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A Multidisciplinary Approach to Sediment Provenance Analysis of the Late Silurian-Devonian Lower Old Red Sandstone succession, Northern Midland Valley Basin, Scotland

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Abstract: Sediment provenance analysis is important in reconstructing chronological and spatial relationships between source area erosion/exhumation and sediment deposition in adjacent basins. Here we provide new provenance data from conglomerate clast populations, sandstone petrography, heavy mineral assemblages and U-Pb detrital zircon geochronology from the 9 km thick, Siluro-Devonian Lower Old Red Sandstone (LORS), northern Midland Valley Basin (MVB), Scotland. The MVB developed in the foreland to the Caledonian Orogeny and comprises a mixed succession of conglomerate and pebbly sandstone interbedded with volcanic lithologies. Analysis of 554 samples (137 petrographical thin sections across 22 formations/members; 390 conglomerate clast recordings across seven locations; 17 heavy mineral and 10 detrital zircon samples) from the entire succession shows a proximal, consistent source or sources located to the east/northeast. These results indicate that sediment derived directly from areas of Scandian uplift of Norwegian lithologies is unlikely to have made a significant contribution to the LORS of the northern MVB and the provenance instead lies more proximally in both the neighbouring Dalradian metasedimentary rocks and other contemporaneous lithologies. The coarse-grained nature of the sedimentary rocks suggests consistent and continued uplift of these lithologies throughout deposition of the LORS. Integration of these provenance techniques allows robust interpretation of basin-fill from a tectonically rejuvenating source in the Caledonian foreland. [*End of Abstract*]

Abbreviated Title: *Lower Old Red Sandstone Provenance*

Supplementary Material: [MVB LORS palaeocurrent data; List of sample locations] is available at

Sedimentary provenance analysis using both single and multi-mineral techniques presents opportunities to assess and locate sedimentary source areas and to better understand sediment pathways in source to sink studies. Additionally, provenance analysis can help to evaluate controlling factors in sediment composition such as climate, tectonic setting and relief (e.g. Basu & Molinaroli 1989; Hurford & Carter 1991; Matter & Ramseyer 1985; McLennan *et al.* 1993; Morton 1985; Owen 1987; Renne *et al.* 1990; Vermeesch & Garzanti 2015). An increasingly diverse array of analytical provenance techniques is available, and data can be used to test tectonic models at a range of scales, from fault-block to orogenic. Examples include unravelling the unroofing histories of extensional fault blocks (Horton & Schmitt 1998) or individual thrust sheets (DeCelles 1988; Lawton *et al.* 2010), fault displacement estimation (Gehrels *et al.* 2003; Yue *et al.* 2005), assessment of orogen-scale exhumation (DeCelles *et al.* 1998; Najman & Garzanti 2000), reconstruction of plates or terranes (Carroll *et al.* 1995; DeCelles *et al.* 2000, Thomas *et al.* 2004; Weislogel *et al.* 2006) and assessment of sediment dispersal patterns at the continental scale (Rainbird *et al.* 1992; Dickinson & Gehrels 2003).

The provenance of the Lower Old Red Sandstone (LORS) of the northern Midland Valley Basin (MVB) remains poorly constrained, such that reconstruction of syn- and post- Caledonian orogenic drainage pathways is problematic (e.g. Bluck, 1983; Bluck, 1984; Bluck *et al.* 1992; Bluck *et al.* 1988; Haughton *et al.* 1990; Haughton *et al.* 1988; Haughton 1989; Hartley and Leleu 2015). As such, placing the sedimentary succession within a larger-scale tectonic framework is difficult. Additionally, the basin developed during a time period that is not well-reflected in the current stratigraphic record. As such, the MVB LORS provides a unique record of sedimentation during the final stages of the Caledonian Orogeny in the Mid-Late Silurian through to post-orogenic Caledonian collapse in the latest Lower to early Middle Devonian. In order to better understand syn- and post-orogenic drainage development, provenance-specific characteristics of the sedimentary succession require assessment. Early provenance studies focussed primarily on data derived from conglomeratic units in the northern MVB from which a complex model involving multiple sources of sediment was established (Bluck, 1983; Haughton *et al.* 1990; Haughton & Halliday 1991). Later studies investigated sandstone provenance using petrography and established a locally derived sediment provenance (Phillips & Carroll 1995; Phillips & Aitken 1998; Phillips *et al.* 1998; Phillips 2007). These studies focussed primarily on the lower part of the stratigraphy and used a single provenance technique. Here we aim to determine the source of the Silurian to Devonian sedimentary rocks of the northern MVB through integration of a range of analytical techniques including palaeocurrent analysis, conglomerate clast composition, petrography (point counting), heavy mineral analysis and age spectra of detrital zircon populations. This multi-disciplinary provenance approach across the entire LORS stratigraphy is taken to assess the validity of previous models and establish controls on the development of a Caledonian foreland basin succession.

Previous studies of the depositional history of the LORS of the northern MVB assign great importance to the role and significance of the Highland Boundary Fault (HBF). Two main theories for the development of the MVB exist; the first of these is described by Yardley *et al.* (1982) and Leggett (1980), placing the MVB in a forearc setting during the Ordovician and Silurian. The second model (e.g. Longman *et al.* 1979; van Breemen and Bluck 1981; Bluck 1983, 1986) describes the Midland Valley as an arc-interarc terrane during this time period, an interpretation requiring significant movement on the terrane's bounding faults. Using this model for basin formation, Haughton and Bluck (1988) describe deposition of the LORS within a series of increasingly larger sub-basins from both the north and the south. These basins were attributed to strike-slip movement along a suture concealed by the current line of the HBF, within which large, braided antecedent streams were captured. This implies syn-sedimentary movement along the HBF zone, a proposition later refuted by Hartley and Leleu (2015) due to the lack of syn-sedimentary fault movement indicators observed. Furthermore, an increase in thickness of strata was observed across the HBF, suggesting that there had been no significant post-Ordovician strike-slip movement along the fault line (Hartley and Leleu 2015).

To date, the tectono-sedimentary evolution of the area remains largely unconstrained. Assessing the provenance signature of the LORS using a multidisciplinary approach provides an opportunity to better constrain the evolutionary history of the basin and sediment deposition. This paper aims to employ several approaches to sediment provenance analysis to test the validity of previously described models, and to develop a more constrained interpretation for LORS deposition in the MVB. Ultimately, if deposition occurred from the north and south, as in the model proposed by Haughton and Bluck (1988), two distinct sedimentary provenance signatures consistent with the implicated source areas should be evident, alongside palaeocurrent indicators. Conversely, if deposition occurred due to Scandian deformation in the east, as in Hartley and Leleu (2015), grain size indicators will provide an indication of proximity to the source, and the provenance signature(s) identified should reflect a source area consistent with the tectonic history of the region.

Regional framework

The northern MVB represents the largest accumulation of LORS outcrops in Scotland. Significant outcrops also occur to the north of the Highland Boundary Fault (HBF), recording the history of the relationships between Caledonian terranes (Bluck *et al.* 1988; 1992a). The first LORS deposits of the northern MVB are generally considered to be early Llandovery-Wenlock in age based on palynological data (Marshall 1991) with deposition continuing up to Emsian times in the late Lower Devonian period. The LORS of the northern MVB is largely devoid of opportunities to establish absolute depositional ages. Recent work has suggested, however, that the oldest deposits may be Devonian in age, with samples yielding zircon grains as young as 413.7 ± 4.4 Ma (Suarez *et al.* 2017). These data may not fully account for potential lead loss and may provide an anomalously young age (e.g. Dickinson and Gehrels 2009), particularly as the main zircon age distribution suggests an older age. Given the somewhat low statistical significance of single-grain ages as a measure of depositional age (Dickinson and Gehrels 2009), the original palynologically-derived timeframe of Marshall (1991) is retained here.

The studied succession comprises the LORS exposed in the northern MVB adjacent to the HBF (Fig. 1). The HBF, a reverse fault of mid Devonian to Carboniferous age (Bluck 1984) separates the northern MVB from the Dalradian Supergroup of the Grampian Terrane, a sequence of late Pre-Cambrian metasedimentary and metavolcanic lithologies deformed during the early Ordovician Grampian Orogeny. The LORS succession contains a diverse succession of continental clastic sedimentary rocks and intercalated volcanic lithologies. The thickness of the succession is variable, dependent on location, measuring 9 km at its thickest point in the east of the northern MVB and decreasing to around 4 km towards the west (Armstrong and Paterson 1970). Strata in the northern MVB lie with a basal unconformity on the Arenig to Caradoc Highland Border Complex which forms the basement of the northern Midland Valley (Browne *et al.* 2002).

Stratigraphy

In the northern MVB, the LORS succession is subdivided into the Stonehaven, Dunnottar-Crawton, Arbuthnott-Garvock and Strathmore Groups (Figs. 2 and 3). The oldest of the groups, the Stonehaven Group, is confined to the north east of the basin (Fig. 2) and crops out on the steeply dipping northern limb of the Strathmore Syncline, one of a series of large-scale folds that dominate the structure of the basin. It is largely Wenlock to Ludlow in age, based on palynomorph evidence (Marshall 1991; Wellman 1993). The overlying Dunnottar-Crawton Group is also mainly confined to the north east (Browne et al 2002). Due to its restricted outcrops the true extent of the group is not known, but Armstrong and Paterson (1970) and Browne et al (2002) suggest that it may be progressively overstepped to the south west by younger strata of the Arbuthnott-Garvock Group. The Arbuthnott-Garvock Group is by far the most extensive of the four and stretches the entire width of the northern MVB and volcanic lithologies are abundant within the group. The topmost Strathmore Group is generally poorly exposed but is again laterally extensive (Armstrong and Paterson 1970). Deposition of the LORS continued until late Lower Devonian (Emsian) times, at which point there was a break in sedimentation during the mid-Devonian Period prior to deposition of the Upper Old Red Sandstone (Burgess 1961; Bluck 1967).

Conglomerate Clast Analysis

LORS conglomerates in the northern MVB include massive or rarely horizontally-stratified, mainly clast-supported cobble- to boulder-bearing polymict conglomerates. Often, well-developed *a* (t)*b* (i) (notation of Walker 1975) clast fabrics are present, alongside local enrichment in the abundance of blade- and disc-shaped clasts (Haughton 1989; McKellar 2017). Clasts are typically well- to sub-rounded, and range in size from cobbles to boulders, locally reaching sizes well in excess of one metre, indicating a proximal source, with palaeocurrent data across the area suggesting flow from the east or north east (McKellar 2017).

Conglomerates from the LORS of the northern MVB have been investigated at seven sites for clast size and lithology (Fig. 4): Auchmithie (Auchmithie Conglomerate Member, Scone Sandstone Formation, Arbuthnott-Garvock Group); Crawton (Catterline Conglomerate Formation, Arbuthnott-Garvock Group; Whitehouse Conglomerate Formation, Dunnottar-Crawton Group); Gourdon (Gourdon Sandstone Formation, Dunnottar-Crawton Group); Stonehaven (Dunnottar Castle Conglomerate Formation, Dunnottar-Crawton Group; Downie Point Conglomerate Member, Dunnottar-Crawton Group; Carron Sandstone Formation, Stonehaven Group). A total of 417 conglomerate clasts across seven locations (see Fig. 4 for sample locations) have been assessed for both size (axis length) and lithology (Fig. 5). These are presented as a scatter plot based on measurements of long and short clast axes (Fig. 6), pie charts showing clast lithology abundance through the stratigraphy and across the study area (Fig. 7) and as area graphs giving a modal percentage for the occurrence of various clast types and their size distribution based on long axis length (Fig. 8).

In the Carron Sandstone Formation of the Stonehaven Group, clast long axes are up to c. 20 cm with an average length of c. 7 cm (Fig. 6). Clast proportions (Figs. 7 and 8) are dominated by quartzites (41%) and fine-grained volcanic rocks, typically weathered basalt and basaltic andesites (41%). Small numbers of hypabyssal lithologies are observed (11%) as cobbles of quartz porphyry and porphyritic andesite, and a minor (7%) metamorphic component is represented by small (up to 10 cm) psammite cobbles, but no granite clasts were noted. While metamorphic clasts are typically smaller than 10 cm, clasts for the other lithologies have similar dimensions (Fig. 8).

The overlying Downie Point Conglomerate Member shows a marked increase in the abundance of quartzite clasts (58%) alongside a significant proportion of hypabyssal quartz porphyry and porphyritic andesite (13%) and fine-grained volcanic (27%) clasts of a similar character to those observed in the Carron Sandstone Formation (Figs. 7 and 8). No granite clasts were observed and metamorphic clasts were scarce (2%). Clast sizes are larger than those of the underlying Carron Sandstone Formation, with long axes reaching around one metre locally, but typical clast sizes average 10 to 40 cm (Fig. 6). Metamorphic clasts are slightly larger than those observed in the Carron Sandstone Formation, with long axis lengths reaching 20 – 30 cm. The largest clasts are dominated by quartzites and fine-grained volcanic lithologies (Fig. 8).

Clasts in the Dunnottar Castle Conglomerate Formation were some of the largest noted, with long axis measurements reaching up to c. 1.5 m, but typically measuring between 10 – 50 cm (Fig. 6). The clast assemblage of the formation hosts the first appearance of granite (18%), represented by both pink and grey granites as well as red microgranite and macroporphyritic granite. As with the underlying lithologies there is a significant quartzite component (32%), although fine-grained volcanic rocks again dominate the assemblage (40%). Smaller proportions of hypabyssal (8%) and metamorphic (2%) lithologies were recorded (Fig. 7). In addition to the clast types observed, small pebbles of vein quartz and red chert are common. Clast sizes by type show a little variation, with metamorphic clast long axes typically measuring around 10 cm, with no metamorphic clasts over 20 cm noted. Other clast types observed occur in a range of sizes but the largest clasts observed were granitic or volcanic, both of which were over 1 m (Fig. 8).

