water to investigate subsurface resistivities beneath the lake and to map the bathymetry of the lake bed. The ERT data has identified significant conduits up to 40m in diameter at depths from 20m to 60m below ground level.

Multidisciplinary characterisation of methane seepage features in Irish waters

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Vast amounts of methane (CH_4) are stored and produced in the oceans seafloor[1], in particular as sites of active CH_4 seepage and seabed seepage is a significant component of the global carbon cycle. In addition seepage facilitates the formation of dramatic geological features on the oceans seafloor, supports unique biodiversity, and commercially are sites of potentially vast energy resources. Most produced CH_4 is consumed by microbial processes in the water column or by anaerobic oxidation of methane (AOM)[2]. However the formation, physical and geochemical processes, and biological composition of these methane seepage settings are poorly understood. In Irish waters, seabed fluid flow features such as pockmarks, mud diapirs and methane-derived authigenic carbonate (MDAC) mounds have been documented [3][4][5][6]. This project aims to characterise pockmarks in the Irish, Sea, Malin Sea and Dunmanus Bay, the Lambay Deep mud diapir and the MDAC mound Codling Fault

site by a multidisciplinary geophysical, molecular biological and geochemical approach. The goal is to improve understanding of the formation and evolution of these features and also their importance in biogeochemical cycling, marine biodiversity and from commercial viewpoints, such gas and petroleum resources and novel and bioactive compound discovery - both for Ireland and globally.

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A large glacio-tectonic raft of Carboniferous Limestone in Killala Bay, Co. Mayo

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A glacio-tectonic raft complex >400 m long is exposed on the E side of Kilcummin Head. The largest element in the complex is a thrust sheet >300 m long and <14 m thick consisting of interbedded limestone (<1 m) and shaly units (<2 m). The northern 120 m of this thrust sheet is ramped up over a lower sheet of the same beds. Vertical joints in the limestones have locally developed into S-dipping “domino” faults, while the topmost bed of the raft is undeformed (“bookshelf faulting”) reflecting ice-induced northward shear. Glacial striations are orientated N-S. The main thrust sheet is covered by blocky, sandstone-dominant, de-glacial-phase diamicts enclosing “floating” rafts <35 m long.

The northernmost 70 m of the cliff section consists of a stack sub-horizontal thrust sheets >30 m long. Each consists of a highly deformed shaly unit, capped by a little-deformed limestone, which at the N end forms an enclosing terminal overfold.
The extensive sub-horizontal form of these thrust sheets and the absence of listric faults indicate that the thrust sheets were emplaced successively upwards, not as piggy-backs.

Northward thrusting of the raft complex is in line with drumlin orientation through the Ox Mountains, but relative timing is unknown.

Implications for crustal accretion and evolution within the Caledonian Orogen: Results from anisotropic Rayleigh-wave tomography in Ireland

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The Irish landmass was formed in the Caledonian Orogeny during the Palaeozoic assembly of Pangea. The closure of the Iapetus Ocean is recorded in NE–SW structural trends that dominate Ireland. The deep-crustal dynamics of the orogeny and effect on the Irish crust of the subsequent extension and magmatism in the North Atlantic are debated. Deep crustal fabrics preserve a record of deformation during and after continental collisions. Rayleigh-wave phase velocities are measured and the data inverted for phase-velocity maps, including azimuthal anisotropy. The isotropic phase-velocity heterogeneity reflects moderate crustal thickness and seismic velocity variations across Ireland. Anisotropy of Rayleigh waves at 10–20 s periods shows a NE–SW fast-propagation direction, and is largest (up to 2%) at 15 s period, at which Rayleigh waves sample primarily the middle and lower crust. The NE–SW trend of the deep-crustal anisotropic fabric is parallel to tectonic trends, in particular the Iapetus Suture Zone, which indicates that suture-parallel flow in the middle and lower crust accommodated the continental collision. Preservation of Caledonian-age fabric also shows that the deep crust of Ireland was neither stretched by NW–SE extension associated with opening of the North Atlantic, nor modified significantly by Cenozoic magmatism in the region.

Topographic and climatic controls on sand dispersal into NW European Triassic basins

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The Northwest European Triassic succession comprises the Early – Middle Triassic Sherwood Sandstone Group (SSG) and the Middle – Late Triassic Mercia Mudstone Group. These represent the deposits of large-scale endorheic drainage systems which accumulated in the arid to semi-arid interior of the Pangaean Supercontinent. Analysis of the Pb isotopic composition of detrital K-feldspar from arkosic SSG-equivalent sandstones has allowed regional Triassic palaeodrainage patterns to be constrained. The provenance results suggest that both topography and flooding associated with an annual monsoon are likely to have been responsible for pre-sorting and ultimately transporting sediment from upland areas. This combination of processes can also account for the textural maturity, but mineralogical sub-maturity, of the sandstones. The data highlight the presence of two distinct drainage domains: 1) the ‘Budleighensis’ domain, where systems flowed from south to north and were derived from the remnant Variscan Uplands; and 2) the Atlantic Margin domain, where drainage was oriented NW-SE and sediments were dominantly sourced from Archaean-Palaeoproterozoic rocks within eastern Greenland, from the Rockall Bank and from Lewisian equivalents northwest of Scotland. The drainage divide separating these domains coincides with the Irish and Scottish massifs. Although these areas were of sufficient relief to act as a drainage barrier, they appear not to have been a significant source for sediment.

