IS06/10:
Petrographic and geochemical characterisation of the Porcupine High using recently recovered MeBo shallow cores

February 2008

J.S. Daly, S. Tyrrell, E. Badenszki, P.D.W. Haughton and P.M. Shannon.
UCD School of Geological Sciences, University College Dublin
E-mail: stephen.daly@ucd.ie

SUMMARY

Core retrieved from the north Porcupine High (site BII, borehole 25/7-sb(MeBo)3) comprises an *in-situ* orthogneiss. Geothermobarometric data are consistent with petrological observations and suggest the metamorphic grade peaked at granulite facies. U-Pb zircon geochronology has revealed a Mesoproterozoic age (1314 Ma) for the orthogneiss. This is interpreted as the age of crystallization of the granitic protolith, indicating an episode of magmatism not previously known in the region. These data suggest later reworking during the Grenville Orogeny (c. 1038 Ma). Hf isotopic analysis of the dated zircons suggest that the orthogneiss is derived, in part, by melting of pre-existing continental crust. The Pb isotopic analysis of K-feldspar indicates that the most likely source for the magma from which the Porcupine High orthogneiss crystallised are the 1750 Ma Rockall Bank gneisses, suggesting that these rocks may underlie the northern Porcupine area.

K-feldspar Pb isotopic data also supports the contention that the Porcupine High area was the sourceland for Upper Jurassic sandstones in the Northern Porcupine Basin, and the orthogneiss is highlighted as a potential source of one of the two dominant detrital K-feldspar populations.

Material retrieved from site L (borehole 25/27-sb(MeBo)2) in the south Porcupine High has tentatively been interpreted as representing a rocky shoreline deposit of uncertain age. The core comprises a possible *in situ* fossiliferous limestone and large boulders of various metamorphic rocks. Constraining the age of this deposit remains one of the outstanding aims of this research.

Background:
A programme of sea floor drilling (MeBo), funded jointly by the ISPSG and Marine Institute and managed by the PAD, was carried out on the northern Porcupine Bank in July 2006. Core was recovered from two sites within Quadrant 25 – site BII and site L, corresponding to cores 25/7-sb(MeBo)3 and 25/27-sb(MeBo)2 respectively (Fig. 1). A total thickness of 1.35 m was penetrated in 25/7–sb(MeBo)3, from which 0.8m of core of *in-situ* orthogneiss (the main topic of this report) was recovered at the base. The 25/27-sb(MeBo)2 borehole penetrated 8.58m, and the recovered core has been provisionally interpreted as a weakly-cemented calcareous matrix-supported breccia/conglomerate, comprising pebbles and blocks of a variety of metamorphic rock-types (amphibolite, anorthosite and gneiss).

The importance of the Porcupine High as a potential source for Jurassic sandstones in the North Porcupine Basin has been highlighted by the recent pilot provenance study (IS05/19), which indicates that it may also have been important structural feature during the Cretaceous. However, the nature of the Porcupine High, its age, crustal affinity, and its uplift history has never been determined through direct sampling. These cores, therefore, offer a unique opportunity to characterise this important portion of the Irish Continental Shelf.

Summary of interim report, June 2007
The previous interim report, submitted June 2007, detailed the initial work carried out on a representative sample from the *in-situ* material recovered from 25/7-sb(MeBo)3. The main conclusions of this report are summarised below.

- Core retrieved from 25/7-sb(MeBo)3 includes 0.8m of an *in-situ* single lithology, which can be termed an orthogneiss.
- The weakly-foliated orthogneiss comprises pink K-feldspar megacrysts (up to 2.5 cm across) in a darker matrix of quartz, feldspars and ferromagnesian minerals (clinopyroxene, biotite, opaques and hornblende) and has experienced granulite-facies metamorphism.
- The K-feldspar megacrysts are recrystallized to a granular aggregate of polygonal K-feldspar and are surrounded by rims of plagioclase (originally a "rapakivi" texture). The plagioclase crystals are, in turn surrounded by irregular ringlets of garnet, the growth of which is a likely the response to increasing pressure.
- Major element data indicate that the composition of the K-feldspar varies from $Or_{95}Ab_5$ to $Or_{75}Ab_{25}$, with no indication of compositional zoning.
- The garnets ($Alm_{68}Grs_{22}Prp_7Sps_3$) are predominantly almandine (Fe) with minor grossular (Ca) and lesser amounts of pyrope (Mg) and spessartine (Mn). Only minor chemical zoning is present, consistent with high temperature granulite-facies metamorphism.

