D2 microlithons from lower limb of the Tay Nappe on Bute, viewed to the SSW, showing top-to-ESE shear sense.

Highland Workshop 2008. - Programme
Thursday 24th April

9.00 – 9.10 Intro and welcome by Denis Peach, Martin Smith

1.	9.10 – 9.30	Constraining high-grade metamorphism in the Lewisian *Quentin Crowley, Stephen Noble & Roger Key*
2.	9.30 – 9.50	The age of the Laxford Shear Zone *Kathryn Goodenough, Q uentin Crowley & Maarten Krabbendam*
3.	9.50 – 10.10	Isotopic evidence for early Neoproterozoic and Ordovician tectono-thermal events within the Yell Sound Division, Shetland Islands *Rob Strachan, Pete Kinny, Chris Clark, Martin Hand, Kathryn Cutts & Mike Fowler*
4.	10.10 – 10.30	Age resolution of polymetamorphic events in the Scottish Northern Highlands using Lu - Hf methods *Anna Bird, Matthew Thirlwall, Rob Strachan & Wolfgang Müller*
5.	10.30 – 10.50	Morar = Torridon = Grenville Foreland Basin: outstanding problems *Maarten Krabbendam*

10.50 – 11.30 ***Discussion, Coffee and Posters***

6.	11.30 – 11.50	Sourcing sediment from the Laurentian interior – a case study and some constraints on tectonic models *Paul Smith*
7.	11.50 – 12.10	Laurentian provenance for the Erris Group and Inishkea Division (=Dalradian Grampian Group?) rocks of NW Mayo, Ireland *Claire McAteer, Stephen Daly, Michael Flowerdew,* *Martin Whitehouse & Chris Kirkland*
8.	12.10 – 12.30	Global C cycle perturbations recorded in marbles: a record of Neoproterozoic Earth history within the Dalradian succession of the Shetland Islands, Scotland. *Tony Prave, Rob Strachan, & Tony Fallick*

12.30 – 14.15 ***Thursday Lunchtime – Ken Hitchen – pitch from S.J.G***
Discussion then Lunch

9.	14.15 – 14.35	New rocks from old - Proterozoic tuffs ("brown beds") *Richard A. Batchelor*
10.	14.35 – 14.55	New fossil discoveries in the Late Neoproterozoic rocks of Charnwood Forest: descriptions and palaeoenvironmental interpretations of an Ediacaran deep-water 'garden' *John Carney, Mike Howe and Phil Wilby*
11.	14.55 – 15.15	Post-Grampian top-to-WNW Caledonian ductile shear in the Grampian Highlands? *Graham Leslie & Diarmad Campbell*
12.	15.15 – 15.35	Penobscottian-type accretionary tectonics in Southern Britain? *David Schofield*

15.35 – 16.15 ***Discussion, Tea & Posters.***

13.	16.15 – 16.35	Grampian high-pressure-granulite-facies metamorphism of the Slishwood Division, NW Ireland and its enigmatic eclogite-facies precursor *Stephen Daly, Michael Flowerdew & Martin Whitehouse*
14.	16.35 – 16.55	An alternative model for the Grampian Orogeny in Scotland *Geoff Tanner*
15.	16.55 – 17.15	New ideas about the type-area of Barrovian regional metamorphism *G.J.H. Oliver, D.R. Viete, M.A. Forster, S.W. Richards, J. Hermann, G.S. Lister & A.F. Corvino*
16.	17.15 – 17.35	The Shetland Mega-monocline: a continuation of the Tay Nappe? *Derek Flinn*

Friday 25th April

17. 9.00 – 9.20 *In-situ* Hf isotope measurements of complex zircons from Irish granitoids reveal hidden Palaeoproterozoic and Archaean sources at depth
Michael Flowerdew, Stephen Daly, David Chew, Ian Millar & Matthew Horstwood

18. 9.20 – 9.40 Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic flare-up in the Grampian Terrane, Scotland
Joanne C. Neilson, B. Peter Kokelaar & Quentin G. Crowley

19. 9.40 – 10.00 Caledonian high Ba-Sr granites: comparisons with sanukitoids
Mike Fowler

20. 10.00 – 10.15 Timing of post-orogenic cooling in the Grampian Terrane, Scotland: evidence from a multi-technique $^{40}Ar/^{39}Ar$ dating study
Clive Gerring, Sarah Sherlock, Rob Strachan, S.P. Kelley & N.Arnaud

10.15 – 10.55 ***Discussion, Coffee and Posters***

21. 10.55 – 11.15 SW Highland Moine
Tony Harris

22. 11.15 – 11.35 Eclogite facies metamorphism in the Central Highland Migmatite Complex, Grampian Highlands
Simon Cuthbert

23. 11.35 – 11.55 The older mafic and ultramafic of the East Grampians, similarities to the UAE-Oman ophiolite and the tectonic implications
Mike Styles

24. 11.55 – 12.15 The Highland Border – an introduction

12.15 -14.00 ***Friday Lunchtime – Discussion then Lunch***

Lunchtime Talk - National Parks: Delivering a Sustainable Future, Grant Moir

25. 14.00 – 14.30 Arc-continent collision and the Taconic/Grampian problem
John Dewey & Paul Ryan.

26. 14.30 – 15.00 The nature, origin, and palaeogeographical setting of the Highland Border Ophiolite.
Geoff Tanner, Howard Armstrong & Alan W. Owen.

27. 15.00 – 15.30 How does the discovery of "Iberia-type margins" change the interpretation of collisional orogens?
Gianreto Manatschal

15.30 – 16.00 ***Discussion, Tea & Posters.***

28. 16.00 – 16.30 Constraints on the timing of deformation in the Highland Border Complex and correlative rocks in western Ireland
David Chew, Laurence Page, Tomas Magna, Stephen Daly, Chris Kirkland, Martin Whitehouse & Richard Spikings

29. 16.30 – 17.00 A U-Pb zircon age constraint for the Ordovician Tyrone Plutonic Group ophiolite, Tyrone Igneous Complex, Northern Ireland: implications for plate models and Grampian orogenic amalgamation
Mark Cooper, Steve Noble, Quentin Crowley & Richard Merriman

Posters:

1. Geochemistry of Caledonian microdiorites from Ardgour.
Mike Fowler
2. Precise U-Pb zircon ages for the Loch Borralan and Flannan syenites, and their relationship to the Caledonian orogenic front.
Ian Millar, Derek Ritchie, Kathryn Goodenough, Steve Noble & Geoff Kimbell
3. Zonation and structure of the Late Caledonian Newry Igneous Complex, Northern Ireland from Tellus geophysical datasets
M*ark Cooper, Chris Van Dam and Ian Meighan*
4. The Shetland Mega-monocline: a continuation of the Tay Nappe?
Derek Flinn

Oral Presentations (*in running order*):

Constraining high-grade metamorphism in the Lewisian

Quentin G. Crowley[1], Stephen R. Noble[1], Roger Key[2]
[1]NERC Isotope Geoscience Laboratory, Kingsley Dunham Centre, Keyworth, Nottingham, UK.
[2]British Geological Survey, Murchison House, Edinburgh, Scotland.

The Lewisian complex of NW Scotland is dominantly composed of Archaean tonalitic to granodioritic gneisses, ultramafic bodies and minor metasedimentary components. Although the area is internationally well known and has been much studied for over a century, the recognition and precise timing of some high-grade metamorphic events has proven difficult to ascertain. This is partly due to repeated deformational and metamorphic episodes in the Palaeoproterozoic which overprint and obscure earlier events. We present data from both laser ablation (LA) ICP-MS and an adaptation of a U-Pb chemical abrasion ID-TIMS technique applied to multi-age component zircons from the Assynt ("*Central*") block of this region. The new data reveal a previously unrecognised complexity and provide the first unequivocal proof of an Archean to Paleoproterozoic granulite metamorphic event in the Assynt area.

LA-ICP-MS U-Pb dating has indicated a ca 2.8 Ga protolith age for a tonalitic gneiss with evidence for a ca. 3.5 Ga xenocrystic component (the oldest discovered in the UK). Non-conventional U-Pb ID-TIMS utilising a combination of high-temperature annealing followed by multi-step incremental dissolution on single grains allows identification of Pb-loss and multi-generational age trajectories on $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ plots. A combination of LA-ICP-MS and this non-conventional TIMS work has dated zircon growth at ca 2.7 Ga ("*Badcallian*") and 2.5 Ga ("*Inverian*") with later Pb-loss occurring at ca 1.9 Ga and ca 1.7 Ga (early and late "*Laxfordian*" respectively). This TIMS method is unique in that it combines a pseudo-spatial resolution normally associated with an in-situ technique but benefits from the high-precision analysis required to differentiate between these metamorphic events at ca 2.7 and 2.5 Ga.

Zircon Hf isotopes indicate that some gneisses from the Assynt area are typical of Archaean continental crust (epsilon Hf ca -1). The tonalite gneisses however have strongly negative epsilon Hf values of -7 to -10 indicating a more complex history of derivation through partial melting of ancient crust with residual garnet as a long-lived control on Hf. Moreover, consistent zircon epsilon Hf values from inherited cores, igneous overgrowths and two separate metamorphic events indicate that the tonalitic gneisses were formed by crustal recycling, rather than new additions to the crust.

These events may be summarised as: zircon crystallisation from a magma at ca 3.5 Ga, partial melting and crustal recycling producing the tonalite gneiss protoliths at ca 2.8 Ga, a prolonged lower crustal residence in granulite P-T conditions by ca 2.7 Ga, further metamorphism in amphibolite conditions at ca 2.5 Ga and later deformation associated with punctuated terrane amalgamation events between ca 1.9 Ga and ca 1.7 Ga. The occurrence of a 2.7 Ga metamorphic event preserved in gneisses from Assynt contradicts the assertion of some previous studies that it does not exist in this region and suggests at least some local terrane amalgamation occurred in the Archean.

The age of the Laxford Shear Zone.

Kathryn Goodenough[1], Quentin Crowley[2] and Maarten Krabbendam[2]
[1]British Geological Survey, West Mains Road, Edinburgh EH9 3LA
[2]NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG

Recent work (Kinny et al. 2005) has suggested that the Lewisian Gneiss Complex of North-west Scotland comprises a collage of small-scale Archaean terranes, assembled and variably reworked during the Proterozoic. The Laxford Shear Zone is one likely terrane boundary, separating two crustal blocks with different protolith ages, metamorphic histories, and chemical compositions. To the south are granulite-facies TTG gneisses of the 'Assynt terrane' which have undergone only limited Proterozoic deformation. To the north of the shear zone are amphibolite-facies granodioritic gneisses of the 'Rhiconich terrane', which show extensive Proterozoic deformation, migmatisation and metamorphism.

The Laxford Shear Zone itself forms a zone a few kilometres wide, along which early movement occurred during the Inverian event, before emplacement of the Scourie Dyke Swarm at c. 2400-2000 Ma (Heaman and Tarney, 1989). Later reactivation occurred during the Laxfordian event (c. 1740 Ma; Corfu et al., 1994), chiefly along discrete, mappable shears. Along the shear zone itself are a variety of granitic sheets, some foliated, others undeformed. These granitic sheets die out rapidly to the south of the shear zone, whereas to the north they grade into migmatitic gneisses.
If the hypothesis that the Laxford Shear Zone represents a terrane boundary is correct, then the two main questions are: when were the two terranes accreted, and what tectonic processes were operating at that time? To fully answer the first question, we have carried out U-Pb zircon dating, using both spatially constrained LA-ICPMS (zircon) and single crystal TIMS (zircon and titanite) methods.