Clasts observed in conglomerate beds of the Gourdon Sandstone Formation were smaller overall than the Dunnottar Castle Conglomerate Formation, with clast long axes generally reaching c. 40 cm but averaging around 20 cm (Fig. 6). The clast assemblage contained pink and grey granite clasts (10%), with low proportions of porphyritic andesite and quartz porphyry hypabyssal (10%) and metamorphic (10%) clasts. Quartzite clasts (30%) are abundant but the assemblage is dominated by weathered fine-grained volcanic clasts (40%) (Fig. 7). As observed in the previous formations, metamorphic clasts are typically small (< 20 cm). Quartzite clasts are present in a variety of sizes, as are volcanic and hypabyssal lithologies, but the largest clasts were typically volcanic with lesser numbers of hypabyssal clasts (Fig. 8).

In the upper part of the northern MVB stratigraphy, clasts of the Whitehouse Conglomerate Formation are of a similar size overall to those of the Gourdon Sandstone Formation, but clast long axes are up to a maximum of c. 60 cm (Fig. 6). The formation contains a number of plutonic clasts (30%) of pink and white granite, red microgranite and a macroporphyritic granite similar to those observed in the Dunnottar Castle Conglomerate Formation. As with previous lithologies, fine-grained volcanic rocks are still abundant (23%) with minor amounts of hypabyssal (7%) and metamorphic (10%) clasts. The proportion of quartzites (13%) is somewhat reduced from those observed lower in the stratigraphy. In addition to the clast types previously seen, a number of “other” (17%) clasts of red banded chert and serpentinite were recorded (Fig. 7). Quartzites, metamorphic and "other" lithologies only occur as smaller clasts (up to 20 cm), and hypabyssal clasts are typically less than 30 cm (Fig. 8). Granite clasts occur in a variety of sizes up to c. 35 cm with the largest clasts being the macroporphyritic granite with microgranite representing the smaller clast sizes (<10 cm). Volcanic clasts are present in a range of sizes but dominate the largest clast sizes (Fig. 8).

Clasts of the Catterline Conglomerate Formation at the base of the Arbuthnott-Garvock Group are of a similar size to those of the Whitehouse Conglomerate Formation (Fig. 6). This formation also contains moderate proportions of granite (20%) and quartzite (20%) clasts. Again, pink and grey granites were observed alongside red microgranite and macroporphyritic granite. Fine-grained volcanic clasts (41%) dominate the assemblage, with small amounts of hypabyssal quartz porphyry and porphyritic andesite clasts (7%). Metamorphic clasts (typically psammite) account for 10% of the clast types observed (Fig. 7). Metamorphic and hypabyssal clasts are typically smaller (< 30 cm), while quartzite clasts occur in a range of sizes up to c. 40 cm (Fig. 8). Granites and fine grained volcanic rocks represent the largest clasts and are present across the full range of sizes. As with the Whitehouse Conglomerate Formation, the largest granite clasts are macroporphyritic (up to c. 55 cm), although other granites are represented in a variety of clast sizes (Fig. 8).

Clasts of the Auchmithie Conglomerate Formation are smaller than most of those previously described, with long axes reaching c. 30 cm and an average of c. 10 cm (Fig. 6). The formation contains a small proportion of granites (8%) alongside a low proportion of metamorphic clasts (6%). The assemblage is dominated by fine-grained volcanic (31%) and quartzite (41%) clasts, and also an appreciable percentage (20%) of hypabyssal lithologies (Fig. 7). Metamorphic clasts are only represented in the smaller clast sizes (< 20 cm), and volcanic lithologies less than 30 cm. The largest clasts observed, with long axis measurements up to c. 30 cm, were mostly quartzite, with some granite, and hypabyssal clasts occurring in a range of sizes up to c. 20 cm (Fig. 8).

The bulk of the clasts in the conglomerates of the MVB LORS have a provenance in extrusive, hypabyssal and plutonic volcanic rocks (Figs. 7 and 8) which are likely derived from uplift and erosion of contemporaneous volcanic lithologies. Fine-grained volcanic clasts are often large, well in excess of a metre in places, suggesting restricted transportation and thus a local source. Metamorphic lithologies similar to those of the Dalradian Supergroup are also present in small amounts, alongside an appreciable quartzite component. It is postulated therefore that the conglomerate provenance is a mixture of two distinct sources, one being the metamorphic lithologies of the Dalradian Supergroup, and the other local contemporaneous volcanic and occasional plutonic rocks. The LORS of the MVB has a general NE - NNE provenance indicating a consistent south westerly palaeoflow direction (McKellar 2017). Variations in clast size and type thus appear to occur independent of palaeoflow direction and, as such, may reflect lithological variations within the source area including episodic contemporaneous volcanism.

Sandstone Petrography

Methodology

Medium- to coarse-grained sandstones from the northern MVB have been analysed petrographically. Petrographical analysis using a standard transmitted light petrological microscope was undertaken on 143 thin sections from the northern MVB stratigraphy (see Fig. 4 for sample locations). Point-count data (minimum 300 points per sample) were used to determine the modal proportion of the matrix and various detrital components within the sandstones. Modal compositions of the sandstones were calculated as volumetric proportions of detrital grains (techniques of Dickinson 1970; Dickinson and Suczek 1979). This dataset includes raw point count data from Phillips *et al.* (2007), supplied by the British Geological Survey, which has been cross-checked for methodology and consistency.

Sandstone Composition

Modal compositional data obtained for sandstones of the northern MVB groups are shown in Figure 9, and several general observations can be made. Proportions of the main detrital components observed (mono- and poly-crystalline quartz; plagioclase and potassium feldspar; sedimentary, metamorphic and volcanic lithic fragments) are variable within formations in the northern MVB (Fig. 9). Stratigraphic members generally contain significant proportions of volcanic lithic fragments, particularly in formations within the Dunnottar-Crawton and Arbuthnott-Garvock groups, while there is a slight reduction in proportion of these fragments in the Cowie Sandstone Formation at the base of the LORS and in the formations near the top of the succession in the Strathmore Group. Volcanic lithic fragments are particularly abundant in the Gourdon Sandstone Formation near the top of the Dunnottar-Crawton Group, accounting for almost 75% of the main detrital components measured. This abundance of volcanic material is observed alongside an increase in plagioclase feldspar grains. Metamorphic lithic fragments are present throughout the stratigraphy (average c. 3 - 10% of total grains counted); however, a slight increase in proportion is observed in the formations of the Strathmore Group, reaching up to 18% of the total grains. Sedimentary lithic fragments are scarce to absent in the majority of the samples, typically accounting for 0 – 4% of the total grains counted, although a slight increase in these is noted in the higher stratigraphic members of the

Strathmore Group where sedimentary grains reach proportions of up to 11% in the Glenvale Sandstone Formation.

All samples analysed contained an appreciable mono- and polycrystalline quartz component. While there is slight variation between the different stratigraphic members, proportions between most are generally comparable with the exception of the Gourdon Sandstone Formation. In this formation, polycrystalline quartz is scarce or absent, and only a very small fraction of the grains is composed of monocrystalline quartz.

Interpretation of Petrographical Data

Minor changes in the abundance of volcanic lithic fragments in sandstone modal populations are observed through the stratigraphy of the northern MVB. Volcanic lithic fragments occur in the greatest proportions in the Dunnottar-Crawton and Arbuthnott-Garvock groups in which a number of volcanic stratigraphic members occur, suggesting that local volcanism may be a significant contributing factor. This is particularly well displayed in the detrital grain assemblage of the Gourdon Sandstone Formation which immediately overlies the Tremuda Bay Volcanic Formation and the modal composition of which may be related directly to penecontemporaneous volcanic activity. Additionally, volcanic lithic fragment proportions are lowest in the formations of the Strathmore Group which may be attributed to the absence of volcanic members in the group. The increase in proportion of volcanic lithic fragments in the Gourdon Sandstone Formation occurs together with an increase in the proportion of plagioclase feldspar. This increase may also be a direct result of proximity to the Tremuda Bay Volcanic Formation which includes a number of macroporphyritic, olivine-bearing hawaiite lava flows (Browne *et al.* 2002), providing a source of plagioclase.

Modal proportions of sandstone detrital components of the northern MVB LORS are discussed by Phillips *et al.* (2007), showing negative correlation between the modal proportion of volcanic lithic fragments and monocrystalline quartz. This is interpreted to indicate an increase in the compositional maturity of the sandstones. Phillips *et al.* (2007) also describe a negative correlation between modal proportions of volcanic lithic fragments and plagioclase feldspar, and a positive correlation between polycrystalline quartz and metamorphic lithic fragments. The negative correlation between the volcanic lithic fragments and plagioclase feldspar may indicate changes in maturity of volcanic detritus, such as that observed in the Tremuda Bay Volcanic Formation Hawaiites, as fragments are reworked before deposition and/or a reduction in grain size. Unstable lithic clasts will be preferentially removed from sediment in transport through mechanical breakdown, resulting in an associated increase in proportion of more stable plagioclase feldspar in deposits (Slatt & Eyles 1981; Phillips *et al.* 2007). As such, high proportions of lithic fragments are associated with first-cycle sandstones. Finally, the positive correlation between polycrystalline quartz and metamorphic lithic fragments is interpreted to indicate a common source for the two components.

Sandstone Provenance

Comparison of sandstone compositions can give an indication of proportional detrital component variation through stratigraphy. This can also be related to tectonic setting through establishment of the provenance of sedimentary rocks by compositional data analysis (Dickinson 1970; Dickinson & Suczek 1979). A QFL plot (Dickinson 1970) for sandstones of the northern MVB is shown in Figure 10. Distribution of data for each of the formations is generally spread across the recycled orogen and magmatic arc sectors of the plot, owing to low relative proportions of feldspar grains and high quartzose/lithic fragment contents. Specific localisation of datasets in one or the other of the sectors is only observed in the Gourdon Sandstone Formation, which plots exclusively in the magmatic arc sector, with most datapoints falling particularly close to the lithic fragments pole of the ternary plot. This demonstrates a small quartzose component with low to moderate feldspar.

As the data are distributed across two provenance categories, this is interpreted to suggest mixing of two distinct sources for the LORS. As the majority of formations are distributed across both categories with significant overlap, no overall change in provenance throughout the stratigraphy is evident (Fig. 11).

The metamorphic and stable quartzose components of the sandstones most likely represent recycling of, and derivation from, the Dalradian Supergroup exposed immediately to the north and northwest of the northern MVB (Fig. 1) which records a history of regional metamorphism (e.g. Rogers *et al.* 1989). Proximity to the Dalradian is also interpreted to have influenced the increase in relative proportions of metamorphic lithic fragments observed in the formations of the Strathmore Group. A second source is suggested, interpreted as the contemporaneous Lower Devonian volcanic rocks of the northern MVB (i.e. primarily the Crawton, Montrose and Tremuda Bay Volcanic formations) which would have been subject to uplift and erosion at this the time (Phillips & Carroll 1995). The compositionally distinct Gourdon Sandstone Formation is interpreted to be derived directly from a proximal volcanic source.

Overall, the source of the LORS of the northern MVB is likely to be within the Dalradian Supergroup, with additional input from local contemporaneous volcanism and subsequent compositional variation due to stratigraphic location. Previously, Haughton (1989, 1993), Haughton *et al.* (1990)

and Phillips and Carroll (1995) had attributed Silurian – Devonian sandstone provenance to derivation from gravel deposits mantling the Dalradian, or lying in small, periodically inverted basins. However, sedimentary lithic fragments are limited in the sandstones, which are much more indicative of a first cycle metamorphic and/or volcanic source. It is postulated therefore that composition of the LORS was influenced by proximity to and interplay between two distinct sources: the Dalradian Supergroup and contemporaneous Silurian-Devonian volcanism.

Heavy Mineral Analysis

Methodology

A total of 17 samples were prepared for heavy mineral analysis using standard crushing, washing and heavy liquid separation procedures (Mange and Maurer 1992). Slides were mounted using Canada Balsam for conventional heavy mineral analysis. Heavy mineral samples were investigated under a polarising microscope and counted by ribbon counting (Mange and Maurer 1992). At least 200 non-opaque detrital grains were counted in each sample to provide an overview of the heavy mineral assemblage. To obtain heavy mineral index values (Morton and Hallsworth 1994), counting continued until 200 heavy minerals were assessed per mineral pair.

Due to the possibility of post-depositional alteration of relative heavy minerals (e.g. Morton 2012), only those mineral pairs which exhibit similar behaviour during transport, deposition and diagenesis have been used for analysis. Based on the observed assemblages these include apatite-tourmaline (ATi), garnet-zircon (GZi) and rutile-zircon (RuZi) indices. Additionally, the grain size for this study was restricted to a narrow size range (63-125 μm) to lessen the effects of different hydraulic behaviour due to grain size variations (e.g. Morton and Hallsworth 1994).

Results

Samples were taken from outcrops in the Midland Valley Basin (see Fig. 4 for sample locations). The heavy mineral assemblages of the 17 samples (Fig. 12) contain rare chrome spinel, staurolite and chloritoid, moderate amounts of apatite (ca. 10 – 41.5%), white and brown mica, opaque grains, rutile (2.5 – 13%) and tourmaline (max 10%). Zircon (14.5 – 58%) makes up a substantial component, and the garnet content was variable throughout the samples (0 – 49%). The samples are characterised by intermediate to very high ATi (50 – 100), with highly variable GZi (0 – 75) in combination with low to moderate RuZi (ca. 10 – 24.5).