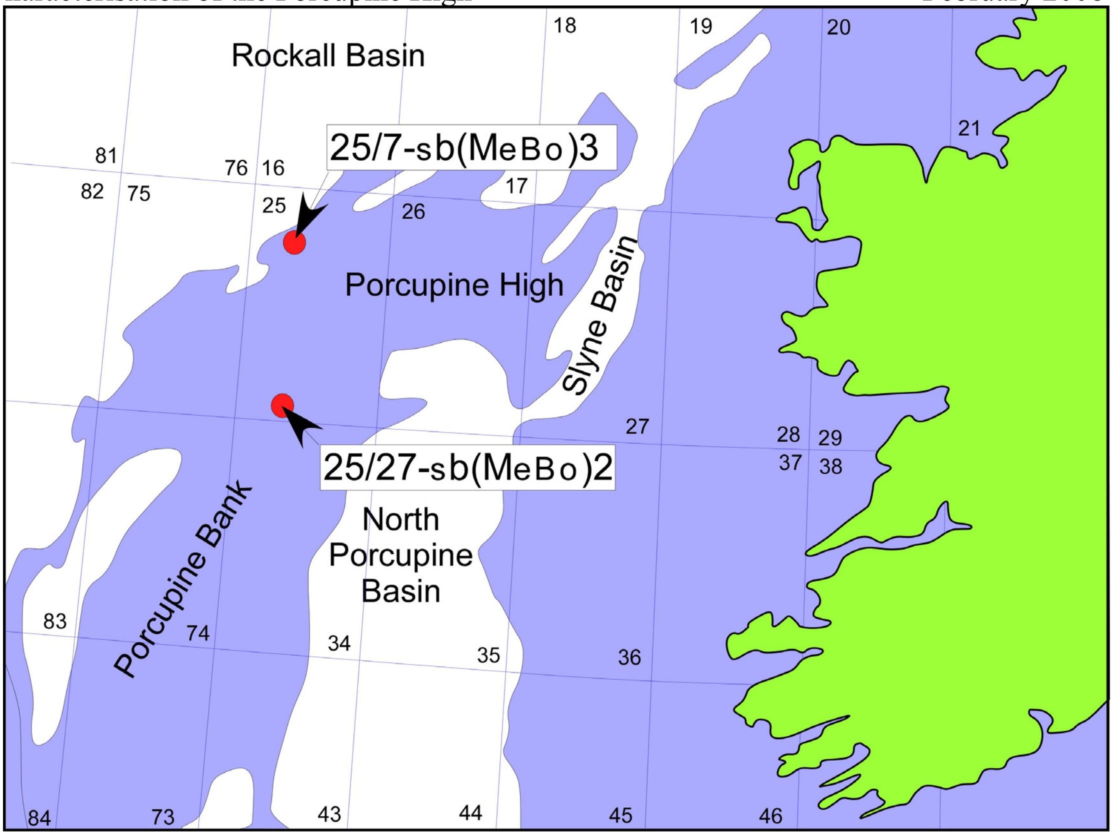

Figure 1: Map showing the location of sites on the Porcupine High, from which cores 25/7-sb(MeBo)3 and 25/27-sb(MeBo)2 were recovered.

Work carried out June 07 – December 07

Work during this period has focussed on acquiring geochemical and geochronological data from a representative sample of the *in-situ* orthogneiss retrieved from 25/7-sb(MeBo)3 on the North Porcupine High (Fig. 1; Fig. 2), in order to constrain the age, origin and crustal affinity of this piece of previously unsampled basement. These data help in the characterisation of what may be an important clastic source area during the Mesozoic and Cenozoic, and also provide an additional and crucial data point in efforts to understand the geological evolution of the Irish Continental Shelf.

These newly acquired data include Pb analysis of the K-feldspar component of the orthogneiss, U-Pb geochronology and Hf isotopic analysis of zircon and thermobarometry calculations from the metamorphic mineral assemblage. The results and the implications of these data are detailed in section A, below.

During this period, work was also carried out on material retrieved from borehole 25/27-sb(MeBo)2 (Fig. 1). This includes a description and interpretation of the core, and the basic petrography of distinct lithological components within the core. These are detailed in section B below.

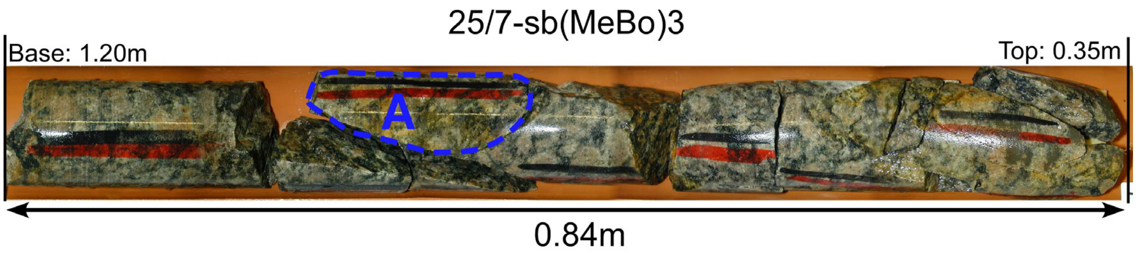

Figure 2: Photograph of the core retrieved from 25/7-sb(MeBo)3, which comprises 85 cm of *in situ* orthogneiss. The position of the representative sample, from which thin sections were made and mineral separates obtained, is shown (A).

A: Geochemical analysis of orthogneiss, borehole 25/7-sb(MeBo)3

1. Geothermobarometry:

In an attempt to constrain the metamorphic temperature and pressure experienced by the orthogneiss, electron microprobe analyses of its constituent minerals were carried out by E. Badenszki at the Geowissenschaftliches Zentrum, at the University of Göttingen, Germany, in June 2007. Backscattered electron images showing the positions of selected electron microprobe analyses are shown in Fig. 3. Representative mineral analyses are given in Table 1.

Mineral	grt-core	grt-rim	cpx-core	cpx-rim	pl	bt	amph	Kfsp
Analysis number	**339**	**338**	**335**	**334**	**330**	**349**	**345**	**328**
SiO_2	37.86	37.45	50.54	50.79	65.08	35.31	40.37	63.82
TiO_2	0.05	0.00	0.26	0.24	0.01	4.83	2.00	0.04
Al_2O_3	20.70	20.49	2.82	2.85	21.62	13.36	11.02	18.77
Cr_2O_3	0.01	0.01	0.00	0.03	0.01	0.00	0.02	0.00
FeO	31.18	31.94	19.31	19.42	0.03	27.42	25.61	0.08
MnO	1.12	1.20	0.16	0.13	0.00	0.09	0.16	0.00
MgO	1.69	1.58	6.43	6.41	0.01	5.94	5.02	0.01
CaO	7.95	7.56	18.33	18.42	2.37	0.02	10.42	0.03
Na_2O	0.01	0.00	1.80	1.69	10.23	0.14	1.82	0.60
K_2O	0.00	0.00	0.02	0.00	0.10	9.02	1.73	15.52
BaO	0.01	0.00	0.04	0.01	0.06	0.24	0.03	0.65
TOTAL	100.57	100.23	99.70	99.97	99.51	96.37	98.20	99.51

Table 1: Representative electron microprobe mineral analyses. Grt = garnet; cpx = clinopyroxene; pl = plagioclase; bt = biotite; amph = amphibole; Kfsp = K-feldspar.