Our new dating of highly deformed granites and paragneisses within the shear zone provides clear evidence for a metamorphic event at c. 2500 Ma, considered to be the Inverian event. Since the younger intrusions (Scourie Dykes, granitic sheets) are found within and on both sides of the Laxford Shear Zone, initial terrane assembly is considered to have occurred at c. 2500 Ma. The age of the younger Laxfordian event is constrained by dates for the granitic sheets. Our dates on these intrusions confirm the existence of two intrusive events, one at c. 1880 Ma and the other at c. 1775 Ma. Thick (up to 50 m) granitic sheets intruded at c. 1880 Ma are focused along the core of the shear zone, and almost certainly represent the introduction of new magma. In contrast, the c. 1775 Ma event at Laxford is associated with more localised crustal melting, and may perhaps be correlated with the c.1740 Ma titanite age for the metamorphic event. Laxfordian deformation and melting was focused in the less-competent, more fertile amphibolite-facies gneisses of the Rhiconich terrane.

References

Corfu, F., Heaman, L. M. and Rogers, G. 1994. Polymetamorphic evolution of the Lewisian complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile. *Contributions to Mineralogy and Petrology*, **117**, 215-228.
Heaman, L. and Tarney, J. 1989. U-Pb baddeleyite ages for the Scourie dyke swarm, Scotland: evidence for two distinct intrusion events. *Nature, London*, **340**, 705-708.
Kinny, P. D., Friend, C. R. L. and J, L. G. 2005. Proposal for a terrane-based nomenclature for the Lewisian Complex of NW Scotland. *Journal of the Geological Society of London*, **162**, 175-186.

Isotopic evidence for early Neoproterozoic and Ordovician tectonothermal events within the Yell Sound Division, Shetland Islands

Rob Strachan[1], Pete Kinny[2], Chris Clark[2], Martin Hand[3], Kathryn Cutts[3] & Mike Fowler[1]
[1]School of Earth & Environmental Sciences, University of Portsmouth, Portsmouth, UK.
[2]School of Applied Geology, Curtin University of Technology, Perth, West Australia.
[3]Department of Geology & Geophysics, University of Adelaide, Australia.

The Yell Sound Division outcrops east of the Walls boundary Fault (= Great Glen Fault?) on Yell and Mainland Shetland (Flinn 1988 and references therein). It comprises a thick sequence of strongly deformed and variably gneissose/migmatitic psammite with minor horizons of schist and quartzite. The Yell Sound Division has been correlated with the Moine Supergroup, and in particular the Glenfinnan Group (Flinn *et al.* 1972, 1979). Infolds and/or tectonic slices of hornblende gneisses are thought to have 'Lewisianoid' affinities (Flinn 1988). Two main types of meta-igneous intrusions are present within the metasediments, both emplaced at an early stage in the tectonic history of the host rocks. These are: 1) granitic gneiss bodies including those that outcrop at Brekon and Gutcher (Yell) and Lunna Ness (Mainland Shetland), and 2) common sheets of garnet amphibolite. New U-Pb zircon SIMS ages obtained from the Yell Sound Division and three granitic gneiss bodies provide evidence for: 1) the depositional age and provenance of the sedimentary protolith of the Yell Sound Division, and 2) two major tectonothermal events, one during the early Neoproterozoic, and the other during the Ordovician (= Grampian phase of the Caledonian orogeny).

Age resolution of polymetamorphic events in the Scottish Northern Highlands using Lu-Hf methods

Anna F Bird*, Matthew F Thirlwall*, Rob A Strachan** and Wolfgang Müller*
* Dept. Earth Science, Royal Holloway University of London, Egham, TW20 0EX
** School of Earth and Environmental Science, University of Portsmouth, Portsmouth, PO1 3QL
e-mail: a.f.bird@rhul.ac.uk

Trace and major element data for garnets from the Northern Highland terrane have been determined using the new RHUL LA-ICPMS system and the Natural History Museum electron microprobe. Garnets show wide variation between the Moine stratigraphic units and basement rocks. Morar Group garnets show marked MnO zoning, changing from 0.1 wt% at the rim to 5.8 wt% in the core. Fe and Mg show the opposite trend, with FeO decreasing from 34.7 to 30.8 wt% in the core. Garnet cores are quite homogeneous in samples from southern Morar rocks near Polnish and Glenuig; rims are much more heterogeneous with several inclusions of zircon, apatite and monazite. HREE show a general decrease from core to rim. The chemical differences correlate with textural changes within the garnets. In thin section the garnets form idio- to xenoblastic crystals with three different textural zones: an orange core and the outer two zones being purple or pink in colour. In some garnets a planar inclusion fabric represents a pre-garnet fabric, which in some cases is preserved as a smoothly curving inclusion trails. Preservation of these trails is probably the result of garnet growth during continuous deformation. The inclusions in the garnets are smaller than crystals of the same mineral in the matrix, which could indicate that substantial matrix recrystalisation has taken place. Vance et al. (1998) have previously dated garnets from Polnish using Sm-Nd, and achieved c. 788-823 Ma ages providing strong evidence for Proterozoic (Knoydartian) amphibolite facies metamorphism. We will present new Lu-Hf ages from these garnets. The Lu-Hf ratios from these rocks are much higher than the Sm-Nd ratios; this means they have the potential to yield more precise ages than Sm-Nd. Sm and Nd concentrations are strongly controlled by inclusions in the garnets, whereas Lu and Hf are not which is an advantage of Lu-Hf dating.

Garnets from a pelitic gneiss from the Glenfinnan Group also show MnO zoning, but to a much lesser extent that the Morar garnets. These garnets have a Ca and HREE rich core with many inclusions including apatite, monazite, quartz, and zircon. The zoning is much less obvious in thin section. The garnet has 176Lu/177Hf ratios of >30 and we will present a Lu-Hf age based on the new data. We have determined Rb-Sr ages from muscovite and biotite of 444.4 ± 1.9 Ma and 414.4 ± 3.9 Ma respectively from this sample. The muscovite age is interpreted as dating cooling following regional deformation and metamorphism during the Ordovician (Grampian) orogenic event. The younger biotite age could reflect cooling from the Grampian event. Or it could reflect cooling following regional D3 folding and associated metamorphism during the Silurian (Scandian) formation of the Northern Highland Steep Belt (Strachan & Evans in press). Evidently this event was not of sufficient intensity to result in widespread resetting of Rb-Sr systems within muscovites.

Morar = Torridon = Grenville Foreland Basin: Outstanding problems

Maarten Krabbendam [1] & Tony Prave [2]
[1] British Geological Survey, Murchison House, Edinburgh EH9 3LA
[2] School of Geography & Geosciences, University of St Andrews, St Andrews, KY16 9AL

Recently, sedimentary structures in the Morar Group in Sutherland have been shown to be similar to those in the Torridon Group, both indicating deposition in high-energy braided river systems. A review of detrital zircon data in the literature shows that the sources are similar and mainly derived from the Grenville Belt in Canada. The geochemistry, stratigraphic thickness and stratigraphy have also been shown to be similar. It has been proposed that the Morar and Torridon groups were formed in a single, orogen-parallel foreland basin to the Grenville Orogen – similar to the Ganges basin in front of the Himalayas (Krabbendam *et al*. 2008).

Assuming this being the case, there are a number of outstanding challenges in the Northern Highlands, concerning the Moine Supergroup and Torridonian rocks.

1) The correlation between Morar and Torridon groups has been made in the Northern Highlands only and questions remain concerning correlations farther south: How do the different formations within the Morar Group correlate between north and south: does the Altnaharra Formation in the north correlate with the Upper or the Lower Morar Psammite Formation in the south? The sedimentological interpretations of the Altnaharra (fluvial / braided river) and Upper Morar Psammite Formation (tidal shelf, Glendinning 1988) are currently incompatible: is a reinterpretation of the Upper Morar Psammite Formation in order?
2) What is the correlation between the Torridonian rocks and the Morar rocks in the south? Sutton & Watson (1964) suggested that Sleat Group = Lower Morar and Torridon Group = Upper Morar; this hypothesis is worth studying again. Also, where does the Tarskavaig Moine fit in here?
3) What is the relationship between the Morar Group and the Grenville Belt in Scotland, e.g. the eclogite-facies rocks of the Eastern Glenelg Inlier? In some other orogens (Ligurian Alps, Trans Sahara Belt in Mali) eclogite-bearing rocks are in close proximity to the Foreland basin.
4) What is the depositional environment and tectonic setting of the Glenfinnan and Loch Eil groups? These units have different (younger) sources than the Morar – Torridon rocks. In the upper part of the Morar group (Glascarnoch Formation) preliminary work shows fining-upward cycles alternated with massive sand bodies, possibly indicating deposition in meandering rivers or in shallow marine/deltaic setting. This may suggest an overall more distal / lower energy setting in the Moine Supergroup.
5) What was the disposition of the Morar and Torridon Group just prior to Caledonian thrusting? In the southern part of the Moine Thrust Belt, Morar and Torridon group rocks occur directly on either side of the Moine Thrust. In the northern part, no Torridon Group rocks occur in the immediate foreland (hence the 'Double Unconformity), whilst in the hangingwall there is >3000m of Morar Group. How can this be explained?

Glendinning, N. R. W. 1988. Sedimentary structures and sequences within a late Proterozoic tidal shelf deposit; the upper Morar Psammite Formation of northwestern Scotland. *In*: Winchester, J. A. (Eds). *Later Proterozoic stratigraphy of the Northern Atlantic Regions*. Blackie, Glasgow and London, 17-31.

Krabbendam, M., Prave, A. P. & Cheer, D. 2008. A fluvial origin for the Neoproterozoic Morar Group, NW Scotland; implications for Torridon - Morar group correlation and the Grenville Orogen Foreland Basin. *Journal of the Geological Society of London*, **165**, 379-394.

Sutton, J. & Watson, J. 1964. Some aspects of Torridonian stratigraphy in Skye. *Proceedings of the Geologists' Association*, **75**, 251-289.

Sourcing sediment from the Laurentian interior – constraints on tectonic models

Paul Smith
School of Geography, Earth & Environmental Sciences, University of Birmingham, Edgbaston Birmingham, B15 2TT. Email: m.p.smith@bham.ac.uk

In recent years, significant advances have been made in understanding the timing of deformation in the Dalradian terrane, together with elucidation of the nature of the southern margin of that terrane and the recognition of stratigraphic continuity between the Southern Highland and Trossachs groups. When taken in conjunction with documented linkages between the Torridon, Moine and Dalradian supergroups, there is an increasing temptation to view the Trossachs Group as representing a Laurentian margin succession that was once part of a continuous sedimentary drape extending as far as the Durness Group of the NW Highlands, and beyond. However, a number of properties relating to the respective successions suggest that caution is warranted before such a model is adopted.