Lithostratigraphic variation in heavy mineral assemblage

<u>Stonehaven Group</u>

Heavy mineral assemblages from the Stonehaven Group are dominated by zircon (40 – 58%) and apatite (31 – 41%), with low counts of tourmaline (max 9%), rutile (max 13%) and garnet (0 – 2.5%) (Fig. 13). The GZi is therefore very low (max 6), with a high ATi (79 – 100) (Fig. 13). Rare chloritoid (max 2%) was observed in two of the samples.

Dunnottar-Crawton Group

The Dunnottar-Crawton Group samples show an increase in garnet (max 23.5%) (Fig. 12) and have more variable GZi values (ca. 5 – 43) relative to the Stonehaven Group. The highest GZi values were obtained from the Gourdon Formation. ATi values remain high to very high (75 – 83) with low proportions of tourmaline (max 10%). RuZi remains low at <20 (Fig. 13). Again, rare chloritoid was observed in the samples with small amounts of staurolite and spinel.

Arbuthnott-Garvock Group

Heavy mineral assemblages of the Arbuthnott-Garvock Group are more diverse than the underlying groups, again most notably in garnet abundance, with garnet accounting for 47.5 and 49% of the observed assemblage respectively for the Catterline Conglomerate Formation and the Montrose Volcanic Formation (Fig. 12). GZi values range from low to high (18.5 – 77). ATi values are predominantly high (75 – 82), although the Catterline Conglomerate Formation is anomalously low at 50. RuZi values remain consistently low at <20 throughout (Fig. 13).

Strathmore Group

In the Strathmore Group, the assemblage has high ATi (>80) and low RuZi (<20) values. The garnet component of the assemblage remains at ca. 20% (Fig. 13), consequently GZi values appear to stabilise at around 28 (Fig. 13).

Implications for provenance

Garnet is often scarce in samples the lower stratigraphical members of the LORS, with staurolite only being observed in the more garnet-rich samples. Garnet dissolution has been recognised in a number of deep basins, such as the central North Sea (Morton 1984), offshore New Zealand (Smale and Morton, 1987) and the Vøring Basin, offshore Norway (Morton et al, 2005), but in all cases is considered to be more stable than staurolite due to its persistence at greater burial depths. Garnet is observed to decline in abundance with burial depth relative to the stable mineral zircon and where garnet geochemistry is assessed, this is noted in association with preferential dissolution of more calcium-rich garnets (Morton 1987). At depths greater than 3500 m, garnet is noted to virtually disappear (Morton and Hallsworth 1994).

While the lack of garnet and staurolite in some of the samples may suggest a different provenance, no significant change in provenance is indicated through conglomerate clasts analysis or sandstone petrography. It is therefore likely that differences in heavy mineral assemblages are not indicative of a change in provenance, but instead are a result of burial dissolution. As such, heavy mineral assemblages in the studied samples largely indicate derivation from moderate- to high-grade staurolite- and garnet-rich metasedimentary rocks.

Within the north Atlantic region, comparable lithologies occur in the Neoproterozoic to Early Palaeozoic Moine and Dalradian successions of Scotland and their equivalents in East Greenland and Scandinavia (Allen and Mange-Rajetzky 1992; Morton *et al.* 2010). Overall, there is little change through the stratigraphy in the observed heavy mineral ratios, other than in the case of garnet with abundance increasing upwards through the stratigraphy, thus affecting the GZi index value. Additionally, elevated GZi index values and garnet abundances are observed in sediments from or located in close proximity to volcanic members in the stratigraphy, as seen in the Catterline Conglomerate and Montrose Volcanic formations. Previous work shows similar subtle variations in garnet populations within LORS conglomerates adjacent to Dalradian metapelites with the same variations (Haughton and Farrow 1989), suggesting a Dalradian source. Therefore, based on the heavy mineral data it appears that one largely metamorphic source exists for the sedimentary rocks of the northern MVB with possible influence from a local volcanic source.

Detrital Zircon Geochronology

Methodology

After preparation of bulk heavy mineral samples using conventional heavy liquid separation, arbitrary and presumed representative zircons from 10 samples from the northern MVB (Fig. 14) were handpicked under a polarising microscope and initially mounted on double-sided sticky tape. One-inch circular resin mounts were then produced at the Central Analytical Facility (CAF), Stellenbosch University in South Africa. U–Pb age data were acquired 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 Resonetics Resolution S155 excimer 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 10–15 µm. 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 91500 (Wiedenbeck *et al.* 1995) 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. The calculation of concordia ages and plotting of concordia diagrams were performed using Isoplot/Ex 3.0 (Ludwig 2003). Probability density distribution and histogram diagrams were generated by AgeDisplay (Sircombe 2004).

Results

Results of LA-ICP-MS analyses are displayed as frequency age histograms in combination with probability density distributions (Fig. 15). In total, 1124 grains from 10 samples have been analysed from the northern MVB.

Zircons fall into three main age groups: Phanerozoic (31.5 % of all analyses), Proterozoic (65.2 % of all analyses) and Archaean (3.3 % of all analyses). The Proterozoic zircons define two groups between c. 800 and 1250 and c. 1300 and 2100 Ma respectively. All samples have a marked absence of zircon grains aged between c. 2100 and 2500 Ma and c. 600 to 800 Ma. On the basis of differences in age spectra, two main sample types can be distinguished: 1) those dominated by Phanerozoic zircons and 2) those dominated by a combination of Phanerozoic and Proterozoic zircons.

<u>Samples dominated by Phanerozoic zircon grains</u>

Samples in which most zircons yield Phanerozoic ages between c. 400 and 500 Ma are from the lowermost Cowie Sandstone Formation, Stonehaven Group (sample 1) and the Whitehouse Conglomerate and Gourdon Sandstone formations, Dunnottar-Crawton Group (samples 6 and 7) (Fig. 15). In all three samples, two closely spaced peaks can be distinguished in the Palaeozoic, separated from more amalgamated peaks in the Proterozoic by sections of the age spectra that are poorly represented. While Cowie Sandstone Formation sample still contains an appreciable number of Proterozoic zircons, the Whitehouse Conglomerate and Gourdon Sandstone samples are composed almost entirely of Phanerozoic zircons. Archaean grains are scarce (Cowie Sandstone and Whitehouse Conglomerate formations) or absent (Gourdon Sandstone Formation).

<u>Samples dominated by Phanerozoic and Proterozoic zircon grains</u>

The remaining samples comprise significant quantities of both Phanerozoic and Proterozoic zircons, with gaps in age spectra between c. 600-800 Ma and 2100-2500 Ma (Fig. 15). As with the samples dominated by Phanerozoic zircons, Archaean grains are scarce in all samples, typically forming less than 10 % of the population.

Age groups and temporal trends

The analyses show that detrital zircon age ranges and proportions of specific age intervals are variable across the samples. Most samples show multimodal age spectra (Fig. 15), which indicate a diverse provenance involving either rock units of a range of ages and/or reworking of older sedimentary deposits. Palaeozoic input is significant, likely due to penecontemporaneous volcanic and/or plutonic activity.

Proterozoic grains are distributed as a continuous array of most concordant analyses ranging from c. 2.0 to 0.9 Ga in all samples except for those from the Whitehouse Conglomerate and Gourdon Sandstone formations (samples 6 and 7) where the dominant input is from Palaeozoic zircons. All samples, other than those dominated by Palaeozoic zircons (lowermost Cowie Sandstone, Whitehouse Conglomerate and Gourdon Sandstone formations), display noticeable age peaks at c. 1.1 and 1.7 Ga. The recognition of common age peaks between samples as well as the broad temporal trends such as the paucity or absence of Archaean grains suggests that the relatively limited number of analysed samples provides a representative coverage of the northern MVB. In addition, the provenance record suggests mixing of two sources, likely from recycling of the Dalradian Supergroup which shows similar Proterozoic age peaks and data distribution (e.g. Cawood *et al.* 2003) and first cycle material from penecontemporaneous volcanic rocks and unroofing of granite plutons. It is unclear exactly from which group of the Dalradian Supergroup the detritus originates due to significant variability in the zircon age distribution, and as such there is likely a level of mixing of the groups. The youngest single-grain detrital zircon age does largely decrease upward through the stratigraphy of the MVB (Table 1), but the overall age distributions do not change, suggesting a continued common source or combination of sources. Overall the sedimentary rocks are likely derived from a combination of two sources, Caledonian and Dalradian, with the Caledonian material periodically swamping the Dalradian-derived detritus.

Discussion

Petrographical and heavy mineral point counting data indicate that there is no significant change in provenance throughout the 9 km of stratigraphy in the northern MVB. U-Pb zircon age data, in conjunction with the other provenance indicators, have established that the source of the sediment is a combination of two separate sources, one predominantly Palaeozoic and one mainly Proterozoic, with minor Archaean input. Aside from those from the lowermost Cowie Sandstone, Whitehouse Conglomerate and Gourdon Sandstone formations, samples have a significant Proterozoic content, generally with large volumes of Palaeozoic zircons. Apart from periodic influxes of Palaeozoic detritus dominating the provenance signature, the Proterozoic signature remains consistent throughout the stratigraphy. Influxes of large amounts of Palaeozoic material may be due to contemporaneous volcanism or exhumation of granitic plutons, indicated by the proximity of samples dominated by Palaeozoic grains to interbedded volcanic units.

Clast data suggest a proximal source, given the maximum clast size of the conglomerates reaches in excess of one metre. When considered together with the NE-SW palaeocurrent trend (McKellar 2017), it would appear that the source terrane was located to the east and north of the northern MVB. Taking into account the zircon data, two potential source areas can be identified, the Dalradian Supergroup and the Norwegian Caledonides. On comparison of the detrital zircon data, the Caledonian signature in the MVB is similar to that of the rocks in the Sveconorwegian and Caledonian belts in SW Scandinavia (Fig. 16). While some similarities exist with the Moine Supergroup, it can be ruled out as a potential first cycle source due to its geographical location. In order for the Norwegian Caledonides to be a potential source, however, they must have been adjacent to Scotland at the time of sediment deposition. This would require unrealistic displacement on the Great Glen Fault zone to bring the MVB and the Norwegian Caledonides into close enough proximity to produce the coarse grain-size observed in the LORS. In southern Norway, Caledonian age granites are virtually absent, and only minor evidence of magmatism exists (Bingen and Solli 2009). These strata are unlikely to yield a significant population of detrital zircons and would also provide quantities of chrome spinel, which is only present in very minor amounts in the observed samples. As such, this area is unlikely to have formed a potential source. The detrital zircon data for the Upper and Uppermost Allochthons of western Norway (Fig. 16) do, however match the Scottish samples (Bingen and Solli 2009). However, this would entail even greater displacement on major fault zones to place Scotland adjacent to mid-Norway and as such is unlikely. Furthermore, analysis of garnets from Midland Valley conglomerates shows a lack of almandine-pyropes typical of the exhumed high-pressure Norwegian Caledonides, while showing similar compositional variation to Dalradian lithologies (Haughton and Farrow 1989) In summary a contribution directly from the Norwegian Caledonides appears unlikely, with the clast size and compositional data indicating a source terrain proximal to the northern MVB composed of the Dalradian Supergroup and associated Caledonian volcanic and plutonic rocks.

Palaeocurrent data for the northern MVB LORS indicate flow towards the southwest (McKellar 2017; Davidson and Hartley, 2010; Hartley and Leleu 2015), which suggests that Dalradian strata or similar lithologies extended eastwards beneath what is now the North Sea (e.g. Fazlikhani *et al.* 2017). Fluvial systems are considered to have been derived from this region of the Caledonian foreland which was undergoing uplift and tectonic rejuvenation (Fig. 17). LORS deposits identified offshore of similar age suggest further regional uplift and basin development (Arsenikos et al. 2018).

While there is periodic swamping of the sediment with Palaeozoic detritus, the provenance signature does not change overall. Were this solely to be a product of unroofing, as discussed in van Breemen and Bluck (1981), the provenance signature would reflect an inverted stratigraphy relative to the source area with episodic granitic input as plutons are exhumed. Reasoning for an unroofing sequence was based on interpretation of episodic granite plutonism in the Scottish Caledonides with exposure and erosion of granite plutons represented in the clast assemblages of some of the northern MVB conglomerates. This model entails an influx of granitic material as the granites were progressively exposed and eroded. In addition to the production of more mature material, reduction in younger detritus through continued unroofing would be reflected in the zircon age profile of associated deposits by increasing age spectra. While an increase in granite clasts is observed in several of the northern MVB LORS conglomerate formations, overall maturation of sediment is not suggested by the petrographical point count data. Conversely, youngest detrital zircon single-grain ages decrease upwards through the stratigraphy. Were deposition to solely have been as a product of simple unroofing of a source area, this would not be observed. As such, the unroofing of a Dalradian-like source must also be accompanied by periodic contemporaneous volcanism in a tectonically rejuvenating source area.

The rate of unroofing, or lag-time, is a critical factor in controlling detrital zircon populations (Thomas 2011; Cawood *et al.* 2012). For example, the lack of younger detrital zircons closer to the expected depositional age in the lowermost Stonehaven Group, alongside limited clasts in the older conglomerates, suggest delayed exhumation of younger plutons. Granite input is seen to increase through the Dunnottar-Crawton Group and the lowermost Arbuthnott-Garvock Group, evidenced by conglomerate clast assemblage and size before noticeably diminishing higher in the stratigraphy. Zircon age spectra, however, continue to reflect younger detritus, with many single-grain ages suggesting a much lower lag-time despite the decreased granitic input. The source area must therefore have ongoing episodic volcanism, accounting for the periodic swamping of the Dalradian signature.

