DETRITAL ZIRCON AGE CONSTRAINTS ON BASEMENT HISTORY ON THE MARGINS OF THE NORTHERN ROCKALL BASIN

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ABSTRACT

Detrital zircon dating has proven to be an effective way to constrain ages of submerged basement terranes on the margins of the northern Rockall Basin, a region where direct evidence of crustal affinities is scarce or absent. Zircons have been dated from sandstones of Palaeocene-Oligocene age known to have been derived from the east (Hebridean Platform) and west (Rockall and George Bligh highs). The results show that the Hebridean Platform is a westward extension of the Lewisian Complex, with Archaean and Palaeoproterozoic ages that can be directly correlated with events identified in the Outer Hebrides and northwest Scotland. The detrital zircons derived from the Hebridean Platform also provide evidence for a Mesoproterozoic thermal event and two phases of intrusions in the Palaeozoic. The Rockall High consists of a Palaeoproterozoic terrane dated as c. 1760-1800 Ma, similar to ages previously determined from both basement samples and detrital sediment. The data also provide evidence for the subsequent intrusion of alkaline igneous rocks in the Palaeocene-Eocene. The George Bligh High represents an Archaean terrane heavily affected by Palaeoproterozoic tectonothermal events, and was also the site of intrusion of alkaline igneous rocks in the Palaeocene.

The northern Rockall Basin lies to the west of the Hebridean margin of the British Isles and east of a number of structural and bathymetric highs ranging from the Rockall High in the south to the George Bligh High and the Rosemary Bank Seamount in the north (Fig. 1). The present bathymetric expression of the Rockall Basin represents a large sediment-starved, highly extended rift basin. Although the timing of rifting remains somewhat ambiguous, the general consensus is that the Rockall Basin is probably a Cretaceous rift, with earlier pulses of rifting during Permo-Triassic and Jurassic times (cf. Ritchie et al., 2013a, and references therein). The region remains a frontier area for hydrocarbon exploration, with comparatively few wells having been drilled despite many years of activity, starting with the stratigraphic test well 163/6-1A. Consequently, comparatively little is known either of the stratigraphic development within the basinal areas or of the age of the basement rocks on the flanks of the rift.

The basement on the Hebridean margin is considered to represent a westward extension of the Precambrian Lewisian Complex of the Outer Hebrides and mainland NW Scotland, on the basis of borehole and sea bed samples together with geophysical observations (Jones et al., 1986; Stoker et al., 1993; Ritchie et al., 2013b). On the eastern margin of the Rockall Plateau, the only direct evidence concerning basement ages comes from samples recovered from the Rockall High during diving expeditions (Roberts et al., 1973) and more recently from boreholes drilled on the Hatton High by the British Geological Survey (Hitchen, 2004). Sm-Nd model (T_{DM}) ages from these samples range from 1.89-2.14 Ga (Morton and Taylor, 1991: Hitchen, 2004). U-Pb zircon age data have been acquired from some of these samples, and although the results have not been formally published, they yielded results similar to that of the Annagh Gneiss of north Mayo (Ireland), which has a U-Pb zircon crystallisation age of c. 1750 Ma (Daly et al., 1995; Scanlon and Daly, 2001). These limited data suggest that the Rockall High metamorphic basement comprises a juvenile Palaeoproterozoic terrane (Morton and Taylor 1991; Dickin, 1992).

Crystalline basement rocks have not been recovered from the other bathymetric highs in the northern Rockall Basin area (George Bligh High and Rosemary Bank Seamount). However, Palaeogene basalts recovered from the George Bligh High display evidence of contamination by Archaean crust (Hitchen et al., 1997), suggesting that the boundary between the Archaean and Palaeoproterozoic terranes lies between the Rockall High and the George Bligh High, as proposed by Dickin (1992) and Dickin and Durant (2002). A borehole drilled on the Rosemary Bank Seamount also proved the existence of basalts, in this case dated as Late Cretaceous, but these rocks do not display any evidence of crustal contamination (Morton et al., 1995).

In this paper, we present an alternative approach for constraining the crustal history of the basement rocks on the flanks of the northern Rockall Basin, by utilising detrital zircon ages of sediment known to be shed from the basin margins. The same approach was previously adopted in order to determine ages of basement rocks comprising the Edoras and Hatton highs (Fig. 1) on the western flank of the Rockall Plateau (Morton et al., 2009). The data have been acquired from Palaeogene sandstones recovered from two hydrocarbon exploration wells (154/1-1 and 164/25-1) and three British Geological Survey (BGS) boreholes (94/1, 94/4 and 94/7). The locations of these sites are shown in Figure 1. The sandstones recovered in 154/1-1 and 164/25-1 were derived from the Hebridean margin, whereas those recovered in BGS boreholes 94/1, 94/4 and 94/7 were derived from the Rockall and George Bligh highs. The zircon age data reported herein therefore provide constraints on the nature of the crystalline basement forming the Rockall High and George Bligh High and the westward extension of the Hebridean margin outboard of the Outer Hebrides High, thereby adding considerably to our knowledge of the crustal history of the northern Rockall Basin region.

ZIRCON U-Pb ANALYSIS

All U-Pb age data were obtained at the Central Analytical Facility, Stellenbosch University, by laser ablation - single collector - magnetic sectorfield - inductively coupled plasma - mass spectrometry (LA-SF-ICP-MS) employing a Thermo Finnigan Element2 mass spectrometer coupled to a NewWave UP213 laser ablation system. All age data presented here were obtained by single spot analyses with a spot diameter of 30 µm and a crater depth of approximately 15-20 µm, corresponding to an ablated zircon mass of approximately 150-200 ng. The methods employed for analysis and data processing are described in detail by Gerdes and Zeh (2006) and Frei and Gerdes (2009). For quality control, the Plešovice (Sláma et al., 2008) and M127 (Nasdala et al., 2008; Mattinson, 2010) zircon reference materials were analysed, and the results were consistently in excellent agreement with the published ID-TIMS ages. Full analytical details and the results for all quality control materials analysed are reported in Table 1. Plotting of concordia diagrams was performed using Isoplot/Ex 3.0 (Ludwig 2003) and probability-density plots were generated using AgeDisplay (Sircombe, 2004). For zircons younger than 800 Ma, the radiogenic ^{206}Pb/^{238}U age has been used for the probability density plots, whereas the ^{207}Pb/^{206}Pb age has been used for grains older than 800 Ma.

HEBRIDEAN MARGIN

Detrital zircon age data have been acquired from two Palaeocene sandstone samples from wells adjacent to the Hebridean margin, one from well 154/1-1 and one from well 164/25-1.

Both wells are located on the eastern flank of the Rockall Basin, though 164/25-1 was drilled in the West Lewis Basin, which is separated from the Rockall Basin by the West Lewis High (Fig. 2). The West Lewis High is part of a complex of basement structural highs and Late Palaeozoic–Mesozoic basins on the Hebridean margin (Ritchie et al., 2013a). The Palaeogene sequences in both wells were derived from the Hebridean margin, which has been a constant source of sediment throughout the Cenozoic (Stoker, 2013) (Fig. 2).