Firstly, the composition of sediment that constitutes the Southern Highlands and Trossachs groups – a series of lithic arenites with abundant volcanic debris – should be considered in the context of the Laurentian margin. During the Cambrian–Ordovician, the Laurentian interior contained very low gradient topographies and, partly as a consequence of this, there are no preserved fluvial systems in terrestrial areas, and extreme tidal attenuation in fringing marine environments. Sediment composition and texture suggests that aeolian transport was dominant in terrestrial areas. Shelf sandstones deposited at the Cambrian–Ordovician boundary in central and western North Greenland provide a case exemplar for sandstones derived from these cratonic interiors. At outcrop, the sandstone bodies have a sheet-like large-scale geometry, and extend for over 300 km along strike within a shallow marine, carbonate-dominated, platform sequence. Sand was derived by reworking of older, quartzite-dominated formations following the uplift and unroofing of a platform bulge to the east. During the Cambrian, this sediment was transported northwards from the uplifted area across an unstable platform into a deep-water trough. However, during sea-level lowstands within the Cambrian-Ordovician boundary interval this clastic material was deflected westwards and transported across the stable platform by progradation of tide- and storm-dominated shorelines. Facies sequences in the thickness part of the Permin Land Formation suggest that at least three such regressive cycles combined to form a composite sand body. Each regressive cycle comprises a shallowing upward transition from tide- and storm-deposited marine sediments to clean sandstones of marine or terrestrial origin. The cycles are separated by thin but laterally extensive dolomites interpreted to represent drowning events. Thinner sequences farther to the east are attributed to reduced accommodation space as a consequence of lower subsidence rates close to the uplifted source area, whilst thin sequences in the west are ascribed to the effect of increasing distance from the sediment source so that only the youngest of the three regressive cycles is present. In terms of sediment composition, texture and facies architecture, the Permin Land Formation is quite unlike the Southern Highlands and Trossachs goup sediments, but is very similar to other Laurentian cratonic sheet sandstones, such as the Eriboll Formation.

A further consideration with regards to the Scottish sector of the Laurentian margin is the extent of the Durness Group carbonate succession and its correlatives. All available evidence suggests that the Durness Group was part of a continuous carbonate fringe to Laurentia that extended from New York to North Greenland, and the only clastic sediment within the Durness Group is hyper-mature windblown silt and millet-seed sand. Large volumes of clastic sediment accumulating on continental margin would have to bypass the carbonate shelf, and there is no evidence for such a bypass zone.

Overall, therefore, a model that invokes the Southern Highlands and Trossachs groups as representing deposition on the outer edge of a simple and continuous Laurentian margin is not supported by considerations of continental topography, sediment source, transport paths, facies architecture, or sediment composition and texture.

The sedimentary history of the major Cryogenian glacial unit of central Africa; evidence against the Snowball Earth theory.

M. Wendorff[1] & Roger Key[2]
[1]University of Botswana, Dept. of Geology, P. Bag 0022, Gaborone, Botswana
[2]BGS Edinburgh

The Cryogenian Grand Conglomerat Formation (<765 & >735 Ma) is an association of interbedded glaciogenic, clastic periglacial and non-glacial deposits, within the Katanga Supergroup of central Africa. Correlation of regional unconformities and facies distribution suggest that the Grand Conglomerat strata were deposited (during and after eruption of flood basalts) in an asymmetrical rift, with a strongly uplifted southern shoulder, and a graded shelf defining the northern margin. Glaciomarine sediments along the southern margin of the Katangan rift are preserved within fan-delta conglomerates supplied from an elevated rift shoulder. By contrast, the northern margin of the rift was the site of continental glaciation with cross-bedded glaciofluvial and marginal marine sandstones and conglomerates, associated with massive tills (diamictites) that pass laterally towards the south into glaciomarine mixtite interlayered with wedges of dolomitic sandstone. A cap carbonate (Kakontwe Limestone) is present only in the distal parts of the basin. Its absence in proximal regions is considered to reflect very high rates of sedimentation of fine-grained glaciogenic debris derived from deglaciated source areas. Palaeomagnetic data indicates that the Grand Conglomerat glaciogenic sediments were deposited close to the Equator during the Cryogenian. This low-latitude setting, coupled with the absence of a topographical trigger would suggest that glaciation was related to global atmospheric cooling. However, the presence of water-borne glaciogenic on-shore sediments and offshore sediments derived from floating glaciers suggests that the ocean during this part of the Cryogenian was not completely frozen. Associations of glaciogenic facies with non-glaciogenic sediments imply glaciation with interglacial periods and gradual deglaciation, instead of severe conditions of permanent sea ice cover and rapid change to the greenhouse environment.

Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia

Peter A. Cawood[1], Alexander A. Nemchin[2], Rob Strachan[3], Tony Prave[4], & Maarten Krabbendam[5]

[1]*School of Earth and Geographical Sciences, University of Western Australia, 35 Stirling Hwy, Crawley, W.A. 6009, Australia*
(e-mail: peter.cawood@uwa.edu.au)
[2]*Western Australian School of Mines, Curtin University, Bentley, WA, 6102, Australia.*
[3]*School of Earth & Environmental Sciences, University of Portsmouth, Portsmouth, PO1 3QL, UK.*
[4]*School of Geography and Geosciences, University of St Andrews, St Andrews,KY16 9AL Fife, Scotland*
[5]*British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA*

Tectonic processes associated with supercontinent cycles result in a variety of basin types, and the isotopic dating of detrital minerals within sedimentary sequences assists palaeogeographic reconstructions. Basins located along the Laurentia/Baltica margin prior to assembly of Rodinia at 1.2-1.0 Ga are dominated by zircon detritus derived from contemporaneous magmatic arcs. Basins formed during assembly are also dominated by zircon detritus similar to the age of sediment accumulation, reflecting syn-collisional magmatism and rapid exhumation of the developing Grenville-Sveconorwegian orogen. Post-collision intracratonic basins lack input from syn-depositional magmatism, and are dominated by significantly older detritus derived from the mountain range as well as its foreland. Basins formed during late Neoproterozoic to Cambrian breakup of Rodinia are divisible into two types. Those within the Caledonides lie on the Grenville-Sveconorwegian foreland. The Cambro-Ordovician shallow-marine successions of NW Scotland are dominated by Archaean and Palaeoproterozoic detritus derived from the cratonic interior to the NW. In contrast, coeval Dalradian sedimentary rocks mainly contain Mesoproterozoic detritus derived from the eroded remnants of the Grenville orogen to the SW. In the Appalachian orogen, such basins are dominated by Mesoproterozoic detritus with older detritus forming only a minor component suggesting restricted input from the cratonic interior either due to the Grenville orogen still forming a drainage divide or the formation of rift shoulders.

Laurentian provenance for the Erris Group and Inishkea Division (=Dalradian Grampian Group?) rocks of NW Mayo, Ireland

Claire A. McAteer[1] (claire.mcateer@ucd.ie), J. Stephen Daly[1], Michael J. Flowerdew[2], Martin J. Whitehouse[3] and Chris L. Kirkland[3]
[1]UCD School of Geological Sciences, Belfield, Dublin 4, Ireland.
[2]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, United Kingdom.
[3]Laboratory for Isotope Geology, Swedish Museum of Natural History, S-104 05, Stockholm, Sweden.

Metasediments of the early Dalradian Grampian Group (Erris Group) and probable equivalents (Inishkea Division) structurally overlie Annagh Gneiss Complex (AGC) orthogneisses in NW Mayo, Ireland. Sm-Nd data suggest a Palaeoproterozoic source for both sequences. Three granitoid clasts from Erris Group pebbly horizons yield U-Pb zircon ages of *c*. 1740 Ma comparable with *c*. 1730-1750 Ma Mullet Gneisses of the AGC. A *c*. 970 Ma clast is consistent with Grenvillian pegmatites and migmatitic leucosomes in the AGC. U-Pb detrital zircon data reveal that the Erris Group was deposited after *c*. 918 Ma with predominant input from a *c*. 1640 Ma source. Limited detrital zircon data from the Inishkea Division yield similarly aged detritus and record a maximum depositional age of *c*. 980 Ma. Correlation of both sequences with the Scottish Dalradian Grampian Group is considered valid on the basis of the detrital zircon data. The clast data support the assumption that the AGC represents the depositional basement to the lower Dalradian in north Mayo, whilst the detrital zircon data implies a more distal, possibly Labradorian (c. 1.71-1.62 Ga) source for the sandier material. Dalradian deposition is thereby tied to the margins of Laurentia.

Global C cycle perturbations recorded in marbles: a record of Neoproterozoic Earth history within the Dalradian succession of the Shetland Islands, Scotland.

A. R. Prave[1], R. A. Strachan[2] & A. E. Fallick[3]
[1]Geosciences, University of St Andrews, St Andrews, KY16 9AL, UK
(email: Tony Prave ap13@st-andrews.ac.uk)
[2]School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth, P01 3QL, UK (email: Rob.Strachan@port.ac.uk)
[3]Scottish Universities Environ. Research Centre, East Kilbride, G75 0QF, UK (email: Tony Fallick T.Fallick@suerc.gla.ac.uk)

The Shetland Islands in Scotland contain a c. 12 km thick, mostly metasedimentary succession that has been correlated with the Dalradian Supergroup of mainland Scotland and Ireland (Flinn et al. 1972). However, lithostratigraphic correlation even at Group level has remained problematic so far. Here we show that the four marble units that punctuate the Shetland succession, in stratigraphic order, the Weisdale, Whiteness, Girlsta and Laxfirth Limestones, have distinctive $\delta^{13}C_{carbonate}$ profiles and that these confirm their stratigraphic uniqueness. In addition, two of these units exhibit lithological characteristics and/or C–isotopic profiles that can be matched to two hallmark depositional events of Neoproterozoic time, the 635 Ma Marinoan–equivalent cap carbonate and the c. post-580–pre-551 Ma Shuram–Wonoka isotopic excursion. The Whiteness Limestone, with a distinctive basal dolostone exhibiting a nadir to values of -4 to -5‰ followed by many hundreds of metres of thin-bedded limestone with values rising to and oscillating around 0‰, can be correlated with the Marinoan post-glacial cap carbonate sequence; the Girlsta Limestone, with values of -9 to -11‰ through its entire 700–900 m thickness, records the Shuram–Wonoka event. The Iapetan rift–related rocks in the Shetlands (the Asta–Clift Hills–Dunrosness spillites and phyllites) are thus younger than the Shuram–Wonoka event. These correlations are consistent with: (1) the entire Dalradian succession in the Shetland Islands being younger than the base of the Argyll Group elsewhere in Scotland and Ireland (thus potentially accounting for the absence within the Shetland Islands of the Port Askaig Tillite); and (2) diachronous opening of the Iapetus Ocean, from c. 700 Ma in east-central Laurentia to c. 550 Ma in NE Laurentia.

New rocks from old - Proterozoic tuffs ("brown beds")

Richard A. Batchelor
School of Geography & Geosciences, University of St. Andrews

The discovery of many albite-rich "brown beds" with a porous saccharoidal texture in Dalradian and Torridonian sequences in Scotland has raised questions about their origin and provenance. Field relationships and mineralogy support their origin as tephra-fall deposits. New discoveries of grey facies cognate to some "brown beds" have led to an hypothesis which proposes that these beds originated as tephra-fall deposits of intermediate to mafic composition. Geochemical analyses consistently show Fe>Mg and Na>K, which reflect tholeiitic compositions. Subsequent prehnite-pumpellyite and low greenschist facies metamorphism generated a grey albite – chlorite – quartz – muscovite – calcite assemblage. Recent sub-aerial weathering selectively dissolved interstitial calcite and oxidised iron in the grey bed, leaving a brown porous rock. Crucially, the weathered "brown beds" betray the existence of otherwise cryptic grey metamorphosed tuffs which tend to blend in with their host metasediments.

