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Early basin development of the Dalradian Supergroup

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Abstract

The Dalradian Supergroup represents an important phase of Neoproterozoic sedimentation on the eastern margin of Laurentia, yet its early depositional history and palaeogeographic context remain incompletely understood. This study integrates lithostratigraphic, sedimentological, and detrital zircon U–Pb data to refine correlations between the early Dalradian Supergroup of mainland Scotland and the Colonsay and Bowmore Groups of the Inner Hebrides. Multidimensional scaling of detrital zircon age spectra, coupled with lithological and geochemical similarities, supports a threefold subdivision of the Colonsay Group that parallels the Glenshirra Group and the Corrieyairack and Glen Spean Subgroups of the Grampian Group of the mainland Dalradian. Coarse fluvial-deltaic and alluvial fan deposits in the initial basin infill of the Colonsay Group yield unimodal Palaeoproterozoic zircon populations dominated by local Makkovik–Ketilidian–Rhinnian basement sources, whereas younger shallow marine sediments show increasing Grenville-aged input. These trends, mirrored in the Glenshirra and Grampian Group succession, suggest a shared tectonic regime and sediment routing system. The Bowmore Group, although tectonostratigraphically distinct, displays detrital zircon signatures comparable to the upper part of the Glen Spean Subgroup and early Appin Group of

the Dalradian Supergroup. Collectively, the data support early Dalradian sedimentation within a foreland basin setting, potentially initiated during the mid-Tonian Knoydartian Orogeny. Shifts in the detrital zircon spectra are interpreted here to record a transition from proximal to more distal sediment sourcing in a flysch setting, the progressive infilling of topographic lows and the expansion of a molasse apron across eastern Laurentia.

Introduction

The late Tonian through early Ordovician Dalradian Supergroup occurs between the Great Glen and Highland Boundary faults and as scattered outcrops across the southern Inner Hebrides, the most extensive of which are on Islay (Fig. 1). The latter, along with the islands of Colonsay and Oronsay, comprise the Colonsay Group, a dominantly siliciclastic sedimentary succession some 5,000 m thick (Muir et al., 1995; Stewart and Hackman, 1973). No stratigraphic contact exists between the Colonsay rocks in western Islay (on the Rhinns Peninsula) and the Dalradian of eastern Islay and, given a dearth of depositional age constraints for these successions, their original spatial-temporal relationship to one another is uncertain. This leaves open the possibility that the Colonsay Group could correlate with any one of the Wester Ross, Loch Ness (formerly Moine and Torridonian) or Dalradian Supergroups. Additional uncertainty exists about the relationship of those rocks to the Bowmore Sandstone Group, a unit only found on Islay. Here we report new detrital zircon age data and field-based observations that address these uncertainties and assess the postulate made by previous workers (e.g. McAteer et al., 2010b, 2010a; Rock, 1985; Stewart and Hackman, 1973) that the Colonsay Group and Bowmore Sandstone are broadly correlative with the lower part of the Dalradian Supergroup. We then use this strengthened lithostratigraphic framework and new detrital zircon age data to assess the provenance and development of the early basin infill of the Dalradian Supergroup.

Dalradian Supergroup, Colonsay Group and Bowmore Sandstone

The Dalradian Supergroup is a variably metamorphosed and deformed sedimentary succession at least 10 km thick that is divided into, from base to top, the Glenshirra, Grampian, Appin, Argyll, Southern Highland and Trossachs Groups (Fig. 1; see Prave et al. (2024) for a synthesis). On the Scottish mainland, the overall geographic distribution of the Dalradian rocks is such that the older units (Glenshirra-Grampian Groups) are present mostly in the northern and central parts of the outcrop belt whereas the younger units (Appin through Southern Highland Groups) are more extensively developed in southwest areas of the mainland and adjacent islands of the Inner Hebrides. The Trossachs Group is only preserved in patches

adjacent to the Highland Boundary Fault. Metamorphism and deformation during the Caledonian/Grampian Orogeny show a similar pattern with the highest-grade and most intensely deformed rocks (amphibolite facies and locally migmatitic) located in the north-central core of the outcrop belt and enveloped by successively less deformed rocks (mostly greenschist facies) outward from there.

The Colonsay Group is restricted in its occurrence, being present only on the Rhinns of Islay and nearby Colonsay with its adjacent small island of Oronsay (Fig. 1). Although 18 formations have been identified (British Geological Survey, 1996, 1997) an informal stratigraphic framework has been used here to group these into three 'Subgroups': a lower 'Kilchiaran' Subgroup (Octofad Sandstone through Coul Grit Formations), a middle 'Saligo' Subgroup (Kilchoman Phyllite through Oronsay Formations) and an upper 'Kilchattan' Subgroup (Dun Gallian Grit through Staosnaig Phyllite Formations; Fig. 1). The Kilchiaran Subgroup forms the central and northern part of the Rhinns of Islay where its basal deposits (Octofad Sandstone and Eilean Liath Grit Formations) are sheared, patchily developed pebbly mudstone and arkosic sandstone deposited above an unconformity on c. 1.8 Ga orthogneiss of the Rhinns Complex. This contact has subsequently been sheared and deformed by later Caledonian Orogeny. The top of the middle unit (Oronsay Formation; Saligo Subgroup) occurs on Oronsay and the contact between it and the Kilchattan Subgroup is interpreted as an unconformity at the base of the overlying Dun Gallian Grit Formation due to truncation of the underlying greywacke beds (Stewart 1962). The Kilchattan Subgroup becomes progressively younger south to north across Colonsay; its top is not exposed. The Bowmore Sandstone has no preserved stratigraphic top or base and occurs as a structurally isolated outcrop bounded by the Loch Skerrols (thrust) Fault to the east and Loch Gruinart Fault to the west (Muir et al., 1995; McAteer et al. 2010b).