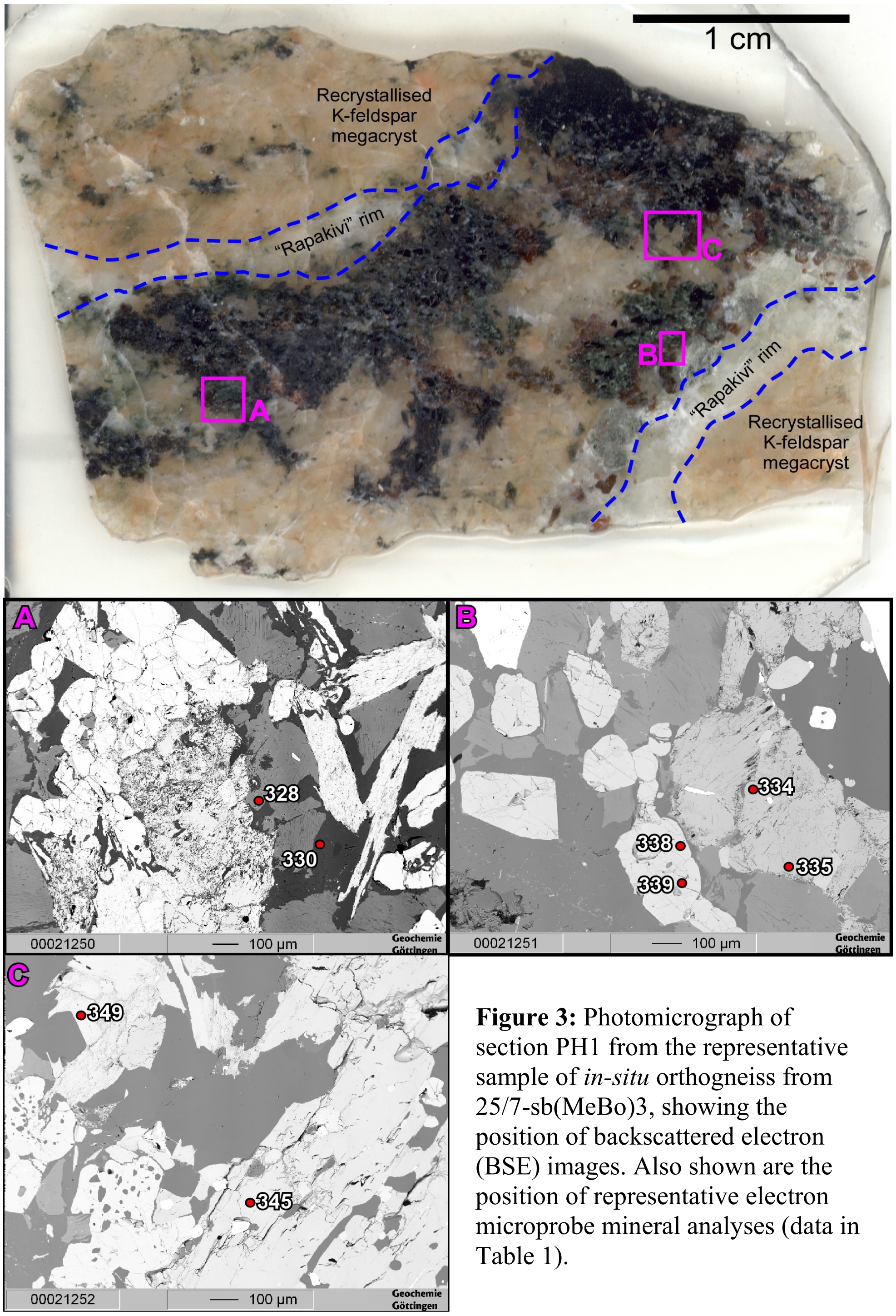

Figure 3: Photomicrograph of section PH1 from the representative sample of *in-situ* orthogneiss from 25/7-sb(MeBo)3, showing the position of backscattered electron (BSE) images. Also shown are the position of representative electron microprobe mineral analyses (data in Table 1).

The garnet – clinopyroxene geothermometer was used to constrain temperature based on the experimentally calibrated equilibrium partitioning of Fe and Mg between garnet and clinopyroxene. Using the calibration of Ai (1994), the cores of garnets and clinopyroxenes yielded temperatures in the range 705-725°C consistent with the previously reported (Daly *et al.,* 2007) granulite-facies mineral assemblage of garnet-plagioclase-clinopyroxene and quartz. Garnet and clinopyroxene rims yield somewhat lower temperatures of 670-700°C suggesting retrograde exchange of Fe-Mg during cooling. Essentially, relative to other Fe-Mg minerals such as clinopyroxene, the Fe/Mg ratio of garnet increases from core to rim (Table 1) in response to decreasing metamorphic temperature. Further chemical mapping would be required to evaluate the extent and significance of the chemical zoning.

The Thermocalc programme (Holland and Powell, 1998; Powell and Holland, 2001) was also used to calculate metamorphic pressures and temperatures. Calculations based on the anhydrous assemblage garnet-clinopyroxene-plagioclase-quartz yield temperature and pressure of 739 ± 159°C and 11.8 ± 3.4 kbar for garnet and clinopyroxene cores and 681 ± 143°C and 10.4 ± 3.0 kbar for the rims. Assuming that amphibole and biotite are in equilibrium with the garnet and clinopyroxene, a more rigorous set of calculations was attempted. However because hydrous minerals (biotite and amphibole) are included, it is necessary to make assumptions about the composition of any fluid present during metamorphism. For a pure water fluid (100% H_2O), Thermocalc yields a temperature of 890 ± 58°C and a pressure of 14.0 ± 1.3 kbar. For a mixed fluid (10% H_2O – 90% CO_2), the resulting PT conditions are 595 ± 30°C and 8.1 ± 1.0 kbar with no significant difference between core and rim compositions. Without some constraint on the fluid composition, it is difficult to discriminate the metamorphic conditions within this wide range. In addition further work is needed to confirm that the hydrous minerals are in equilibrium with the high grade assemblage.

2. Pb K-feldspar data

Pb isotopic analysis of the K-feldspar megacrysts was carried out by S. Tyrrell at Memorial University, St John's, Newfoundland, Canada in September 2007. Data were collected on a Finnigan Neptune Multi-Collector ICPMS after ablation of samples with a 193 nm excimer laser. Two separate analyses of a single K-feldspar crystal were obtained, and the data form a tight range of $^{206}Pb/^{204}Pb$ (16.38±0.04 to 16.40±0.05) and $^{207}Pb/^{204}Pb$ (15.32±0.02 to 15.33±0.02). When plotted, these data show a Pb basement affinity similar to gneisses from the Rockall Bank and Rhinns Complex with slightly more radiogenic Pb isotopic composition (Fig. 4). There is no correlation with crystalline basement from onshore Ireland, or with Lewisian basement (Fig. 4).