Well-rounded quartzite clasts are prominent across the conglomerate members of the northern MVB. Previous works have suggested several possibilities for the provenance of these, including derivation from quartzites of the Southern Uplands (Bluck 1984; 2000; 2010); recycling of a source located within the MVB (Bluck 2015); recycling of material of Grampian origin through prolonged cycles of uplift and erosion (Bluck 2000) and reworking of pre-existing quartzite gravels within or mantling the Dalradian to the north (Haughton 1989; Haughton and Farrow 1989; Haughton *et al.* 1990). Given that palaeocurrent data suggest a source to the east, the Southern Uplands cannot be considered a potential source for the quartzite clasts. Additionally, clast size indicates a proximal source. While a source within or related to the Dalradian to the north is suggested (Haughton 1989; Haughton and Farrow 1989; Haughton *et al.* 1990), the current position of the block is problematic in that the quartzite clasts cannot be readily assigned to a specific Dalradian lithology. However, since the source of the LORS lay to the east in a currently unexposed or absent source of uplift in the Caledonian foreland there are no data to suggest that the quartzite is derived from any other source.

While few distinguishably Dalradian clasts are found within the conglomerates, the heavy mineral signatures and point count data strongly suggest a Dalradian source. Furthermore, previous provenance work (e.g. Phillips 2007) has identified metamorphic indicator minerals common to Dalradian lithologies within smaller grain-size fractions. This suggests that Dalradian lithologies more prone to weathering have been eroded, becoming well represented within smaller grain-size fractions, while the more resistant quartzites have been incorporated into conglomerate clast assemblages.

The source terrane for the MVB must have been dynamic, with continuous uplift and rejuvenation of topography in the catchment to provide a continuous source of coarse grained, conglomeratic sediment, including granites. Exhumation of older lithologies is paired with an influx of contemporaneous material. This suggests a link with the uplift and erosion of an emerging Caledonian mountain belt and is in direct contrast to previous models (e.g. Haughton and Bluck 1988) which describe sedimentation into strike-slip controlled basins related to movement along the HBF. As discussed in Hartley and Leleu (2015), a strike-slip model can be discounted due to lack of evidence for syn-sedimentary fault movement alongside increase in stratal thickness across the HBF, indicating lack of lateral fault movement. Through a multidisciplinary approach to provenance analysis, MVB LORS sedimentation can thus be attributed to tectonic rejuvenation of a dynamic, proximal source to the east within the active Caledonian foreland.

Conclusions

Detrital zircon, heavy mineral, petrographical point count and clast count data allow a reinterpretation of potential source areas for the LORS of the MVB. Petrographical point count and heavy mineral data suggest a consistent source or combination of sources, and clast size and type suggest a proximal source. The provenance signature shows no significant changes throughout the 9km of LORS stratigraphy in the MVB. Detrital zircon age data indicate Palaeozoic sources alongside Proterozoic and minor Archaean sediment sources. Most of the sedimentary rocks in the MVB are interpreted as being supplied from the Dalradian Supergroup together with periodic increases in

Caledonian or volcanic sources associated directly with volcanic activity. Despite palaeocurrent data suggesting a predominantly southwesterly palaeoflow (McKellar 2017), palaeogeographical reconstructions suggest that Norway is unlikely to be a feasible source for the sediment, as fault-reconstructions are unrealistic and Scotland would have to have been adjacent to the Uppermost or Upper Allochthons in mid-Norway to allow the supply of Caledonian zircons.

The provenance of the LORS of the northern MVB lies in the Dalradian Supergroup and Caledonian volcanic rocks. Previous models (e.g. Haughton and Bluck 1988; Haughton 1989) have suggested unroofing of an unspecified source terrane, discounting the Dalradian Supergroup as a potential sediment source. As the data presented here suggest no significant change through the stratigraphy as a whole, these models cannot be sustained and are rejected in favour of sediment supply due to uplift and erosion of an emerging mountain belt in the Caledonian foreland. As such, the Midland Valley Basin Lower Old Red Sandstone provides a robust example of the necessity of a multidisciplinary approach to provenance study in palaeogeographic reconstructions of orogenic drainage development.

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Figure Captions

Fig. 1. Sites of Lower Old Red Sandstone across Scotland alongside the dominant lithological groups for the Grampian and Northern Highland terranes (After Hartley and Leleu 2015).

Fig. 2. (**a**) Simplified map and cross-section of the northern Midland Valley Basin (MVB) showing distribution of stratigraphic groups across major folds (Modified from Hartley and Leleu 2015); (**b**) Simple stratigraphic column showing relative thicknesses of the main stratigraphic LORS groups of the northern MVB.

Fig. 3. Late Silurian to Early Devonian formations in the northern Midland Valley of Scotland, located between the Highland Boundary Fault (HBF) and Southern Upland Fault (SUF). Numbered sections show the location of the listed formations, which are laterally variable across the area. Initial table modified from Browne *et al.* 2002.

Fig. 4. Map of the northern Midland Valley Basin (MVB) showing the location of conglomerate clast counts, point count sample distribution, heavy mineral and detrital zircon sample locations. Numbers show point count sample numbers. See supplementary data for sample locations.

Fig. 5. Dunnottar Castle Conglomerate Formation with high percentage of volcanic clasts, showing clast long axis location for measurement(A); Camera lens (white arrow) for scale.

Fig. 6. Scatter plot of distribution of individual clast sizes recorded across sample sites, showing variation in clast size between the formations, with the largest clasts occurring in the Dunnottar Castle, Downie Point and Whitehouse conglomerates of the Dunnottar-Crawton Group.

Fig. 7. Pie charts showing variation in the percentage of different clast types upwards through the stratigraphy of the northern MVB LORS.

Fig. 8. Area graphs showing variation of clast types by size through the LORS stratigraphy.

Fig. 9. Modal composition data showing variation in sandstone detrital components through the stratigraphy of the northern MVB.

Fig. 10. Ternary diagram for determining sandstone provenance (after Dickinson and Suczek 1979) for the LORS of the northern MVB for formations in the Stonehaven (SH), Dunnottar-Crawton (DC), Arbuthnott-Garvock (AG) and Strathmore (SM) groups.

Fig. 11. Ternary diagram for determining sandstone provenance (after Dickinson and Suczek 1979) with data-point distributions marked as areas showing significant and consistent overlap between formations.

Fig. 12. Composition of heavy mineral assemblages indicating no major change in overall provenance through the northern MVB LORS.

Fig. 13. Heavy mineral index values from the northern MVB showing variations in ATi, GZi and RuZi for the Stonehaven (SH); Dunnottar-Crawton (DC); Arbuthnott-Garvock (AG) and Strathmore (SM) groups.

Fig. 14. Locations of samples for detrital zircon geochronology. (**a**) Northern MVB LORS samples according to stratigraphy. Stratigraphical section after Browne *et al.* (2002). (**b**) Map showing locations of the samples within the northern MVB. Samples: 1. Cowie Sandstone Formation, Stonehaven Group; 2. Castle of Cowie Member, Cowie Sandstone Formation, Stonehaven Group; 3. Cowie Sandstone Formation, Stonehaven Group; 4. Carron Sandstone Formation, Stonehaven Group; 5. Dunnottar Castle Conglomerate Formation, Dunnottar-Crawton Group; 6. Whitehouse Conglomerate Formation, Dunnottar-Crawton Group; 7. Gourdon Sandstone Formation, Dunnottar-Crawton Group; 8. Scone Sandstone Formation, Arbuthnott-Garvock Group; 9. Scone Sandstone Formation, Arbuthnott-Garvock Group; 10. Teith Sandstone Formation, Strathmore Group.

Fig. 15. Combined frequency age and probability density diagrams through the stratigraphy of the northern MVB, where n means concordant data between -10% and 10% discordance of all data. Dashed lines show the upper and lower limits of the Proterozoic.

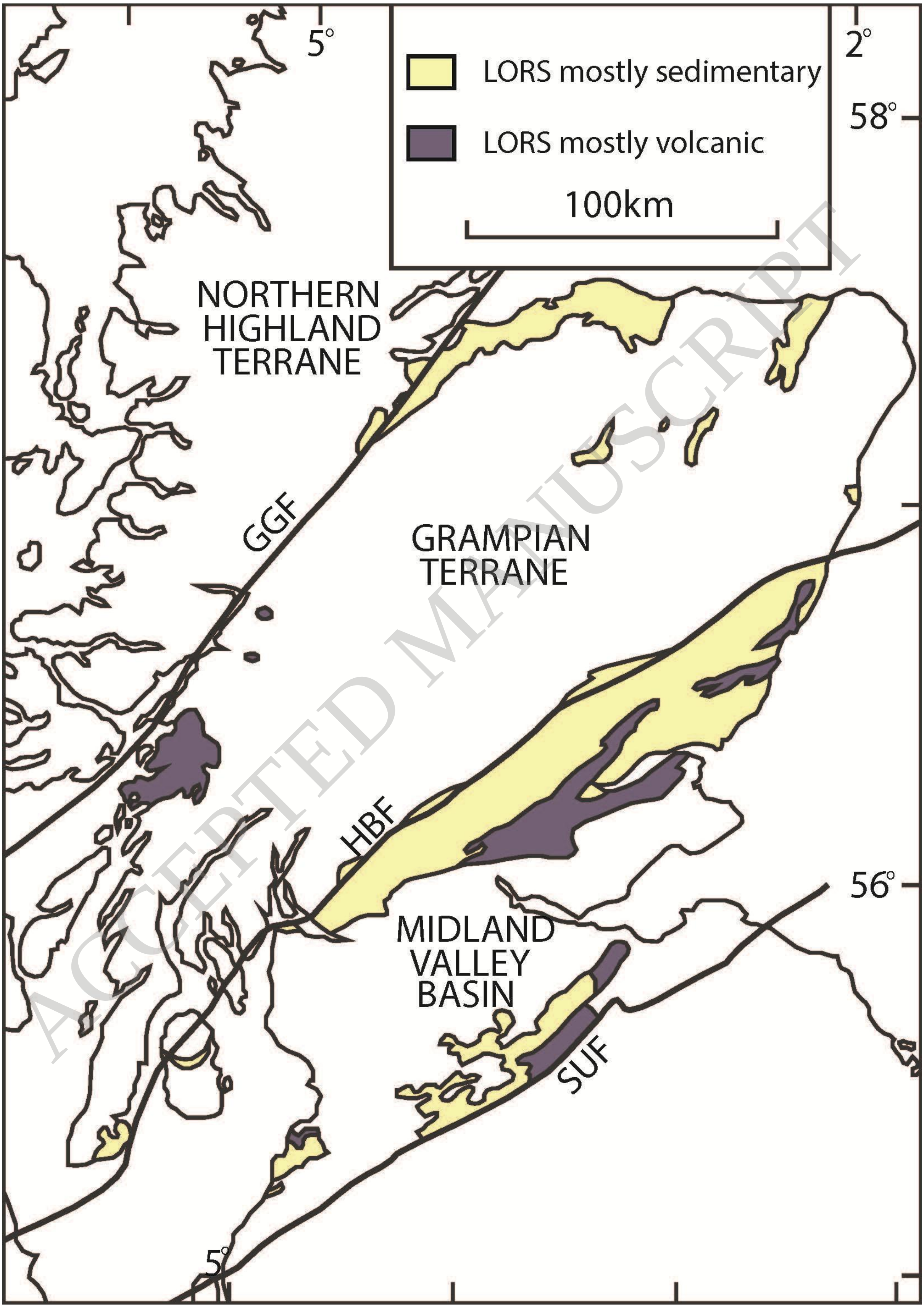
Fig. 16. Probability density plots: (**a**) Northern MVB samples dominated by Palaeozoic and Proterozoic zircons; (**b**) Northern MVB samples dominated by Palaeozoic zircons; (**c**) the Dalradian Supergroup of mainland Scotland (Cawood *et al.* 2004); (**d**) the Moine Supergroup of mainland Scotland (Kirkland *et al.* 2008); (**e**) the Moine Supergroup of mainland Scotland (Cawood *et al.* 2004); (**f**) Norwegian river sediments draining the Caledonian Nappe Domain (Morton *et al.* 2008); (**g**) compilation of the intrusion age of magmatic rocks in the Sveconorwegian and Caledonian belts in SW Scandinavia (mainly zircon U-Pb ages)(Bingen and Solli 2009). Age spectra taken from the literature show average zircon age data from the areas and/or successions described in the publications listed.