The Colonsay-Glenshirra-Grampian rocks display intriguingly similar depositional histories (Fig. 2). In general, the successions (many hundreds of metres in thickness) begin with fluvial-deltaic-shallow marine strata that are then overlain by deeper-marine shelf and/or turbiditic strata and then by more fluvial-deltaic-shallow marine successions. This general pattern is exhibited by the various formations within the Kilchiaran, Saligo and Kilchattan Subgroups of the Colonsay Group (Stewart, 2002, 1962a, 1962b; Stewart and Hackman, 1973). Likewise, that pattern is recorded in the Glenshirra through lower Grampian groups (Corrieyairick Subgroup; Banks et al., 2007; Banks and Winchester, 2004) and again in the upper Grampian into lower Appin Groups (Glen Spean through Ballachulish Subgroups; Banks et al., 2007; Glover, 1993; Glover et al., 1995; Glover and Winchester, 1989).

Carbonate-bearing strata are rare in the Colonsay-Glenishirra-Grampian groups; where present, they occur as discontinuous units that are typically less than a few decimetres thick and commonly only as individual metre-thick beds interlayered with fine-grained siliciclastic rock. Examples include the Colonsay Limestone (on Colonsay) and Kincaig Limestone (on the mainland). The earliest extensive carbonate-bearing units in the Dalradian succession occur in the lower part of the Appin Group; the Ballachulish Limestone on the Scottish mainland and its likely equivalent, the Kintra Dolomite, on Islay. The Bowmore Sandstone has received less attention, but it is probably a deltaic/shallow-marine deposit (Fitches and Maltman, 1984).

Depositional age constraints for all the above rocks are scarce. The Colonsay Group must be younger than late Stenian (late Mesoproterozoic) to early Tonian, the age of the youngest detrital zircons (McAteer et al., 2010; this study), and older than a c. 439 Ma appinite at Kiloran Bay which intrudes those rocks (Muir et al., 1997). For the Dalradian as a whole, a sparse trilobite fauna in the Trossachs Group (Curry et al., 1984; Ethington, 2008; Fletcher and Rushton, 2008) shows that sedimentation persisted at least into the early Ordovician whereas the start of Dalradian sedimentation must postdate c. 806 Ma, constrained by the U-Pb age of monazites that grew during shearing in mylonitised gneissic rocks of the Badenoch Group that form the basement to the Dalradian (Noble et al., 1996). However, a clear-cut relative age relationship between this shear zone and the Dalradian Supergroup has not been observed and thus the only conclusive maximum age for the succession is defined by ca. 840 Ma Knoydartian metamorphism present in the unconformably underlying Badenoch Group (Highton et al., 1999).

The only robust depositional age for the Dalradian Supergroup is a U-Pb zircon age of 601 ± 4 Ma (Dempster et al., 2002) for a tuff in the Tayvallich Volcanic Formation at the top of the Argyll Group. Based on Sr and C isotope data, and detrital zircon maximum depositional age data, the glaciogenic Port Askaig Formation (Spencer, 1971) at the base of the Argyll Group has been equated to the 716–660 Ma Sturtian glaciation (Brasier and Shields, 2000; Fairchild et al., 2018; Prave et al., 2009; Rugen et al., 2024; Sawaki et al., 2010; but see Rooney et al., 2011 and Moles and Selby, 2023). Carbonate rocks within the Easdale Subgroup (lower Argyll Group) have also been identified as a likely 635 Ma Marinoan-equivalent cap carbonate (McCay et al., 2006; Prave et al., 2009).

As with the Dalradian Supergroup in the Islay area, the Colonsay and Bowmore Sandstone Groups are folded and metamorphosed to lower greenschist facies. Several deformational events have been proposed and revised by researchers over the years but the consensus now is that the major structures, characterised by large-scale NE–SW trending

upright folds and slaty cleavage, are a consequence of the Grampian phase (*c.* 470–460 Ma) of the Caledonian Orogeny (Fitches and Maltman 1984, their ‘D3’). Conversely, interference fold patterns (such as the Kiloran Bay) syncline (their D4), appinite intrusions (dated at *c.* 439 Ma by Muir et al. 1997) and NE-SW trending high-angle faults that transect Colonsay and are likely splays of the Great Glen Fault, can all be attributed to the Scandian phase (*c.* 440–400 Ma) of the orogeny. Older structures (e.g. D1 and D2 of Fitches & Maltman 1984 Fig 5) are minor and often localised and some are facies restricted. Many can be interpreted as original soft-sediment deformation features; however, some are tectonic and either developed during the early stages of Grampian deformation or possibly during an earlier (Neoproterozoic) deformation event. The latter interpretation has led to the suggestion of a correlation of the Colonsay Group with the Wester Ross/Loch Ness Supergroups (e.g. Fitches & Maltman 1984, McAteer et al. 2010), but to date there is no metamorphic evidence of such an event on either Islay or Colonsay. Previous authors (Bentley, 1988; Fitches and Maltman, 1984) have suggested that fault-controlled basement relief played a significant role in Colonsay Group deposition, suggesting some element of syn-depositional faulting. Such an explanation could account for the juxtaposition in northern Colonsay of metasediments of the Kilchattan Formation being in fault contact with Rhinns Complex orthogneisses with possibly some 5 km of ‘missing’ stratigraphy. Alternatively, the most recent interpretation of the Grampian and Glenshirra Groups on the Scottish mainland as a Knoydartian flysch and molasse succession (Prave et al., 2023) allows for the possibility that deposition of the Glenshirra, Grampian and Colonsay Groups and Knoydartian deformation could have been essentially synchronous.

The Knoydartian (*ca.* 725–840 Ma) is the younger of two Neoproterozoic orogenic events that proceeded the main collision (Grenville Orogeny) of Laurentia, Amazonia and Baltica during Rodinia assembly (Cawood et al., 2010). Together with the older Renlandian Orogeny (*ca.* 910–950 Ma), these events are collectively referred to as the Valhalla Orogen and are interpreted to reflect subduction related tectonism along the margins of the Asgard Sea, which opened following the rotation of Baltica into Laurentia (Cawood et al., 2010). The extent of the Knoydartian orogen remains poorly constrained mainly due to Caledonian overprinting; however, its impact is most clearly recorded as metamorphic evidence within the Loch Ness Supergroup (Strachan et al., 2024 and references therein). Knoydartian metamorphism is absent in the Dalradian Supergroup, however, its close temporal proximity to the onset of Dalradian sedimentation raises the possibility that the Knoydartian orogen was the tectonic driver of early foreland basin development of the Dalradian Supergroup (Prave et al., 2024). If so, Knoydartian sources—particularly the metamorphosed sedimentary rocks of the Wester Ross

and Loch Ness supergroups—may have supplied detritus to the early Dalradian basin. Constraining this provenance could be key to evaluating the foreland basin hypothesis.

