Provenance of the Highland Border Complex: constraints on Laurentian margin accretion in the Scottish Caledonides

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Abstract

Contrasting tectonic models for the Highland Border Complex in the Scottish Caledonides view it either as part of the rifted Laurentian margin of the Iapetus Ocean or as an oceanic terrane. Detrital zircon data from sandstones of the complex yield age peaks at 2.8-2.6, 1.3 and 1.1-1.0 Ga and minor peaks of ~1.7-1.9 Ga. These characteristics compare closely with the upper Dalradian Supergroup of the adjacent Grampian terrane, and with the record of eastern Laurentia. The data are also consistent with the Laurentian provenance indicated by palaeontological evidence from the complex, and field evidence for continuity with the Dalradian Supergroup. Detrital ages for the Cambrian Salterella Grit of the Caledonian foreland compare with that for approximately age-equivalent sandstone from the Highland Border Complex. Both were contemporaneous with the regressive Hawke Bay event, accounting for similarities in provenance, and further linking the Highland Border Complex to Laurentia. The Grampian terrane was being uplifted and shedding detritus throughout the Ordovician and Silurian. The absence of this event from the

detrital zircon records of either the Midland Valley or Southern Upland terranes, suggests that these blocks cannot have been in their current location relative to the Grampian terrane before the end Silurian.

Introduction

Establishing the existence and origin of lithotectonic successions (terranes) outboard of the continental margin within orogenic belts requires a variety of data sets, including stratigraphic, biogeographic, geochronological, geochemical and paleomagnetic. Increasingly, detrital zircon data, for which tens of thousands of analyses are now available worldwide, are being used to characterize the nature of the foreland source regions, which then provides a basis for comparison with the detrital zircon records of internal terranes. Such comparisons provide a benchmark to constrain the potential degree of allochthoneity of terranes and the paleogeography of lithotectonic elements of the orogen (e.g. Gehrels *et al.* 1995, 1996; Colpron & Nelson 2009).

In this paper detrital zircon data are used to assess the provenance and tectonic setting of the Highland Border Complex, a controversial sequence of sedimentary and igneous rocks within the Scottish Caledonides. The Highland Border Complex in Scotland occurs along the junction between the Grampian and Midland Valley terranes (Fig. 1; Bluck 1983, 1984 and references therein), and correlative lithologies may also be exposed along strike in the same structural setting in west Ireland (Chew 2003). The Grampian terrane is underlain mainly by a thick sequence of deformed and metamorphosed mid-Neoproterozoic to early Ordovician shallow- and deep-water sedimentary and volcanic rocks, the Dalradian Supergroup. Deposition occurred on the eastern margin of Laurentia during the breakup of Rodinia and evolution of the Iapetus Ocean (Anderton 1985; Harris *et al*. 1994; Strachan *et al*. 2002; Leslie *et al*.

2008). In contrast, the Midland Valley terrane to the southeast is thought to be underlain by a volcanic arc that developed in the Iapetus Ocean and collided with the Laurentian margin during the mid-Ordovician Grampian orogenic event (Lambert & McKerrow 1976; Dewey & Shackleton 1984; Dewey & Ryan 1990; Bluck 2002). The intervening Highland Boundary Fault is currently interpreted as a steep reverse fault that formed during the Devonian, and presumably obscures an older Ordovician suture between Laurentia and the oceanic terranes (Tanner 2008; cf. Soper & Hutton 1984; Dewey & Strachan 2003). The low-grade Ordovician to Silurian sedimentary rocks of the Southern Uplands terrane farther to the southeast represent an accretionary prism developed above a NW-dipping subduction zone (McKerrow *et al.* 1977; Leggett *et al*. 1979; Stone & Merriman 2004).

The Highland Border Complex occupies a zone <1.3 km wide and 250 km long, located adjacent to the Highland Boundary Fault and between the Dalradian Supergroup to the northwest and an unconformable cover of late Silurian-Devonian strata (Old Red Sandstone facies) to the southeast (Fig. 1). It consists of a diverse sequence of weakly deformed, low-grade metasedimentary rocks of Cambrian-Ordovician age, associated locally with pillow lavas and with ultramafic rocks of the Highland Border Ophiolite. Two contrasting tectonic models have been proposed for the Highland Border Complex. One views it as an exotic oceanic terrane that was once considerably separated from the Dalradian Supergroup (Curry *et al*. 1984; Bluck 2002), whereas the other divides it into two parts: a newly defined Trossachs Group, viewed as the youngest part of the Dalradian Supergroup, and the allochthonous Highland Border Ophiolite (Tanner & Sutherland 2007).

In order to test these conflicting models, we present analyses of detrital zircons obtained from four samples from the Highland Border Complex and compare them with published data-sets from the Dalradian Supergroup (Cawood *et al*. 2003). In addition, we present new detrital zircon data from a sample of the Cambro-Ordovician shallow-water sedimentary succession that accumulated on the Hebridean foreland of the Scottish Caledonides (Fig. 1). This succession is broadly time-equivalent to upper deep-water parts of the Dalradian Supergroup as well as the Highland Border Complex. Its provenance is relevant to the origins of the latter as well as informing wider debate on basin evolution and sedimentary drainage patterns on the Laurentian margin (Cawood *et al*. 2007a, b). We then integrate our results into a brief overview of the assembly and accretion of terranes onto the margin of Laurentia.

Geological setting of the Highland Border Complex

The stratigraphical succession and age of the Highland Border Complex and its relationship to the Dalradian Supergroup are highly controversial issues (Curry *et al.* 1984; Bluck 1983, 1984, 1985, 1990; 2002, 2010, 2011; Bluck *et al.* 1992; Tanner 1995, 1997, 1998, 2011; Bluck & Ingham 1997; Tanner & Pringle 1999; Tanner & Sutherland 2007). The rationale behind the view that the Highland Border Complex developed as an exotic oceanic terrane some distance from the Laurentian margin can be summarised as follows (Tanner & Sutherland 2007). Radiometric and palaeontological data available in the 1980s showed that the Dalradian Supergroup was undergoing post-orogenic uplift and rapidly shedding detritus at the same time as the (now contiguous) Dounans Limestone in the Highland Border Complex at Aberfoyle with an Arenig (~470 Ma) fauna, was being deposited (Curry *et al.* 1984; Bluck 1985, 1990; Bluck *et al.* 1992). The Highland Border Complex was thought to be underlain by an ophiolite, and as the structurally overlying Cambrian-Upper

Ordovician sequence contained no Dalradian detritus, it was concluded that these sediments were deposited far from the Laurentian margin. According to this model, the Highland Border Complex was first proximal to the Dalradian Supergroup in late Silurian-early Devonian times after the former had been deformed and metamorphosed during the mid-Ordovician Grampian orogenic event. The spatial distribution of stratigraphical ages across the Highland Border Complex outcrop, mainly from chitinozoa, appeared to show that it youngs towards the Dalradian (Bluck 2002).