U-Pb isotopic compositions and ages of detrital zircons in the Palaeocene sandstones from wells 154/1-1 (2865.0 m) and 164/25-1 (2651.0 m) are shown in Figs 3 and 4. Most of the zircons in the sandstone from 154/1-1 have Archaean ages between 2700-2900 Ma, together with a subsidiary group in the 1700-1900 Ma range, and five young zircons dated as c. 280-320 Ma. There are also small numbers of older Archaean zircons ranging back to c. 2970 Ma, and younger Archaean grains down to c. 2510 Ma. The detrital zircon age spectrum in 164/25-1 is similar, with the majority having Archaean ages between 2700-2900 Ma, a subsidiary group of zircons in the 1700-2000 Ma range, and two young zircons, one dated as 296 Ma and 433 Ma. The oldest dated Archaean zircon is c. 3060 Ma and the youngest is c. 2530 Ma.

ROCKALL HIGH

The eastern margin of Rockall High is fringed by a series of sediment wedges of Early to Late Eocene age that prograde eastwards and northeastwards into the Rockall Basin (Figs 1 and 5). A detailed analysis of BGS borehole 94/3, which penetrated 210 m into the East Rockall Wedge (Fig. 5), proved that the material that forms these wedges was derived locally from the Rockall High (Stoker et al., 2012). BGS borehole 94/1 also sampled the East Rockall Wedge, albeit the collapsed outer part of the wedge (Fig. 5), and a sample from this borehole was chosen to provide constraints on the nature of the Rockall High source. In addition, an Upper Oligocene mass-flow deposit, which accumulated as part of a lowstand fan on the eastern flank of the Rockall Basin (Fig. 6), was similarly derived from the top of Rockall High (Stoker et al., 2001; McInroy et al., 2006). BGS borehole 94/4 recovered sediment from this deposit, and zircons from a sandstone sample were included in the analytical programme.

U-Pb isotopic compositions and ages of detrital zircons in the Eocene sandstone from BGS borehole 94/1 (58.8 m) and the Oligocene sandstone from BGS borehole 94/4 (41.0 m) are shown in Figs 7 and 8. In both cases, the great majority of the zircons have compositions that are 90-110 % concordant. In borehole 94/1, the zircon spectrum displays a single large peak at c. 1800 Ma, together with a small number of older zircons, four in the 2030-2170 Ma range and one at c. 2900 Ma. Owing to the small sample size and relatively low proportion of detrital zircons, it was possible to make only 48 analyses from this sample, and hence there is a possibility that some minor age components have not been recognised. This is not the case for borehole 94/4, where zircons proved to be more abundant and > 100 analyses were possible. Virtually all the zircons in borehole 94/4 form a single group between 1670-1850 Ma, peaking at ~ 1760 Ma, the only exceptions being a small Palaeocene-Eocene group dated as 53-60 Ma comprising two concordant zircons and two with similar ages but with > 10% discordance.

GEORGE BLIGH HIGH

A prograding wedge has been identified on the southeastern margin of the George Bligh High (Fig. 1). On seismic data, the form of the wedge is defined by the top basalt reflector (underlying the wedge) and the sea bed. Internal reflections, although weak, show a consistent dip away from the top of the high towards the Rockall Basin (Fig. 9). This wedge was penetrated by BGS borehole 94/7 and proved to consist of bioclastic, carbonate-rich sandstones of Mid- to Late Eocene age (McInroy et al., 2006; Stoker et al., 2012).

Analysis of the sample from borehole 94/7 (11.2-11.8 m) was hampered by the relatively small amount of siliciclastic material owing to its predominantly bioclastic composition. In total, only 33 zircons were available for analysis, of which 21 have isotopic compositions that are 90-100% concordant (Fig. 10). The majority of the concordant grains have young ages, with 14 zircons falling in the 55-64 Ma range. The young zircons display an almost Gaussian distribution (Fig. 11) with a peak at c. 57 Ma, although there is a hint of a slightly older population as well. In addition, a significant proportion of the population comprises Proterozoic and Archaean grains (Fig. 11). The concordant zircons appear to define two groups, one of Palaeoproterozoic age (1760-1930 Ma) and one of Neoarchaean-Mesoarchaean age (2760-2930 Ma), in approximately equal proportions.

DISCUSSION

Hebridean margin

The zircon spectra from wells 154/1-1 and 164/25-1, which mainly comprise a large Archaean group between 2700-2900 Ma and a subsidiary Palaeoproterozoic group in the 1700-1900 Ma range, are consistent with derivation from crystalline basement similar to that found on the Outer Hebrides massif, which consists of three of the terranes that form the Lewisian complex of NW Scotland (Fig. 12). The most northerly (Tarbert Terrane) comprises tonalite-trondhjemite-granodiorite (TTG) gneisses dated as 2800-3125 Ma, with metamorphic reworking and granite intrusion at ~ 1675 Ma (Kinny et al., 2005). The Roineabhal Terrane, located in Harris, comprises metasediments and metamafic rocks, with TTG gneisses dated as 1880 Ma (Kinny et al., 2005). The Uist block further to the south has not been as precisely dated but comprises Archaean protoliths with Proterozoic reworking (Kinny et al., 2005), similar to the Tarbert Terrane. The limited amount of data from the offshore part of the Outer Hebrides High are consistent with observations from the onshore region, where both Archaean (c. 2713 Ma, c. 2767 Ma and c. 2838 Ma) and Palaeoproterozoic (c. 1633 Ma, c. 1745 Ma and c. 1791 Ma) ages have been recorded (Ritchie et al., 2013b).

The latest Carboniferous to earliest Permian zircons in the samples from 154/1-1 and 164/25-1 probably represent derivation from lamprophyre dykes of this age that occur across northwest Scotland, such as the Loch Roag dyke on Lewis (Upton et al., 1999). The zircon dated as 433 Ma in 164/25-1 is likely to have been derived from the mid-Silurian syenite dated as c. 427 Ma recovered from the Flannan High west of Lewis (Ritchie et al., 2013b).

The discordant zircon compositions in the sample from 164/25-1 can be interpreted as being due to late Mesoproterozoic disturbance. A regression line fitted through the entire data set (Fig. 3) intersects the concordia line at 1026 ± 140 Ma and 2752 ± 55 Ma. A thermal event at ~ 1100 Ma was identified on Lewis and North Harris by Cliff and Rex (1989) on the basis of variations in Rb-Sr biotite ages. This thermal event was attributed by Imber et al. (2002) to tectonic burial of the footwall gneisses during ductile thrusting along the Outer Hebrides Fault Zone. It is possible that the discordance observed within the 164/25-1 zircon population also reflects this event.

Rockall High

The zircon age data from BGS boreholes 94/1 and 94/4 derived from Rockall High show a marked difference in character compared with sediment shed from the Hebridean margin. The abundance of c. 1800 Ma zircons in borehole 94/1 is closely comparable with data previously acquired from an Albian sandstone recovered from BGS borehole 99/2A on the Hatton High (Fig. 12), which indicated the existence of c. 1800 Ma crust on the Rockall Plateau (Morton et al., 2009). The presence of a small number of older Palaeoproterozoic zircons and a very minor c. 2900 Ma component indicates that the basement dated as c. 1800 Ma on the Rockall High may not be entirely juvenile, and may have a prehistory as far back as the Mesoarchaean. Hf isotopic compositions of zircons in the Albian sandstones from borehole 99/2A indicated a significant Archaean prehistory for the c. 1800 Ma zircons on the Hatton High (Morton et al., 2009).

The dominant zircon group in borehole 94/4 is dated as c. 1760 Ma, slightly younger than the main group in borehole 94/1. This indicates the existence of geochronological heterogeneities within the Rockall High basement. This heterogeneity is consistent with observations from the Hatton High and Edoras High (Morton et al, 2009), with zircons derived from the Edoras High being dated as c. 1750 Ma and those from the Hatton High at c. 1800 Ma. The zircons in borehole 94/4 have ages that compare well with those acquired from Rockall Bank basement samples, which yielded zircon U-Pb crystallization ages similar to that of the c. 1750 Ma Annagh Gneiss of north Mayo (Daly et al. 1995; Scanlon and Daly 2001).