Ductile deformation of late Pleistocene peat and altered Palaeogene basalt by possibly sub-glacial mass-wasting into a gypsum karst fluvial system at Knocknacran, Co Monaghan, Ireland

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Late Pleistocene organic-rich deposits, gravely till and altered Palaeogene basalt overlying Permo-Triassic gypsum at Knocknacran opencast gypsum mine, Co. Monaghan show thrust faulting and recumbent folding. Deformation ranges from gentle sag folding to fully recumbent, nappe-like anticlines incorporating altered basalt, with associated synthetic thrusting and en echelon veining. Abundant fossil wood in peat layers provides evidence of structural transport directions. Uranium thorium disequilibrium dating suggests the organic-rich deposits in the upper section were hydrologically isolated at >41 ka old and in the lower section were hydrologically isolated at >86 ka old. Interpretation of the pollen content suggests the organic material originated in a warm stage possibly warmer than post-Eemian interstadials. Dating, palynology and field relations suggest that warm-stage peat deposits were remobilised during a change in hydrological conditions and flushed as a slurry onto supra sinkhole depressions in the Tertiary basalt surface. Ductile deformation of the combined peat, till and basalt unit suggests relatively high confining pressure, combined with mass-wasting into the gypsum sinkhole system (which is still active today), presents the possibility that deformation occurred beneath a wet-based glacier.. Lack of deformation in the overlying drumlinized diamicton indicates that deformation pre-dates deposition of this unit.

Petrography of fluid inclusions in sandstones of Es4x-Ek1s formations in Dongying depression, China

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The Dongying depression, an important hydrocarbon producing depression in China, is located at the southern part of Jiyang Subbasin in Bohai Bay basin, East China. Es4x-Ek1s formations are the main exploration targets in resent years. Fluid inclusion petrography of thirty three samples of sandstones taken from wells located in the Dongying depression is reported here. Fluid inclusions occur in authigenic quartz, calcite and dolomite. Five fluid inclusion morphologies occur: oblate, ellipsoidal, tubular, triangular and negative crystal shape. Dimensions of fluid inclusions are generally < 10μm and mainly ranging between 2μm and 7μm. Both

hydrocarbon and aqueous inclusions are present, the former are mainly liquid-rich two-phase and develop varied fluorescent characteristics under UV, the latter could be classified into monophase, two-phase and multiphase solid inclusions based on phases observed at room temperature but dominated by two-phase types. The degree of fill of two-phase inclusions is generally > 0.8.

Constructing a model of 3D radiogenic heat production in Ireland

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Heat production values in the crust and mantle inform heat flow density data to provide crucial information about the structure of the lithosphere. In addition, accurate models of horizontal and vertical distribution of heat production can help to define geothermal exploration targets.

Ireland is located within stable lithosphere, unaffected by recent tectonism and volcanism, and has an estimated heat flow range below the measured global continental average. Nevertheless, borehole data indicate that heat production is variable, with anomalously high rates observed, for example, in Cavan, Meath and Antrim. Data coverage is, however, poor.

Heat production rates are calculated using established heat production constants and the concentrations of uranium, thorium and potassium, along with rock density values. With the objective of compiling the first comprehensive heat production database for the Irish lithosphere, in three dimensions, the authors present initial results obtained from whole-rock major and trace element analyses.

Offering insight into the vertical component of heat production distribution, Irish deep crustal xenoliths act as a proxy for the present-day lower crust. Their composition gives higher heat production values than expected for the depths indicated by thermobarometric data, suggesting that heat production rates do not simply reduce with depth.

Geothermal energy potential of the Greater Dublin area and the Mourne Mountains Granite Complex

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The Greater Dublin area has a range of potential geothermal targets including sedimentary rocks of the Dublin Basin and the Caledonian Kentstown and Drogheda granites. Dublin Basin rocks, if porous and permeable, could provide Hot Sedimentary Aquifer potential, or provide a fault-hosted aquifer at the faulted basin margins. The Newcastle geothermal exploration borehole encountered waters at

46.2°C at 1400 m depth. The Kentstown (500 m depth) and Drogheda (surficial) granites are both radiogenic, heat-producing bodies (Kentstown; 3.64 μWm^{-3}) that may support Enhanced Geothermal System (EGS) exploitation. We present 2D forward gravity models for the area to gauge the depth and size of the bodies.

Another EGS target, the Mourne Mountains Granite Complex has granite heat production values of 3.69-7.21 μWm^{-3} and projected temperatures at 5000 m of ~114°C. 2D isotropic models from magnetotelluric data suggest that the western and eastern granite plutons may extend to depths of 3 and 8 km respectively. New 2D anisotropic models which account for current flow parallel and orthogonal to the profile possibly provide a proxy for micro-fracture alignment, an important engineering parameter. 2D forward gravity models, coincident with magnetotelluric profiles help constrain the depth of the bodies and resolve lithological ambiguities.