In contrast to the exotic terrane model, the possibility of stratigraphical (and structural) continuity between undoubted Dalradian rocks and the Highland Border Complex was first recognised by Clough (cited by Geikie 1897) and developed by Johnson & Harris (1967). The case for this interpretation was strengthened further as follows.

1) Way-up structures, although uncommon, invariably show that the Highland Border Complex youngs away from the Dalradian Supergroup (e.g. Tanner 1995, see however Bluck 2002, 2010, 2011). For example, Tanner (1995) demonstrated that at Keltie Water, the Ben Ledi Grits (Southern Highland Group) are in stratigraphic continuity, albeit with a possible cryptic non-conformity, with the Keltie Water Grit Formation (formerly Highland Border Complex), which includes the Lower Cambrian Leny Limestone. There is also evidence for stratigraphical continuity between the Dalradian rocks and the Highland Border Complex at Glen Sannox, Isle of Arran and the River North Esk (Fig. 2; Tanner 1995).
2) Throughout the Highland Border Complex and the adjacent Dalradian rocks of the ‘steep belt’, the early penetrative cleavage has the same relationship to

bedding: S1 faces down irrespective of whether the rocks are right-way-up or have been inverted by later D4 folding (Tanner 1995, see also Johnson & Harris 1967). It follows from this that the Highland Border Ophiolite is located at the *structural top* of the Highland Border Complex. .

3) Re-assessment of the supposed chitinozoa featured in publications on the Highland Border Complex (Burton et al. 1983), has concluded that this evidence is unreliable (Tanner & Sutherland 2007). It remains the case that precisely constrained stratigraphical ages are available for only three localities, at each of which the fossil faunas have Laurentian affinities. Trilobites from the Leny Limestone at Callander (Fig. 2) yielded a late Early Cambrian (~515 Ma) age; trilobites and conodonts from the Dounans Limestone at Aberfoyle (Fig. 2) gave a middle Arenig (~470 Ma) age (Rushton & Owen 1999); and the conodonts from the Margie Limestone of the River North Esk gave a late Tremadocian to lowermost Arenig age (Ethington 2008). Consequently, there are no sedimentary rocks of proven age younger than Arenig in the Highland Border Complex (Tanner & Sutherland 2007).

4) The results of modern isotopic dating indicate that the Grampian orogenic event was relatively short-lived and occurred at 475-465 Ma (Oliver et al. 2000; Chew *et al.* 2010 and references therein). This is consistent with the palaeontological evidence that the Trossachs Group does not include any strata younger than the Arenig. Published Cambrian to early Ordovician K-Ar and Rb-Sr mineral ages obtained from the Dalradian Supergroup (Dempster 1985; Dempster *et al.* 1995) are likely unreliable and of uncertain significance (Evans & Soper 1997; Tanner & Pringle 1999).

Given the unreliability of the chitinozoan ages, recognition that the Highland Border Ophiolite lies at the top of the Highland Border Complex, and tighter constraints on the age of the Grampian orogenic event, a radically different stratigraphical template of the sequence has emerged (Fig 3; Tanner & Sutherland 2007). In this model, the Highland Border Complex is now divided into two parts (Figs 2, 3): an older Trossachs Group in continuity with, and part of, the Dalradian but probably containing undetected unconformities and/or non-conformities, and an upper sequence comprising the obducted ophiolite.

Recent reappraisal of the Highland Border Ophiolite has concluded that much of it comprises serpentinized continental mantle and associated sediments, which formed part of the floor to an extended Dalradian basin, and was thrust on to the Trossachs Group immediately prior to the start of the Grampian orogeny (Tanner 2007: Henderson *et al.* 2009). The ophiolite is thus likely to have formed at the rift-drift transition of the Iapetan rifting cycle, which on the basis of regional considerations probably occurred at ~540 Ma (Cawood *et al.* 2001). However, this new view of the 'ophiolite' is not critical to the current debate concerning the affinities of the sedimentary rocks assigned to the Trossachs Group by Tanner & Sutherland (2007).

Geology of the Cambro-Ordovician succession on the Laurentian foreland in Scotland

Passive margin strata related to the final break-up of Rodinia are represented by the Cambrian to Ordovician sedimentary rocks in the Hebridean (Laurentian) foreland of Scotland, northwest of the Moine Thrust (Fig. 1; Park *et al.* 2002 and references therein). The succession ranges in age from Early Cambrian to Middle Ordovician. It can be divided into a lower, mainly clastic part, the Ardvreck Group (~250 m thick), and an upper carbonate sequence, the Durness Group (~750 m thick). The Ardvreck Group is Early Cambrian and composed of the Eriboll and An t-Sron formations (Fig. 3), each of which consists of two members. The oldest unit, the 75-125 m thick Basal Quartzite Member of the Eriboll Formation, is a feldspathic to quartzitic sandstone with locally abundant cross-bedding (McKie 1990). The overlying 75-100 m thick Pipe Rock Member is a quartz arenite characterised by abundant *Skolithos* burrows. The An t-Sron Formation consists of the lower dolomitic siltstones of the Fucoid Beds, 12-27 m thick, and the upper quartz arenites of the Salterella Grit, up to 20 m thick. The Fucoid Beds contain Early Cambrian *Olenellus* trilobites and brachiopods which indicate an absolute age of ~520 Ma (Prigmore & Rushton 1999). The Ardvreck Group has been interpreted by McKie (1990) as a transgressive sequence of barrier island to tidal shelf arenites (Eriboll Formation) overlain by storm-dominated clastic carbonate sediments (Fucoid Bed) and regressive sandsheets (Salterella Grit).

The Ardvreck Group is interpreted to be time-equivalent to the deep-water (meta) sedimentary rocks of parts of the Southern Highland Group and the Highland Border Complex. In particular, the Salterella Grit is essentially the same late Lower Cambrian age (~515 Ma; Smith & Rasmussen 2008) as the Leny Limestone (Fig. 3). Strachan & Holdsworth (2000) suggested that the foreland succession and the upper parts of the Southern Highland Group and the Highland Border Complex represent, respectively, shallower and deeper parts of the same passive margin basin. Detrital zircon data from the Ardvreck Group has so far been published only from the Eriboll Formation (Cawood *et al.* 2007b).