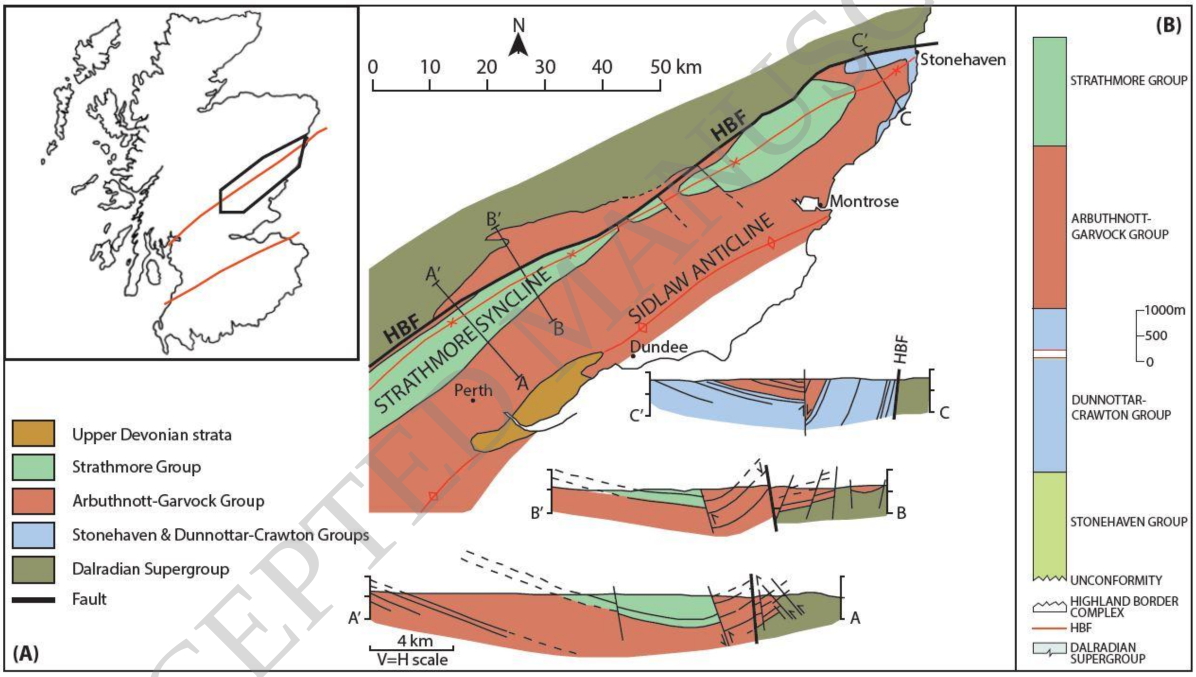
Fig. 17. Palaeogeographic reconstruction of the north Atlantic region showing the close relationship between rock types in Scotland, Norway and Greenland and distribution of main sediment supply routes for the LORS of the northern MVB (MV) with the location of the Upper and Uppermost

Allochthon sample site (Bingen & Solli 2009). Map also shows possible extension of the Dalradian Supergroup of the Grampian Terrane offshore (modified from Fossen 2010), with a palaeogeographical reconstruction of fluvial systems draining the uplifted foreland of the Caledonian Orogeny

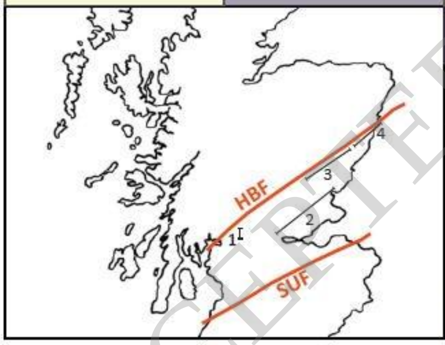
Table 1. *Youngest single grain age for each of the MVB LORS detrital zircon samples*

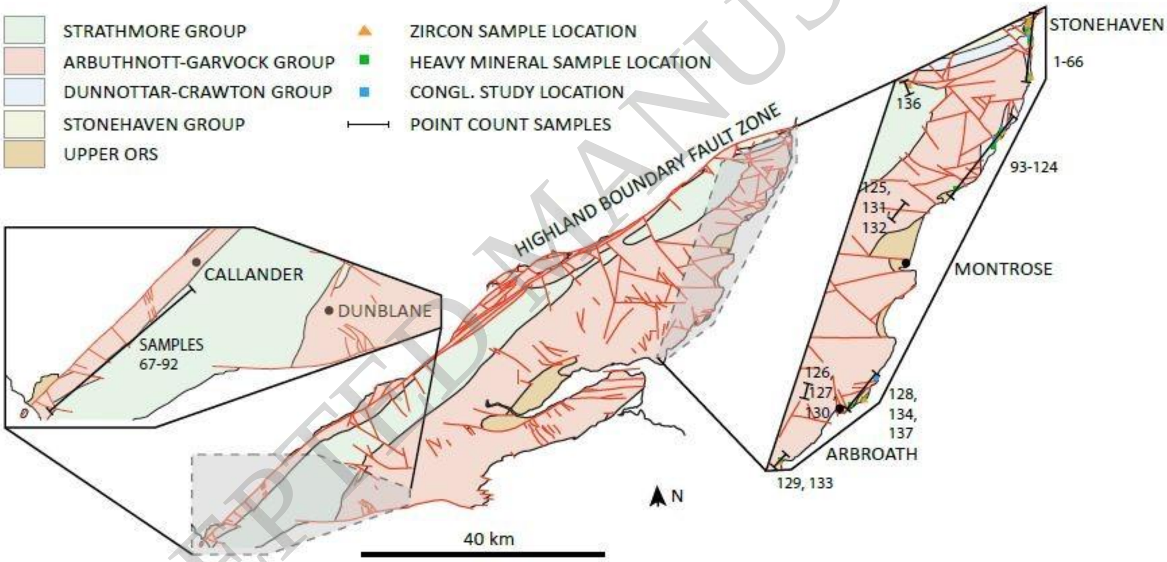
Sample	**Group**	**Formation**	**Youngest Single Grain (Ma)**
10	Strathmore	Teith Sst Fm	402 ± 5
9	Arbuthnott-Garvock	Scone Sst Fm	425 ± 6
8	Arbuthnott-Garvock	Scone Sst Fm	423 ± 7
7	Dunnottar-Crawton	Gourdon Sst Fm	425 ± 5
6	Dunnottar-Crawton	Whitehouse Congl Fm	426 ± 4
5	Dunnottar-Crawton	Dunnottar Castle Congl Fm	422 ± 5
4	Stonehaven	Carron Sst Fm	430 ± 6
3	Stonehaven	Cowie Sst Fm	470 ± 7
2	Stonehaven	Castle of Cowie Mbr	478 ± 4
1	Stonehaven	Cowie Sst Fm	439 ± 4


5°
2°
58°
LORS mostly sedimentary
LORS mostly volcanic
100km
NORTHERN
HIGHLAND
TERRANE
GGF
GRAMPIAN
TERRANE
HBF
56°
MIDLAND
VALLEY
BASIN
SUF
5°


N
0 10 20 30 40 50 km
HBF
Stonehaven
Montrose
STRATHMORE SYNCLINE
SIDLAW ANTICLINE
Dundee
Perth
Upper Devonian strata
Strathmore Group
Arbuthnott-Garvock Group
Stonehaven & Dunnottar-Crawton Groups
Dalradian Supergroup
Fault
(A)
4 km
V=H scale
(B)
STRATHMORE GROUP
ARBUTHNOTT-GARVOCK GROUP
1000m
500
0
DUNNOTTAR-CRAWTON GROUP
STONEHAVEN GROUP
UNCONFORMITY
HIGHLAND BORDER COMPLEX
HBF
DALRADIAN SUPERGROUP

1	2	3	4		
Teith Sandstone	Teith Sandstone	Teith Sandstone Gannochy Conglomerate	Teith Sandstone	**Strathmore Group**	DEVONIAN
Cromlix Mudstone	Cromlix Mudstone	Cromlix Mudstone	Cromlix Mudstone		DEVONIAN
Ruchill Flagstone	Scone Sandstone	Scone Sandstone	Scone Sandstone Deep Conglomerate	**Arbuthnott-Garvock Group**	DEVONIAN
Craig of Monievreckie Conglomerate	Dundee Flagstone Ochil Volcanic	Craighall Conglomerate	Montrose Volcanic Catterline Conglomerate		DEVONIAN
		Lintrathen Tuff Member	Crawton Volcanic	**Dunnottar-Crawton Group**	SILURIAN
			Whitehouse Conglomerate		SILURIAN
			Gourdon Sandstone		SILURIAN
			Tremuda Bay Volcanic		SILURIAN
			Dunnottar Castle Conglomerate		SILURIAN
		MOSTLY VOLCANIC	Carron Sandstone	**Stonehaven Group**	SILURIAN
		MOSTLY SEDIMENTARY	Crawton Sandstone		SILURIAN