Detrital zircon age spectra: a tool for postulating correlations and tracing source terranes

Due to the dearth of robust and reliable temporal constraints, detrital zircon age spectra are heavily relied upon to establish maximum depositional ages alongside testing stratigraphic correlations by comparing a sample's provenance, and tracing sediment sources (see Fedo et al., 2003 for examples). At present, the youngest detrital zircon age clusters for the Glenshirra-Grampian-Colonsay-Bowmore rocks yield Stenian or early Tonian maximum depositional age constraints (Banks et al., 2007; Cawood et al., 2003; McAteer et al., 2010b, 2010a). These data also strongly suggest that the main provenance for those rocks were Palaeo-Mesoproterozoic regions of Laurentia (e.g. Banks et al., 2007; Cawood et al., 2003) or their reworked equivalents, the Wester Ross and Loch Ness Supergroups. As a basis for assessing correlations between rock units in the Dalradian Supergroup, the shapes and amplitudes of detrital age spectra have played a central role (e.g. Banks et al., 2007; Johnson et al., 2016; Strachan et al., 2013). Existing data (Fig. 3) for the Colonsay Group and Bowmore Sandstone (McAteer et al., 2010a, 2010b) show that: (i) both successions lack Archean-age zircons; (ii) samples from the Kilchiaran and Saligo Subgroups of the Colonsay Group are either unimodal with a yield a dominant 1.5–1.8 Ga spectra or yield a more varied Palaeo-Mesoproterozoic distribution and a high-amplitude late-Palaeoproterozoic peak that contrasts with the pattern of broader age distribution to as young as Stenian obtained from samples of the Kilchattan Subgroup; and (iii) a sample from the Bowmore Sandstone shows a dominance of late Mesoproterozoic ages along with a minor Palaeoproterozoic component (McAteer et al., 2010a). Detrital titanite U-Pb ages obtained on samples that bracket the contact between the lower (Oronsay Formation) and upper units (Dun Gallain Grit) of the Colonsay Group yield ages as young as 942 ± 26 Ma (McAteer et al., 2010b). Taken together, the characteristics of the detrital zircon age spectra for the Colonsay-Bowmore rocks are remarkably like those known of the Glenshirra and Grampian Groups (Fig. 3). It is that aspect, combined with their shared depositional patterns, that have underpinned ideas that the Glenshirra-Grampian and Colonsay-Bowmore rocks are correlatives (e.g. McAteer et al., 2010b, 2010a; Rock, 1985; Stewart and Hackman, 1973). It should be noted that previous detrital zircon analyses have rather small datasets ($n < 50$) (McAteer et al., 2010b, 2010a; Cawood et al., 2003; Banks et al., 2007). Therefore, our data enable us to test and further refine that interpretation with an expanded, more statistically robust (high n) zircon

dataset, while assessing the potential source terranes and extent of sedimentary reworking that may be present during the early basin development of the Dalradian Supergroup.

Materials and Methods

A total of six sandstone samples from the Colonsay Group (5 samples) and Grampian Group (1 sample) were collected for detrital zircon analysis; the locations of the samples are given in the supplementary materials (Fig. 1). On Islay, two samples of Eilean Liath Grit (RL-1 and RL-2) and one sample of Rubha Gaidhealach Grit (RL-3) were taken at Kilchiaran Bay, along a previously unsampled northward transect from the contact with the Rhinns Complex. This sampling location was selected to help resolve stratigraphic uncertainties surrounding the isolated Octofad Sandstone's position relative to strata overlying the Rhinns complex elsewhere on Islay. The one Grampian Group sample from the Eilde Flags (EF-1) was collected east of Loch Leven in the Central Highlands to investigate similarities between the late Grampian Group on the mainland and the late Colonsay Group and Bowmore Sandstone on Oronsay and Islay, respectively. We chose to also sample the Octofad sandstone (OF-3) just above the contact with the Rhinns Complex and the Bowmore Sandstone (BS-1) from Blackrock in similar the localities to that sampled by (McAteer et al., 2010b, 2010b) in order to analyse a higher number of zircons and make more statistically robust provenance interpretations (Vermeesch, 2004).

Mineral separation and analysis were performed at the London Geochronology Centre, University College London. Zircon minerals were extracted from approximately 5 kg of sample material using a combination of heavy liquid and magnetic separation methods. The extracted grains were embedded in epoxy, polished, and subsequently analysed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), using a NWR193 excimer laser coupled with an Agilent 7900 ICP-MS. The analysis employed a 25 μm laser spot size, operating at 10 Hz with an energy fluence of approximately 2.2 J cm^{-2} .

Isotopic ratios were processed using GLITTER 4.4.2 software (Griffin et al., 2008), with Plešovice zircon (Sláma et al., 2008) serving as the primary reference standard. Additional secondary standards included GJ-1 (Jackson et al., 2004) and 91 500 (Wiedenbeck et al., 2004), which yielded mean ages of 599.1 ± 3.42 Ma (MSWD 1.3, $n = 18$) and 1051.5 ± 6.3 Ma (MSWD 1.3, $n = 16$), respectively. Uranium and thorium concentration measurements were calibrated using NIST SRM612 glass as a reference material (Pearce et al., 1997).

Concordia ages were determined by identifying the maximum likelihood intersection between the concordia curve and the uncertainty ellipse of $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios

(Ludwig, 1998; Vermeesch, 2021). A discordance threshold of $-2.0/+7.0$ was applied, using the log ratio distance of Vermeesch (2021). Data processing, including zircon age calculations, kernel density estimation, visualization and finite mixture modelling, were conducted using IsoplotR 6.3 (Vermeesch, 2018). The full dataset can be accessed in the supplementary data.