Sample descriptions

Five samples were collected for detrital zircon analysis: three from the Highland Border Complex (Trossachs Group); one from the Highland Border Ophiolite; and one from the Cambrian succession of NW Scotland. In order of inferred decreasing ages they are as follows:

Sample **A266** is a reddish-brown sub-litharenite sampled from the Highland Border Ophiolite in the Loch Ard Forest, near Aberfoyle (Fig. 2) [NN 46808 96083]. This sample was taken from a stratified arenite that lies between the banded amphibolite at the base of the ophiolite, and a thick unit of serpentine conglomerate that constitutes the main body of the ophiolite. An approximate age of ~540 Ma is inferred on the basis of the suggested age of formation of the ophiolite (see above), which formed part of the floor of the Dalradian basin. The sample consists of irregularly shaped, unsorted, matrix-supported quartz and lithic clasts (to 1.5 mm) set in a matrix of sericite, with stringers and patches of indeterminate opaque material, some of which appears to be oxidized serpentinite. The lithic clasts consist largely of mosaic or multi-grain quartz or of dark, unidentified material.

Sample **A265** is a grey psammite from the transition between the Southern Highland Group and the Trossachs Group in the Loch Ard Forest, near Aberfoyle (Figs. 2, 3) [NN 45579 96150]. This sample is inferred to be slightly older than the Lower Cambrian Leny Limestone, and is included because it further extends the vertical range of Dalradian strata from which detrital zircon analyses have been obtained (Cawood *et al*. 2003). This rock consists of quartz clasts (0.1 – 0.2 mm across) with some plagioclase grains, set in a matrix of sericite, chlorite, quartz, plagioclase and opaque minerals. Also present are numerous flakes of detrital white mica, of the same size as the quartz grains.

Sample **A472** is an arenite from the topmost part of the Lower Keltie Water Formation. It lies stratigraphically immediately below the late Lower Cambrian (~515 Ma) Leny Limestone of the Trossachs Group in Leny Quarry near Callander (Figs. 2, 3) [NN 6157 0988]. This sample is clast-supported and consists of quartz and plagioclase (to 0.5 mm across) accompanied by detrital white mica of the same size and set in a matrix that consists largely of sericite, quartz, plagioclase and opaque grains.

Sample **SG07** was collected from the middle of the late Lower Cambrian Salterella Grit (~515 Ma) on the east shore of Loch Eriboll (Fig. 1) [NC 4416 5807]. The sample is a grey, medium-grained, equigranular quartz sandstone. It is clast-supported and consists mainly of sub-rounded grains of quartz with interstitial carbonate cement.

Sample **NE148** is a quartz arenite from the Lower Margie Grit in the River North Esk, near Edzell (Fig. 2) [NO 58663 73310]. The sample was taken from immediately southeast of, and stratigraphically above, the Margie Limestone from which a conodont assemblage of uppermost Tremadoc to lowermost Floian (~478 Ma) was reported by Ethington (2008). This sample consists of sub-angular quartz clasts (to 0.5mm) and detrital white micas of similar size, set in a carbonate-dominated matrix. There are some lithic grains, mainly of composite quartz.

Analytical procedures

For each sample, 1 to 5 kg of rock was crushed and the zircons were extracted using LST heavy liquid and Frantz magnetic separator. From the non-magnetic, heavy fraction of each sample, approximately 100 zircons were selected by hand picking under binocular and mounted in an epoxy resin. The mounts were polished to expose the interior of the zircons. All the grains were investigated to characterize the possible internal structures by cathodoluminescence imaging (CL) using a Philips XL 30 scanning electron microscope at Curtin University. The acceleration voltage applied during the several sessions, ranged between 12 and 20 KV. The U-Pb dating work was performed with a high-resolution ion microprobe (Shrimp II instrument) at Curtin University. The analytical conditions were identical to those described by Compston *et al.* (1984), Nelson (1997) and Williams (1998). The samples were analysed over several sessions during which the intensity of the O^{2-} primary beam was set between 0.8 nA and 5.3 nA. Pb/U and Pb/Th calibration was performed relative to the 556 Ma-old CZ3 zircon standard (Pidgeon *et al.* 1994) which was analyzed after every five unknowns throughout the analytical session. The raw data were reduced using the Squid macro (Ludwig, 2001) and the plots made with Isoplot (Ludwig, 2003). Common Pb was corrected for by using ^{204}Pb using the present-day terrestrial ratios from Stacey & Kramer (1975). Although less precise than corrections based on ^{207}Pb or ^{208}Pb for young zircons, this correction can be applied to both old and young grains and hence results in consistency of data treatment. The errors were calculated by propagating analytical uncertainties and are shown as 1-sigma level.

The number of scans of each mass for a single analysis was reduced from seven to five in order to investigate approximately 50-60 grains during each session. This number of analysed grains provides a 95% probability of finding any population that makes up 5% of the total (Dodson *et al.* 1988). Considering that the main purpose of this work is to decipher the provenance of the zircons, the cores of the grains were preferentially investigated.

Results

Concordia and frequency distribution plots for the individual samples are presented in Figures 4 and 5. The complete analytical data set can be obtained from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK as Supplementary Publication No. SUPxxx (yy pp.). It is also available online at http://www.geolsoc.org.uk/SUPxxx. The probability density distribution diagrams of the ages have been constructed following the methodology of Nemchin & Cawood (2005). This involves double weighting of the data based on the probability of concordance and errors highlighting the most concordant data.

The grains extracted from the samples have an average size of 150 µm, with occasional grains exceeding 200 µm in length. The grains display smoothed faces with a length-width ratio of 2:1. Rounded morphologies are common excepting in sample SG07 where they are dominant. The cathodoluminescence images revealed a large range of internal structures. Oscillatory zoning indicative of a magmatic origin is common but complex growth patterns reflecting local resorbtion also occur. Faint zoning and multi-stage dissolution and growth zoning features are widely observed. Homogeneous, dark, zoned grains are rare.

Sample A266 (arenite from Highland Border ophiolite)

55 analyses were made in 53 grains with ages ranging from 962 ± 17 Ma ($^{206}Pb/^{238}U$ age, 1σ) to 3208 ± 16 Ma ($^{207}Pb/^{206}Pb$ age, 1σ). The uranium and thorium content and the Th/U ratio are generally in the range of igneous zircons (U = 24-608 ppm, Th = 1-235 ppm, Th/U = 0.23-1.89 with only one analysis having a Th/U = 0.01) and variations are not related to the age of the grains.

Six analyses have discordance higher than 10%. On the frequency distribution diagram (Fig. 5), two main peaks are centred at ~1050 Ma and ~2700 Ma. Subordinate peaks occur at 1350 Ma, 2350 Ma, 2950 Ma and 3200 Ma.

Sample A265 (psammite from transition between Southern Highland and Trossachs groups)

42 analyses were made on 38 grains. The uranium content of the grains ranges from 25 to 965 ppm, the thorium content from 13 to 808 ppm and the Th/U ratio is generally from 0.28 to 1.31, which overlaps the range of expected values for magmatic zircons. Three analyses with a Th/U lower than 0.28 (~ 0.055) display very high discordance. No correlation between the chemical composition and age was observed.