The data from boreholes 94/1 and 94/4 therefore confirm that the crust underlying the Rockall High and Hatton High represents a Palaeoproterozoic terrane, apparently similar to gneisses found in Islay and Inishtrahull (Fig. 1), which are dated as c. 1780 Ma (Marcantonio et al., 1988; Daly et al., 1991). However, there are increasing indications, both from Hf and U-Pb isotopic data, that the crust in this region has a prolonged history dating back to the Archaean.

The small group of Palaeocene-Eocene zircons in borehole 94/4 is interpreted as representing input from Early Tertiary magmatic rocks on the Rockall High. The associated heavy mineral assemblage includes sodic pyroxene (aegirine) and sodic amphibole (riebeckite-arfvedsonite), which together form > 20% of the population. These minerals are characteristic of an alkaline igneous provenance and are known to occur in the Early Eocene Rockall Granite (Harrison, 1975). The Palaeocene-Eocene zircon dates from borehole 94/4 (53-60 Ma) are consistent with input from the Rockall Granite, or from equivalent alkaline intrusions elsewhere on the Rockall High.

George Bligh High

Given the small numbers of grains involved, caution is needed when interpreting the data from borehole 94/7. Nevertheless, it appears that the George Bligh High basement has both Palaeoproterozoic and Archaean crustal components. The Palaeoproterozoic zircons have closely comparable ages to those found in sediments derived from the Rockall High and Hatton High (Fig. 8), and suggests that the George Bligh High formed part of the extensive Palaeoproterozoic terrane that characterises the Rockall-Hatton area to the south and west, together with its onshore representation in Islay and Inishtrahull (Fig. 1). However, the presence of c. 2760-2930 Ma zircons indicates the basement underlying the George Bligh High also had a significant Archaean component.

The heavy mineral assemblage in borehole 94/7 includes a high proportion of minerals with alkaline igneous provenance (aegirine, aenigmatite, riebeckite-arfvedsonite and sodic-calcic amphibole), which together form nearly 50% of the population. This indicates the presence of alkaline magmatic rocks on the George Bligh High, similar to those that occur on the Rockall High, in addition to the basalts in which BGS borehole 94/7 terminated (Hitchen et al., 1997). The Palaeocene zircon age of c. 57 Ma is interpreted as representing the age of this alkaline magmatic event.

CONCLUSIONS

Detrital zircon ages from Palaeogene first-cycle sediments in the northern Rockall Basin have provided important constraints on the nature and distribution of basement terrains, as well as dating penecontemporaneous magmatic events in the region. Sediments shed westwards from the Hebridean Platform contain zircons of Archaean and Palaeoproterozoic age, consistent with derivation from rocks with Lewisian affinities. They also contain a minor Permian-Carboniferous group, which is likely to be derived from lamprophyre dykes such the Loch Roag dyke on Lewis. One sample also contains a mid-Silurian zircon, probably derived from the Flannan High. The pattern of discordance in one sample suggests that a Mesoproterozoic thermal event affected a part of the source region, supporting previous evidence for a Grenville-age event identified on the Outer Hebrides.

The zircon spectra in the two samples derived from the Rockall High are dominated by Palaeoproterozoic grains, one being dominated by a group at c. 1760 Ma and the other by a group at c. 1800 Ma. These results confirm previous data, both from direct dating of basement and from detrital zircon studies, that the crust underlying the Rockall High and Hatton High represents a Palaeoproterozoic terrane. The samples also contain a small number of Palaeocene-Eocene zircons, which together with heavy mineral evidence for input from alkaline igneous sources, can be tied back to the Rockall Granite or equivalent rocks in the Rockall High region.

Detrital zircons in sediment shed from George Bligh High have provided the first direct indications of the age of the curst underlying this area. Although only a small number of zircons were recovered from the analysed sample, the data positively identify both Palaeoproterozoic and Archaean zircons, indicating the crust beneath George Bligh High represents an Archaean terrane heavily affected by Palaeoproterozoic tectonothermal events. In addition, the zircon and associated heavy minerals indicate George Bligh High was the site of Palaeocene alkaline magmatism.

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FIGURE CAPTIONS

Fig. 1. Location map showing positions of borehole and well sites described in this paper, the distribution of Eocene prograding wedges on the eastern and western margins of the northern Rockall Basin, and of Upper Oligocene mass-flow deposits, as well as the lines of geoseismic/seismic sections illustrated in Figs 2, 5, 6 and 9. Bathymetric values in metres. Inset map shows area covered by main map, as well as expanded area (incorporating the Rockall Plateau) that is illustrated in Fig. 12. Abbreviations on inset map: EH – Edoras High; FSB, Faroe-Shetland Basin; GBH, George Bligh High; HB, Hatton Basin; HH, Hatton High; HM, Hebridean Margin; IS – Islay; MH - Malin Head (adjacent to Inishtrahull); NSB, North Sea Basin; RH, Rockall High. Adapted from McInroy et al. (2006) and Stoker et al. (2012). Structural terminology from Ritchie et al. (2013a).

Fig. 2. Schematic geoseismic profile showing location of well 164/25-1 in the West Lewis Basin, and its relationship to the Eocene prograding wedge. Profile is based on information derived from several sources including Tate et al. (1999), Isakson et al. (2000), British Geological Survey (2007) and Ritchie et al. (2013a). See Fig. 1 for location of profile.

Fig. 3. U-Pb isotopic compositions of detrital zircons derived from the Hebridean margin of the northern Rockall Basin, plotted on Wetherill concordia diagrams.

Fig. 4. Probability-density plots of zircon ages in sediment derived from the Hebridean margin of the northern Rockall Basin. Dark grey areas are zircons with 90-110% concordance, light grey areas are zircons with > 10% discordance.

Fig. 5. Illustrative seismic sections through the Eocene prograding sedimentary wedge on the eastern margin of the Rockall High, sampled by BGS boreholes 94/1 and 94/3. Borehole 94/1 sampled the collapsed outer margin of the wedge, following rapid Late Eocene deepening of the Rockall Basin; the borehole site was subsequently buried beneath onlapping, upslope-accreting, deep-water Neogene strata. See Fig. 1 for location of sections. Adapted from Stoker et al. (2001, 2012) and McInroy et al. (2006). Abbreviations: C10, Early Pliocene unconformity; C30, Late Eocene unconformity.

Fig. 6. Illustrative seismic line across the Upper Oligocene mass-flow deposit (lowstand fan) on the north-east slope of the Rockall High, sampled by BGS borehole 94/4. See Fig. 1 for location of section. Adapted from Stoker et al. (2001) and McInroy et al. (2006). Abbreviations: C10, Early Pliocene unconformity; C20, late Early/early Mid-Miocene unconformity; C30, Late Eocene unconformity.

Fig. 7. U-Pb isotopic compositions of detrital zircons derived from the Rockall High, plotted on Wetherill concordia diagrams.

Fig. 8. Probability-density plots of zircon ages in sediment derived from the Rockall High. Dark grey areas are zircons with 90-110% concordance, light grey areas are zircons with > 10% discordance.

Fig. 9. Illustrative seismic line across the Eocene prograding sedimentary wedge on the SE George Bligh High that was sampled by BGS borehole 94/7. See Fig. 1 for location of section. Adapted from McInroy et al. (2006).