Previously, it had been postulated that the most northerly segment of the Porcupine High comprised basement of Proterozoic 1 affinity. This was based on (1) Pb data obtained from locally-derived detrital K-feldspar from Cretaceous sands and sandstones from the margins of the high, and (2) the likely offshore extension of onshore Pb domain boundaries and structural lineaments (Tyrrell *et al*., 2007). These new data clearly support this interpretation. The new data also supports one of the general conclusions of project IS05/19 - that the northern Porcupine High is potentially one of the sources for Jurassic reservoir sandstones in the North Porcupine Basin. Some Pb data from detrital Jurassic K-feldspar, obtained as part of project IS05/19 (Group 1), (Tyrrell *et al*., 2007) plot within error of the field defined by these new data from the Porcupine High (Fig. 4).

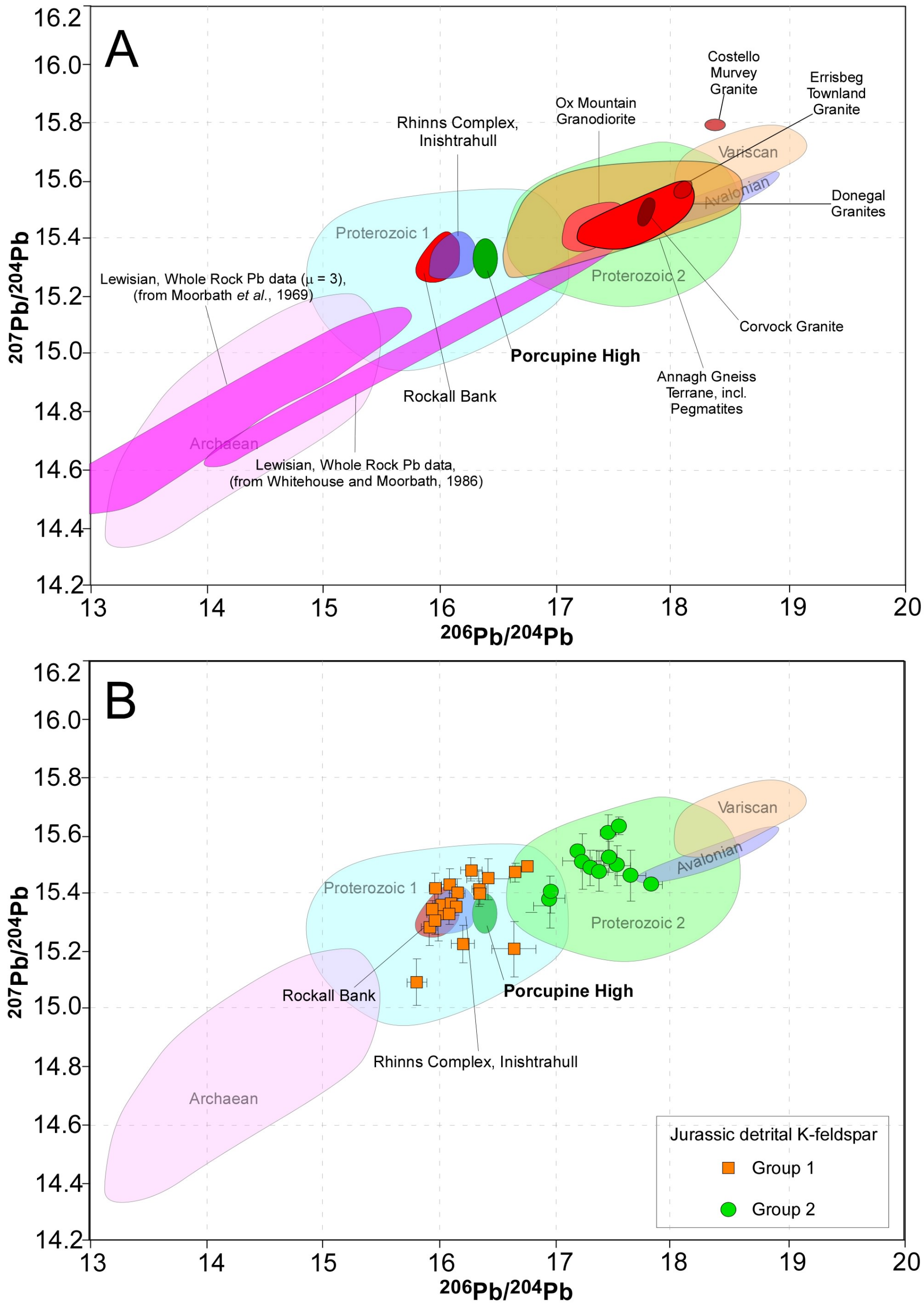

Figure 4: Plots of $^{206}Pb/^{204}Pb$ against $^{207}Pb/^{204}Pb$ for K-feldspar from Porcupine High orthogneiss showing A) a comparison with the Pb isotopic composition of NE Atlantic crystalline basement and B) a comparison with detrital K-feldspar grains from Upper Jurassic sandstones in the Porcupine Basin.

3. U-Th-Pb zircon geochronology

U-Pb dating of zircon was carried out by S. Daly at the Nordsim Laboratory, Swedish Museum of Natural History, Stockholm in September 2007. Zircons separated from a small (c. 100g) fragment of the representative sample from the core in 25/7-sb(MeBo)3 (Fig. 2) using standard heavy liquid methods were mounted in epoxy and polished to reveal grain interiors. The zircons are variable in size, typically 200-300 μm, but range up to 500 μm long. Many were fractured during processing and thus few display double terminations. Those that do so tend to be rounded prisms with aspect ratios of about 3. The interiors of most grains are CL-dark and display oscillatory zoning (Fig. 5), sometimes idiomorphic and conformable with the grain exteriors, sometimes convoluted as a result of resorption and regrowth, all of which are features typical of magmatic growth. Some grains display Cl-bright overgrowths, generally less than 25 microns across and thus too narrow to analyse. However a few of the CL-bright rims were sufficiently wide to permit analysis (Fig. 5).

42 U-Th-Pb analyses were obtained from 21 zircon grains by secondary ion mass spectrometry using the Cameca 1270 ion microprobe. Analytical methods followed those described by Kirkland *et al.* (2007), which follow Whitehouse *et al.* (1999).