New fossils from the Late Neoproterozoic rocks of Charnwood Forest: descriptions and palaeoenvironments of an Ediacaran deep-water 'garden'.

John Carney, Mike Howe and Phil Wilby
BGS, Keyworth, Nottingham

A highly cosmopolitan fossil assemblage has been discovered in the course of research initiated during recent surveys to upgrade the geological maps (Sheets 141 and 155) that include Charnwood Forest. Fifty years ago, the same locality yielded the world's first frondose megafossils that could with certainty be ascribed to the Neoproterozoic Era. Fossils such as *Charnia* and *Charniodiscus*, established Charnwood Forest as a globally important focal point for what has since become known as the 'Ediacaran biota'.

The fossils are preserved as impressions on three bedding planes, encompassing 0.63 m of vertical sequence. They are mainly sessile organisms and the new studies show that their long axes are in parallel orientation, indicating that they represent a tethered, 'life' assemblage that was felled by a directed current and/or influx of sediment across the sea-floor. Given this mode of preservation, together with the diversity and palaeoenvironment of the assemblage, Charnwood should now be considered equal to the Avalon Peninsula of Newfoundland in terms of its palaeontological significance. Notably giant forms are present, some of which may be new species or genus; they are up to 0.5 m long and feature large and robust basal discs or 'holdfasts'. There are also clusters of apparently juvenile forms, and amorphous areas that may be microbial colonies.

Evidence that these organisms flourished in an island arc tectonic setting is provided by the strong subduction zone geochemical signature of Charnian igneous rocks. Volcaniclastic strata at the fossil locality seldom exceed silt grain size, however, and evidently accumulated in the later stages of arc activity, at an estimated distance of 14 km (tectonically corrected) from volcanic centres identified farther to the north-west. A distal slope or basin-floor environment that was below storm wave-base, and probably at considerable water depth, is suggested by sedimentary structures that include parallel bedding or lamination, wavy disrupted lamination and normal grading; such features are appropriate to Stow Sequence categories T2-T7 for fine-grained turbidites. The presence of sporadic fresh volcanic ash shards nevertheless indicates contemporary volcanism, and suggests that some laminations may be of subaqueous ash-fallout origin.

A substantial amount field and laboratory work remains to be done, but material already collected shows that this locality has the potential to significantly advance our understanding of the somewhat enigmatic Ediacaran biota, which constitutes the world's first viable ecosystem.

Post-Grampian top-to-WNW Caledonian ductile shear in the Grampian Highlands?

Leslie, A.G. and Campbell, S.D.G.
British Geological Survey, Murchison House, Edinburgh, EH9 3LA.

The Glendoe Hydro Scheme involves construction of an 4.6 m diameter bored tunnel, extending 8.6 km SSE-ward from Fort Augustus and the Great Glen, through mainly Grampian Group Dalradian rocks deformed in the Grampian orogeny. The great prize though is access to an 8 km long borehole driven perpendicular to regional strike through the footwall and hanging wall of the Eilrig Shear Zone. The Eilrig Shear Zone is unique in the geology of the Grampian Highland 'terrane' and is revealed as 1.5 km thick in the NW-end of the continuous tunnel section. The shear zone is a low temperature ductile (quartz-muscovite mylonite) to brittle-ductile structure. No similar structure is recorded anywhere else in the Grampian terrane, late stage Grampian structures in the southern Highlands are represented by ductile folds and crenulation fabrics. The Grampian Group lithostratigraphical succession (Corrieyairack Subgroup) in the hanging wall of this structure has experienced a typical NW-vergent Ordovician (Grampian) orogenic deformation sequence and accompanying garnet-amphibolite facies metamorphism. In stark contrast, the footwall succession (Glen Buck Pebbly Psammite Formation) comprises fluviatile to shallow marine? deposits of uncertain stratigraphical affinity and has not experienced the orogenic effects pervasive in the hanging wall. If Grampian (Ordovician) deformation is absent in the footwall of the Eilrig Shear zone then that structure represents the Grampian Orogenic Front.

The net translation on this low temperature/high level shear zone must surely be considerable (100 km+?). Is the displacement late Grampian (Ordovician) in age or Scandian (Silurian)? If the latter, what might be the relationship to the Moine Thrust Zone in the Northwest Highlands terrane across the GGF? Is the footwall succession to the ESZ comparable in any way to the 'foreland' succession in the Northwest Highlands?

Penobscottian type accretionary tectonics in Southern Britain?

David Schofield[1], Ian Millar[2] & Jane Evans[2]
[1]British Geological Survey, Kingsley Dunham Centre, Nottingham, NG12 5GG. (e-mail: dis@bgs.ac.uk)
[2]NERC Isotope Geoscience Laboratories, Kingsley Dunham Centre, Nottingham, NG12 5GG.

Conventional models for tectonic and stratigraphic evolution of the Southern Britain envisage Cambrian to Early Ordovician sedimentary basin development in terms of vertical movements of essentially autochthonous crustal units. However, this is clearly at odds with the wider understanding of the Gondwanan margin of Iapetus elsewhere around the northern Atlantic region, where development of complex subduction systems and patterns of dispersal and assembly are preserved.

In the Northern Appalachians of New England and Atlantic Canada, evolution of the peri-Gondwanan margin during the Ordovician is thought to have involved emplacement of the Penobscot (513-486 Ma), Victoria (478-460 Ma) and Exploits (473-455Ma) arcs and accretionary complexes against a composite Ganderia – Avalonia continental margin, significantly pre-dating latest Silurian, Acadian tectonism associated with terminal Laurentia – Gondwana collision.

In their attempt to synthesise Iapetus evolution throughout the transposed remanats of the belt, Van Staal et al. (1998) suggested that deformation in the ensalic Welsh Basin during the Tremadoc, followed by formation of a late Tremadoc/Early Arenig arc was related to diachronous Penobscottian collision and a renewed cycle of suprasubduction zone magmatism equivalent to the Popelogan arc.

Within Southern Britain, evidence in support this hypothesis is relatively sparce. However a new, concordant, U-Pb date for the Twt Hill Granite of the Arfon Sub-Basin of NW Wales of 615.2 ± 1.3 (2σ) Ma contrasts with an Rb-Sr isochron age of 491 ± 12 (2σ) Ma from the same body. The latter is thought to result from isotopic resetting during regional low grade metamorphism. In this context, the Rb-Sr isochron age is taken to reflect the onset of latest Cambrian to Early Tremadoc tectonic uplift that ultimately led to basin inversion prior to the Arenig overstep at around 478 Ma, and that this in turn reflects plate-scale processes analogous to the Penobscottian event.

Although the extent and influence of this event cannot be fully assessed at present, it perhaps puts into context some earlier studies that have noted the presence of pre-Arenig folding and early cleavage formation within the Harlech Dome area of the Northern Welsh Basin. Also, it questions the earlier conclusion that the outboard Monian Composite Terrane represents a single, purely pre-Iapetan, accretionary complex. In the light of this data and in response to a need to develop new expertise and support promotion of geology within the region (such as the GeoMôn UNESCO Geopark initiative), further investigation of the tectonic assembly of this region will form part of a multi-disciplinary project that the BGS has just commenced in NW Wales.

VAN STAAL, C. R., DEWEY, J. F., MACNIOCAILL, C. & MCKERROW, W. S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *In:* BLUNDELL, D. J. & SCOTT, A.C. (eds), *Lyell; the Past is the Key to the Present.* Geological Society, London Special Publication **143**, 199-242.

Grampian high-pressure-granulite-facies metamorphism of the Slishwood Division, NW Ireland and its enigmatic eclogite-facies precursor

J. Stephen Daly[1], Michael J. Flowerdew[1,2,3] and Martin J. Whitehouse[3]
[1]UCD School of Geological Sciences, University College Dublin, Dublin 4, Ireland.
[2]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK.
[3]Swedish Museum of Natural History, Box 50007, SE-104 05 Stockholm, Sweden

The unusual metamorphic history of the Slishwood Division in NW Ireland (with eclogite-facies and later high-pressure-granulite-facies assemblages) is a unique feature of the Irish Caledonides and has long been regarded as evidence for pre-Grampian orogeny. In contrast the adjacent Dalradian rocks exhibit a more moderate Barrovian greenschist- to amphibolite-facies metamorphism, some of it associated with late Grampian extensional detachment across tectonic contacts with the Slishwood Division.

The last of a series of migmatitic leucosomes affecting a Slishwood Division paragneiss crystallized under granulite-facies conditions and was emplaced during sinistral transtension associated with decompression from the eclogite facies. Dating the leucosomes has been challenging because the majority of zircons within them are inherited and little zircon growth took place during migmatisation. Euhedral magmatic overgrowths are thin (typically less than 15 µm) and have very low U contents. Earlier attempts to date them by ion microprobe U-Pb analysis resulted in spurious Concordia ages of c. 576 Ma (Daly *et al.* 2004) in spite of careful SEM imaging prior to analysis.

Re-investigation of the same leucosomes made possible by improved spatial resolution and higher ion yields from the ion microprobe has shown that the spurious ages were the result of inadvertent mixtures of c. 470 Ma rims overgrowing Proterozoic inherited zircons. Thus the decompression melting event giving rise to the leucosomes is of Grampian age, consistent with the U-Pb zircon age of c. 470 Ma of a suite of cross-cutting granite pegmatites, previously dated at c. 455 Ma by Rb-Sr muscovite ages (Flowerdew *et al.* 2000).

A maximum age for the eclogite-facies event is provided by a clinopyroxene-plagioclase Sm-Nd isochron age of 580 ± 36 Ma from relict magmatic minerals in a metabasite (Flowerdew and Daly 2005) and by a U-Pb age of 596 ± 6 Ma from a single zircon grain in another metabasite. The latter may date crystallization of the metabasite protolith, or may record the age of a xenocrystic grain, like most of the zircons in the same rock. The metabasites are attributed to basic magmatism associated with extension that heralded the opening of the Iapetus ocean, and the eclogite-facies event to a collision involving the Slishwood microcontinent before it impinged upon the Laurentian margin.

Daly, J.S., Flowerdew, M.J. and Whitehouse, M.J. 2004. Confirmation of a pre-Grampian high-grade history within the Slishwood Division, NW Ireland. *In: Daly, J.S. (ed.) Programme and abstracts for Discussion Meeting 4th May 2004, Tectonics Studies Group Highlands Workshop 2004,* p 6.

Flowerdew, M.J., Daly, J.S., Guise, P.G. and Rex, D.C. 2000. Isotopic dating of overthrusting, collapse and related granitoid intrusion in the Grampian orogenic belt, NW Ireland. *Geological Magazine* 137, 419-435.

Flowerdew, M.J. and Daly, J.S. 2005. Sm-Nd mineral ages and PT constraints on the pre-Grampian high grade metamorphism of the Slishwood Division, northwest Ireland. *Irish Journal of Earth Sciences*, 23, 107-123.