Fig. 10. U-Pb isotopic compositions of detrital zircons derived from the George Bligh High, plotted on Wetherill (upper) and Tera-Wasserburg (lower) concordia diagrams.

Fig. 11. Probability-density plots of zircon ages in sediment derived from the George Bligh High. Upper diagram shows all zircons, middle diagram shows the Precambrian zircons, and the lower plot shows the Palaeocene zircons. Dark grey areas are zircons with 90-110% concordance, light grey areas are zircons with > 10% discordance.

Fig. 12. Compilation of zircon U-Pb data from the northern Rockall Basin and Rockall Plateau (Rockall High–Hatton Basin–Hatton High) areas. Locations identified as black circles are detrital age data. Locations shown as black squares are dive sites from Rockall High with zircon ages inferred from Daly et al (1995). Data from DSDP Site 555 and BGS borehole 99/2A are from Morton et al. (2009). Tarbert Terrane, Roineabhal Terrane and Uist block are from Kinny et al. (2005). Area of map is located in Fig. 1. Abbreviations: ADS, Anton Dohrn Seamount; HTS, Hebrides Terrace Seamount.

TABLE 1. LA-SF-ICP-MS U-Th-Pb dating methodology at CAF, Stellenbosch University

Laboratory & Sample Preparation	
Laboratory name	Central Analytical Facility, Stellenbosch University
Sample type / mineral	Detrital zircons
Sample preparation	Conventional mineral separation, 1 inch resin mount, 1 μm polish to finish
Imaging	CL, LEO 1430 VP, 10 nA, 15 mm working distance
Laser ablation system	
Make, Model & type	ESI/New Wave Research, UP213, Nd:YAG
Ablation cell & volume	Custom build low volume cell, volume ca.3 cm^3
Laser wavelength	213 nm
Pulse width	3 ns
Fluence	2.5 J/cm^{-2}
Repetition rate	10 Hz
Spot size	30 μm
Sampling mode / pattern	30 μm single spot analyses
Carrier gas	100% He, Ar make-up gas combined using a T-connector close to sample cell
Pre-ablation laser warm-up (background collection)	40 seconds
Ablation duration	20 seconds
Wash-out delay	30 seconds
Cell carrier gas flow	0.3 l/min He
ICP-MS Instrument	
Make, Model & type	Thermo Finnigan Element2 single collector HR-SF-ICP-MS
Sample introduction	Via conventional tubing
RF power	1100 W
Make-up gas flow	1.0 l/min Ar
Detection system	Single collector secondary electron multiplier
Masses measured	202, 204, 206, 207, 208, 232, 233, 235, 238
Integration time per peak	4 ms
Total integration time per reading	Approx. 1 sec
Sensitvity	20000 cps/ppm Pb
Dead time	16 ns
Data Processing	
Gas blank	40 second on-peak
Calibration strategy	GJ-1 used as primary reference material, Plešovice and M127 used as secondary reference material (Quality Control)
Reference Material info	M127 (Nasdala et al., 2008; Mattinson, 2010); Plešovice (Slama et al., 2008); GJ-1 (Jackson et al., 2004)
Data processing package used / Correction for LIEF	In-house spreadsheet data processing using intercept method for laser induced elemental fractionation (LIEF) correction
Mass discrimination	Standard-sample bracketing with $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ normalised to reference material GJ-1
Common-Pb correction, composition and uncertainty	204-method, Stacey and Kramers (1975) composition at the projected age of the mineral, 5% uncertainty assigned
Uncertainty level & propagation	Ages are quoted at 2 sigma absolute, propagation is by quadratic addition. Reproducibility and age uncertainty of reference material and common-Pb composition uncertainty are propagated.
Quality control / Validation	Plešovice: Wtd ave $^{206}Pb/^{238}U$ age = 337 ± 4 (2SD, MSWD = 0.2) M127: Wtd ave $^{206}Pb/^{238}U$ age = 520 ± 5 (2SD, MSWD = 0.8)
Other information	Detailed method description reported by Frei and Gerdes (2009)