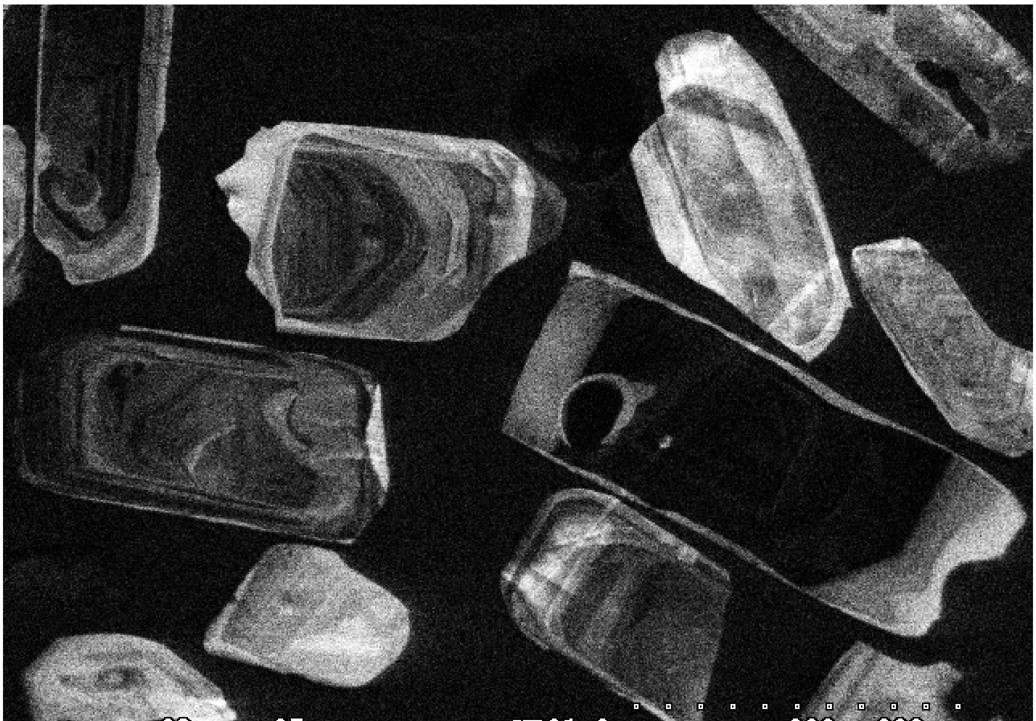

Figure 5: Representative cathodoluminescence images of zircons from the representative sample of 25/7-sb (MeBo)3 orthogneiss. Many grains have CL-dark interiors and display features typical of magmatic growth including idiomorphic zoning and resorption surfaces. Some grains have narrow irregular CL-bright rims. Analyses of three of these yielded a Concordia age of 1038 ± 12 Ma and are interpreted as overgrowths that developed during the high grade metamorphism discussed above.

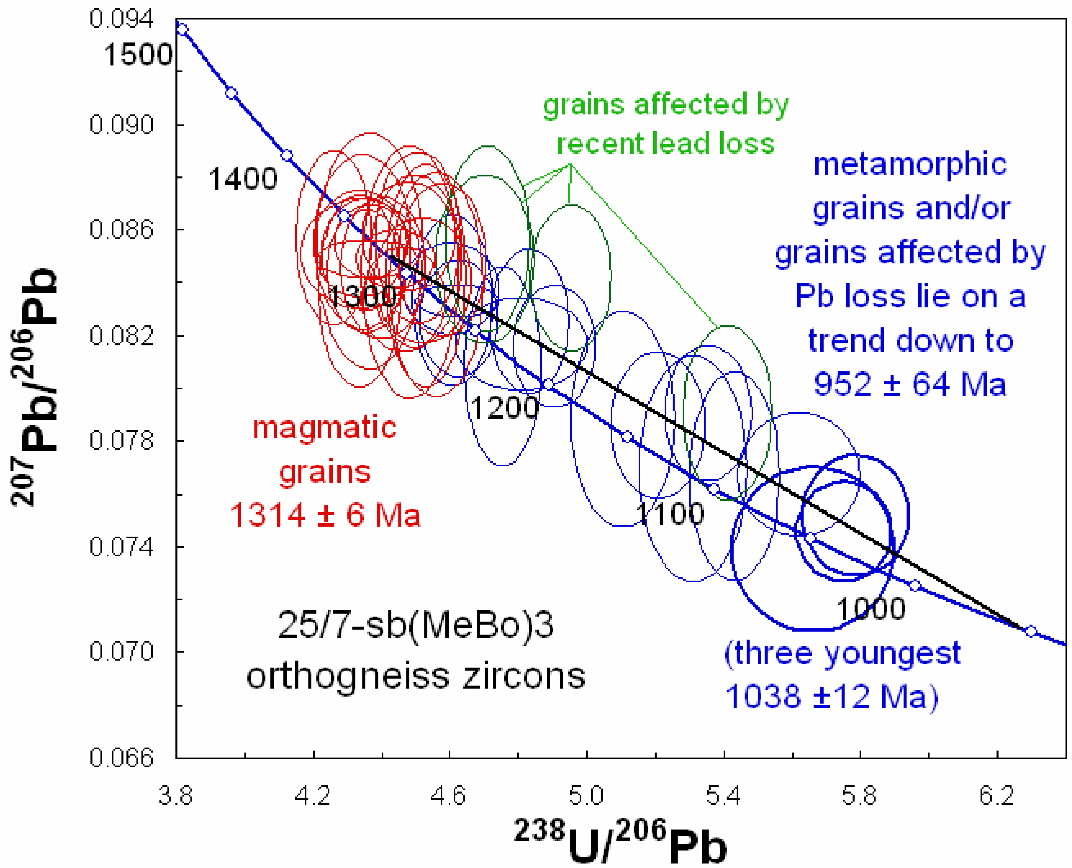

Figure 6: Tera-Wasserburg Concordia diagram displaying U-Pb zircon analyses and 2σ error ellipses for the representative sample of orthogneiss from 25/7-sb (MeBo)3 and calculated ages. The data are colour-coded according to their position on Concordia. Red = undisturbed magmatic domains; green = analyses displaying recent Pb loss; blue = magmatic grains affected by Pb loss during Grenville metamorphism and inadvertent mixtures between magmatic domains and rims (heavy blue ellipses) that grew during Grenville metamorphism.

