Research article

JGS
Journal of the Geological Society

https://doi.org/10.1144/jgs2024-085 | Vol. 181 | 2024 | jgs2024-085

How great is the Great Glen Fault?

A. R. Prave[1]*, W. E. Stephens[1], A. E. Fallick[2], I. S. Williams[3] and K. Kirsimäe[4]

[1] School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9TS, UK
[2] Scottish Universities Environmental Research Centre, East Kilbride G75 0QF, UK
[3] Research School of Earth Sciences, The Australian National University, Acton, ACT 2601, Australia
[4] Department of Geology, University of Tartu, Ravila 14A, 50411 Tartu, Estonia
ARP, 0000-0002-4614-3774; AEF, 0000-0002-7649-6167
* Correspondence: ap13@st-andrews.ac.uk

Abstract: A popular conceptual tectonic model envisages the Great Glen Fault to be part of a sinistral strike-slip system active during the mid-Silurian to early Devonian with *c.* 700 km of displacement. Here we use sedimentological, geochemical and detrital zircon age data to show that restoring 250–300 km of displacement suffices to fulfil key geological constraints and reveal three new pre-strike-slip relationships: (1) Paleoproterozoic Makkovik–Ketilidian crust becomes placed proximal to numerous immature sandstone units in the Grampian and Northern Highlands of Scotland and County Mayo, Ireland, that are marked by single-mode peaks of 1.8–1.6 Ga detrital zircons sourced from that crust; (2) the two most concentrated occurrences of appinite and metadolerite/gabbro in the Scottish–Irish Caledonides become matched; (3) the Donegal and Argyll granite suites can be paired. That amount of displacement provides, at least in part, the separation required between the Northern and Grampian Highlands to account for Scandian-age (Silurian) deformation in the former and its absence in the latter.

Supplementary material: Supplementary tables and figures are available at https://doi.org/10.6084/m9.figshare.c.7389974

Received 29 April 2024; **revised** 1 August 2024; **accepted** 1 August 2024

The Great Glen Fault is part of a strike-slip fault system present across Scotland and the northern part of Ireland (Fig. 1). A widely accepted interpretation is that it was a major tectonic boundary between Laurentia, Baltica and Avalonia during the Ordovician–Silurian Caledonian orogeny (e.g. Dewey and Strachan 2003). In that interpretation, the orogeny resulted from both orthogonal (hard) continent–continent and oblique (soft) arc–continent collisions associated with flips in subduction polarities. When estimated displacements along the Highland Boundary and Southern Uplands faults are considered, the combined fault system may have had as much as 1200 km of sinistral movement. A recently proposed alternative view is that Caledonian orogenesis was a consequence of continuous SE-directed (present-day orientation) subduction and sequential continent–island arc–continent collision (Searle 2021). In that view, the Great Glen Fault is inferred to be a relatively minor structure with an order-of-magnitude smaller displacement. It should be noted that this view has been contested strongly by Dewey and Ryan (2022), who highlighted aspects of the Caledonides circumscribing the North Atlantic realm that do not fit readily into Searle's reimagined Caledonian Orogeny.

It is not the purpose of this paper to assess the entirety of the Caledonian orogenic belt. Rather, we focus on evaluating the large- versus small-magnitude displacement models for the Great Glen Fault. Here we report new U–Pb age data for inherited zircons in Caledonian granites and for detrital zircons from the Tarskavaig nappe on the Sleat Peninsula of Skye (reported in Supplementary material Tables S1 and S2). We integrate these data with published data for detrital zircons in metasedimentary units of the Scottish and Irish Highlands (the latter identified as the region incorporating the geology of the northern part of Ireland), and with published data on the timing, geochemistry and sources of Caledonian plutons and related intrusions in Scotland and Ireland. Central to what follows is the significance of distinctive detrital and inherited zircon age distributions for the granites and metasedimentary rocks, and the sedimentology of the latter from which the detrital zircons were derived. Our findings lead us to conclude that offset along the Great Glen Fault is much less than the *c.* 700 km popularly envisaged. The geological features on opposite sides of the Great Glen and related faults can be explained by having a total amount of mid-Silurian to early Devonian left-lateral displacement of 250–300 km. Consequently, plate-tectonic reconstructions that incorporate or depend on the Great Glen Fault having much larger magnitudes of offset need to be rethought and revised.