Fig. 1

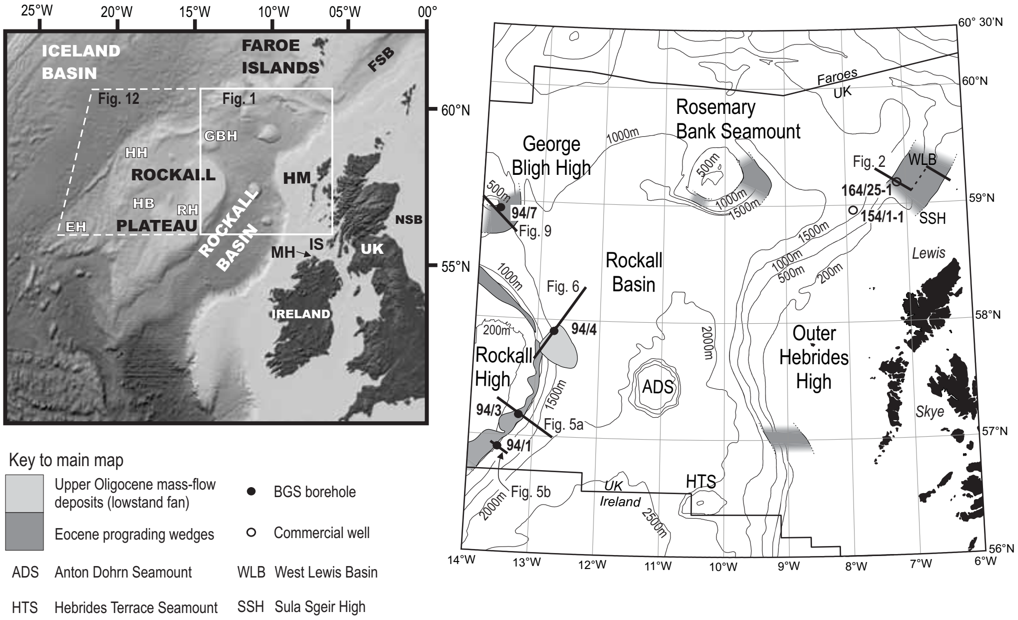
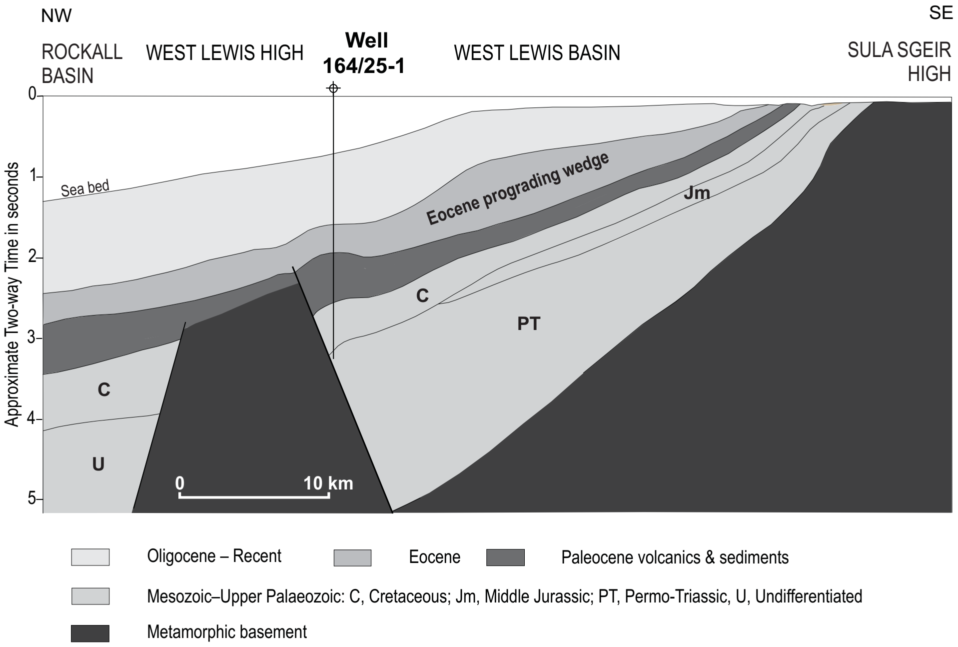
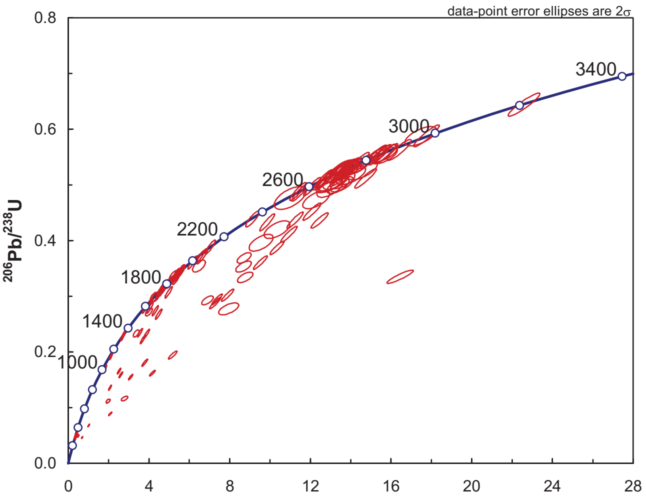
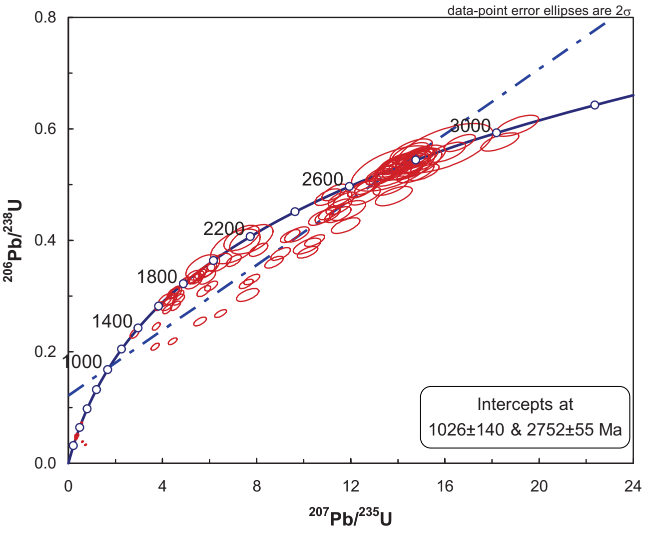
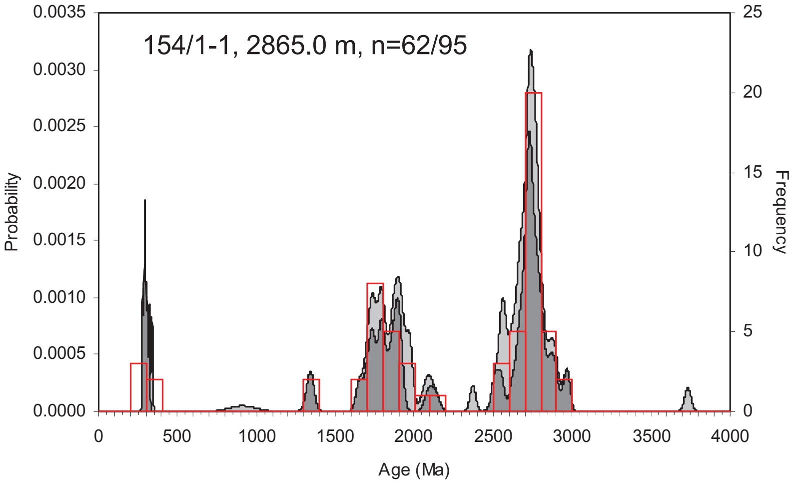

25°W
20°W
15°W
10°W
05°W
00°
60°N
55°N
ICELAND BASIN
FAROE ISLANDS
FSB
Fig. 12
Fig. 1
GBH
HH
ROCKALL
PLATEAU
HB
RH
EH
HM
ROCKALL BASIN
MH
IS
NSB
UK
IRELAND
Key to main map
Upper Oligocene mass-flow deposits (lowstand fan)
Eocene prograding wedges
BGS borehole
Commercial well
ADS Anton Dohrn Seamount
HTS Hebrides Terrace Seamount
WLB West Lewis Basin
SSH Sula Sgeir High
60° 30'N
60°N
59°N
58°N
57°N
56°N
14°W
13°W
12°W
11°W
10°W
9°W
8°W
7°W
6°W
Faroes
UK
Rosemary Bank Seamount
George Bligh High
1000m
500m
1500m
Fig. 2
WLB
164/25-1
154/1-1
SSH
94/7
Fig. 9
Rockall Basin
Lewis
Fig. 6
94/4
200m
2000m
Outer Hebrides High
Rockall High
ADS
Skye
94/3
Fig. 5a
94/1
Fig. 5b
UK
Ireland
HTS
2500m

Fig. 2


NW
SE
ROCKALL BASIN
WEST LEWIS HIGH
Well 164/25-1
WEST LEWIS BASIN
SULA SGEIR HIGH
Approximate Two-way Time in seconds
0
1
2
3
4
5
Sea bed
Eocene prograding wedge
Jm
C
PT
C
U
0
10 km
Oligocene – Recent
Eocene
Paleocene volcanics & sediments
Mesozoic–Upper Palaeozoic: C, Cretaceous; Jm, Middle Jurassic; PT, Permo-Triassic, U, Undifferentiated
Metamorphic basement


data-point error ellipses are 2σ
0.8
0.6
0.4
0.2
0.0
206Pb/238U
3400
3000
2600
2200
1800
1400
1000
0
4
8
12
16
20
24
28


data-point error ellipses are 2σ
0.8
0.6
0.4
0.2
0.0
206Pb/238U
3000
2600
2200
1800
1400
1000
Intercepts at
1026±140 & 2752±55 Ma
0
4
8
12
16
20
24
207Pb/235U


154/1-1, 2865.0 m, n=62/95
Probability
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Frequency
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)

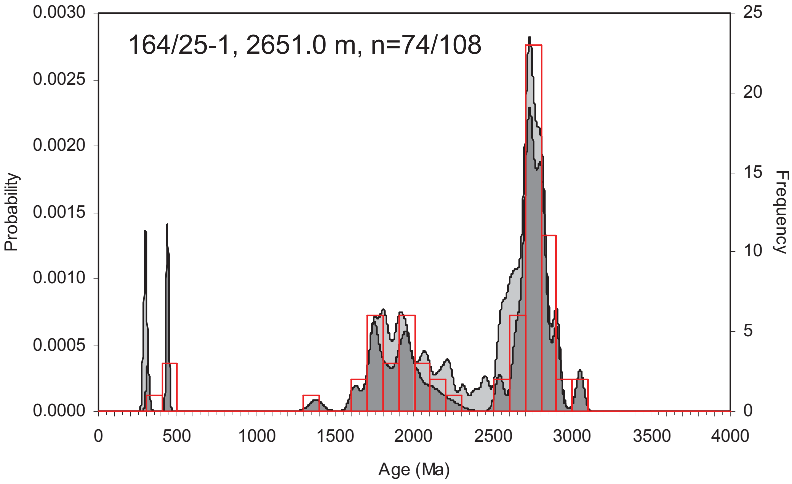

164/25-1, 2651.0 m, n=74/108
Probability
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Frequency
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)