Ages of detrital zircon grains range from 621 ± 16 Ma (^{206}Pb/^{238}U age, 1σ) to 2901 ± 5 Ma (^{207}Pb/^{206}Pb age, 1σ). Nineteen analyses display discordance higher than 10%. Following the procedure of Nemchin & Cawood (2005), the frequency diagram (Fig. 5) shows four main peaks at ca. 600 Ma, 1050 Ma, 1400 Ma and 2700 Ma. Two minor peaks are observable at 1200 Ma and 1700 Ma.

Sample A472 (arenite adjacent to Leny Limestone)

55 analyses were made on 53 grains from sample A472. Uranium and thorium contents (16-546 ppm and 5-294 ppm respectively) and their Th/U ratios (main range: 0.23-1.88 with three outliers) are similar to those of the other samples.

The ages range from 1158 ± 15 Ma (^{206}Pb/^{238}U age, 1σ) to 2973 ± 9 Ma (^{207}Pb/^{206}Pb age, 1σ) with only seven analyses having discordance higher than 10%. On a Concordia diagram (Fig. 4), the analyses plot close the curve in three groups at

~1200 Ma, ~2000 Ma and ~2800 Ma. On the frequency plot two main populations are present at ~2000 Ma and ~2700 Ma but with ages spread over 400 Ma (Fig. 5). Three minor peaks can be distinguished at ~1050 Ma, ~1450 Ma and ~1700 Ma.

Sample SG07 (Salterella Grit sandstone)

60 analyses were performed in 55 grains from sample SG07 and yielded ages ranging from 1758 ± 27 Ma (^{207}Pb/^{206}Pb, 1σ) to 2917 ± 26 Ma (^{207}Pb/^{206}Pb, 1σ). Uranium and thorium contents and Th/U ratios (13-308 ppm, 7-262 ppm and 0.12-2.20, respectively) are similar to those from the other samples analysed. Only one sample displays discordance higher than 10 %. The remaining analyses plot on the Concordia curve forming a spread from 1800 Ma to 2900 Ma (Fig. 4). On the probability density distribution diagram, analyses show a main peak at 1800 Ma with a series of minor peaks between 2100 Ma and 2850 Ma (2100 Ma, 2400 Ma, 2550 Ma, 2700, 2850 Ma), each corresponding to only a few analyses (Fig. 5).

Sample NE148 (Margie Grit sandstone)

Uranium concentrations of the 65 analyses from 63 grains largely range from 20 to 280 ppm, with one analysis having a concentration reaching 600 ppm, and thorium content ranges from 4 to 262 ppm. The Th/U ratio varies from 0.24 to 2.90 which overlaps the range of expected values for magmatic zircons. No obvious variations of the U and Th content and Th/U ratio correlated to the calculated age are observed, which range from 1004 ± 34 Ma (^{206}Pb/^{238}U age, 1σ) to 3650 ± 7 Ma (^{207}Pb/^{206}Pb age, 1σ). Plotted on a Concordia diagram (Fig. 4), the analyses plot close to the Concordia curve, displaying 2 groups (Fig. 4). Only eight analyses display discordance higher than 10%. On the frequency diagram, there are two main age populations at ~1100 Ma and ~2600 Ma with subordinate peaks occurring at 600 Ma and 1400 Ma (Fig. 5).

Discussion

The detrital zircon age spectra obtained for the Trossachs Group have a number of features in common. Overall they are characterized by age peaks at 2.8-2.6, 1.3 and 1.1-1.0 Ga along with variable amplitude peaks in the range 1.7-1.9 Ga (Fig. 5). Rare Palaeoarchaean grains are present in some samples. These gross characteristics compare closely to those of the upper Dalradian Supergroup, notably the Green Beds sample from the Southern Highland Group (Fig. 6), and with major periods of crust generation and orogenic activity within eastern Laurentia (e.g. Hoffman 1989). The age spectrum is entirely distinct from that associated with early Palaeozoic successions derived from Gondwana that occur within the Caledonian-Appalachian orogen elsewhere (Schofield & Waldron 2011 and references therein). The data is therefore consistent with a Laurentian provenance for the Trossachs Group, as indicated by the palaeontological evidence, and with the interpretation that this lies in stratigraphic continuity with the Southern Highland Group, and is therefore part of the Dalradian Supergroup (Tanner & Sutherland 2007).

There is no published palaeocurrent data available for the Trossachs Group. However, evidence from some of the underlying Dalradian Supergroup shows that it was supplied by sustained flow parallel to the Laurentian shoreline, along the basin axis from the southwest (Anderton 1985). In this context, the overall age range of detritus is consistent with derivation from the Laurentian foreland, especially the Labrador-Greenland region (Cawood *et al.* 2003). Archaean detritus overlaps with that of Archaean cratons, notably the Superior, and the variable proportions of

Palaeoproterozoic detritus corresponds to the timing of suturing of Archaean cratons by a series of orogenic belts (Ketilidian-Makkovik, New Quebec, Nagssugtoqidian, Torngat belts). Mesoproterozoic detritus is consistent with derivation from the Grenville Orogen. The presence of detrital age peaks in the late Palaeoproterozoic and early Mesoproterozoic (1.8-1.5 Ga) and the evidence for a tectonothermal event between 1.2-1.0 Ga is typical of the Labrador-southern Greenland region of eastern Laurentia (Cawood *et al.* 2003). The few grains with late Neoproterozoic ages in two samples (A265 & NE148) were probably derived from magmatism associated with rifting along the east Laurentian margin associated with opening of the Iapetus ocean (Cawood *et al.* 2001, 2003).

The detrital age spectrum for the sample of Salterella Grit (SG07) obtained from the Caledonian foreland in Scotland contains minor Neoarchaean peaks between 2.9 and 2.5 Ga, a significant Palaeoproterozoic peak at 1.8 Ga, as well as minor peaks at 2.4, 2.2 and 2.0 Ga (Fig. 5). The new data continues the broad upward trends evident within the Eriboll Formation, *viz* a gradual reduction in the proportion of Archaean detritus, and a corresponding increase in the amount of Palaeoproterozoic material (Cawood *et al.* 2007b). Palaeocurrent data indicate an overall southeasterly palaeoflow with some evidence for bimodal northeasterly and southeasterly flow (McKie 1990). In this context, the overall age range of detritus is consistent with derivation from the west Greenland segment of the North Atlantic craton (Cawood *et al.* 2007b).