STRATHMORE GROUP
ARBUTHNOTT-GARVOCK GROUP
DUNNOTTAR-CRAWTON GROUP
STONEHAVEN GROUP
UPPER ORS
ZIRCON SAMPLE LOCATION
HEAVY MINERAL SAMPLE LOCATION
CONGL. STUDY LOCATION
POINT COUNT SAMPLES
HIGHLAND BOUNDARY FAULT ZONE
CALLANDER
DUNBLANE
SAMPLES 67-92
STONEHAVEN
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93-124
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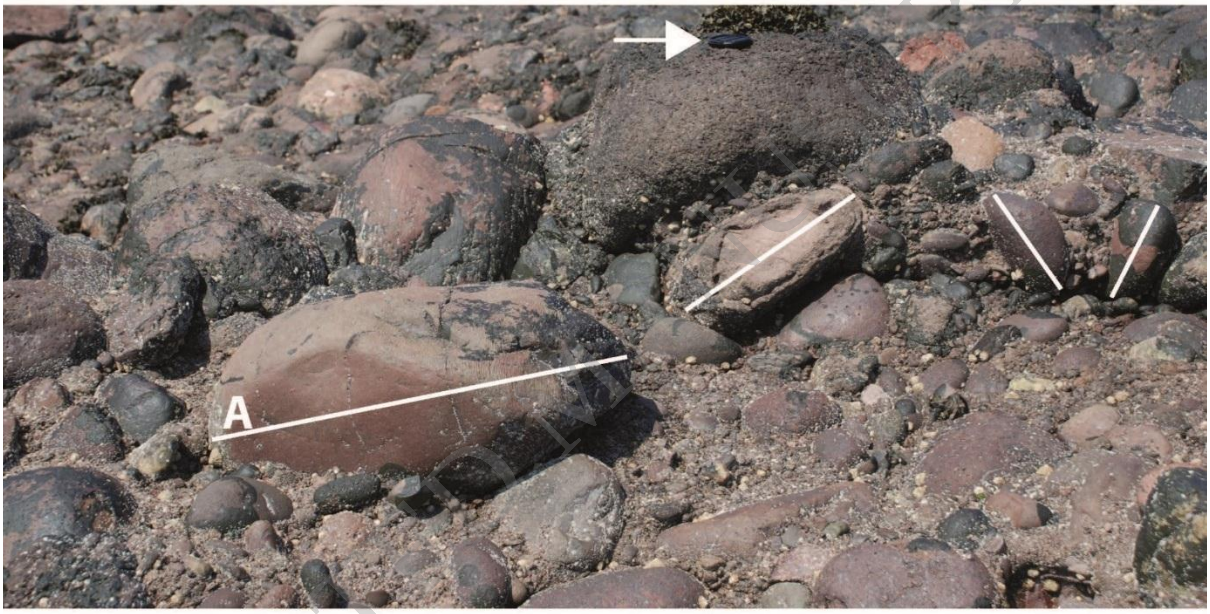
ARBROATH
129, 133
N
40 km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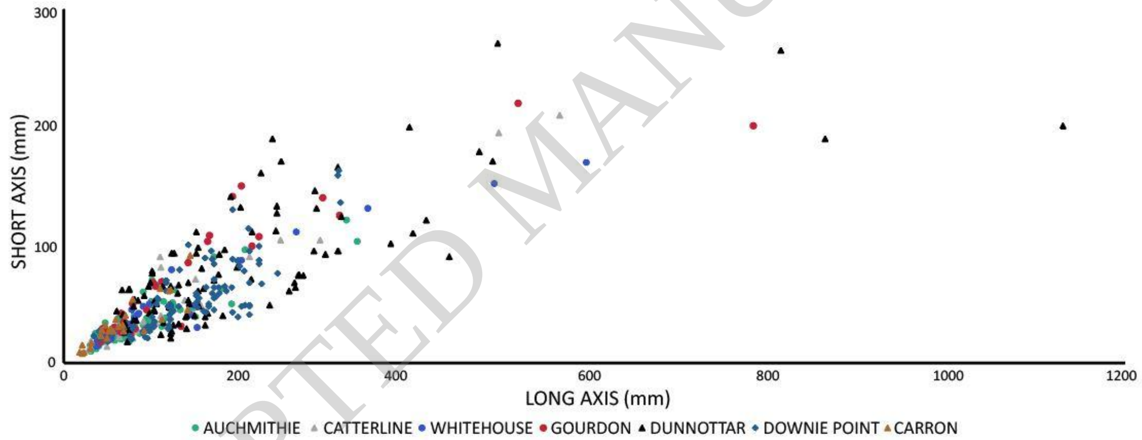
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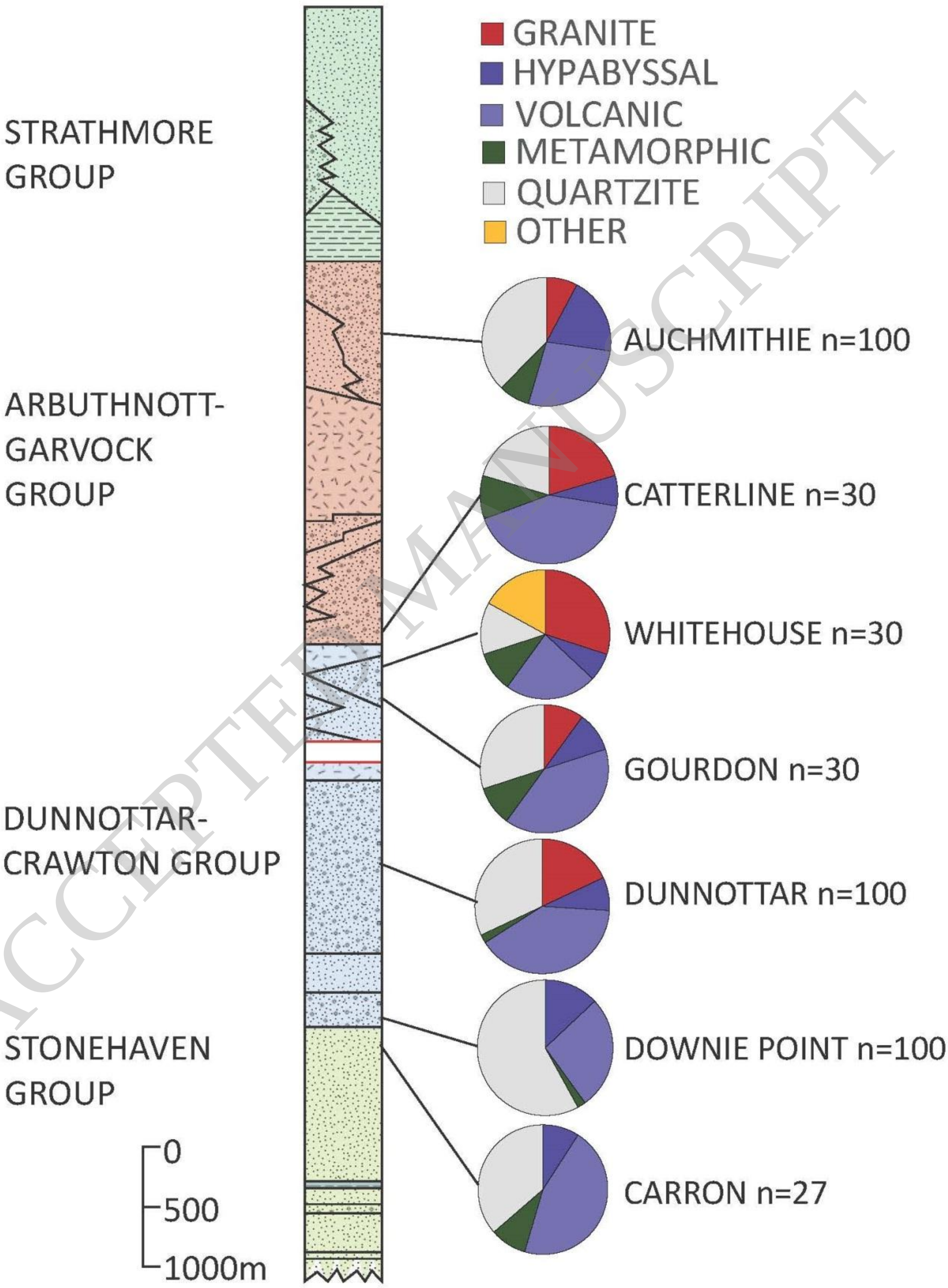
STRATHMORE GROUP
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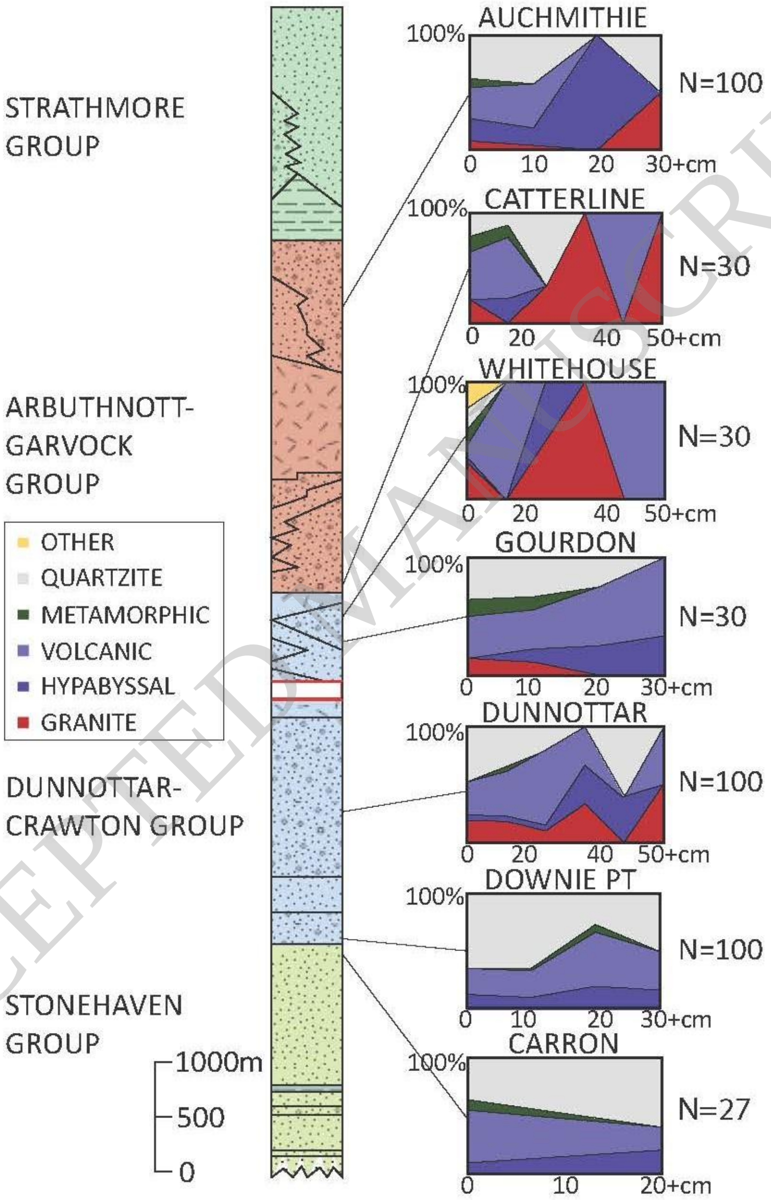
CARRON n=27



STRATHMORE GROUP
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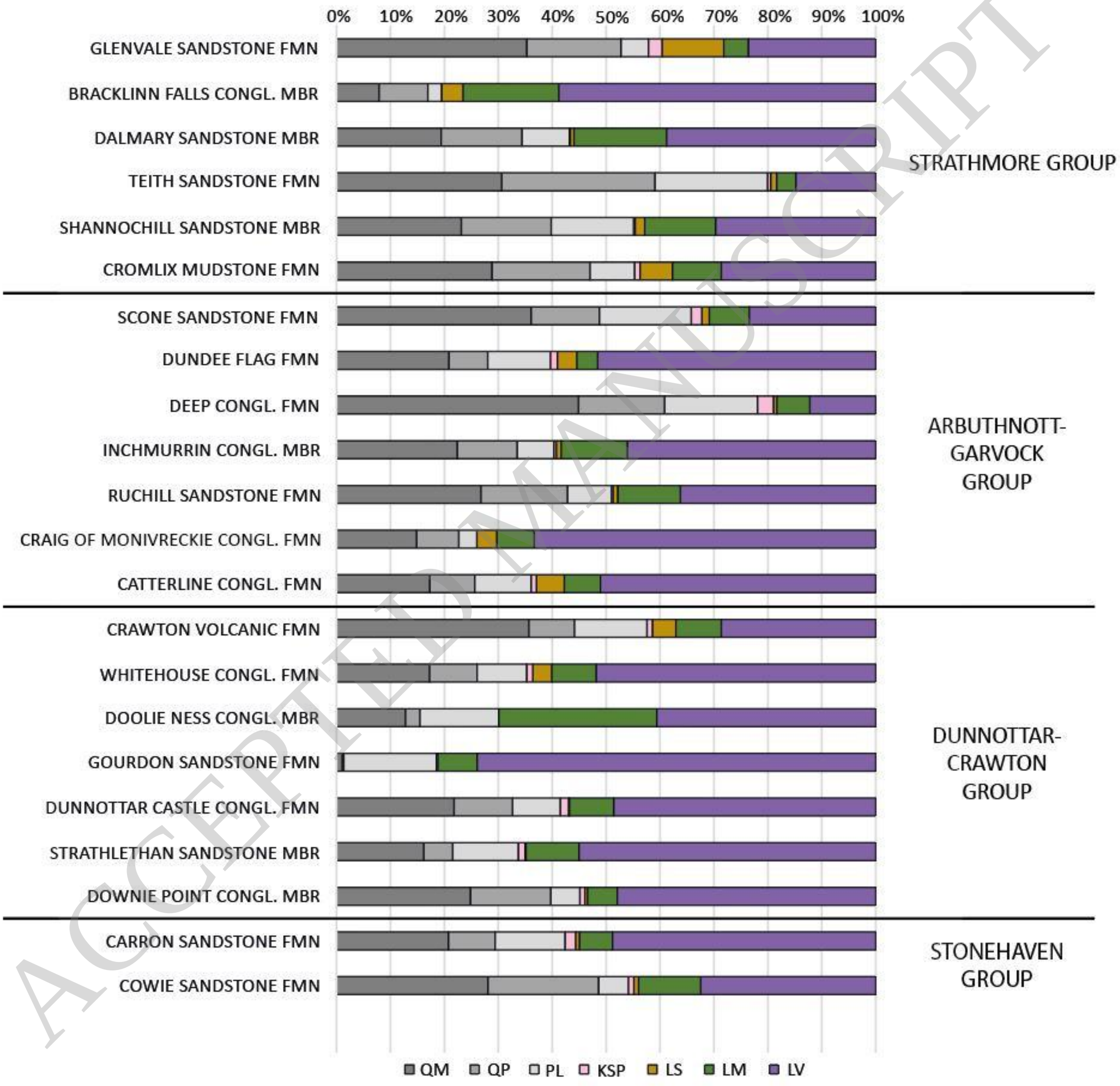
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STRATHMORE GROUP
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DEEP CONGL. FMN
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RUCHILL SANDSTONE FMN
CRAIG OF MONIVRECKIE CONGL. FMN
CATTERLINE CONGL. FMN
ARBUTHNOTT-GARVOCK GROUP
CRAWTON VOLCANIC FMN
WHITEHOUSE CONGL. FMN
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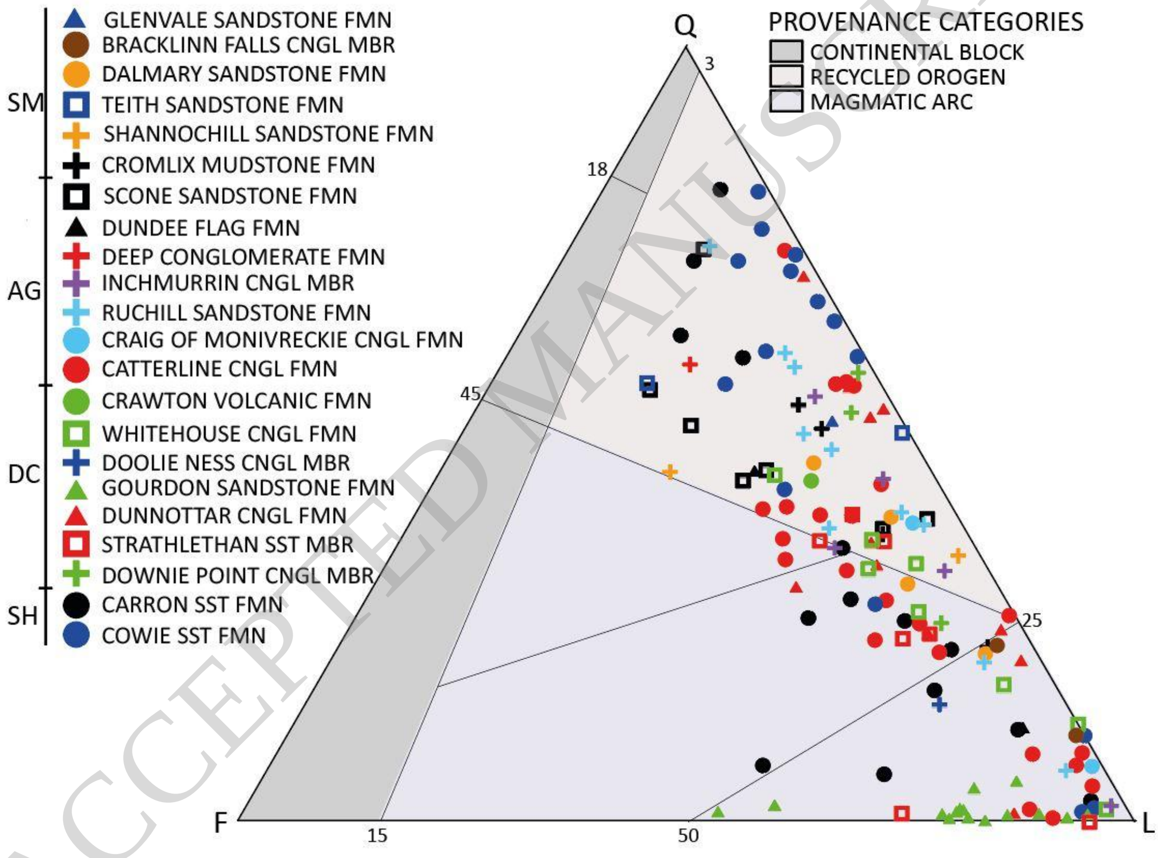
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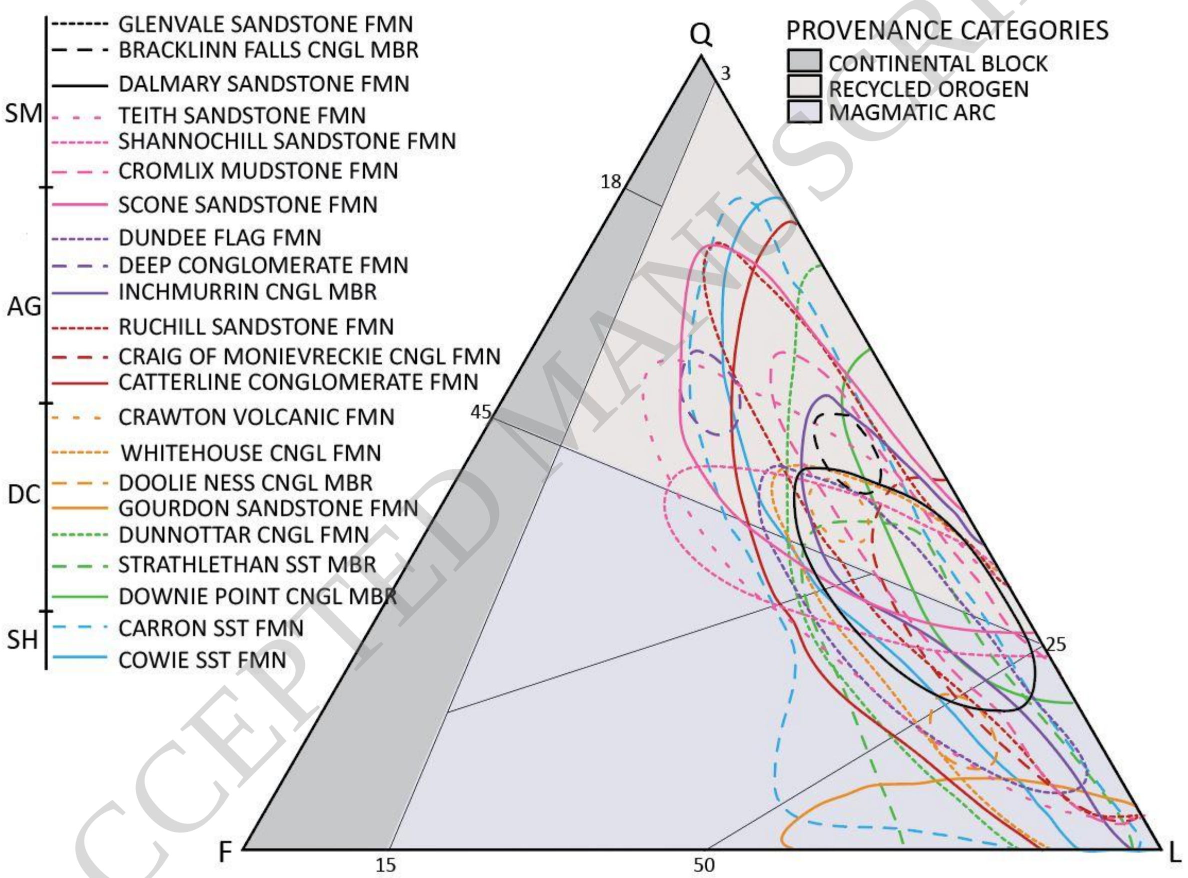
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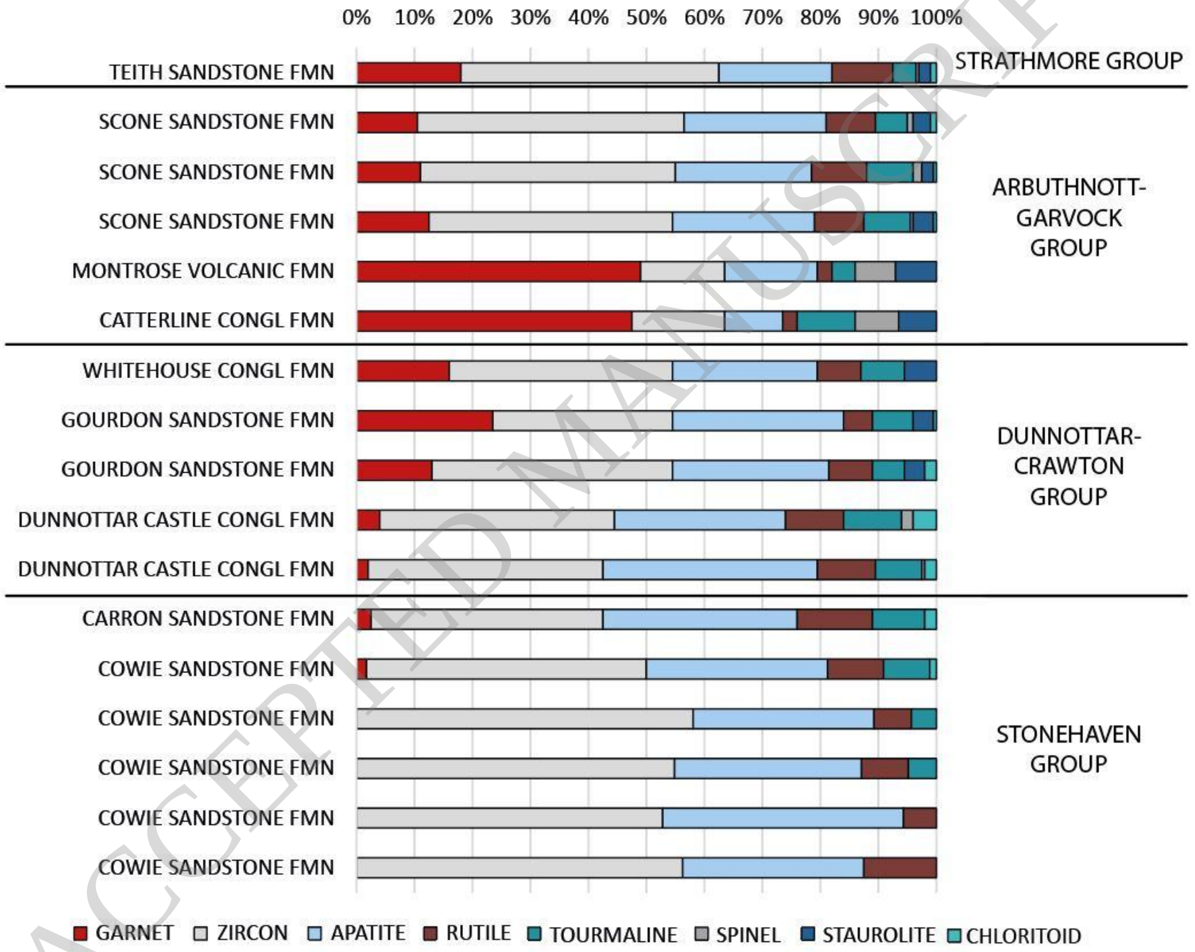