Exploratory data analysis of the detrital zircon datasets from the Colonsay-Bowmore Groups and their possible correlatives was carried out by Multidimensional Scaling (MDS; Vermeesch, 2013). For the basis of comparison, we applied the same discordance threshold outlined above to published datasets. Additionally, the MDS analysis shown in figure 4 uses the Wasserstein-2 (W_2) distance in favour of the conventional Kolmogorov-Smirnov distance because it is better able to capture lateral shifts between age spectra in a stratigraphic sequence (see Section 3.2 of Lipp and Vermeesch, 2023).

Results

Kernel density estimation (KDE) plots for each sample, alongside previously published samples from the Colonsay and Bowmore Groups and Glenshirra and Grampian Groups of the Dalradian Supergroup are shown in Figure 3, along with KDE plots for the Wester Ross and Loch Ness Supergroups for comparison. Two MDS plots are shown in Figure 4, including samples from the early Neoproterozoic Wester Ross and Loch Ness Supergroups. All raw data are given in the supplementary materials.

Octofad Sandstone (OF-3)

OF-3 shows a dominant peak between 1500–1800 Ma with 83% of zircons meeting the concordance thresholds (Fig 3). Post-1500 Ma grains make up 17% of the detrital zircon population with most between 1000 and 1300 Ma. The youngest single grain is 1082 ± 11 Ma, significantly younger than the youngest grain measured in the Octofad Sandstone previously (1337 ± 15 Ma; McAteer et al., 2010b). The detrital zircon spectra of OF-3 is most similar to the Octofad Sandstone and then the Smaull Formation samples of McAteer et al. (2010b) (their samples C37D and C22, respectively) (Fig 4A)

Eilean Liath Grit and Rubha Gaidhealach Grit (RL-1, RL-2 and RL-3)

Sample RL-1 has a dominant 1500–1800 Ma peak with 66% of zircons meeting the concordance thresholds. This peak becomes less dominant upsection from the basement contact, declining in RL-2 (54%) and again in RL-3 (46%) whereas the proportion of 1000–1500 Ma grains increases from RL-1 (30%) to RL-2 (35%) to RL-3 (45%) (Fig. 3). The

youngest single grains also become younger stratigraphically, from 1040 ± 10 Ma in RL-1, to 981 ± 10 Ma in RL-2, and 950 ± 11 Ma in RL-3. The detrital zircon spectrum of RL-1 shares the most similarity with the Inverlair Psammite of the Dalradian Supergroup and secondary with the Kiloran Flags Formation (C14) of the Colonsay Group. RL-2 and RL-3 are similar and share the most similarities with the Creag Dhubh Psammite and secondly with the Loch Laggan Psammite, both from the Dalradian Supergroup (Fig. 4A).

Bowmore Sandstone (BS-1)

In sample BS-1, the dominant population spans 1000–1300 Ma and constitutes ca. 67% of zircons that meet the concordance thresholds (Fig. 3). Pre-1300 Ma grains make up ca. 25% of the remaining detrital zircon population and mostly fall between 1300–1400 Ma and 1500–1800 Ma, with one single concordant Archean grain analysed (2613 ± 23 Ma). A small, but notable, population (ca. 8%) of grains span 950–1000 Ma, with 954 ± 13 Ma marking the youngest single grain. Previously, the youngest grain in the Bowmore Sandstone was 1337 ± 15 Ma (McAteer et al., 2010a). BS-1 compares most closely with the Eilde Flags (EF-1) and secondarily with the Gaick Psammite (SMS509) (Fig. 4A).

Eilde Flags (EF-1)

A 1000–1300 Ma population is also dominant in EF-1 with 61% of zircons meeting the concordance thresholds. Just 14% of ‘concordant’ grains fall between 1500–1800 Ma and two Archean grains are recorded. The youngest single grain is 956.8 ± 11 Ma and, like BS-1, ca. 8% of grains fall within 950–1000 Ma. The most similar sample to EF-1 is the Gaick Psammite (SMS509) and its second closest is the Maol an Fhithich Formation (RS-18-32), of the late Grampian and early Appin Groups in the Dalradian, respectively (Fig. 4A).

Defining early Dalradian Supergroup sedimentation

Three lithotectonic groupings, or ‘megasequences’, make up the Neoproterozoic stratigraphy of Scotland, the Wester Ross, Loch Ness and Dalradian Supergroups (see Krabbendam et al., 2022, 2024; Prave et al., 2024). These three megasequences, which are consistent across the circum-North Atlantic region (Fig. 1 of Olierook et al., 2020), are broadly linked through their shared tectonostratigraphic histories in which each is bracketed by a major orogenic episode. Firstly, the Wester Ross Supergroup was deposited in a foreland basin to the ca. 1.3 – 1.0 Ga Grenville Orogen prior to the Renlandian Orogeny (>960 Ma). Secondly, the Loch Ness

Supergroup was deposited post-Renlandian Orogeny but pre-Knoydartian Orogeny (>840 Ma) with evidence for both foreland basin and rift related deposition. Lastly, the Dalradian Supergroup was deposited syn/post-Knoydartian Orogeny. The ages of metamorphism and/or igneous activity within strata from this region are often used to assign strata to one of these megasequences, however, if such data is absent or difficult to obtain (as is the case with the Colonsay Group), U-Pb ages from detrital zircons, alongside sedimentological studies, remain integral.

Each Scottish supergroup was deposited on the eastern margin of Laurentia with access to somewhat similar source terranes (Krabbendam et al., 2022, 2024; Prave et al., 2024), and consequently similarities in provenance, lithofacies and detrital zircon signatures might be expected. Similarities in detrital zircon signatures can also arise from reworking i.e. detritus from the Wester Ross Supergroup being reworked into the Loch Ness Supergroup, and detritus from both the Wester Ross and Loch Ness Supergroups being reworked into the Dalradian Supergroup (and Colonsay Group). That said, distinct signatures do exist in each supergroup. Multidimensional scaling (MDS) analysis (Fig. 4A) illustrates that the detrital zircon U–Pb age spectra across the Colonsay and Bowmore Groups are most similar to that of the Glenshirra and/or Grampian Group in the Dalradian Supergroup.

Eleven of the twelve Colonsay and Bowmore samples are most similar to either the Dalradian Supergroup or to another unit within the Colonsay Group, with second-nearest neighbours also predominantly from these two groups (Fig. 4A). This spectral similarity, when considered alongside lithostratigraphic correlations, strengthens earlier suggestions that the Colonsay Group correlates with the early Dalradian Supergroup.