U-Th-Pb data are presented in Fig. 6. Most of the analyses are concordant though they are distributed along Concordia between c. 1320 Ma and 1040 Ma. Four analyses (green ellipses in Fig. 6) fall off Concordia probably as a result of recent lead loss. 21 analyses making up the oldest group of concordant data (red ellipses in Fig. 6) define a Concordia age of 1314 ± 6 Ma, which is interpreted as the crystallization age of the granitic protolith of the orthogneiss.

The remaining 17 analyses lie on Concordia but account for the large spread in age. These are interpreted mainly as analyses of magmatic grains that formed at 1314 but suffered Pb loss during a metamorphic event in Grenville times. Apart from the analyses interpreted as having suffered recent lead loss (green ellipses in Fig. 6), all of the data points fit a discordia anchored at 1314 Ma (the magmatic age), which yields a lower intercept age of 952 ± 64 Ma. CL-imaging after analysis revealed that some of these data points were inadvertently sited on healed fractures, which might account for the lead loss during metamorphism. However, the three youngest analyses (heavy blue ellipses in Fig. 6) come from CL-bright overgrowths that are interpreted to have grown during metamorphism. These define a Concordia age of 1038 ± 12 Ma, which is tentatively interpreted as the age of the metamorphic event. Some of the intermediate analyses (between 1314 and 1038) may also represent inadvertent mixtures between CL-bright overgrowths and magmatic interiors (fine blue ellipses in Fig. 6). These data illustrate the particular difficulty in interpreting U-Pb data from zircons of this age (late Mesoproterozoic to early Neoproterozoic) that have experienced high grade metamorphism within a few hundred million years of their formation. As a result of the low curvature of Concordia at this time, it is generally difficult to obtain precise data from discordia intercept calculations.

4. Hf isotopic analysis of zircon

Ten zircon grains previously dated by ion microprobe were analysed for Lu-Hf and Yb isotopes by laser-ablation ICPMS on a NuPlasma HR instrument at the National Isotope Geology Laboratory at Keyworth, Nottingham, England in September 2007. The data fall within a narrow range, all within analytical error of one another and define Lu-Hf depleted mantle model ages with a weighted mean value of 1.77 ± 0.03 Ga. Epsilon Hf values calculated at 1314 Ma are equivalent within error and are chondritic (0.0 ± 2.2). The Hf isotopic data suggest that the Porcupine orthogneiss is not a juvenile addition to the crust but is instead derived, at least in part, by melting of pre-existing continental crustal material. The Porcupine data overlap (at the 2σ level) the range calculated at c. 1314 Ma for 1750 m.y. old orthogneiss from Rockall Bank and also the Mullet Gneisses that form the major protolith of the Annagh Gneiss Complex, of similar age. Thus either of these protoliths is a potential source for the magma that crystallized to form the northern Porcupine orthogneiss and therefore may underlie the northern Porcupine area. The Hf data alone cannot discriminate between the two. However, Pb isotopic data from K-feldspar (see above), likely of magmatic origin and therefore original, suggests an affinity with Rockall Bank rather than the Annagh Gneiss Complex. This suggests that a major crustal boundary occurs to the east of the MeBo3 location, potentially along the axis of the Slyne Basin.

The 1314 Ma age obtained for the orthogneiss from the northern Porcupine High reveals an episode of Mesoproterozoic magmatism not previously known in the region. For example, the Cross Point Gneisses from the Annagh Gneiss Complex are considerably younger (c. 1270 Ma; Daly, 1996). However both rocks were possibly produced in similar circumstances, i.e. as high-temperature anorogenic magmas produced as a result of melting the lower crust triggered by the injection of a mafic, mantle-derived magmas. The lack of inherited zircon is consistent with this scenario.

However, the metamorphic features documented above probably require tectonic burial and re-heating in order to explain the development of fine-grained garnet associated with rapakivi rims around K-feldspar megacrysts. This event probably took place at c. 1038 Ma during the Grenville Orogeny, whose effects are well known from the Annagh Gneiss Complex and from the southern Rockall Bank. It is possible that juxtaposition of the geochemically contrasting crustal segments underlying Rockall and north Porcupine in the west and the Annagh Gneiss Complex in the east took place in Grenville times.

B: Description of core from borehole 25/27-sb(MeBo)2

Fragmentary core was also retrieved from site L on the southern part of the Porcupine High (Fig.1). The basal 1 metre (8.58m - 7.58m) of this core has been examined in detail but additional fragmentary material from above was also retrieved during drilling. The examined core, although believed on initial ship-board assessment to comprise *in-situ* crystalline basement, consists of uncemented clasts of varying size (8 cm - 40 cm) and lithology, with a single ~20 cm thick bed of buff, fossiliferous limestone (Fig. 7). Buff, calcareous mud may act as a partial matrix which appears to thinly coat the various clasts. The base of the core is marked by a K-feldspar megacrystic orthogneiss (3cm across; red asterisk on Fig. 7), which, on close examination and given its relationship with the lithology above, appears to be a clast within the limestone and, for the purposes of this report, is not regarded as one of the main lithologies present.

The four main lithologies present in the basal 1 meter core are as follows:

A. Amphibolite
Occurring as a 12cm cobble-sized fragment, this is a dark, strongly foliated rock, with occasionally folded, pale (presumably quartz-rich) bands (varying in thickness from mm to cm scale). Optical microscopy indicates a composition dominated by amphibole (hornblende, blue-green pleochroism), with minor plagioclase and quartz.

B. Gabbroic anorthosite
This occurs as a cobble-sized (12cm) block (Fig. 7) with distinctly rounded upper and lower edges. Optical microscopy indicates it is dominantly plagioclase, with hornblende, garnet, quartz, opaque (probably magnetite) and minor K-feldspar. The hornblende defines a weak foliation.

C. Foliated Gneiss
A large (40cm) block with sub-rounded edges (Fig. 7) occurs above the limestone bed. The gneiss consists dominantly of quartz and K-feldspar, with a distinct foliation defined by biotite.