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ARBUTHNOTT-GARVOCK GROUP
DUNNOTTAR-CRAWTON GROUP
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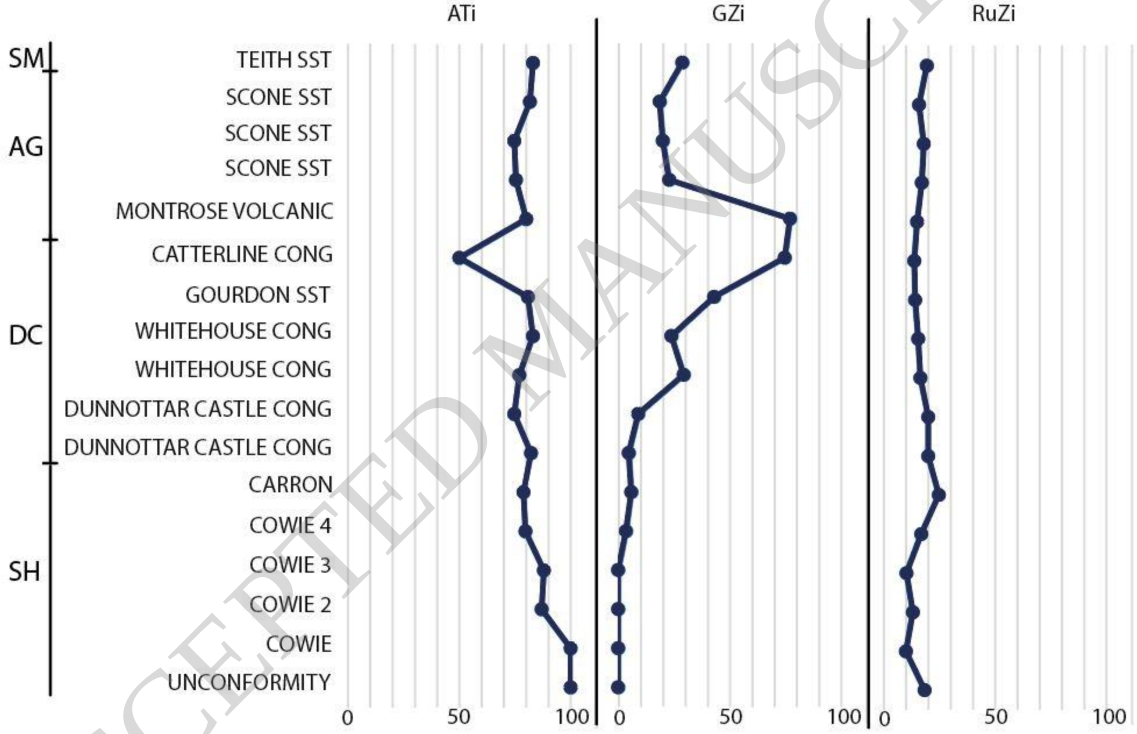
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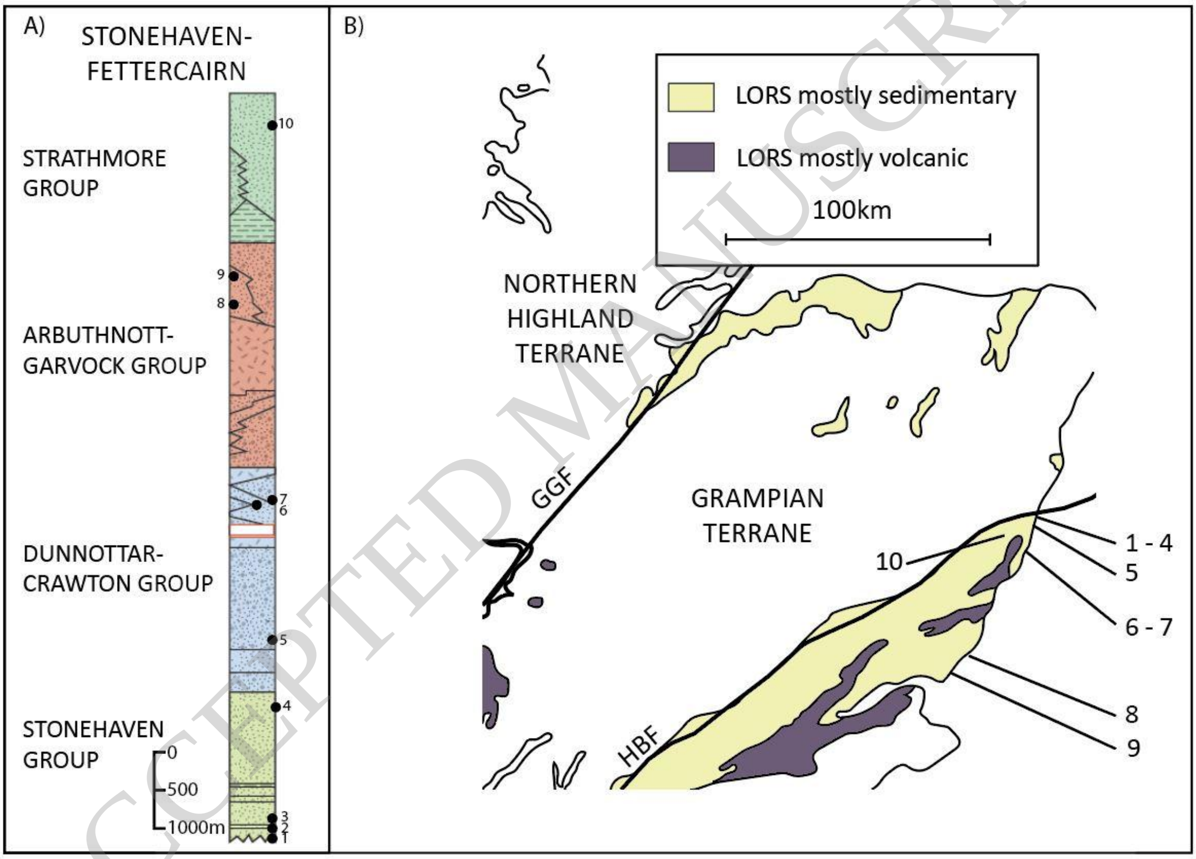
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STONEHAVEN-
FETTERCAIRN
STRATHMORE
GROUP
ARBUTHNOTT-
GARVOCK GROUP
DUNNOTTAR-
CRAWTON GROUP
STONEHAVEN
GROUP
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1000m
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3
2
1
B)
LORS mostly sedimentary
LORS mostly volcanic
100km
NORTHERN
HIGHLAND
TERRANE
GGF
GRAMPIAN
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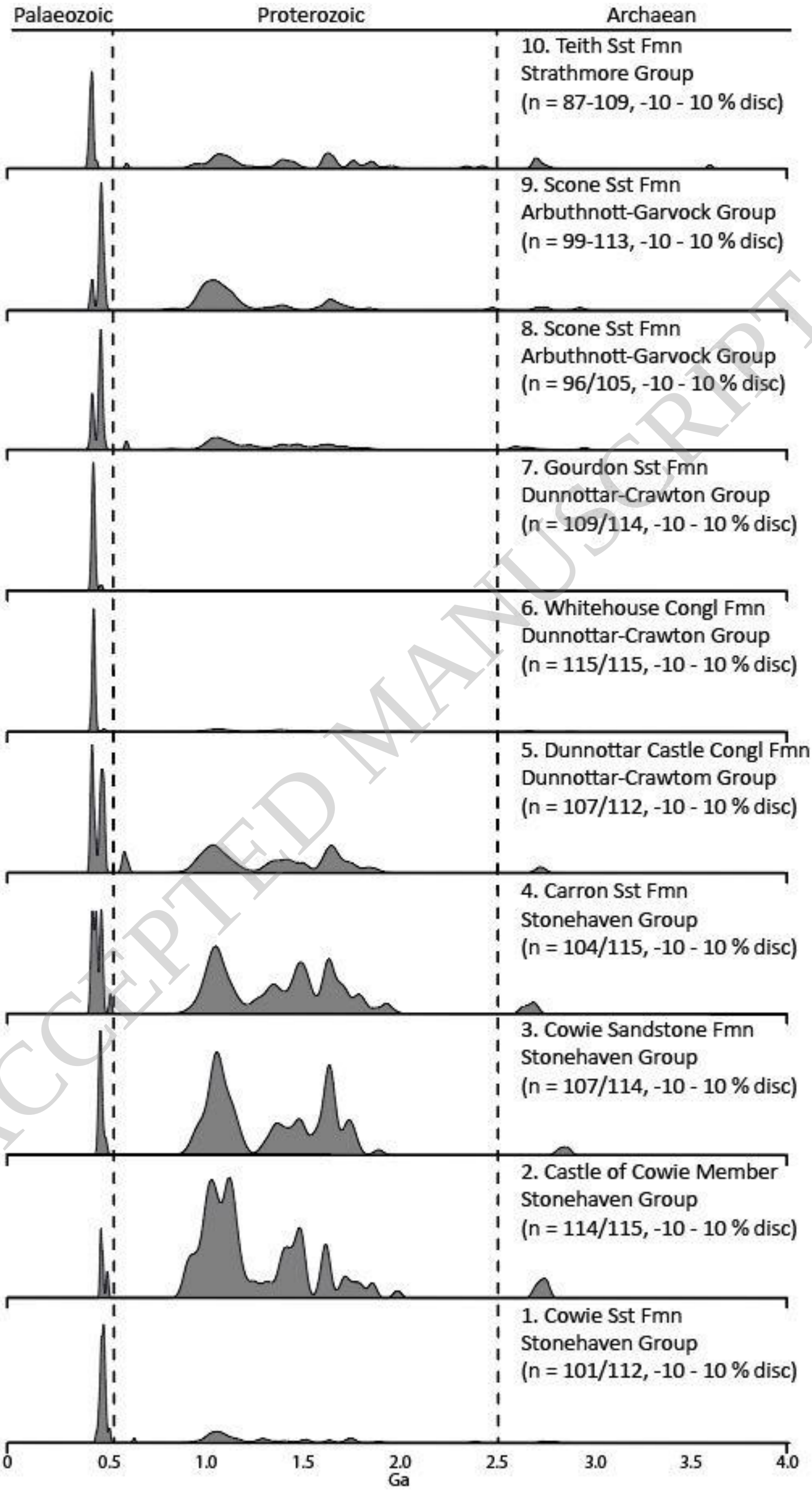
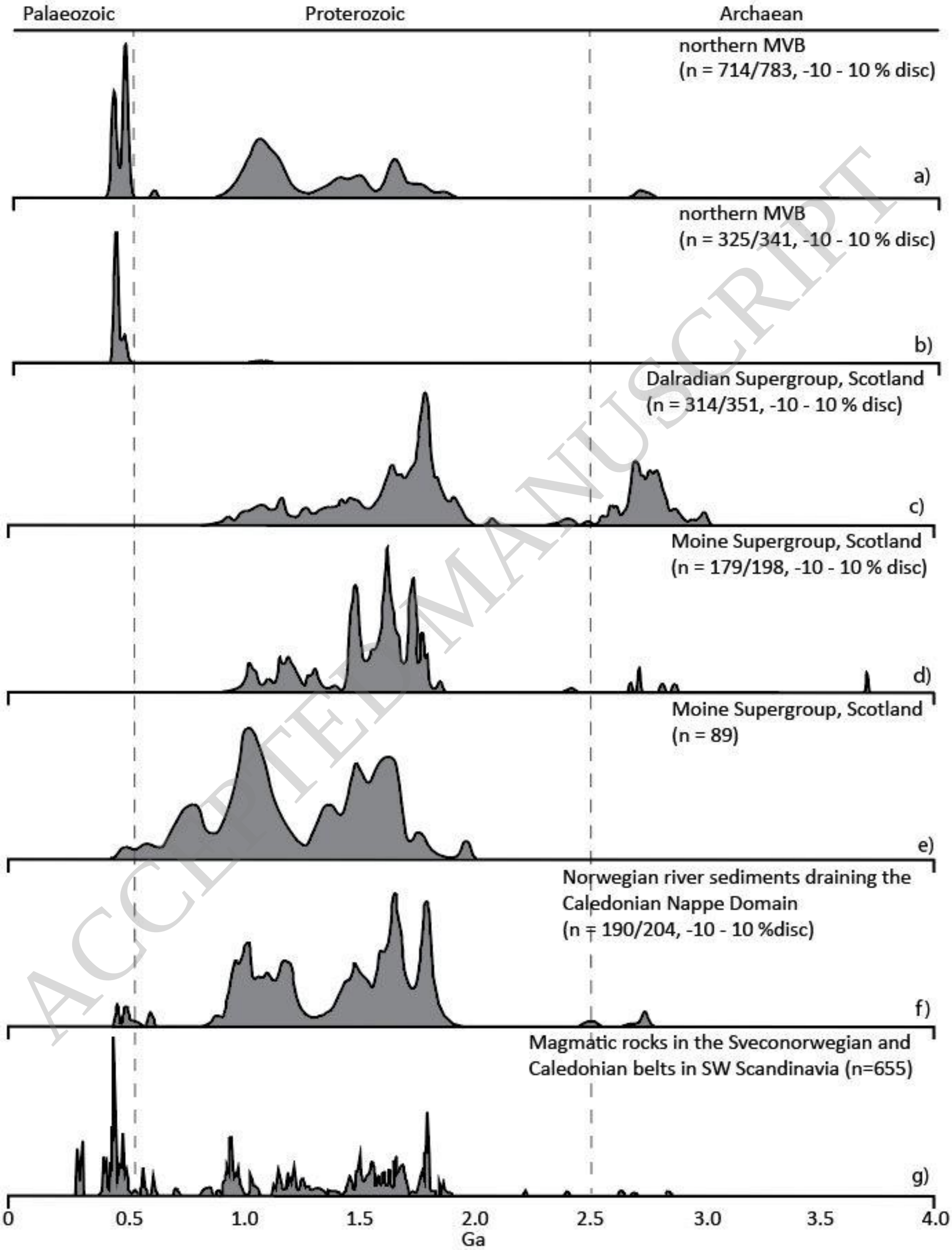
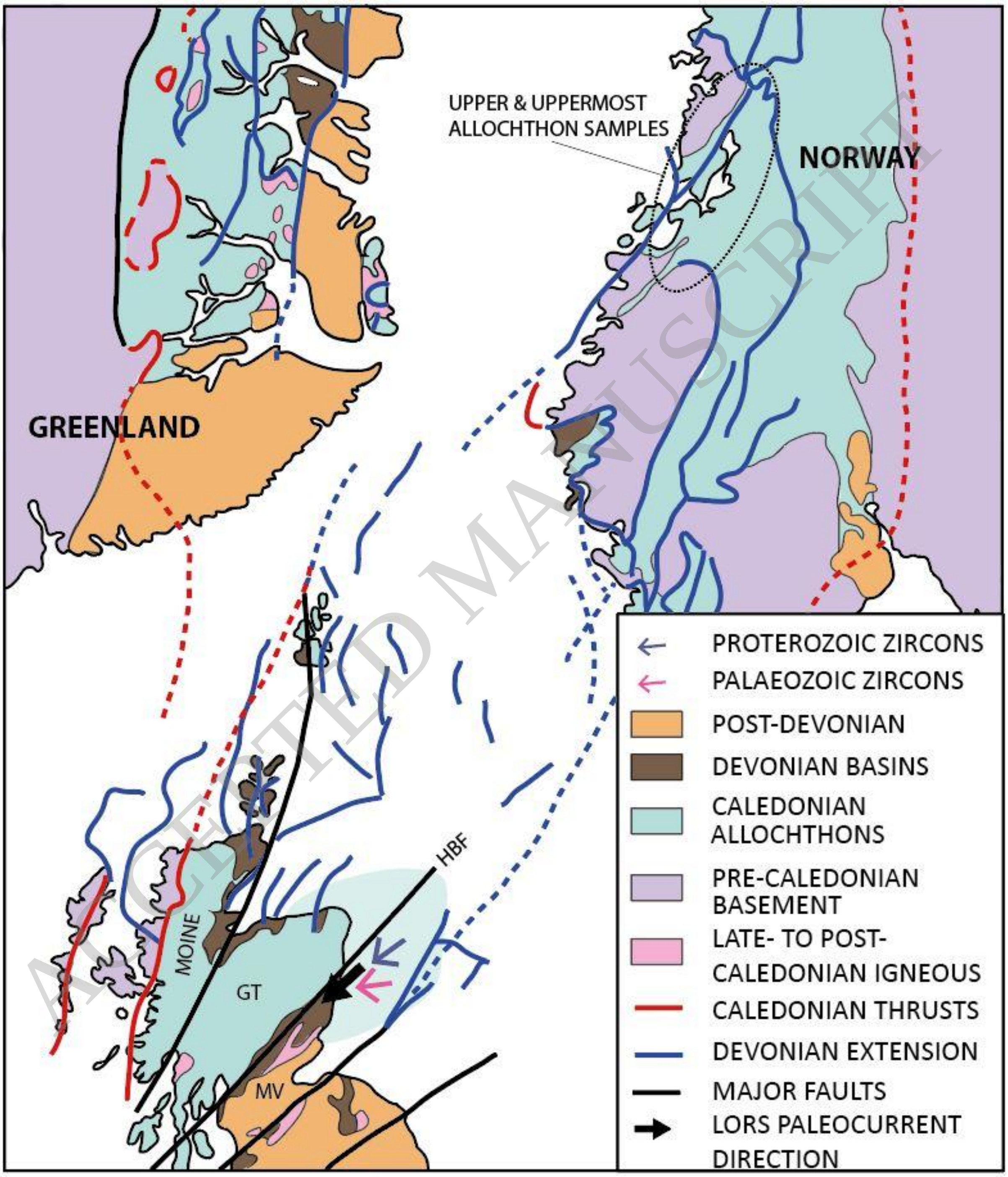