A strengthened case for correlating the Colonsay and Bowmore Groups with the early Dalradian Supergroup

On Islay, the Octofad Sandstone and Eilean Liath Grit are considered correlatives due to their similar structural position overlying the Rhinns Complex and their similar major and trace element compositions (McAteer et al., 2010b). The Octofad sandstone contains both granite and syenite pebbles with SIMS zircon ages of c. 1795 Ma and 1400 Ma, respectively (McAteer et al., 2010b), whereas the Eilean Liath Grit lacks any observable pebbles. Despite this grain-size difference, the two formations yield nearly identical detrital zircon age spectra, dominated by 1600–1800 Ma grains (Fig. 2), corroborating the previous interpretation of their correlation (McAteer et al., 2010b).

The lowermost parts of the stratigraphy of the Dalradian Supergroup in the Grampian Highlands is similarly represented by coarse-grained fluvial-deltaic units of the Glenshirra Group, including the Glen Buck Pebbly Psammite and Garva Bridge Psammite (Banks and Winchester, 2004). Like the Octofad Sandstone, the Glen Buck Pebbly Psammite contains 1800 Ma and 1500 Ma pebbles and a similarly unimodal Palaeoproterozoic zircon population, whereas the Garva Bridge Psammite, sampled higher in the stratigraphy, displays an increased proportion of 1000–1300 Ma grains, more akin to the Rubha Gaidhealach Grit of the Colonsay Group (Fig. 3). This differs from the detrital zircon make-up of the initial stratigraphy in the Wester Ross and Loch Ness Supergroups. The Iona and Sleat Groups (Wester Ross) and the Glenfinnan Group (Loch Ness) contain Archean and late Mesoproterozoic detrital zircon components (Cawood et al., 2015; Friend et al., 2003; Kirkland et al., 2009; Krabbendam et al., 2017), as well as Archean clasts interpreted to be sourced from the Lewisian Complex (McAteer et al., 2014).

Moving up stratigraphy, the Colonsay Group transitions to deeper marine turbiditic facies (Stewart and Hackman 1973), beginning with the Kilchoman Phyllite, and continuing through the Oronsay Greywacke (Saligo Subgroup). This transition is consistent with the Corrieyairack Subgroup of the Dalradian Supergroup, which likewise reflects a deepening depositional environment (Banks and Winchester, 2004). Both the Corrieyairack and Saligo Subgroups additionally show a notable shift in the sediment's dominant feldspar composition from K-feldspar to plagioclase (Banks et al., 2007; Stewart and Hackman, 1973). However, there is a slight variation in the Subgroups' detrital zircon make up. Turbidites from the Saligo Subgroup (C22, C29, C13) contain dominantly Palaeoproterozoic zircon spectra, though with less abundant 1000–1500 Ma components compared to their Corrieyairack counterparts (CJB1, CJB3). These differences may reflect one or a combination of limited zircon sampling (Vermeesch, 2004), lateral facies variability within the basin or variability in provenance feeding different sub-basins. Deeper marine facies are rare in either the Wester Ross or Loch Ness Supergroups and the detrital zircon spectra measured in the Colonsay Group turbidites plot closer to Dalradian samples than samples from either of the older two supergroups (Fig. 4A).

The overlying Dun Gallain Grit marks a return to shelfal facies, including the Colonsay Limestone, comparable to the transition from the Corrieyairack to the Glen Spean Subgroups on the mainland. A concomitant increase in 1000–1500 Ma zircons is observed in both the Dun Gallain Grit and the Glen Spean Subgroup (Fig. 3), reinforcing this correlation. Equivalent

transitions and zircon patterns are not observed in either the Wester Ross or Loch Ness Supergroups, which lack carbonate rocks and show differing zircon trends.

The Bowmore Group on Islay is fault-bounded, hampering correlation with the mainland. Nevertheless, it shows a detrital zircon signature closely matching that of the Eilde Flags and Gaick Psammite of the upper Glen Spean Subgroup. The Maol an Fhitich Formation Quartzite, part of the lowermost Appin Group of the Dalradian Supergroup on Islay and sampled by Kirkland et al. (2025), also shares this same signature (Fig. 4A and B), hinting strongly at a correlation between the Bowmore Group rocks and those of the upper Grampian or lower Appin Groups.

Collectively, these data support a revised threefold subdivision of the Colonsay Group, in line with that of the pre-Appin Group stratigraphy of the Dalradian Supergroup on the mainland : (1) the Kilchiaran Subgroup, comprising alluvial and deltaic deposits equivalent to the Glenshirra Group; (2) the Saligo Subgroup, encompassing the turbidite-dominated succession correlated with the Corrieyairack Subgroup; and (3) the Kilchattan Subgroup, a shelf-deltaic package mirroring the Glen Spean Subgroup (Fig. 2).

Source terranes and palaeogeography of early Dalradian sedimentation

During the Neoproterozoic, the three Scottish megasequences developed as sedimentary basins along the eastern margin of Laurentia. Detrital zircon spectra from the Dalradian Supergroup and the Colonsay and Bowmore Groups indicate derivation from Laurentian source terranes (Banks et al., 2007; Cawood et al., 2003; Kirkland et al., 2025; McAteer et al., 2010b; Rugen et al., 2024; Strachan et al., 2013) and palaeocurrent indicators from the Colonsay and Grampian Groups indicate a general flow direction from the West and South (Banks and Winchester, 2004; Bentley, 1988; Stewart and Hackman, 1973). Sediment supply to the Dalradian Supergroup likely comprised both first-cycle material sourced directly from the metamorphic and igneous basement of the palaeocontinents of Laurentia and possibly Baltica, alongside polycyclic detritus reworked from older sedimentary successions such as the Wester Ross and Loch Ness Supergroups. Unimodal detrital zircon spectra are more likely to be first-cycle sediments sourced from proximal basement terranes, whereas a varied spectra often reflects a more distal dispersal pathway with some degree of reworking highly likely.