The detrital age spectra obtained for the Trossachs Group differ from those available for the broadly coeval Cambrian strata on the Hebridean foreland in one important respect: 1.2-1.0 Ga detritus is entirely absent in the latter, which rules out a common (Labrador-Superior) provenance. None the less, the sample of sandstone adjacent to the Leny Limestone (A472) is distinctive from the other Trossachs Group samples in that it contains a much smaller proportion of Mesoproterozoic (particularly 1.2-1.0 Ga) detritus and a rather higher proportion of Palaeoproterozoic (2.2-1.8 Ga) detritus (Fig. 6). We suggest that the age spectrum for A472 bears comparison with that for the sample of the approximately age-equivalent Salterella Grit (SG07), implying a common provenance. The Salterella Grit was deposited during a global regressive eustatic event known as the Hawke Bay event (Palmer & James 1979). This event would presumably have resulted in the transport of significant amounts of sand offshore into the deep-water Trossachs Group basin, thus accounting for the broad similarities in provenance exhibited by these two samples. If correct, this correlation is critical to the current debate concerning the status of the Highland Border Complex as it ties the latter to the margin of Laurentia and does not support the exotic terrane model.

We emphasise that detrital zircon data on their own cannot provide unambiguous solutions to controversies such as that concerning the Highland Border Complex. The question of whether or not the Midland Valley terrane is underlain by (unexposed) Laurentian basement has been long debated (Bluck 2002 and references therein) and it remains a possibility that it originated as a microcontinental ribbon that rifted from the margin of eastern Laurentia during the development of the Iapetus Ocean. A similar origin has been proposed for the ‘Slishwood Division’ in NW Ireland (Chew *et al.* 2010). If the sedimentary rocks of the Highland Border Complex were deposited on such a microcontinental ribbon, there might be little in their provenance to distinguish them from sedimentary rocks deposited on autochthonous Laurentian basement. In that light, possible linkage of the samples of age-equivalent sandstone deposited on the Caledonian foreland and in the Trossachs Group assume particular importance.

A relative probability plot comparing detrital zircons from the Trossachs Group (including the Keltie Water Grit Formation analysis of Cawood et al. 2003) with data from the Ardvreck Group of the Hebridean foreland (Cawood *et al.* 2007b, and herein), the upper Dalradian Argyll Group (Cawood *et al.* 2003), the Southern Highland Group (Cawood *et al.* 2003), the Midland Valley terrane (Phillips *et al.* 2009) and the Southern Uplands terrane (Waldron *et al.* 2008) is presented in Figure 7. A time-space plot highlighting the age relations between these sample sets is given in Figure 8. The samples display a series of common peaks, the relative proportions of which vary between the different groupings, which are characteristic of Laurentia (e.g. Hoffman 1989). Neoarchaean detritus is present in all groups, notably in the age range 2800-2600 Ma, corresponding with final stabilization of the cratonic nuclei of Laurentia (Hoffman 1989). Neoarchaean detritus only constitutes a minor proportion of analysed samples from the Midland Valley and Southern Uplands terranes. Late Palaeoproterozoic age zircon detritus corresponds with assembly of Laurentia and the supercontinent of Nuna along a series of collisional orogenic belts at around 2000-1800 Ma (Hoffman, 1996; Zhao *et al.* 2002). Detritus of this age constitutes a dominant component of the Ardvreck and Argyll groups. There is a marked decrease in the proportion of late Palaeoproterozoic in the Southern Highland Group and this trend continues into the Trossachs Group and detritus of this age are only a minor component of the Mildand Valley and Southern Uplands terranes (Fig. 7). The late Mesoproterozoic to earliest Neoproterozoic (1250-950 Ma) corresponds with the timing of the Grenville Orogeny and assembly of the supercontinent of Rodinia. Detritus of this age form a dominant proportion of all units except the Ardvreck

Group. Samples with detritus of this age also contain zircons in the range 1500-1300 Ma, which corresponds with earlier accretionary margin activity along eastern Laurentia (Cawood et al. 2003). The late Neoproterozoic to early Palaeozoic Argyll, Southern Highland and Trossachs groups of the Dalradian Supergroup all contain a minor component of grains in the range 650-550 Ma, interpreted here to relate to input of rift-related magmatism associated with Rodinia breakup and opening of the Iapetus Ocean (see Cawood et al. 2001). The Midland Valley and Southern Highland Group contain early Paleozoic zircon detritus (490-460 Ma) related to magmatic arc activity generated during closure of Iapetus Ocean (Phillips et al. 2009).

Despite the strong points of comparison between the different data sets presented in Figure 7, there are also some notable differences that are difficult to reconcile with published models for sedimentary drainage patterns linking the terranes north of the Iapetus suture (Fig. 1) following the Grampian orogenic event. Given the Ordovician and Silurian cooling ages obtained from mineral phases in the Dalradian rocks, it is likely that they were being exhumed and eroded at this time and were thus shedding sediments into adjacent basins. Hutchison & Oliver (1998) proposed that detrital garnet within the Southern Uplands accretionary prism could be matched directly with *in situ* Dalradian garnets. It was envisaged that river systems flowed from an actively uplifting Grampian terrane, transporting detritus derived from the Dalradian Supergroup across the Midland Valley and into the accretionary prism. In this case, it would be expected that the detrital zircon record of the Midland Valley and Southern Uplands samples would match that of the Dalradian samples, in particular that of the Argyll Group, the likely source of much of the detrital garnet. All the Dalradian and Trossachs Group samples contain much higher proportions of detrital Archaean grains than the Midland Valley and Southern Uplands samples (Fig.

7). In addition, the Argyll Group samples are characterised by a large proportion of Palaeoproterozoic detritus, which only exists as a small proportion in the Midland Valley and Southern Uplands samples (Fig. 7). Consequently, it seems unlikely that the Ordovician-Silurian sedimentary rocks in the Midland Valley terrane were derived from erosion of the Grampian terrane (see also Phillips *et al.* 2009) and we suggest that the same conclusion can be applied to the Southern Uplands terrane. The distinctive geochemistry of the Southern Uplands terrane also argues against its derivation by erosion of the Grampian terrane (Stone et al. 1999). The absence of a comparable detrital zircon record in the Midland Valley and Southern Upland terranes suggests that they cannot have been in their current location relative to the Grampian terrane until at least the end Silurian.

These discrepancies in the detrital zircon records of now adjacent terranes support models for significant sinistral strike-slip movement on the bounding Highland Boundary and Southern Upland faults during the late Silurian to early Devonian closure of the Iapetus Ocean (Pickering *et al.* 1988; Soper *et al.* 1992; Dewey & Strachan 2003). It is difficult to be specific about the sources of the detrital zircons within the Midland Valley and Southern Uplands terranes, other than they were derived from Laurentia. Some of the Midland Valley detritus could have been derived from local basement (Phillips *et al.* 2009). Presumably an Ordovician Barrovian-style metamorphic belt extended along the Laurentian margin between west Ireland and Newfoundland, and this could have been the source of the detrital garnet and zircon within the Southern Uplands terrane if the latter was formerly located along strike further to the southwest.