The Great Glen Fault: the swinging pendulum of displacement estimates

The striking geomorphological aspect of the Great Glen of Scotland is its ruler-straight NE–SW trend for 200 km defined by a relatively narrow, steep-sided valley with hundreds of metres of relief. In the middle of the 19th century, geologists identified the Great Glen as the location of an ancient fault line, detailing a normal sense of displacement of at least 1000 m of downthrow on its SE side (as reported by Kennedy 1946). Almost a century later, Kennedy (1946) compiled three lines of evidence to deduce that the fault also had a strike-slip component of 105 km of left-lateral offset (Fig. 2a). His evidence consisted of (1) connecting the Foyers and Strontian granites, (2) linking zones of 'injection complexes' (migmatites) and (3) inferring that the Moine Thrust was a linear structure that extended from the Northern Highlands through the Inner Hebrides to Islay. He also concluded that faulting had begun prior to the early Devonian but had ceased by Carboniferous time. Four decades later, Winchester (1973, 1974) constructed a map of metamorphic zones for the Scottish Highlands. The map pattern was complex but could be made more coherent by removing 160 km of left-lateral motion along the Great Glen Fault (Fig. 2b). Thus, two independent datasets had arrived at a similar conclusion: the Great Glen Fault was principally a strike-slip fault having 100–160 km of left-lateral offset.

However, the concept envisaged by Wilson (1962) that the Great Glen Fault was part of a fault system dismembered by continental

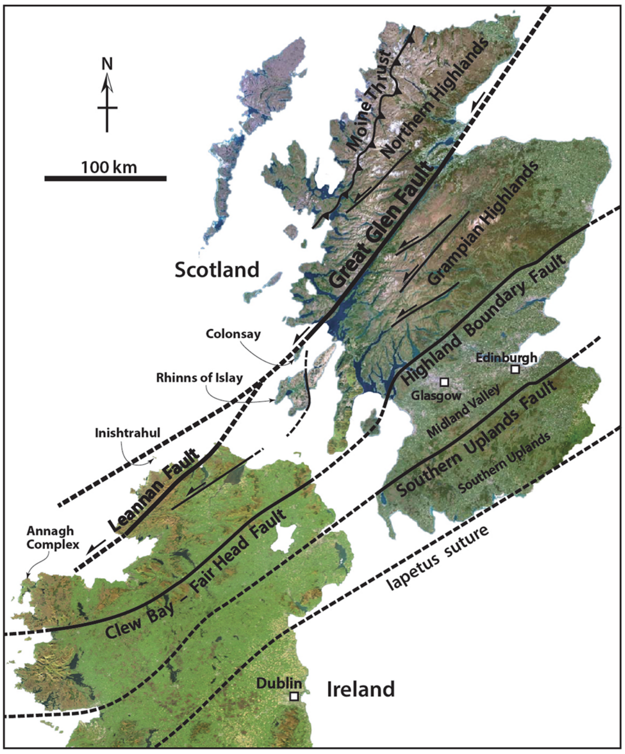

Fig. 1. Geological template of Scotland and Ireland showing main fault systems and regions. Source: Google Earth image (Landsat/Copernicus).