D. Fossilferous Limestone
A single intact bed of buff-coloured fossiliferous limestone occurs near the base of the core (Fig. 7), above a clast of megacrystic orthogneiss. The limestone is dominated by bioclasts (varying in size from the sub-mm to cm scale) with minor intraclastic and terrigenous material (including some cm-scale lithic fragments), set in a micritic mud. The majority of the bioclasts are intact, with algal structures common (red algae) and appearing to bind the sediment and encrust intraclastic material. The assemblage is diverse and includes foraminifera (including thin-shelled planktonic species and globigerinids), bryozoans, sponge spicules, crinoids, echinoderm fragments and shell (molluscs, bivalves) fragments. There are also suggestions of bioturbation, with borings of algal encrustations recognised. Quartz (rounded and angular) and, significantly, glauconite grains occur as accessory minerals. A more detailed palaeontological study is presently being undertaken (see below).

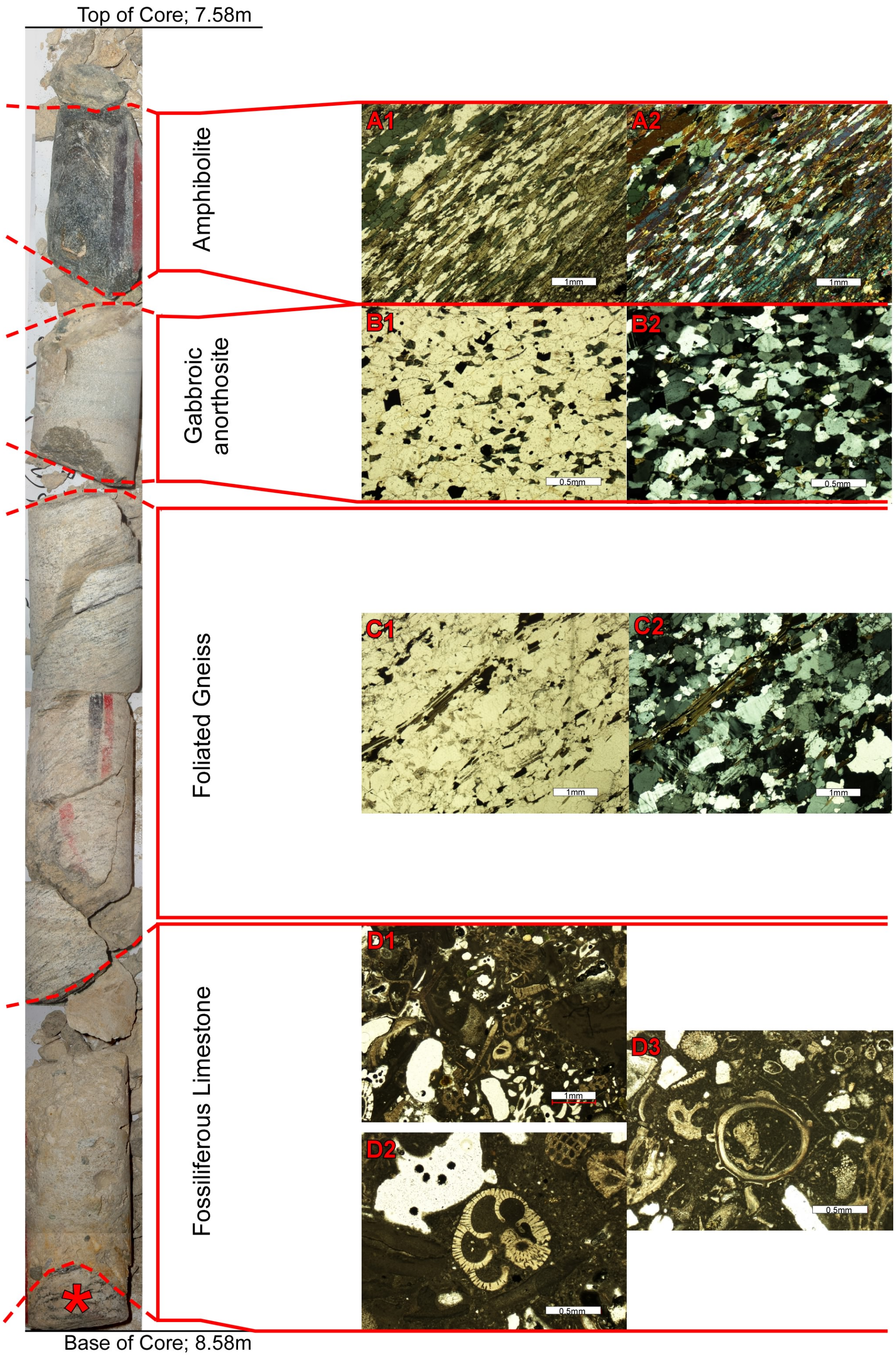

Figure 7: Photograph of core recovered from 25/27-sb(MeBo)2 showing the four main lithological components and photomicrographs of these lithologies. A) Amphibolite in (1) PPL (plane polarised light) and (2) XPL (cross-polarized light); B: Gabbroic anorthosite in (1) PPL and (2) XPL; C) Foliated gneiss in (1) PPL and (2) XPL; D) Fossiliferous limestone showing 1) range of bioclasts present, 2) Globigirinid foraminifera and 3) possible echinoderm.

Origin of material from borehole 25/27-sb(MeBo)2

Given the nature of the material recovered, the origin of these rocks is speculative. However, the diversity of the fauna in the limestone, the presence of glauconite and the presence and roundness of the large boulders/cobbles could indicate that this material was deposited in a shallow marine setting and represents a rocky shoreline. It is difficult, given our present understanding, to envisage how this material could represent a glacial deposit.

This interpretation is intriguing bearing in mind the present depth of water (~250m) where the core was retrieved. Further study may help confirm its origin. Two important constraints which could be garnered from further work are (1) the age of the limestone and (2) the water depth at which the rock accumulated. Accurate dating of the limestone could allow for the tentative reconstruction of a palaeoshoreline on the Porcupine High. In addition, if, as it appears, the boulder material is locally derived and has not been transported by ice, it may be possible to indirectly constrain the basement geology of the southern portion of the Porcupine High. For these reasons, additional work will be carried out on the 25/27-sb(MeBo)2 material (see below).