Conclusions

1. Detrital zircon age spectra for the Highland Border Complex in Scotland are characterized by age peaks at 2.8-2.6, 1.3 and 1.1-1.0 Ga along with variable amplitude peaks in the range 1.7-1.9 Ga. These age peaks compare with the major periods of crust generation and orogenic activity in eastern Laurentia. The data is therefore consistent with the Laurentian provenance of the complex indicated by palaeontological evidence.
2. The detrital zircon age spectra for the Highland Border Complex compare closely to those of the upper parts of the Dalradian Supergroup of the adjacent Grampian terrane. This supports the interpretation that the two successions lie in stratigraphic continuity and questions an exotic status for the Highland Border Complex.
3. The detrital age spectrum for a sample of Cambrian Salterella Grit of the Hebridean foreland is distinguished from the Highland Border Complex by the complete absence of 1.2-1.0 Ga detritus. However, it compares with that for an approximately age-equivalent sandstone from the Leny Limestone of the Highland Border Complex. Both were contemporaneous with the regressive Hawke Bay event which may account for the broad similarities in provenance. This further ties the Highland Border Complex to the margin of Laurentia.
4. The detrital zircon age spectra for the Dalradian Supergroup and the Highland Border Complex show some similarities but also some significant differences with published data sets for Ordovician-Silurian sedimentary rocks of the adjacent Midland Valley terrane and also the Southern Upland terrane to the southeast. This is incompatible with current models that view these sedimentary rocks as derived from the erosion of the Grampian terrane. These

discrepancies in the detrital zircon records of now adjacent terranes support models for significant sinistral strike-slip movement on the bounding Highland Boundary and Southern Upland faults during the late Silurian to early Devonian closure of the Iapetus Ocean.

Acknowledgements

U-Pb zircon analyses were performed on the sensitive high-resolution ion microprobes (SHRIMP II) located at the John de Laeter Centre of Mass Spectrometry, which is operated by a consortium consisting of Curtin University, the University of Western Australia and the Geological Survey of Western Australia.

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Figure Captions

Fig. 1. Lithotectonic divisions of the Caledonian Orogen in Scotland and northern England. Box outlines area of Figure 2. Salterella Grit sample, SG07 occurs on shores of Loch Eriboll in the Hebridean foreland, close to the Moine thrust.

Fig. 2. Geologic map in the vicinity of the Highland Border Complex, Scotland, showing location of analysed samples, A265, A266, A472 and NE148.

Fig. 3. Stratigraphic columns for the Cambro-Ordovician succession in the Hebridean foreland and for the Trossachs Group and Highland Border Ophiolite along the Highland Boundary Fault. Analysed samples shown by numbered triangles. Unnumbered triangles refer to stratigraphic position of samples from the Hebridean foreland analysed by Cawood *et al.* (2007b). Stars show fossil locations in the Trossachs Group and Highland Border Ophiolite.

Fig. 4. Concordia diagrams based on ^{204}Pb-corrected data for analysed samples. Error ellipses are shown at 2 sigma level;.

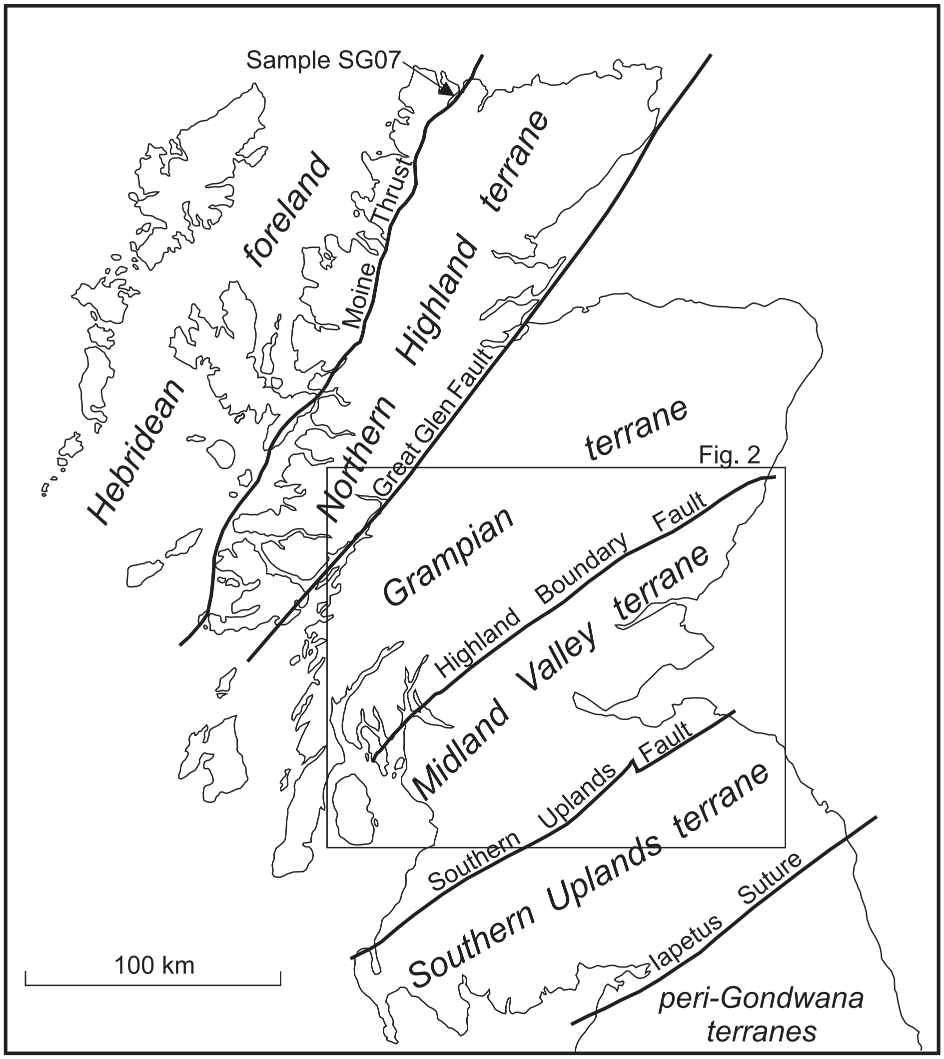
Fig. 5. Probability density distribution diagrams of Concordia ages for analyzed samples, which were constructed using the method of Nemchin and Cawood (2005). Grey shaded bars delineate the age ranges 2800-2600 Ma, 2000-1750 Ma and 1250-950 Ma. *n*—number of analyses; *s*—number of samples.