Palaeozoic
Proterozoic
Archaean
10. Teith Sst Fmn
Strathmore Group
(n = 87-109, -10 - 10 % disc)
9. Scone Sst Fmn
Arbuthnott-Garvock Group
(n = 99-113, -10 - 10 % disc)
8. Scone Sst Fmn
Arbuthnott-Garvock Group
(n = 96/105, -10 - 10 % disc)
7. Gourdon Sst Fmn
Dunnottar-Crawton Group
(n = 109/114, -10 - 10 % disc)
6. Whitehouse Congl Fmn
Dunnottar-Crawton Group
(n = 115/115, -10 - 10 % disc)
5. Dunnottar Castle Congl Fmn
Dunnottar-Crawtom Group
(n = 107/112, -10 - 10 % disc)
4. Carron Sst Fmn
Stonehaven Group
(n = 104/115, -10 - 10 % disc)
3. Cowie Sandstone Fmn
Stonehaven Group
(n = 107/114, -10 - 10 % disc)
2. Castle of Cowie Member
Stonehaven Group
(n = 114/115, -10 - 10 % disc)
1. Cowie Sst Fmn
Stonehaven Group
(n = 101/112, -10 - 10 % disc)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Ga


Palaeozoic
Proterozoic
Archaean
northern MVB
(n = 714/783, -10 - 10 % disc)
a)
northern MVB
(n = 325/341, -10 - 10 % disc)
b)
Dalradian Supergroup, Scotland
(n = 314/351, -10 - 10 % disc)
c)
Moine Supergroup, Scotland
(n = 179/198, -10 - 10 % disc)
d)
Moine Supergroup, Scotland
(n = 89)
e)
Norwegian river sediments draining the
Caledonian Nappe Domain
(n = 190/204, -10 - 10 %disc)
f)
Magmatic rocks in the Sveconorwegian and
Caledonian belts in SW Scandinavia (n=655)
g)
0
0.5
1.0
1.5
2.0
Ga
2.5
3.0
3.5
4.0


UPPER & UPPERMOST
ALLOCHTHON SAMPLES
NORWAY
GREENLAND
MOINE
GT
MV
HBF
PROTEROZOIC ZIRCONS
PALAEOZOIC ZIRCONS
POST-DEVONIAN
DEVONIAN BASINS
CALEDONIAN
ALLOCHTHONS
PRE-CALEDONIAN
BASEMENT
LATE- TO POST-
CALEDONIAN IGNEOUS
CALEDONIAN THRUSTS
DEVONIAN EXTENSION
MAJOR FAULTS
LORS PALEOCURRENT
DIRECTION