Notably, Archean zircons are largely absent from the initial Dalradian basin fill and from older Neoproterozoic successions across Scotland. Archean-aged grains appear abruptly higher in the stratigraphy, in the glaciogenic sediments of the lower Argyll Group, suggesting

input related to Cryogenian glacial unroofing and erosion of Archean crustal blocks during the Sturtian glaciation (Rugen et al. 2024).

The oldest detrital zircon populations from the Glenshirra and lower Colonsay Groups are Palaeoproterozoic (ca. 1600–1800 Ma) grains present in variable proportions in each sample. These are consistent with local sources in the Rhinns Complex, exposed today on Islay, Colonsay, and parts of northwestern Ireland (Muir et al., 1994), as well as with syenitic and gneissose lithologies of the Makkovik–Ketilidian provinces in eastern Canada and southern Greenland (Garde et al., 2002; Hinchey et al., 2020). Syenites of similar age (ca. 1750 Ma) are also present on the Rockall Bank (Daly et al., 1995), a submerged microcontinental block on the western European margin (Fig. 5), thereby supporting a widespread Makkovik–Ketilidian–Rhinnian (MKR) Palaeoproterozoic basement domain extending across eastern Laurentia (Fig. 5).

The occurrence of 1400–1500 Ma granitoid clasts and detrital zircons in both the lower Colonsay and Glenshirra Groups (Banks et al. 2013; McAteer et al. 2010a; this study) presents a more enigmatic provenance. These ages match those of the Pinwarian terrane, exposed today in Labrador, and the Telemarkia terrane in the Sveconorwegian belt of Baltica (Bingen et al., 2005; Wasteneys et al., 1997). However, palaeocurrent indicators in the Colonsay and Grampian Groups preclude a Baltican origin for the clasts, and the considerable distance between Labrador and Scotland would negate the proximal depositional nature of the host sediments (Banks & Winchester 2004). We therefore consider a more plausible scenario, originally suggested by Banks et al. (2013), whereby a concealed Pinwarian basement lay adjacent to the early Dalradian basin. Other concealed source terranes are known from the adjacent Rockall microcontinent (e.g. Chew, 2019; Daly et al., 1995). Additionally, inherited zircon populations (1500–1800 Ma) in Caledonian granitoids intruding the Dalradian Supergroup (Prave et al., 2023) may lend further support to the existence of an Rhinns–Pinwarian crustal substrate beneath the Grampian Highlands, although, these grains could also have been assimilated from the metasediments of the Wester Ross and Loch Ness Supergroups (Milne et al., 2023). Subtle differences in peak zircon ages among lower stratigraphic units (e.g., Octofad Sandstone, Glen Buck Pebbly Psammite and Eilean Liath Grit) likely reflect along-strike variations in the exposed basement terrane, though the dominance of MKR over Pinwarian signals suggests the former represented the majority of the proximal source, much like what is seen in Labrador today.

Younger detrital zircon populations (1000–1300 Ma) increase in relative abundance up-section in both the Grampian and Colonsay Groups. These grains are interpreted as products

of Grenvillian-age magmatism associated with the collision of Laurentia, Amazonia and Baltica during Rodinia assembly. Crystallisation occurred during a sequence of major orogenic events: the Elzevirian (1160–1240 Ma), Shawinigan (1140–1200 Ma), and Ottawan (1050–1090 Ma), which collectively generated a Himalayan-scale orogen across eastern Laurentia (McLelland et al., 2010; Rainbird et al., 2017; Rivers, 1997).

A small number of Tonian-aged grains are present in the Gaick Psammite and Bowmore Sandstone these grains are readily explained by widespread Renlandian calc-alkaline magmatism documented across the North Atlantic (e.g. Kinny et al., 2025; McClelland et al., 2019). In contrast, no grains of Knoydartian age are present in the Glenshirra, Grampian or Colonsay Groups. The scarcity of Knoydartian detrital zircons appears to be a commonality in sedimentary successions across the North Atlantic region (Olierook et al., 2020 and references therein) and suggests limited magmatism associated with this orogeny.

Sedimentological and tectonic controls on early detrital zircon provenance

A long-held view is that deposition of the Dalradian Supergroup was initiated during the protracted extensional break-up of Rodinia (e.g. Soper and Anderton, 1984; Anderton, 1985). However, clear evidence for extensional rifting is absent from the succession until the Argyll Group, several kilometres higher in the stratigraphy and well above the Glenshirra, Grampian and Colonsay Groups. In fact, structural restoration of the Grampian Group in the Central Highlands reveals a relatively flat, undulating basement lacking normal faulting (Prave et al., 2024). An alternative scenario is that sedimentation was initiated as a flysch–molasse–style succession in response to the mid-Tonian Knoydartian Orogeny (Banks and Winchester, 2004; Prave, 1999; Prave et al., 2023) which aligns here with our reinforced lithostratigraphic correlation.

The initial basement cover sedimentation in the Glenshirra Group and Kilchiaran Subgroup falls into two broad clusters: (1) coarse sediments with Rhinnian- and Pinwarian-aged clasts and very narrow, MKR-dominated detrital zircon spectra (e.g., Octofad Sandstone, Glen Buck Pebbly Psammite and Eilean Liath Grit), and (2) finer-grained sediments with more varied detrital zircon age spectra (e.g., Garva Bridge Psammite and Rubha Gaidhealach Grit). Several features of this early infill suggest deposition of first-cycle detritus from proximal basement sources with limited sedimentary transport. Firstly, the Octofad Sandstone and Glen Buck Psammite are clast bearing and were deposited in braided river, sediment gravity flow, and alluvial fan settings precluding long-distance sediment transport for at least part of their load (Banks and Winchester, 2004). Secondly, a more diverse zircon age spectrum would be

expected if reworking from distal or older sedimentary units had occurred. Lastly, the proximity of the Octofad Sandstone and Eilean Liath Grit to the exposed Rhinns Complex—likely the source of the ca. 1800 Ma clasts and detrital zircons in both formations (McAteer et al., 2010b; Banks et al., 2013)—supports a local derivation. Together, the narrow zircon spectra and coarse clast assemblages support an interpretation of localized sedimentation across an MKR-aged basement landscape (Fig. 5A), consistent with structural reconstructions by Prave et al. (2023).