Fig. 6. Probability density distribution diagram of siliciclastic sequences from the the Caledonian Orogen in Scotland northern England. Sources of data: Ardvreck Group, Hebridean foreland – Cawood *et al.* 2007b and this paper (SG07); Argyll Group – Cawood *et al.* (2003); Southern Highlands Group – Cawood *et al.* (2003); Trossachs Group – this paper (samples A265, A472, NE148) and Cawood *et al.* (2003); Highland Border Ophiolite – this paper; Midland Valley

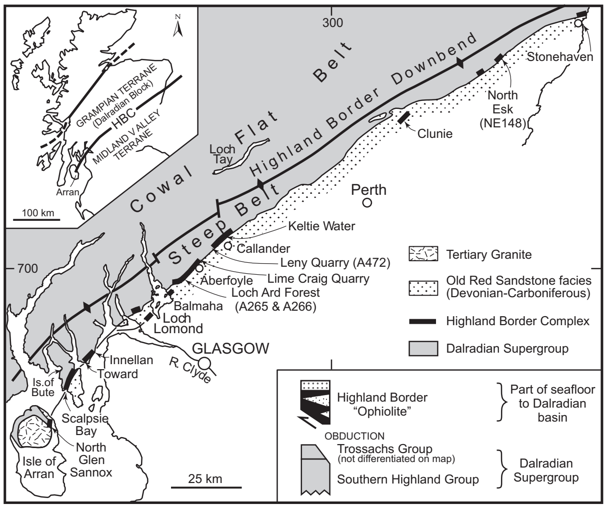
terrane – Phillips *et al.* (2009); Southern Uplands terrane – Waldron *et al.* (2008). Abbreviations: *n*—number of analyses; *s*—number of samples.

Figure 7. Late Neoproterozoic to early Paleozoic lithostratigraphic sequences in the Hebridean foreland and Grampian, Midland Valley and Southern Uplands terranes showing position of analysed samples plotted on figure 6. Tie scale from Gradstein *et al.* (2004). Abbreviaitons: Neoprot. – Neoproterozoic; E – Early; M – Middle; L – Latel T – Tremadoc; A – Arenig.