An alternative model for the Grampian Orogeny in Scotland

Geoff Tanner
Dept. of Earth & Geographical Sciences, University of Glasgow, Glasgow G12 8QQ

Current plate tectonic models for the Grampian Orogeny in the Scottish Highlands invoke either ophiolite obduction or island-arc collision as the driving force, with SE-directed subduction occurring beneath the Midland Valley, followed by subduction-flip. These models are problematical for they do not satisfactorily explain the SE vergence of the Tay Nappe; infer an incorrect sense of shear for early structures resulting from ophiolite obduction; or incorrectly interpret the Tay Nappe as a late structure. Nor do they suggest a mechanism whereby sufficient heat can be introduced rapidly into the system. A viable model must explain (1) how the Tay Nappe became recumbent prior to emplacement of the Highland Border Ophiolite, (2) why the nappe was translated to the SE during D2 by simple shear acting on the lower, inverted limb, and (3) why the facing direction of the early major structures, all apparently of D1 age, rotates through 150° from SE to NW across the fold belt.

All of the above features are consistent with NW-directed subduction having occurred from the outset beneath the leading edge of the passive margin. Longitudinal shortening led initially to the production of upright D1 folds, which were progressively rotated towards the SE, and became tighter, during D2. A slice of 'ophiolite' was then emplaced on to the upper limb of the now recumbent Tay Nappe. As a consequence of crustal thickening, SE-directed transport of the Tay Nappe was followed by the diachronous development of the Islay Antiform and its transport to the NW on an intensely developed D2 shear zone. The same pattern is seen in both the SW and Central Highlands.

The D2 fabric commonly takes the form of strain bands indicating a top-to- SE shear sense, and becomes the dominant fabric in the rock just before, or at, the biotite isograd. This fabric is equated with the transposition foliation in the high-grade nappe association (HGNA) of the Williams & Jiang (2005, *J.Struct.Geol.*, **27**,1486-1504) model. Deformation takes place by means of detachment flow with shear concentrated in rock units that are weaker than average, as is the case in the Dalradian rocks. This model explains most of the features of the Grampian Orogen in Scotland and predicts that its collapse will result in late NW-directed thrusting (?Scandian) to the north of the belt.

New ideas about the type-area of Barrovian regional metamorphism

G.J.H. Oliver[1], D.R. Viete[2], M.A. Forster[2], S.W. Richards[2], J. Hermann[2], G.S. Lister[2], A.F. Corvino[3]
[1]Crustal Geodynamics Group, School of Geog & Geosci, University of St Andrews
[2]Research School of Earth Sciences, Australian National University, Canberra
[3]School of Earth Sciences, University of Melbourne, Australia

Barrovian metamorphism was first described from Glen Esk, Scotland, by George Barrow (1893). He regarded the source of heat for the metamorphism to have originated from syn-metamorphic granite intrusions. Today, many believe that this medium pressure kyanite-sillimanite regional metamorphic series evolved following intense, non-coaxial deformation, crustal thickening, and regional heating in an orogenic wedge as a consequence of nappe emplacement under a *compressional* regime, probably following the collision of the Midland Valley Arc with the Laurentian passive margin.

On the basis of new field mapping in Glen Esk and along the coast between Stonehaven and Aberdeen, followed by studies of microstructure, metamorphic petrology, garnet and white mica geochemistry, $^{40}Ar/^{39}Ar$ mica and U-Pb zircon geochronology, we propose that this type of Barrovian metamorphism developed in an *extensional* regime: i.e. a gentle SE-dipping extensional detachment developed during metamorphic heating in the Grampian Highland Terrane. We are testing the following model: Heating was initiated in the lower thickened crust by contact with a window of hot asthenosphere formed by slab break-off along a subducted spreading ridge. Lower crustal S-type granitoids then intruded and carried heat into the middle and upper crust where Barrovian metamorphism occurred during extension caused by gravity collapse of the orogenic wedge. We therefore agree with Barrow's original hypothesis that granites were the source of heat for the regional metamorphism. This model can also accommodate the low pressure andalusite-sillimanite metamorphic series characteristic of the Buchan Peninsula where mantle sourced gabbros provided the heat.

The Shetland Mega-monocline: a continuation of the Tay Nappe?

D. Flinn
Department of Geology, University of Liverpool

A simplified version of the recently presented paper in the Scottish Journal of Geology 43 (2), 125-142, 2007 entitled Dalradian rocks of Shetland will be outlined.

In-situ Hf isotope measurements of complex zircons from Irish granitoids reveal hidden Palaeoproterozoic and Archaean sources at depth.

Michael J. Flowerdew[1], J. Stephen Daly[2], David M. Chew[3], Ian L. Millar[4] and Matthew S.A. Horstwood[4]

[1]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK.
[2]UCD School of Geological Sciences, University College Dublin, Dublin 4, Ireland.
[3]Department of Geology, Trinity College, Dublin 2, Ireland.
[4]NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG, UK.

Minor *c*. 470 Ma intrusions that cut the Slishwood Division (SLD) and Tyrone Central Inlier (TCI) in northwest Ireland, contain complex zircons with core and rim structures. The advantage of *in situ* Hf isotopic measurements in zircon compared to whole grain solution Hf analyses (or Sm-Nd whole rock isotopic measurements) is that Hf mantle extraction ages for the melts (as deduced from the zircon rim Hf isotopic composition) can be determined without any contribution from inherited material present in the zircon cores.

Zircon rims from intrusions cutting the SLD have weighted mean εHf_{470} values of -7.7 ± 1.1 and t_{DM} model ages of *c*. 1380 Ma, which is more juvenile than the weighted mean of the zircon core population and Sm-Nd t_{DM} model ages for the intrusions. Zircon textures demonstrate that the inherited cores were not dissolving nor contributing their Hf isotope signature to the melt. Cores were scavenged from the host metasediments during intrusion, and yield ages and Hf isotope signatures similar to detrital grains from the SLD metasediments. Therefore they do not reveal any information about the melt source(s). The modelled Lu-Hf evolution of the Rhinns Complex and Annagh Gneiss Complex suggests that either of these protoliths (or sediments derived from them) could be melt sources for the intrusions. Juvenile Grenville rocks (Doolough gneiss) within the Annagh Gneiss Complex were not important contributors to the intrusions cutting the SLD, possibly suggesting that the Grenville Front runs between the SLD and the Annagh Gneiss Complex. Although parts of the Dalradian Supergroup cannot be discounted as a source, we prefer to interpret the data as recording Palaeoproterozoic Rhinns Complex-like crust at depth.

Zircon rims from granitic pegmatites cutting the TCI have εHf_{470} values of *c*. –40 and Hf t_{DM} model ages of *c*. 3200 Ma, which are much more evolved than the cores. As is the case for the SLD, the cores were likely incorporated into the melt from local metasedimentary rocks during intrusion and demonstrate the TCI is itself not a source for the melt. The melt source is therefore Archaean and we suggest that Lewisian Complex basement (or sediments wholly derived from such basement) were melted and are present beneath the TCI at depth.

Given the evidence for Palaeoproterozoic and Archaean elements on the Laurentian margin in western Ireland, it is possible that the present-day disposition of basement rocks may not represent its pre-Grampian architecture. Both the SLD and TCI are thought to represent outboard Laurentian microcontinents, which may have been translated along strike during the Grampian Orogeny.

Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic flare-up in the Grampian Terrane, Scotland

J.C. Neilson[1,3], B.P. Kokelaar[1] & Q.G. Crowley[2]
[1]*Earth and Ocean Sciences Dept., University of Liverpool, Liverpool, L69 3BX*
[2]*NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG*
[3]*Present address: Dana Petroleum plc, 17 Carden Place, Aberdeen, AB10 1UR*
(e-mail: p.kokelaar@liv.ac.uk)

Siluro-Devonian high-K calc-alkaline magmatism in the Grampian Terrane initiated at ~430 Ma, just when subduction of oceanic lithosphere ceased. It followed subduction of the leading edge of continental Avalonia beneath the margin of Laurentia and it persisted for 22-25 million years. Previous U-Pb zircon age data record the earliest plutonic crystallisation at ~429-428 Ma (Rogers and Dunning 1991). New high-precision ID-TIMS U-Pb dating of magmatic zircons yields 425.0 ± 0.7 Ma for the Lorn Lava Pile, 422.5 ± 0.5 Ma for the Rannoch Moor Pluton, 419.4 ± 4.8 Ma for a Fault-Intrusion at Glencoe caldera volcano, 418.0 ± 0.5 Ma for the Clach Leathad Pluton, which cuts Glencoe, 415.0 ± 0.4 Ma for the Cruachan Intrusion of the Etive Pluton and 408.1 ± 0.4 Ma for the Inner Starav Intrusion of the Etive Pluton. The Etive Pluton was assembled in ~8 million years and together with the Clach Leathad and Rannoch plutons constitutes the Lochaber Batholith, which formed in 14 million years. The Etive Dyke Swarm was mostly formed within ~3-4 million years and was part of the plumbing of a large volcano (Etive Volcano;≥2000 km ^{3}) that was intruded by the Etive Pluton and then almost entirely removed by uplift and erosion. The post-collision magmatism is described in terms of a magmatic flare-up that resulted from breakoff of the subducted oceanic lithosphere and consequent rise of asthenosphere, which led to partial melting of LILE- and LREE-enriched lithospheric mantle ***and*** mafic-to-intermediate lowermost crust. Large volumes (1000s of km^3) of andesite and dacite were erupted repeatedly throughout the flare-up but were rapidly removed by contemporaneous uplift and erosion. This essential volcanic counterpart to the 'Newer Granite' plutons has not previously been fully recognised; it is probable that centred volcanoes preceded the plutons widely, from Shetland to Donegal. Most intermediate magmas formed by partial melting of mafic-to-intermediate lowermost crust that derived its high Ba-Sr qualities via a previous partial melting of the LILE-enriched lithospheric mantle, possibly at ~1.8 Ga. This crustal recycling was caused by heat and volatile addition from underplated mantle melts (parental appinite-lamprophyre magmas) and involved uplift related to the rise of asthenosphere through the slab break.

Caledonian high Ba-Sr granites: comparisons with sanukitoids

Mike Fowler
Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth PO1 3QL, UK.

A variety of high Ba-Sr ganites and syenites is intruded into the Caledonian terrane of the Northern Highlands of Scotland. Volumetrically rather small, the plutons display a considerable range of compositions from appinitic, ultramafic and mafic to granitic and syenitic. Although it is generally agreed that they are related in some way to the subduction of Iapetus ocean crust beneath Laurentia, their petrogenesis is still much debated, especially the enigmatic relationship between alkaline syenites and calc-alkaline granites. A recent petrogenetic model, based on elemental and isotope (Sr-Nd-O) constraints, suggest that the parent magmas of both were derived from a Caledonian Parental Magma Array (CPMA) that extended from isotopically-depleted to significantly enriched compositions, with high $\delta^{18}O$ in the latter. The oxygen isotope values and the high Ba-Sr signature in particular strongly suggest that mantle contamination with subducted pelagic carbonates generated the CPMA. Subsequent differentiation involved contamination with local continental crust alongside fractional crystallisation involving different crystallising assemblages and different continental reservoirs.

The lithological and chemical character of the rocks and the derived petrogenetic model are strikingly similar to those of sanukitoids – a group of largely (though not exclusively) Archaean plutonic rocks characterised by an extensive lithological range, common association of granites and syenites, ubiquitous light-REE enrichment, high Ba, Sr and significant negative Nb-Ta anomalies. Petrogenetic models generally appeal to a mantle peridotite source and subduction zone enrichment. Explanation of the lithological range commonly involves open-system crystal fractionation and contamination during ascent and emplacement. Thus, a detailed comparison between sanukitoids and high Ba-Sr granites seems appropriate.