Fig. 5

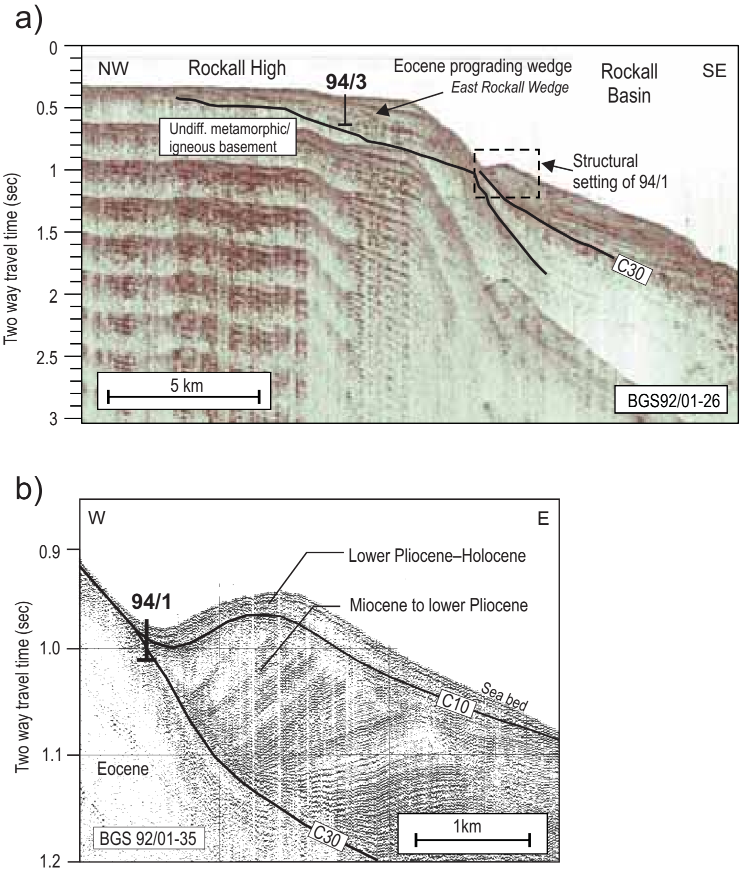
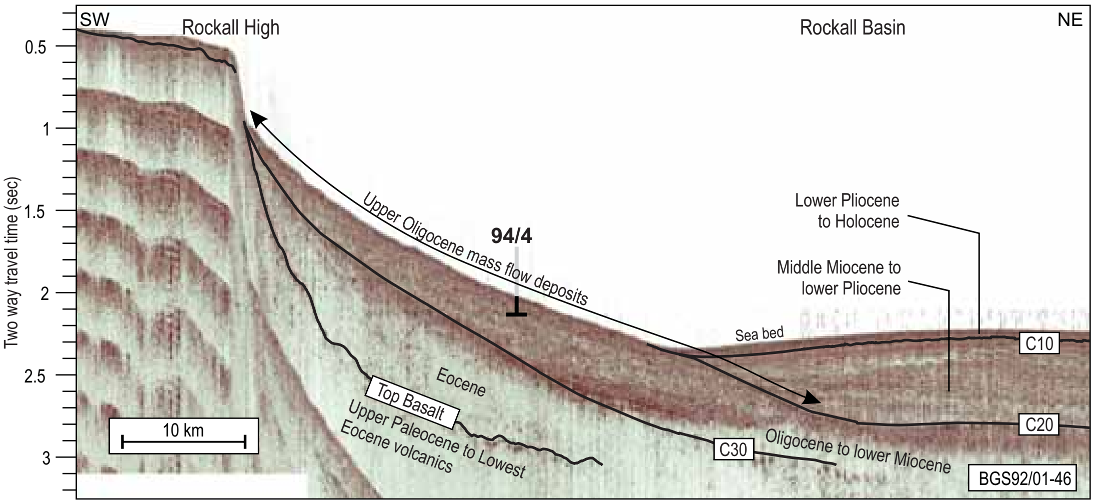
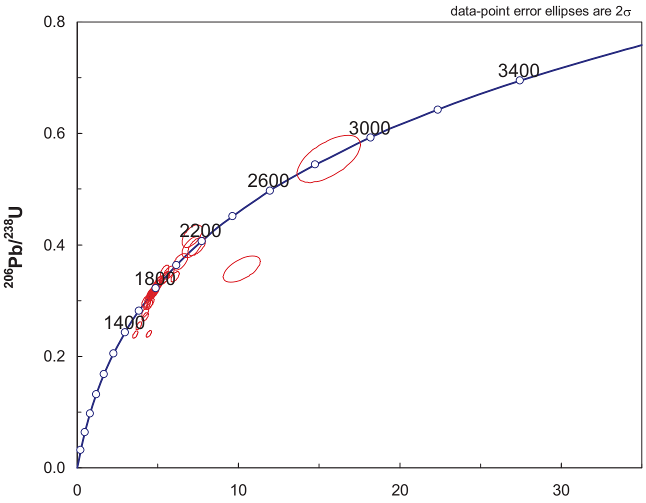
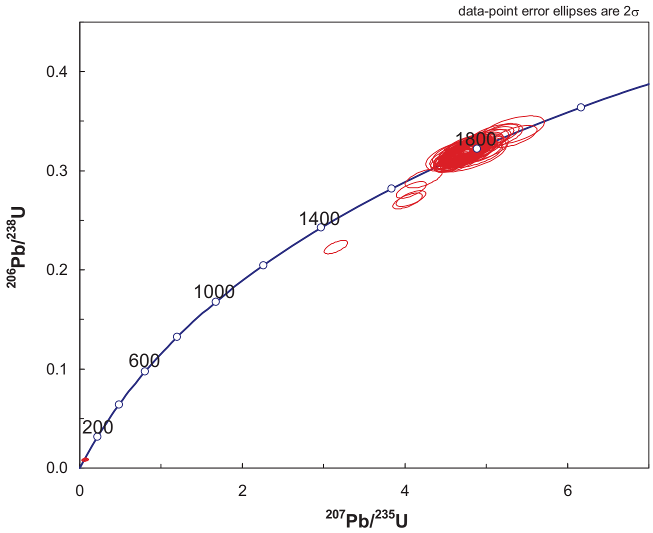
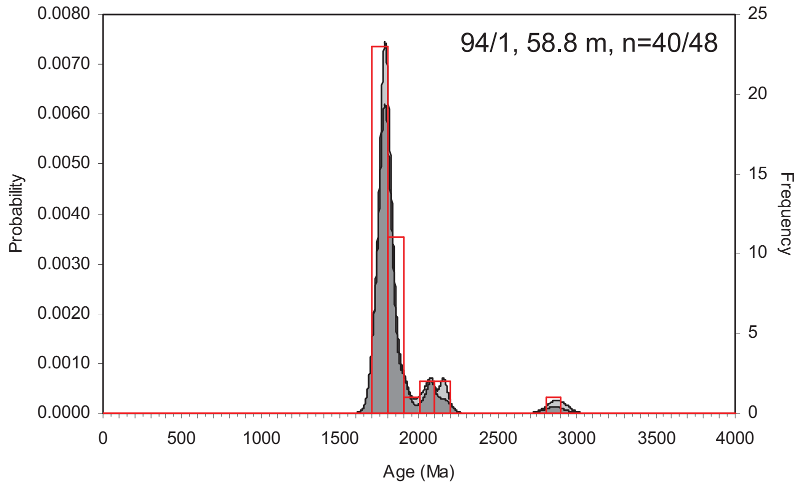

a)
NW
Rockall High
94/3
Eocene prograding wedge
East Rockall Wedge
Rockall Basin
SE
Undiff. metamorphic/ igneous basement
Structural setting of 94/1
C30
5 km
BGS92/01-26
Two way travel time (sec)
0
0.5
1
1.5
2
2.5
3
b)
W
E
Lower Pliocene–Holocene
Miocene to lower Pliocene
94/1
Sea bed
C10
C30
Eocene
BGS 92/01-35
1km
Two way travel time (sec)
0.9
1.0
1.1
1.2