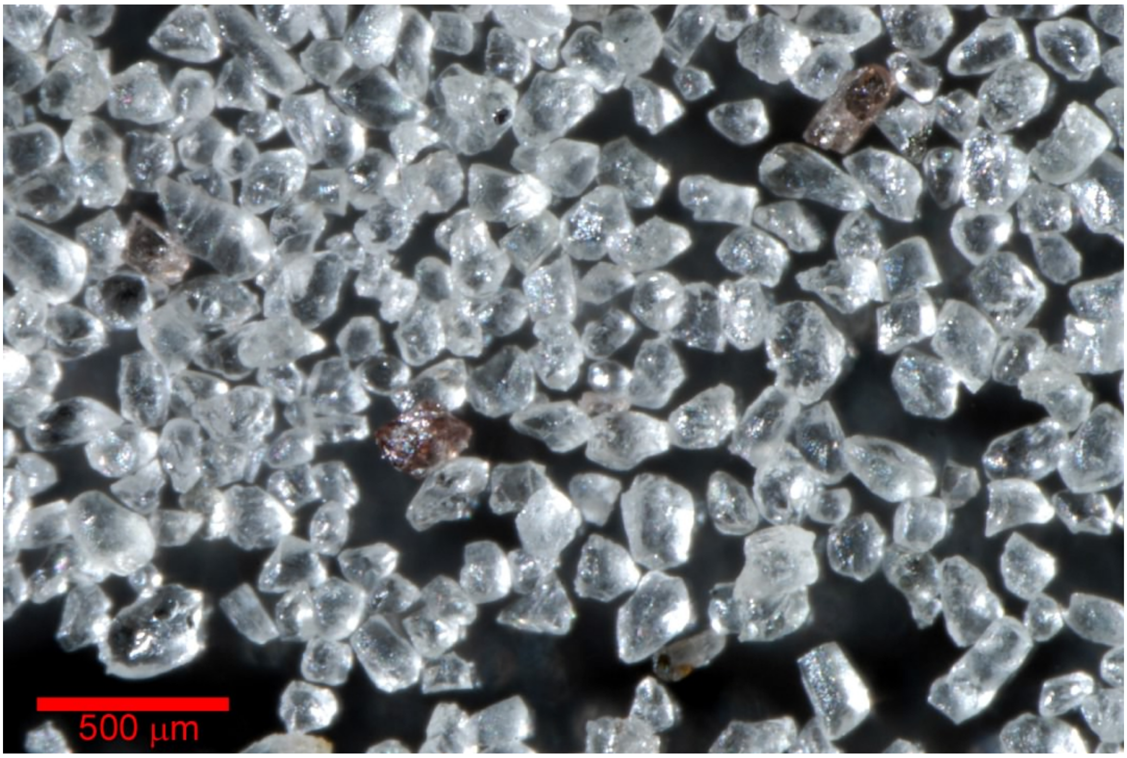

Figure 8: Photomicrograph of apatite crystals recovered from crushed portion of the representative sample of orthogneiss from 25/7-sb(MeBo)3, isolated using heaving liquid and magnetic separation techniques (Photo: D. Chew)

Work in progress:
Two strands of the work which are currently in progress

1) ***Apatite fission track analysis:***

This work is being carried out on the Porcupine High orthogneiss by Dr David Chew, Trinity College Dublin. An apatite fraction has been separated (Fig. 8) from the crushed rock sample and is awaiting irradiation prior to analysis (due for completion May 2008).

2) ***Further assessment of 25/27-sb(MeBo)2:***

   a. Examination of the fragmentary cores retrieved from the same drilling position (two cores were retrieved from depths 7.58 – 7.02m and 7.13 – 5.66m respectively). Initial assessment of the deeper of these two cores indicates the presence of distinct clasts of a variety of rock types, associated with limestone similar to that present in the underlying material (see above), suggesting it may be part of the same unit. However, more detailed assessment of these cores may allow us confirm their origin and place limits on the thicknesses of any sedimentologically distinct units.
   b. Palaeontological / biostratigraphic assessment of limestone: This work is being carried out by Lee Toms, University College Dublin, whose initial assessment of the material is that a macro and micro-fauna is present warranting further detailed palaeontological assessment. As well as determining the age of the material, it may be possible to constrain the water depth at which the limestone was deposited, which will be important in interpreting its depositional environment and stratigraphic significance (due for completion late February 2008).
   c. Further analysis of boulder lithologies: If the boulders are locally derived, then they may indirectly provide information on the local basement geology. For this reason, Pb isotopic analysis of K-feldspar from a number of the clasts will be carried out (due for completion April 2008).

References

Ai Yang, 1994. A revision of the garnet-clinopyroxene Fe^{2+} - Mg exchange geothermometer. *Contributions to Mineralogy and Petrology*, **115**, 467-473.

Daly, J.S., 1996. Pre-Caledonian history of the Annagh gneiss complex, north-western Ireland, and correlation with Laurentia-Baltica**.** *Irish Journal of Earth Sciences*, **15**, 5-18

Daly, J.S., Tyrrell, S., Haughton, P.D.W. and Shannon, P.M., 2007. IS06/10: Petrographic, petrophysical and geochemical characterisation of the northern Porcupine High using recently recovered MeBo shallow cores. Interim Report, June 2007.

Holland, T.J.B. and Powell, R. 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology*, **16**, 309-343.

Kirkland, C.L., Daly, J. S., Eide, E. A. and Whitehouse M. J., 2007. Tectonic evolution of the Arctic Norwegian Caledonides from a texturally- and structurally-constrained multi-isotopic (Ar-Ar, Rb-Sr, Sm-Nd, U-Pb) study. *American Journal of Science*, **307**, 459-526

Powell, R. and Holland, T. 2001. Course Notes for "THERMOCALC Workshop 2001: Calculating Metamorphic Phase Equilibria" (on CD-ROM).

Tyrrell, S., Haughton, P.D.W. and Daly, J.S., 2007. Drainage re-organization during break-up of Pangea revealed by *in-situ* Pb isotopic analysis of detrital K-feldspar. *Geology,* **35**, 971-974.

Whitehouse, M.J., Kamber, B. S. and Moorbath, S., 1999. Age significance of U-Th-Pb zircon data from early Archaean rocks of West Greenland; a reassessment based on combined ion-microprobe and imaging studies. *Chemical Geology*, **160**, 201-224