Throughout the late Glenshirra Group and Kilchiaran Subgroup, detrital zircon populations exhibit a marked increase in 1000–1500 Ma aged grains, a corresponding decline in the proportion of Rhinnian-aged grains, and an increase in sedimentary maturity. The detrital zircon age spectra of the Rubha Gaidhealach Grit, and Garva Bridge, Loch Laggan, Craeg Dubh and Inverlair Psammities closely resemble samples from the Wester Ross and or Loch Ness Supergroups (see figure 4A). The increasing Grenville-aged zircon contribution is unlikely to result solely from progressive unroofing, since such grains were already abundant in the Wester Ross and Loch Ness Supergroups (e.g. Krabbendam et al., 2022 and references therein). Instead, the shift suggests that regional palaeorelief in the Rhinns basement had been infilled, enabling sediment derivation from uplifted Knoydartian orogenic belts composed of sedimentary rocks of the Wester Ross and Loch Ness Supergroups. This shift supports the hypothesis that these uplifted Knoydartian terranes became dominant second-cycle sediment sources during late Glenshirra and Kilchiaran deposition (Fig. 5B).

A return to a unimodal 1600–1800 Ma zircon signature, with minimal Grenvillian overprint, coincides with a marine transgression and a switch to deep-marine turbidite deposition in the Correyairack and Saligo Subgroups. Given the long-distance transport potential of turbidite flows, it is plausible that sediment was once again sourced from a Rhinnian basement with little sedimentary cover (Fig. 5B).

The detrital zircon spectra of the Eilde Flags, Gaick Psammite, Bowmore Sandstone, and Maol an Fhithich Formation are all characterized by dominant Grenville-age peaks (Fig. 3). These spectra differ from both the older Wester Ross and Loch Ness Supergroups (Fig. 4A) and the underlying parts of the Dalradian (Fig. 4B), indicating a broader provenance shift away from the recycling of the Wester Ross and Loch Ness by the time of late Grampian and Colonsay Group deposition. The formations and facies of the Grampian and Appin Groups are notably more laterally continuous across the Central Highlands and Inner Hebrides (Anderton, 1985), which is coupled here with a change in provenance from the proximal source terranes of the Rhinns basement and recycled sediments of the Wester Ross and Loch Ness Supergroups, towards a Grenville-dominant source terrane. In this foreland basin context, the

growing dominance of Grenville-age detritus likely reflects sediment delivery from increasingly distal orogenic sources following widespread topographic levelling, and the establishment of a regional shallow marine molasse apron (Fig. 5C).

Conclusion

This study presents a reinforced correlation between the Colonsay and Bowmore Groups and the early parts of the Dalradian Supergroup, based on shared lithofacies characteristics and coherent detrital zircon age spectra. The narrow, Palaeoproterozoic-dominated zircon signatures of coarse-grained fluvio-deltaic units in both the early part of the Colonsay Group (Kilchiaran Subgroup) and the Glenshirra Group reflect localized, first-cycle sedimentation sourced from nearby MKR-aged basement terranes, particularly the Rhinns Complex. Stratigraphically higher units show a marked increase in Grenville-aged detrital zircon input, a decline in Rhinnian aged grains, and increasing sediment maturity—features best explained by sediment recycling from uplifted Knoydartian-affiliated sedimentary rocks of the Wester Ross and Loch Ness Supergroups. This transition suggests progressive infilling of early basement topographic relief and the establishment of a broader sediment dispersal system across the basin. By the time of Bowmore, upper Grampian, early Appin Group deposition, dominant Grenville-aged zircon spectra and more laterally continuous facies across the Dalradian Supergroup imply a shift toward more distal, orogen-scale sediment sourcing, consistent with a widespread shallow-marine molasse apron developed in a mature foreland basin setting. Overall, this tectonostratigraphic framework unifies the Glenshirra, Grampian, Colonsay, and Bowmore successions and supports a foreland basin model linked to the mid-Tonian Knoydartian Orogeny.

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Figure Captions

Figure 1: Generalised geology of the Colonsay and Bowmore Groups on Islay (A) Colonsay, and Oronsay (B) adapted from Stewart (1973) and McAteer et al. (2010a), and the Grampian Group in the Central Highlands after Stephenson and Gould (2007). The locations of samples analysed for detrital zircon U-Pb geochronology from Cawood et al. (2003), Banks et al. (2007), McAteer et al. (2010a), McAteer et al. (2010b), Kirkland et al. (2025) and this study are shown in red.

Figure 2: Lithostratigraphy of the Colonsay and Bowmore Groups on Islay (A) Colonsay, and Oronsay (B) adapted from McAteer et al. (2010a) to include the Subgroup division defined here (see text), and the Grampian Group in the Central Highlands after Banks and Winchester (2004). Dashed lines highlight potential lithostratigraphic correlations between the successions.

Figure 3: Kernel density estimation (KDE) plots of detrital zircon U-Pb ages from the Colonsay and Bowmore Groups from the isles of Islay, Colonsay and Oronsay and the Glenshirra and Grampian Groups in the Central Highlands. KDE plots of detrital zircon U-Pb ages from the Wester Ross and Loch Ness Supergroups are shown for comparison and to highlight the likelihood of sedimentary recycling. The list of samples and references used in these two plots are listed in the supplementary materials. Colour bars indicate Laurentian craton

provenance age ranges (Rivers, 1997; Krabbendam et al. 2017). MKR = Makkovik–Ketilidian–Rhinnian terranes. References: (1) Cawood et al. (2003); (2) Banks et al. (2007); (3) McAteer et al. (2010a); (4) McAteer et al. (2010b).

Figure 4: Multidimensional scaling plots using the Wasserstein-2 (W_2) distance as a dissimilarity metric (Lipp and Vermeesch, 2023). The closer the samples plot together, the more similar their detrital zircon age spectra. A solid line links the nearest neighbour and a dashed line the second nearest. The goodness-of-fit is evaluated using the 'stress' value of the configuration (0.2 = poor; 0.1 = fair; 0.05 = good; see Vermeesch (2013)). The axes scales have the same units as the W_2 distance (Ma). The list of samples and references used in each plot are listed in the supplementary materials. (A) Comparing samples from the Colonsay Group with those of the Wester Ross, Loch Ness and Dalradian (Glenshirra, Grampian and lower Appin Groups) Supergroups. Coloured swathes are used to highlight the different sample sets. (B) Comparing samples from the Colonsay Group with those of the Glenshirra, Grampian and lower Appin Groups of the Dalradian Supergroup.