Fig. 6


SW
Rockall High
Rockall Basin
NE
0.5
1
1.5
2
2.5
3
Two way travel time (sec)
Upper Oligocene mass flow deposits
94/4
Lower Pliocene to Holocene
Middle Miocene to lower Pliocene
Sea bed
C10
C20
Eocene
Top Basalt
Upper Paleocene to Lowest Eocene volcanics
C30
Oligocene to lower Miocene
10 km
BGS92/01-46


data-point error ellipses are 2σ
0.8
0.6
0.4
0.2
0.0
206Pb/238U
3400
3000
2600
2200
1800
1400
0
10
20
30


data-point error ellipses are 2σ
0.4
0.3
0.2
0.1
0.0
206Pb/238U
1800
1400
1000
600
200
0
2
4
6
207Pb/235U


94/1, 58.8 m, n=40/48
Probability
0.0080
0.0070
0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
Frequency
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)

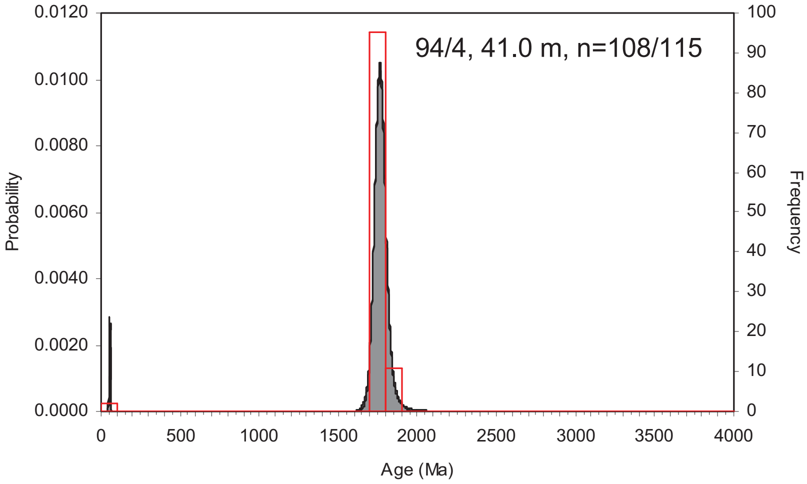
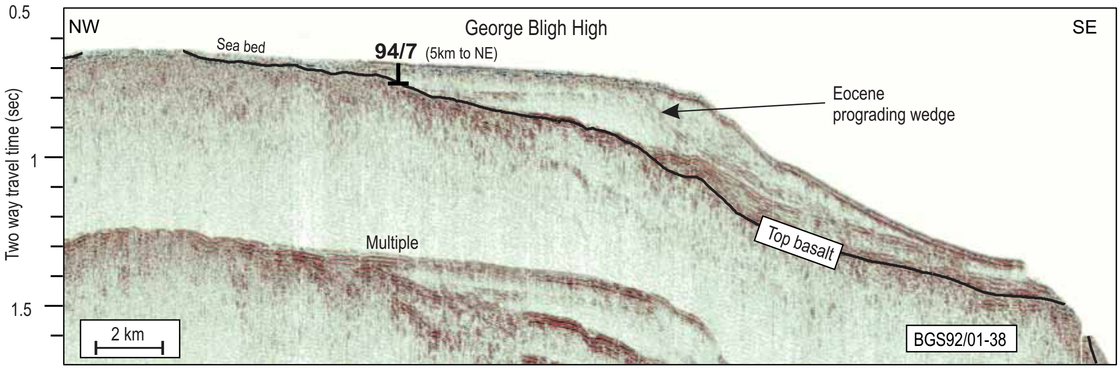
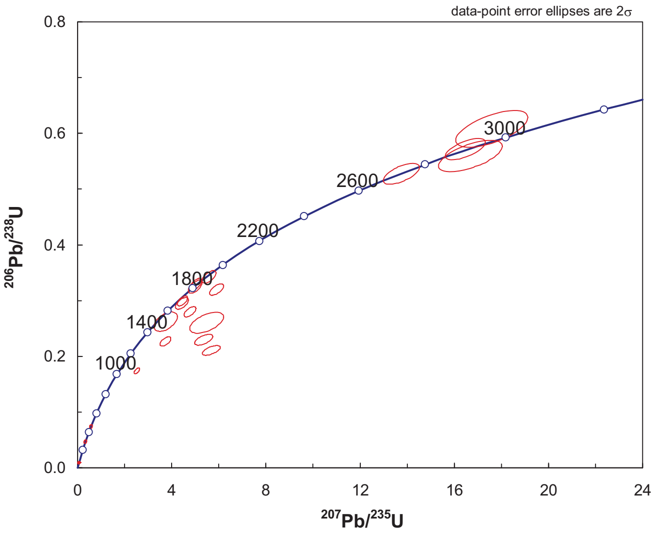
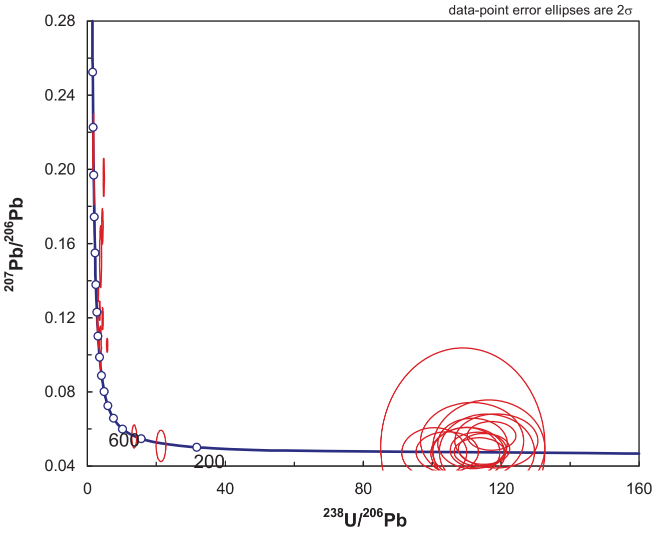
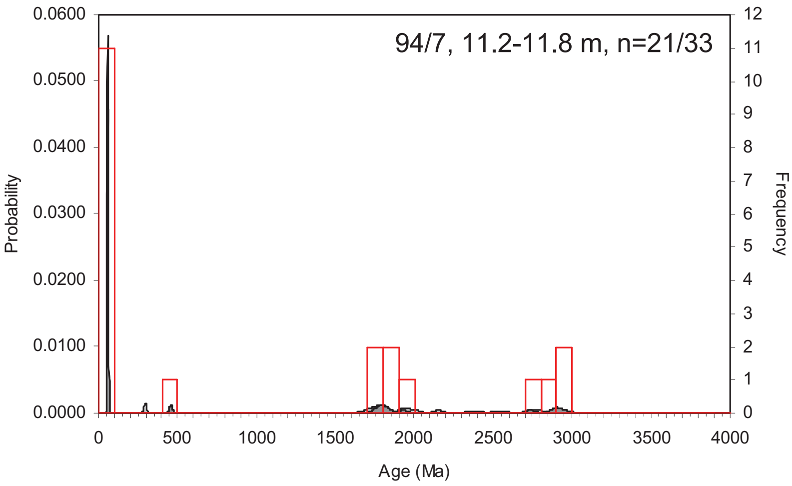