Timing of post-orogenic cooling in the Grampian Terrane, Scotland: evidence from a multi-technique $^{40}Ar/^{39}Ar$ dating study

C. Gerring[1], S.C. Sherlock[1], R.A. Strachan[2], S.P. Kelley[1] & N. Arnaud[3]
[1]Dept of Earth & Environmental Sciences, The Open University, Milton Keynes, MK7 6AA, UK.
[2]School of Earth & Environmental Sciences, University of Portsmouth, Portsmouth, PO1 3QL, UK.
[3]University of Montpellier, France.

Samples of metasedimentary rock from the Dalradian Supergroup were collected along a N-S traverse through the exhumed core of the Grampian Terrane. Phengite and biotite grains were analyzed using infrared and ultraviolet laser microprobes as well as step-heating techniques. Resultant cooling ages track the down-temperature evolution of the region during the late Ordovician following D_1-D_2 nappe stacking and recumbent folding, and D_3 formation of steep belts (e.g. Tummel) during the 470-460 Ma Grampian orogenic event, and the D_4 Highland Border Downbend. The age of the latter appears to be more or less identical to that in Ireland as dated by Chew *et al.* (2003). The present study does not support the overly-complex cooling patterns produced by previous workers which were likely heavily influenced by the presence of excess argon in some samples. There is no evidence for any regional deformation or metamorphism during the Silurian.

SW Highland Moine

Tony Harris
Earth, Ocean and Planetary Sciences, Cardiff University.

Several summers' work on the Moine of Ardnamurchan have largely filled the gap between the well-known sections of Morar and those of the Ross-of-Mull. Among other conclusions:

(1) it appears that, contrary to the suggestion of Johnstone *et al*. (1969, fig.2), the axial surface trace of the F3 Morar Anticline, which becomes reclined southwards, passes to the west of the Ardnamurchan Anticline, and is probably structurally excised southwards;

(2) if the Knoydart ductile fault exists elsewhere than in Knoydart, it may pass out to sea in the Sound of Arisaig, or be linked to the Lewisian inliers of North Morar. It does not exist in Ardnamurchan;

(3) The marked contrasts in detail between the type Morar Group lithostratigraphy of Morar, and that in Ardnamurchan and the Ross-of-Mull may be explained by a considerable cross-strike distances of these localities from the equivalent rocks in Morar;

(4) The apparently anomalously high metamorphic grade assemblage of the mildly migmatitic Ross-of-Mull Moine pelite (almandine + staurolite + kyanite) was thought to imply that it lies in the Knoydart nappe. If the whole of the Morar structure has been excised southwards between South Morar and the Sound of Iona, the high grade of the Mull Moine adjacent to the Lewisian of Iona is no longer anomalous.

Eclogite-facies metamorphism in the Central Highland Migmatite complex, Grampian Highlands

S J Cuthbert
School of Engineering & Science, University of the West of Scotland, Paisley PA1 2BE, UK
simon.cuthbert@uws.ac.uk

The Central Highland Migmatite Complex (CHMC) forms the stratigraphically lowest part of the central and eastern Grampian block. Baker (1986) reported garnet amphibolite pods near Tomatin in the Dava Succession of the CHMC that display relict diopside-plagioclase symplectites and plagioclase + hornblende collars around garnets, indicating the prior existence of omphacite and pyrope-grossular-rich garnet. This observation has been largely ignored, but has profound implications for Neoproterozoic geodynamics in Scotland, because eclogite-gneiss assemblages often indicate transient subduction of continental lithosphere, and they are commonly associated with exhumation structures and successor basins. Clearly, it is important to establish the extent, timing and structural context of eclogite-facies metamorphism in the Grampian block, so a renewed investigation of this early, high-pressure episode is now under way. This contribution is based upon preliminary observations by the author and previous studies on the general geological context by numerous other workers.

Diopside-plagioclase symplectites and plagioclase-hornblende collars around garnets have been confirmed in the Dava Succession, and have now been found at three further localities within the Glen Banchor Succession of the CHMC. Preliminary observations indicate that the amphibolites shared the migmatisation of the gneisses, hence the eclogite-facies metamorphism predates migmatisation (840Ma) and the later (~800Ma) D_2 shear-zones that separate the CHMC from the Grampian Group. Two other types of metabasite are found associated with the CHMC; a suite of metagabbros in the shear zone complex between the CHMC and the Grampian Group has been variably transformed to garnet amphibolite. Intrusion post-dates migmatisation, predates D_2 shearing and they lack petrographic evidence for an eclogite-facies overprint. A further unit of striped garnet amphibolites lying *above* the shear zone in inliers at Ord Ban and Kincraig exhibits plagioclase collars around garnets, but has not yet yielded evidence for omphacite. Their stratigraphic position is uncertain and its resolution is important for determination of the upper extent of high-pressure metamorphism and thus the position of intra-Dalradian unconformities. The age of high-pressure metamorphism is thus constrained to lie between 840Ma and either the youngest reliable detrital zircon age in the Glen Banchor succession (900±17Ma) or possibly the depositional age of the Ord Ban metasediments.

The lowest stratigraphic unit of the Grampian group, the Glenshirra subgroup, contains meta-rudites (e.g. Garva Bridge Formation). Their relationship with the CHMC is obscure, but recent work on their sedimentary facies suggests an alluvial fan environment related to "extension". In this sense they are possibly analogous to late-orogenic extensional molasse basins related to exhumation of high-pressure rocks. In this case, the eclogite-facies episode would have been restricted to the CHMC and would not have affected the overlying Grampian Group or higher Dalradian units. It might also be speculated that the ~800Ma D_2 shear zones accommodated some of the exhumation of the CHMC eclogites.

Reference

A J Baker (1986) *Mineralogical Magazine* 50, 217-221

The older ultramafic rocks of Aberdeenshire, similarities to SSZ ophiolites and significance for regional tectonics

Mike T Styles
British Geological Survey, Keyworth.

It has long been known that there are at least two phases of mafic-ultramafic magmatism in NE Scotland (Read 1919), the well known Younger Gabbro suite and a lesser known ‘Older suite’. A regional study of the ultramafic rocks (Styles 1994, 1999) showed that they comprised three groups, the Lower Zone of the Newer Gabbros and two closely related ones; a harzburgite group and a group of clinopyroxene-rich rocks referred to as the Succoth-Brown hill type (SBH) that were broadly the same as Reeds’ Older suite. The latter two groups are found along major regional scale shear zones, particularly the Portsoy Lineament. It was suggested that SBH type was the root complex of a volcanic arc (Gunn et al 1996) and that the harzburgite type were fragments of upper mantle (Styles 1999).

Mapping of the UAE-Oman ophiolite by BGS (Styles 2006) showed that it consisted of an early mid ocean ridge phase followed by an extensive second phase of hydrous magmatism formed in a supra subduction zone (SSZ) setting that probably formed a proto volcanic arc prior to obduction. It will be shown that the ultramafic rocks of the mantle transition zone formed in this SSZ phase, dunites, olivine-clinopyroxenites, wehrlites and clinopyroxenites are essential the same as those in the SBH type in terms of both rock type and mineral composition.

This provides strong supporting evidence that the older suite of ultramafic rocks are remnants of upper mantle and mantle transition zone of SSZ ophiolites and the shear zones where they are found delineate ‘sutures’ within the Dalradian basin. The ‘Newer gabbro’ intrusions are also closely associated with these regional shear zones, which suggests that these zones formed conduits for the extensive later magmatism.

Arc-continent collision and the Taconic/Grampian problem

John Dewey[1] and Paul Ryan[2]
[1]University College, High Street, Oxford, OX1 4BH, UK.
[2]University College, Galway, Ireland.

From New York to Scotland, the early to mid-Ordovician Taconic/Grampian orogeny was a short-lived (10-20 my) event that was probably caused by the collision of an oceanic arc with the Laurentian rifted margin followed by subduction polarity flip.

The geological expression of this event sequence is extremely complicated and very varied along Appalachian/Caledonian strike. The main suture is the Baie Verte/ Brompton/Clew Bay Line, which, in Scotland, is disrupted by Devonian sinistral motion along the Highland Boundary Fault. In Newfoundland, the obducted SSZ ophiolite arc slab carries the imprint of a complex sequence of late Cambrian/early Ordovician pre-obduction dextral/transtensional polyphase deformation and magmatism. Newfoundland, uniquely, preserves the foreland flexural basin onto which the SSZ ophiolite was obducted. Western Ireland, uniquely, preserves the hanging-wall fore-arc/successor basin (South Mayo Trough), perhaps because the Laurentian margin contained an abundance of mafic material that was eclogitized in the subduction zone, the overiding SSZ slab was very dense, and/or because extensional collapse allowed preservation. The Grampiam Barrovian metamorphism may have been generated by heating from the obducted hot SSZ slab and fron advective heating from the hot mantle beneath the obducted slab.The hints of Pan-African rocks and events along the Ordovician Lauarentian margin raise some difficult tectonic questions. I hope that we can explore the detailed geological evidence for some of these and other ideas about the Taconic/Grampian Zone.

The nature, origin, and palaeogeographical setting of the Highland Border Ophiolite, Scotland

Geoff Tanner[1], Howard A. Armstrong[2] & Alan W. Owen[1]
[1] *Dept. of Earth & Geographical Sciences, University of Glasgow, Glasgow G12 8QQ*
[2] *Dept of Geological Sciences, University of Durham, Durham DH1 3LE*

The Highland Border 'Ophiolite' (HBO) forms a narrow, discontinuous outcrop from Stonehaven to the Isle of Bute, bounded to the NW by a tectonic contact with Dalradian rocks, and to the SE by the Highland Boundary Fault. It comprises a banded amphibolite 'sole'; a lithic arenite showing high Cr and Ni values; a Mg-rich ophicarbonate-conglomerate member; and a unit of pillowed and non-pillowed MORB basalt with graphitic slate, umber, and chert; and bears little resemblance to the classical Penrose ophiolite.

As there is a lack of agreement over which parts of the former 'Highland Border Complex' belong to the ophiolite, the extent and boundaries of the body are first defined. From a detailed study of much of the outcrop it is concluded that: (1) the ophiolite is of largely sedimentary origin, (2) preserves a tectonic fabric unrelated to any seen in the underlying rocks, (3) was obducted on to, and cuts across, the upper limb of the Tay Nappe (Grampian D1-2), and (4) had a negligible emplacement-related structural or metamorphic effect on the footwall rocks. The aim of the field excursion is to examine in detail the evidence supporting these statements.

Based on the fact that the HBO has a close similarity to Ligurian-type serpentinized continental mantle in transitional continent-ocean settings described from the western Mediterranean, the following model is proposed. The Dalradian sequence was deposited in an ensialic, or intracontinental, basin that opened up behind a detached fragment of Laurentian crust (? East Shetland Microcontinent) to the SE. By early Ordovician times, increasing crustal extension resulted in the exposure and subsequent serpentinization of continental mantle on the sea floor. Submarine erosion caused the deposition and reworking of serpentine conglomerates, and during basin closure, a slice of the composite floor was emplaced on to the Laurentian margin. Provenance studies are one means of testing such hypotheses, and the results of a REE study of cherts from these rocks are described.