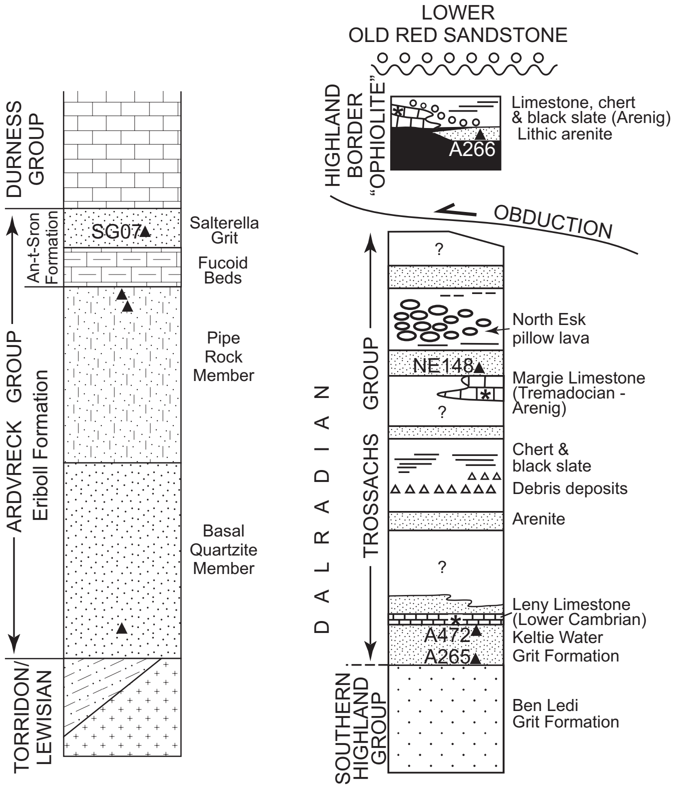
Cawood et al., Fig. 1



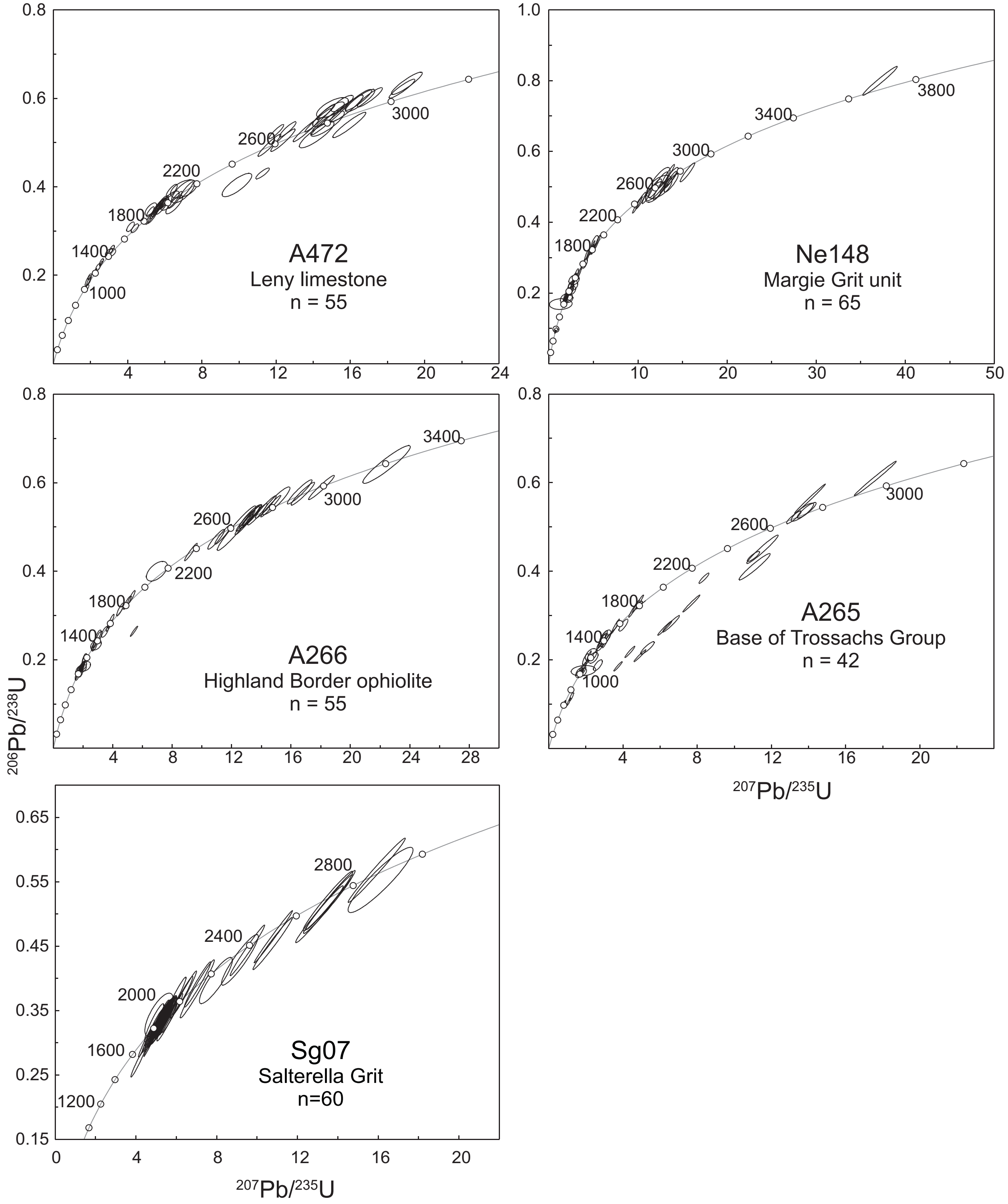
Cawood et al. Fig. 2



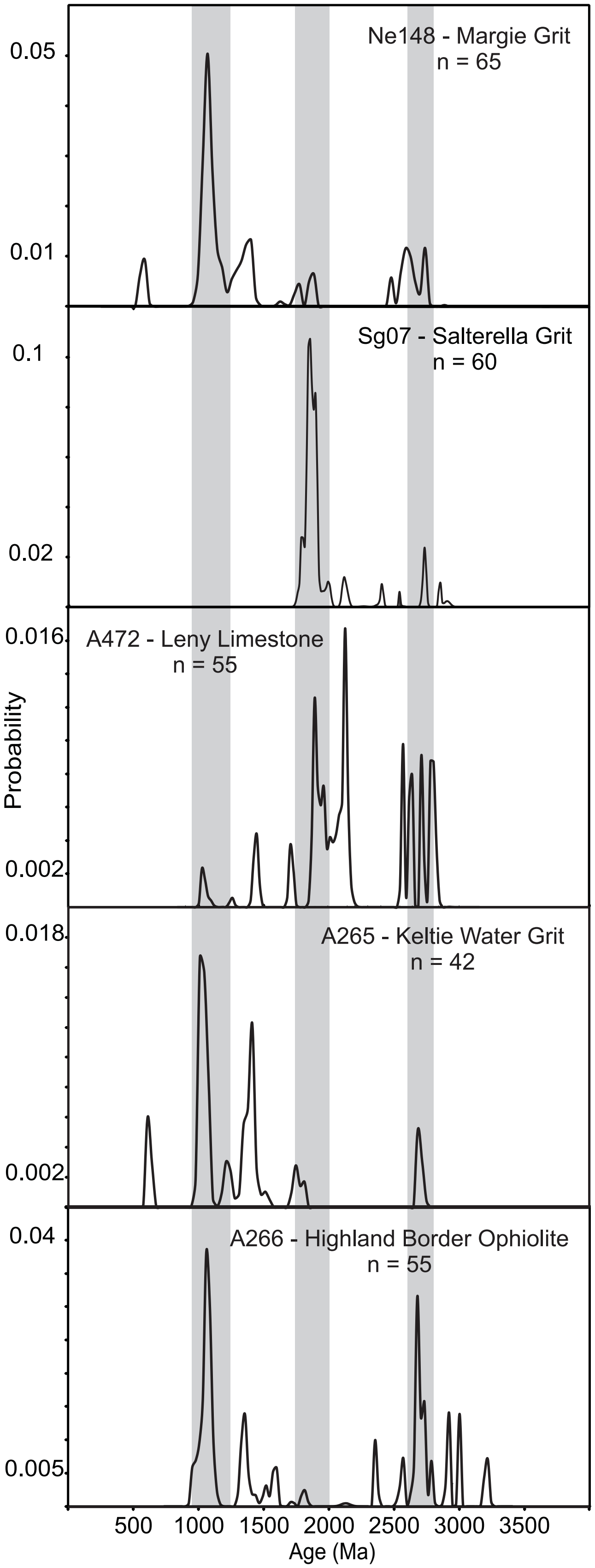
Cawood et al Fig. 3



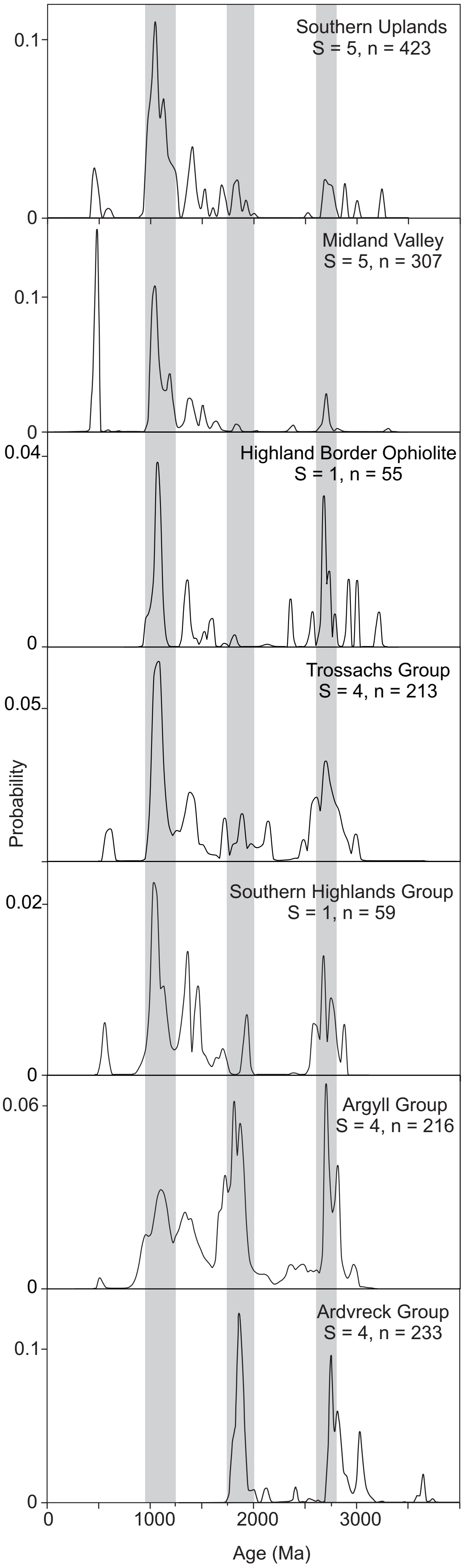
Cawood et al Fig. 4



Cawood et al Fig. 5



Cawood et al Fig. 6



Cawood et al. Fig. 7