Figure 5: Schematic diagrams showing an interpretation of the early basin development of the Dalradian Supergroup. (A) proximal first cycle detritus sourced from the Rhinns complex, (B) uplift of the Wester Ross and Loch Ness Supergroups during the Knoydartian Orogeny (the nature of which is uncertain) and an influx of polycyclic, recycled sediment into the Dalradian foreland basin, and (C) the infilling of topographic lows and spread of molasse-like material from Grenville-aged sources.

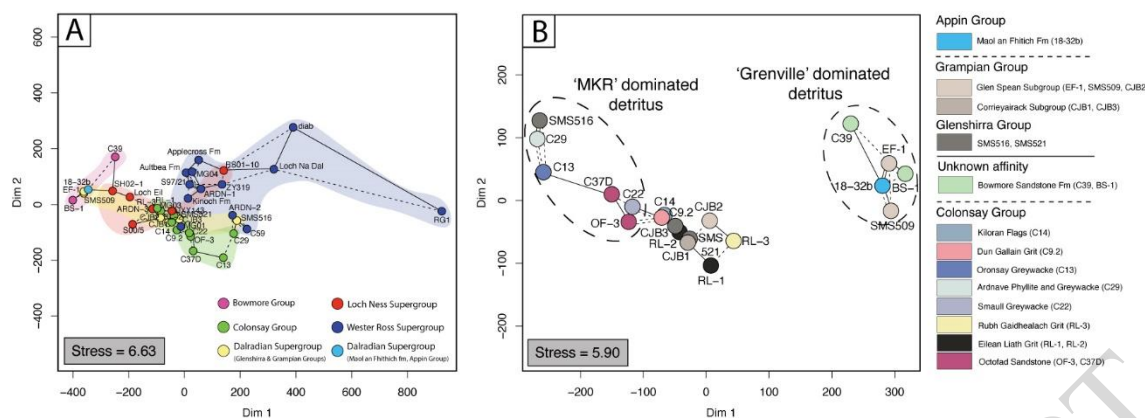


Figure 4

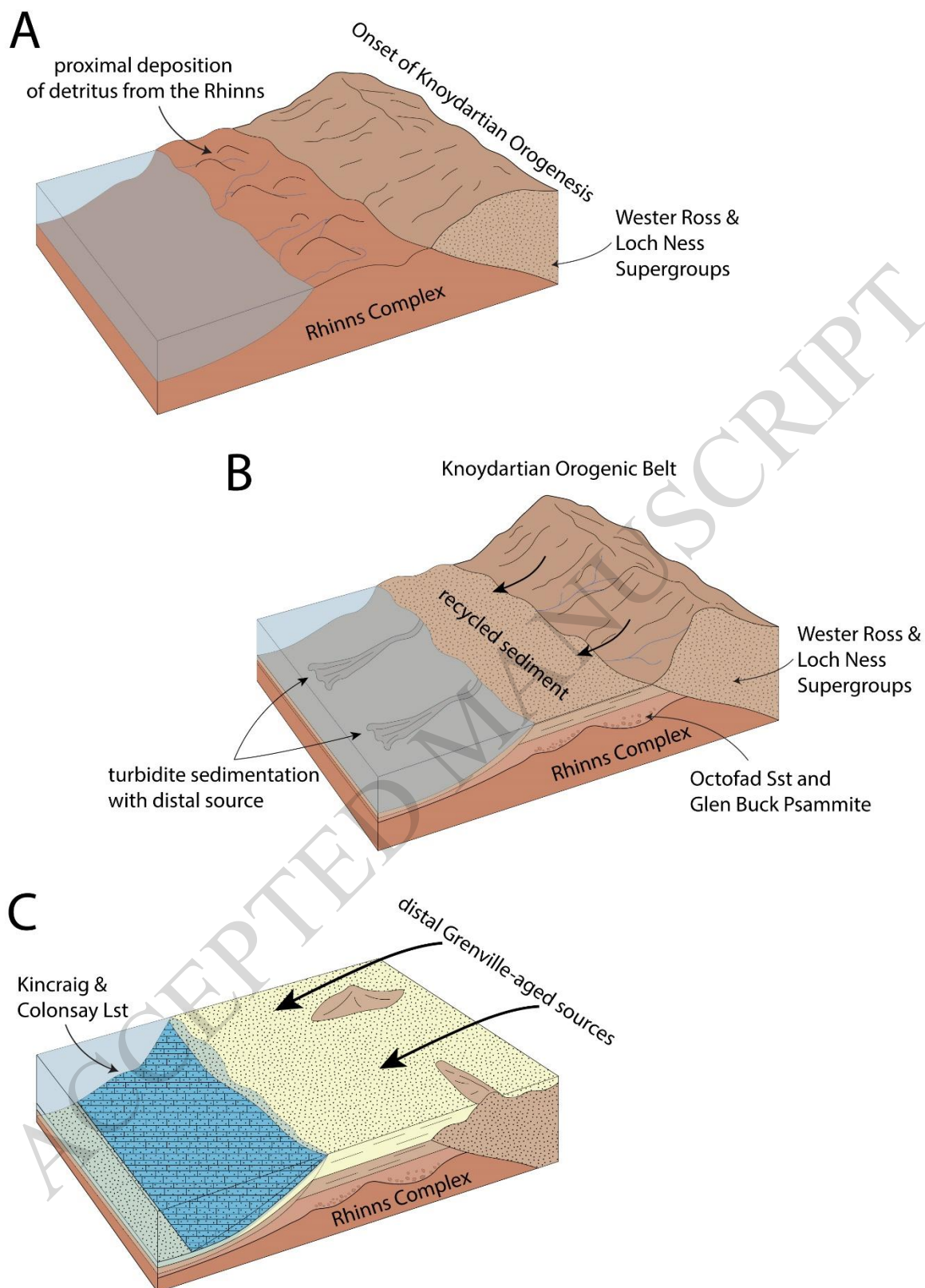


Figure 5