94/4, 41.0 m, n=108/115
Probability
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
Frequency
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)

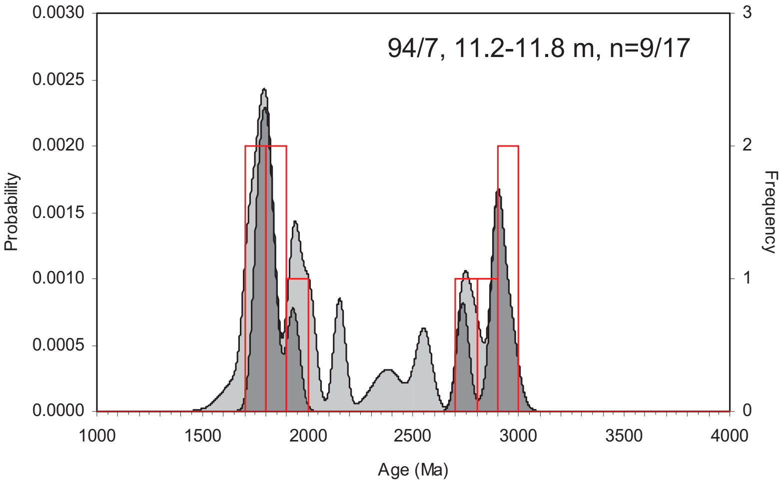
Fig. 9


0.5
1
1.5
Two way travel time (sec)
NW
George Bligh High
SE
Sea bed
94/7 (5km to NE)
Eocene
prograding wedge
Top basalt
Multiple
2 km
BGS92/01-38


data-point error ellipses are 2σ
0.8
0.6
0.4
0.2
0.0
^{206}Pb/^{238}U
3000
2600
2200
1800
1400
1000
0
4
8
12
16
20
24
^{207}Pb/^{235}U


data-point error ellipses are 2σ
0.28
0.24
0.20
0.16
0.12
0.08
0.04
^{207}Pb/^{206}Pb
600
200
0
40
80
120
160
^{238}U/^{206}Pb


94/7, 11.2-11.8 m, n=21/33
Probability
0.0600
0.0500
0.0400
0.0300
0.0200
0.0100
0.0000
Frequency
12
11
10
9
8
7
6
5
4
3
2
1
0
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)


94/7, 11.2-11.8 m, n=9/17
Probability
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
Frequency
3
2
1
0
1000
1500
2000
2500
3000
3500
4000
Age (Ma)

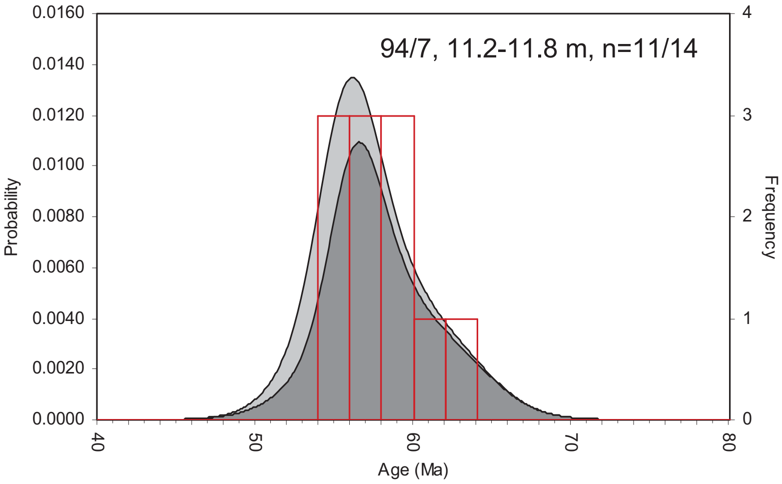
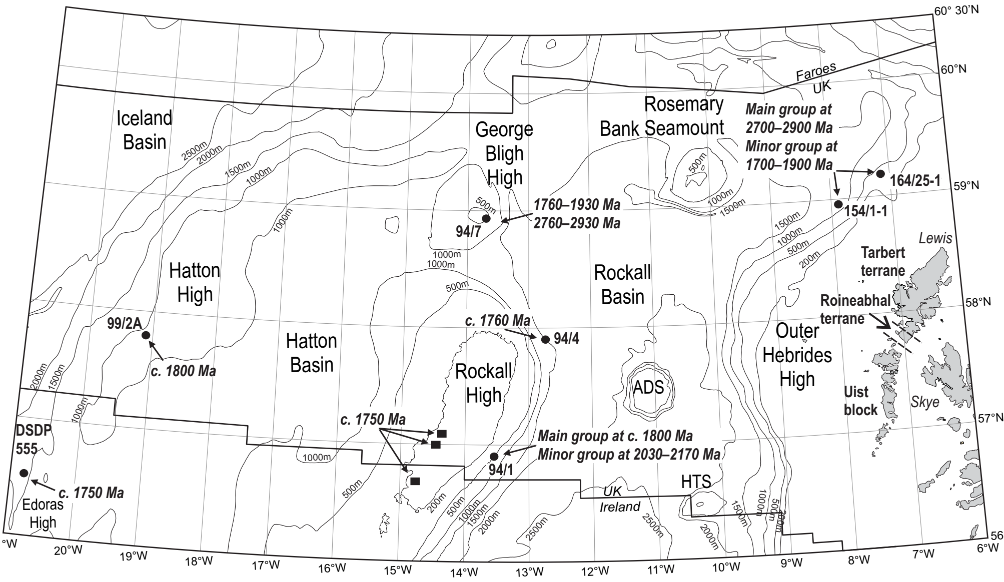

94/7, 11.2-11.8 m, n=11/14
Probability
0.0160
0.0140
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
Frequency
4
3
2
1
0
40
50
60
70
80
Age (Ma)

Fig. 12


60° 30'N
60°N
59°N
58°N
57°N
56°N
Faroes
UK
Iceland Basin
George Bligh High
Rosemary Bank Seamount
Main group at 2700–2900 Ma
Minor group at 1700–1900 Ma
164/25-1
154/1-1
1760–1930 Ma
2760–2930 Ma
94/7
Hatton High
Rockall Basin
Lewis
Tarbert terrane
Roineabhal terrane
99/2A
c. 1800 Ma
Hatton Basin
c. 1760 Ma
94/4
Rockall High
ADS
Outer Hebrides High
Uist block
Skye
DSDP 555
c. 1750 Ma
c. 1750 Ma
Main group at c. 1800 Ma
Minor group at 2030–2170 Ma
94/1
Edoras High
HTS
UK
Ireland
2500m
2000m
1500m
1000m
500m
200m
21°W
20°W
19°W
18°W
17°W
16°W
15°W
14°W
13°W
12°W
11°W
10°W
9°W
8°W
7°W
6°W