The Taconic arc-continent collision in Newfoundland, Northern Appalachians

Cees van Staal[1], Arjan Brem[2], Vicki McNicoll[3], Tom Skulski[3], Joseph Whalen[3], and Alex Zagorevski[3]
[1]Geological Survey of Canada, 625 Robson Street, Vancouver, BC, V6B 5J3, Canada
[2]Shell International, P.O. Box 60, 2280 AB, Rijswijk, the Netherlands
[3]Geological Survey of Canada, 601 booth Street, Ottawa, Ont, K1A 0E8, Canada

The Newfoundland Appalachians have a large and regionally extensive database of radiometric and fossil ages, while the grade of regional metamorphism is generally low. Hence, the vital linkages between deformation, metamorphism, magmatism, exhumation and syn-orogenic sedimentation, essential to understand the dynamic processes responsible for orogenesis, are relatively well preserved for each orogenic event. The Taconic orogeny mainly involves collision between the pericratonic ensialic Notre Dame arc and the Laurentian Humber margin. It also encompasses outboard soft accretion of suprasubduction zone crust to the trailing edge of the Notre Dame arc in the Annieopsquotch accretionary tract.

The hard Taconic arc-continent collision was mainly due to Lower-to Middle Ordovician closure of a narrow seaway between Laurentia and a ribbon microcontinent (Dashwoods). It led to penetrative deformation, metamorphism and magmatism, but these were localised in the arc volcanic and sedimentary rocks of the upper plate, with little evidence preserved of this event in the exposed rocks of the down going Laurentian margin. Here age-dating consistently revealed that greenschist or higher grade metamorphism was Silurian and formed during the Salinic orogeny. One possible solution is that the structurally thickened parts of the Laurentian margin were later overthrust and largely hidden beneath the arc. This explanation is consistent with the presence of narrow sheets of syntectonic, S-type granite (459-455 Ma), which are confined to the narrow shear zone that marks the suture and probably reflect melting of underthrusted Laurentian sediment and channelling of the magmas during the final, post-metamorphic increments of Taconic shearing. Alternative solutions comprise 1. large strike-slip movements that could have excised segments with high grade Taconic metamorphism and juxtaposed parts of the Laurentian margin that structurally were never deeply buried with high grade upper plate rocks; and 2: massive resetting of Taconic radiometric ages by the large magmatic and thermal event generated during breakoff of the west-dipping Salinic slab. Regardless which explanation is correct, the syn-collision burial of upper plate arc volcanic and sedimentary rocks to high pressure amphibolite and granulite facies conditions coeval with a very voluminous flare-up of tonalite, suggest that the A-subduction channel had widened over time, probably due to thermal softening of the channel's margins relative to hardening of its interior.

How does the discovery of "Iberia-type margins" change the interpretation of collisional orogens?

Gianreto Manatschal
CGS-EOST, Université Louis Pasteur, 1 rue Blessig, F-67084 Strasbourg, France manatschal@illite.u-strasbg.fr

More then a century ago, geologists started to understand that mountains are the descendents of seas. With the discovery of plate tectonics, the "sea" became an "ocean", the "mountains" "orogens" and new terms and concepts helped to clarify and unify the way to explain orogens. However, despite of the increasing data sets acquired from collisional orogens and the progress in imaging structures at all scales and analysing and dating rocks and events, some key questions are still not answered, such as the number of oceans, the along strike correlations of paleogeographic domains or the structure of internal parts in collisional orogens. Although it is common knowledge that collisional orogens are the descendants of rifted margins, many interpretations for collisional orogens are still based on concepts of rifted margins and oceans that are outdated and do not correspond with what has really been observed in these domains in the last two decades. Ignoring some of these discoveries are likely responsible for some of the odd and inconsistent interpretations made in collisional orogens.

In the last two decades, geophysical data and drilling results from the Iberia-Newfoundland conjugate margins together with direct observations from the Alps provided compelling evidence for a complex and highly asymmetric architecture of deep margins. The results show that within the Ocean Continent Transition (OCT) thinned continental and oceanic crusts are separated by a 40 to 170 km wide zone of exhumed mid to lower continental crust and subcontinental mantle overlain by extensional allochthons of continental origin. These types of margins show a complex structural evolution with a stratigraphic and magmatic record that is in many instances opposite to that predicted by classical models. Ignoring these observations might falsify not only the interpretation of rifted margins, but also that of collisional orogens.

In my presentation, I will first briefly summarize the key observations from the Iberia-Newfoundland margins as well as other margins worldwide. In a second part, I will, based on the example of the Alpine system in Western Europe, show how these new observations may change the way of interpreting an orogenic system. More particularly, I will address the problem concerning the interpretation of oceanic domains and will scrutinize some of the concepts that were used to define paleogeographic domains in the Alps. The aim of the presentation is to show that the inherited structures derived from the rifting phase are important and need to be considered in order to understand the evolution and ultimately the architecture of Alpine type collisional orogens.

Constraints on the timing of deformation in the Highland Border Complex and correlative rocks in western Ireland

David M. Chew[1], Laurence M. Page[2], Tomas Magna[3], J. Stephen Daly[4], Chris Kirkland[5], Martin J. Whitehouse[5], Richard Spikings[3]

[1]*Department of Geology, Trinity College Dublin*
[2]*Department of Geology, Lund University*
[3]*Département de Minéralogie, Université de Genève*
[4]*UCD School of Geological Sciences, University College Dublin*
[5]*Laboratory for Isotope Geology, Swedish Museum of Natural History*

This study presents new constraints on the timing of ophiolite obduction in the Highland Border Complex (HBC) rocks of SW Scotland and in the Deerpark Complex of western Ireland. Small (c. 50 microns in diameter) zircons have been recovered from garnet amphibolites of the Bute amphibolite of the HBC. These small zircon grains exhibit oscillatory zoning under CL, and are interpreted as magmatic in origin. Thin, U-poor rims are also present, but are beyond the spatial resolution of the ion microprobe. The magmatic grains have yielded a 499 ± 8 Ma U-Pb SIMS Concordia age, interpreted as dating the crystallization of the igneous protolith. Uranium concentrations are low (10 - 80 ppm) and Th/U ratios of the dated grains range from 0.007 – 0.023. Coarse (> 500 microns) muscovite from high-grade metasedimentary slivers intercalated with the ophiolitic rocks yielded a 488 ± 1 Ma ^{40}Ar-^{39}Ar age, which is interpreted as the age of metamorphism. These same high-grade metasedimentary slivers contain small (between 50 and 100 microns in length) zircons, which exhibit enigmatic, "spongy" textures under CL. Uranium concentrations range from 20 - 4000 ppm and Th/U ratios are typically below 0.1. This sample has yielded a 490 ± 4 Ma U-Pb SIMS Concordia age, also interpreted as dating the metamorphism. This metamorphic event, also recorded by the Ar-Ar system in muscovite, is interpreted as dating ophiolite obduction at c. 490 Ma.

HBC rocks also crop out on in North Glen Sannox on the neighbouring Isle of Arran. Mylonitized pillow basalts contain thin seams rich in potassic white mica and may represent sheared interstitial sediment. ^{40}Ar-^{39}Ar dating of this white mica has yielded a 476 ± 1 Ma ^{40}Ar-^{39}Ar age, which is consistent with involvement in a c. 475 Ma - 465 Ma Grampian orogeny. Pebbly grits within the HBC rocks in North Glen Sannox have yielded detrital zircon age spectra characterized by peaks at *c*. 0.95 – 1.3 Ga, 1.4 – 1.5 Ga, 1.7 – 1.9 Ga and 2.5 – 2.9 Ga.

In Clew Bay, western Ireland, the Deerpark Complex, an ophiolitic mélange comprising amphibolite-facies basic and ultrabasic rocks and associated metasediments lies to the south of the greenschist-facies turbiditic metasediments of the Clew Bay Complex. The metabasites have a MORB-like trace element chemistry, but pronounced Nb anomalies and initial Nd isotopic compositions ($\varepsilon_{Nd(480)}$ = +6) consistent with a juvenile subduction-related origin. Small, garnet-grade mica-schist blocks within the ophiolitic mélange may represent distal Laurentian or pelagic sediments caught up during obduction. They exhibit detrital zircon age spectra with peaks at *c*. 0.95 – 1.3 Ga, 1.4 – 1.5 Ga, 1.7 – 1.9 Ga and 2.5 – 2.9 Ga and a minor peak at 3.4 Ga. These data are very similar to detrital zircon age spectra obtained from Clew Bay Complex and (upper) Dalradian Supergroup rocks further to the north. THERMOCALC multi-equilibria yield an average PT value of c. 3.3 kbar and 550 ºC for the mica schist, which is argued to provide a PT constraint on ophiolite obduction since petrographic evidence demonstrates that the metabasites have experienced the same metamorphic event. Muscovite from one of the schist blocks has yielded a Rb-Sr age of 483 ± 7 Ma and a ^{40}Ar-^{39}Ar age of 482 ± 1 Ma. Finer-grained white mica defining the foliation in another sample yielded a 460 ± 1 Ma ^{40}Ar-^{39}Ar age, which is indistinguishable from the c. 460 Ma Rb-Sr and ^{40}Ar-^{39}Ar ages obtained from the low grade CBC and Dalradian to the north which may relate to a phase of pronounced regional exhumation.

A U-Pb zircon age constraint for the Ordovician Tyrone Plutonic Group ophiolite, Tyrone Igneous Complex, Northern Ireland: implications for plate models and Grampian orogenic amalgamation

M. R. Cooper[1], S. R. Noble[2], Q. G. Crowley[2] & R. J. Merriman[3]

[1]Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Malone Lower, Belfast BT9 5BJ mark.cooper@detini.gov.uk

[2]NERC Isotope Geosciences Laboratory, British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, UK

[3]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, UK

Geological history and age determination of the Tyrone Igneous Complex and Tyrone Central Inlier are key to the understanding of Grampian orogenic amalgamation of the Caledonides. The Tyrone rocks are recognized as belonging to the Midland Valley Terrane (Bluck *et al.* 1992), and a strong regional link has been made between the Tyrone Igneous Complex and the Ballantrae Complex of Girvan (Bluck 1985) which together compose the Tyrone-Girvan sub-terrane. In a broader context, the Tyrone Igneous Complex appears to fit most closely with the Notre Dame Subzone of the Dunnage Zone of Newfoundland, as described in Van Staal *et al.* (1998).

The Ordovician Tyrone Igneous Complex is comprised of the ophiolitic Tyrone Plutonic Group and overlying arc-related Tyrone Volcanic Group. Together they structurally overly sillimanite-grade paragneisses of the Tyrone Central Inlier which, based on detrital zircon age profiling, appear to be of Upper Dalradian Laurentian affinity (Chew *et al.* in press). The Tyrone Igneous Complex and Tyrone Central Inlier are pinned together by a suit of arc-related tonalitic-granitic intrusives.

Age constraints for the Tyrone Volcanic Group come from U-Pb dating of zircons from a high level, syn-depositional rhyolite at 473 ± 0.8 Ma, and in addition from a biostratigraphical correlation established by the presence of Isograptus victoriae lunatus, the index fossil of the victoriae lunatus graptolite zone, from Slieve Gallion, which indicates a correlation with the Australasian Castlemainian (Ca1) Stage of the middle Arenig (Cooper *et al.* 2008).

Until now the age of Tyrone Plutonic Group has been based on a magma mixing relationship between gabbro and tonalite at Craigballyharky. The tonalite has been dated at 472 $^{+2}/_{-}$ 4 Ma, and was taken as evidence for the age of the ophiolite and for the timing of obduction (Hutton *et al.* 1985). Although their mixing with gabbro is clear, the tonalites have a volcanic arc geochemical signature. The geological scenario would therefore require obduction of contemporaneous ophiolite and an active volcanic arc. This paper presents a new U-Pb zircon age of 480 ± 1 Ma for layered gabbros (normal-type MORB) of the Tyrone Plutonic Group at Scalp. This direct age for the ophiolite is older than that suggested by the Craigballyharky mixing relationships and dating of tonalite. When viewed against the 473-464 Ma U-Pb zircon age range of the arc-related intrusive suite (Noble *et al*, 2004), it makes more geological sense that the ophiolite is significantly older. This age difference allows time for establishment of northwards directed subduction after obduction (~ 480 and 475 Ma), followed by development of a volcanic arc (~ 475 and 465 Ma) as depicted by Chew *et al.* (opt cit).

BLUCK, B. J. 1985. The Scottish paratectonic Caledonides. *Scottish Journal of Geology*, **21**, 437-464.

BLUCK, B. J., GIBBONS, W. & INGHAM, J. K. 1992. Terranes. In Cope, J. C. W., Ingham, J. K and Rawson, P. F. (eds) Atlas of Palaeogeography and Lithofacies, *Geological Society of London, Memoirs*, **13**, 1-4.

CHEW, D.M., FLOWERDEW, M.J., PAGE, L.M., CROWLEY, Q.G., DALY, J.S., COOPER, M. R. & WHITEHOUSE, M.J. 2008. The tectonothermal evolution and provenance of the Tyrone Central Inlier, Ireland: Grampian imbrication of an outboard Laurentian microcontinent? *Journal of the Geological Society, London*, **165**, 675-685.

COOPER, M.R., CROWLEY, Q.G. & RUSHTON, A.W. A. 2008. New age constraints for the Ordovician Tyrone Volcanic Group, Northern Ireland. *Journal of the Geological Society, London*,**165**, 333-339.

HUTTON, D.H.W., AFTALION, M. & HALLIDAY, A. N. 1985. An Ordovician ophiolite in County Tyrone, Ireland. *Nature*, **315**, 210-12.

VAN STAAL, C. R., DEWEY, J. F., MAC NIOCAILL, C. & MCKERROW, W. S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In Blundell, D.J. and Scott, A. C. (eds) Lyell: The Past is the Key to the Present. *Geological Society, London, Special Publications*, **143**, 199-242.

Poster presentations:

Geochemistry of Caledonian microdiorites from Ardgour

Mike Fowler

Earth and Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth PO1 3QL, UK.

A suite of sharply cross-cutting Caledonian microdiorite dykes is emplaced into the southern part of the Northern Highlands Terrane, concentrated in particular in Ardgour and Moidart. Though none has been radiometrically dated, they appear to be broadly coeval with the granites. According to Smith (1979), they cut the Cluanie granite and are cut by Strontian and Ross of Mull. Emplacement at ca. 420 Ma is therefore indicated. On occasion they can be seen to pillow into, and mix with the granites (e.g. Strontian) in the manner of synplutonic dykes, raising the possibility of a genetic relationship. Similarly, they are said to grade into rocks of the appinite suite, such that a genetic connection with these might also be explored. Their state of deformation is variable, but in the least deformed examples small-scale mixing and mingling textures can be observed between acid and basic variants.

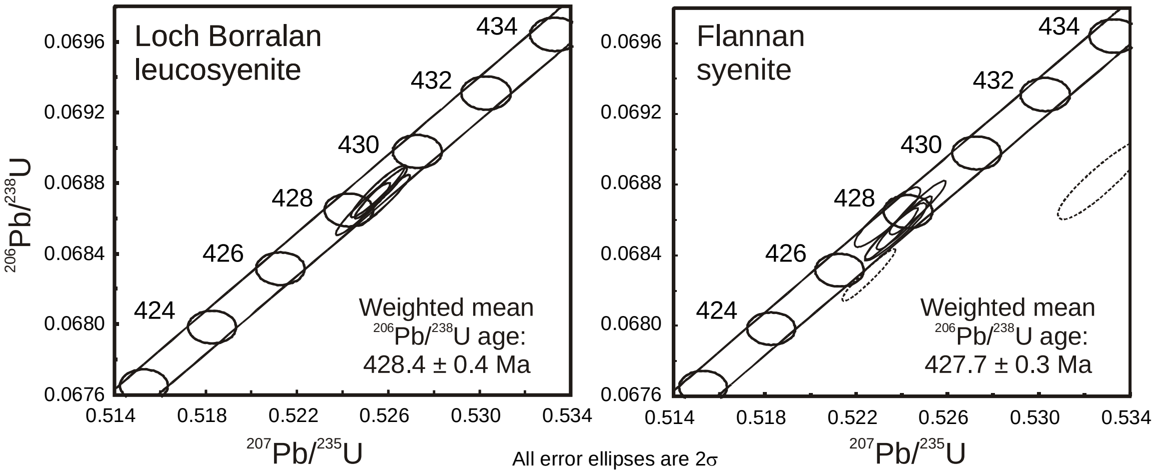
A selection of 40 dykes has ben collected and analysed for major and trace elements, mostly from the environs of Strontian, but also as far north as Cluanie and west to Arisaig. Most are homogeneous microdiorites in various states of deformation, but five acid-basic pairs and two granite-microdiorite hybrids (Cluanie, Strontian) are included. They range chemically from 47% to 69% SiO_2, 18% to <1% MgO, 0.5% to 6% Na_2O and 1% to 5% K_2O. They are moderately light-REE enriched and show negative Nb anomalies on chondrite-normalised plots. However, they do not challenge the extremely high Ba and Sr compositions of some of the contemporaneous granite plutons. Fractionation trends constructed on the basis of the overall data distribution, and more particularly the acid-basic pairs of mingled-magma dykes, constrain the possible genetic relationships outlined above.

U-Pb zircon ages for the Loch Borralan and Flannan syenites, and their relationship to the Caledonian orogenic front.

Ian Millar[1], Derek Ritchie[2], Kathryn Goodenough[2], Steve Noble[1] & Geoff Kimbell[1]
[1]British Geological Survey / NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG.
[2]British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA.

The Caledonian Front has, for many years, been considered to be mid-Silurian in age. An important piece of evidence for this is the age of the Loch Borralan Pluton (430 ± 4 Ma; van Breemen et al., 1979), which lies within the Moine Thrust Zone. The Loch Borralan Pluton comprises early and late magmatic suites; the early suite is poorly exposed and its structural relationships are equivocal, but there is little doubt that the later suite post-dates thrust movement (Parsons and McKirdy, 1983, confirmed by recent BGS mapping).

Rb-Sr and K-Ar dating of mylonites in the Moine Thrust Zone has yielded ages between c. 440 and c. 410 Ma (Freeman et al., 1998; Dallmeyer et al., 2001), suggesting that deformation at the Caledonian Front may extend into the Devonian. This evidence is in direct conflict with the accepted age and structural position of the Loch Borralan Pluton. We therefore set out to re-examine the age of both early and late magmatic suites. To date, we have analysed zircons from a sample of the late (post-thrusting) suite, which has given a U-Pb age of 428.4 ± 0.4 Ma. A further sample, from Bad na h-Achlaise where syenites cut quartzites belonging to a thrust klippe (Parsons and McKirdy,1983), contains inherited zircon and has given only highly discordant zircon data. A third sample, from the early magmatic suite, awaits analysis. The new age of 428.4 ± 0.4 Ma represents a minimum age for movement on thrusts within the Moine Thrust Zone.



In parallel, we have carried out a U-Pb zircon study of an alkaline igneous intrusion, the Flannan syenite, which intrudes crystalline basement 50 km to the west of the Outer Hebrides. This intrusion has been modelled geophysically as saucer-shaped, with a maximum width of 9 km and depth extent of the order of 1 km. Its U-Pb age (427.7 ± 0.3 Ma) and geochemistry indicate close similarities to the Loch Borralan leucosyenite. The location of the Flannan syenite is enigmatic, as it lies 135 km to the NW of the Moine Thrust Zone (after allowing for post-Caledonian extension), in an area normally considered to lie well to the west of the Caledonian Front. This suggests that the influence of the Caledonian Orogeny may extend significantly further to the NW than previously recognised.

VAN BREEMAN, O., AFTALION, M. AND JOHNSON, M.R.W. 1979. Age of the Loch Borralan complex, Assynt, and late movements along the Moine Thrust Zone. *Journal of the Geological Society, London*, **136**, 489-496.

DALLMEYER, R. D., STRACHAN, R. A., ROGERS, G., WATT, G. R. & FRIEND, C. R. L. 2001. Dating deformation and cooling in the Caledonian thrust nappes of north Sutherland, Scotland: insights from $^{40}Ar/^{39}Ar$ and Rb-Sr chronology. *Journal of the Geological Society*, **158**, 501-512.

FREEMAN, S. R., BUTLER, R. W. H., CLIFF, R. A. & REX, D. C. 1998. Direct dating of mylonite evolution; a multi-disciplinary geochronological study from the Moine thrust zone, NW Scotland. *Journal of the Geological Society of London*, **155**, 745-758

PARSONS, I. & MCKIRDY, A. P. 1983. The interrelationship of igneous activity and thrusting in Assynt: excavations at Loch Borralan. *Scottish Journal of Geology*, **19**, 59-67

Zonation and structure of the Late Caledonian Newry Igneous Complex, Northern Ireland from Tellus geophysical datasets.

Mark Cooper, Chris Van Dam and Ian Meighan

The Late Caledonian Newry Igneous Complex was intruded into the Southern Uplands-Down-Longford Terrane just after final closure of Iapetus (c. 425 Ma). Work to date has shown it to be composed of three overlapping, I-type, granodioritic plutons and an intermediate-ultramafic body. The intrusions are aligned and young from NE-SW. Petrographical and geochemical studies have shown the NE and SW plutons to be normally zoned (more basic at margins) and the central pluton reversely zoned, however to date no mapped internal division of the plutons has been published.

Interpretation of high resolution geophysical imagery, from the Geological Survey of Northern Ireland Tellus project, has allowed internal zonation and structures not previously described for the complex to be mapped. Ternary radiometric data show the central pluton and the south-western part of the NE pluton to be relatively rich in potassium, compared to the north-eastern area of the NE pluton which is thorium elevated. Occurring within this thorium elevated zone is the intermediate-ultramafic body and a similar mass in the vicinity of Kilcoo near Lough Island Reavy, which show a mixed potassium/thorium signal. Magnetic data reveal striking magnetite enriched rings inside the central and NE plutons, and also define the intermediate-ultramafic bodies. There are also two circular, parallel structures visible on the magnetic image. The inner defines the outer edge of the magnetic ring of the NE pluton, while the other, outer structure cuts the country rock and north-eastern part of NE pluton. Associated with this structure are outlying granodiorite masses such as that mapped at Ballynafern ~ 6 km NNE of Rathfriland.

The Shetland Mega-monocline: a continuation of the Tay Nappe?

D. Flinn
Department of Geology, University of Liverpool

A simplified version of the recently presented paper in the Scottish Journal of Geology 43 (2), 125-142, 2007 entitled Dalradian rocks of Shetland will be outlined.