drift, one that was comparable in magnitude with the San Andreas fault, seemed to be confirmed by palaeomagnetic data (van der Voo and Scotese 1981). Those data suggested that mid-Devonian North America and Europe were separated by at least 15° of latitude, thereby requiring 2000 km of sinistral motion along the Great Glen Fault for them to converge in the Carboniferous and form Pangaea. Later workers used geological reconstructions (Smith and Watson 1983; Soper and Hutton 1984; Soper *et al.* 1992; Stewart *et al.* 1999) and geochemical similarity of high-Sr and -Ba granites on opposite sides of the Great Glen Fault (Thirlwall 1989) to refute those data and the match-ups of metamorphic zones and Foyers–Strontian granites (e.g. Pankhurst 1979). This led to the conclusion that the Great Glen Fault recorded only a few hundred kilometres of sinistral offset (Fig. 2c and d). It should be noted that the disparate palaeo-latitudinal positions were not necessarily incorrect. What was incorrect was assigning the Great Glen Fault as Laurentia's plate boundary, now recognized as coincident with the Highland Boundary Fault (e.g. Briden *et al.* 1984; Chew and Strachan 2014): north of the Highland Boundary Fault is Laurentian crust (Scottish and Irish Highlands), to its south are Iapetus oceanic arcs and accretionary prisms (Scotland's Midland Valley and Southern Uplands, north–central Ireland) and, farther to the south and approximating the boundary between Scotland and England, the Iapetus suture along which are Avalonian crustal fragments (central and southern Ireland, England).

Ideas about the magnitude of offset along the Great Glen Fault changed again when it became apparent that rocks in the Northern Highlands north of the fault contain evidence for the 435–400 Ma Scandian event of the Caledonian Orogeny (e.g. Freeman *et al.* 1998; Dallmeyer *et al.* 2001; Kinny *et al.* 2003; Sherlock *et al.* 2003) whereas no deformational fabrics of that event have been documented in the Grampian Highlands that lie south of the fault (see synthesis by Chew and Strachan 2014). To explain this, Dewey and Strachan (2003) constructed a conceptual tectonic scheme that resurrected the idea of large-magnitude displacement along the Great Glen Fault (Fig. 2e and f). They postulated that the Northern and Grampian Highlands were separate tectonic blocks and that their juxtaposition resulted from 700 km or more of sinistral movement along the fault during a 40 Myr interval spanning 435–395 Ma. That view has dominated thinking for the past two decades but has been contested by the hypothesis of Searle (2021), within which the offset of the Great Glen Fault is thought to be significantly less, although how much less is not stated explicitly. Thus, the pendulum of displacement estimates for the Great Glen Fault has swung from invoking offsets of 100–160 km, to as much as 2000 km, a subsequent reduction to a few hundred kilometres, followed by reinstating displacements of 700 km (or more) and, most recently, a return to the view that the smaller-offset estimates were more probably correct.

Detrital zircon age distributions and sedimentology: the need for a proximal source

Excepting Caledonian granites and related intrusions, the Scottish and Irish Highlands consist mostly of Meso- to Neoproterozoic (meta)sedimentary successions with lesser (meta)volcanic rocks (Torridonian, Moine and Dalradian supergroups, the first two now reclassified as the Wester Ross and Loch Ness supergroups; see Krabbendam *et al.* 2022). Establishing age constraints for these successions is difficult and researchers have relied on developing detrital zircon age spectra for ascertaining maximum depositional ages, identifying source areas and as a potential means of correlation (e.g. Rainbird *et al.* 2001; Cawood *et al.* 2003, 2007; Banks *et al.* 2007; Kinnaird *et al.* 2007; McAteer *et al.* 2010*a*, *b*; Krabbendam *et al.* 2017). When viewed as a composite (Fig. 3a), each succession shows multimodal peaks with varied amplitudes arrayed across 2 Gyr, and each peak can be confidently tied to Laurentian provenances ranging in age from Mesoarchean to Neoproterozoic.

Our interest in the evolution of the Great Glen Fault was sparked by an observation that certain units are marked by a distinctive detrital zircon age spectrum. That spectrum is dominated by modes of 1.8–1.6 Ga grains with or without a lesser mode of 1.5 Ga grains (Fig. 3b). Such a tight clustering is indicative of derivation from a terrane composed almost exclusively of late Paleoproterozoic rocks with minimal material attributable to older or younger rock units. This dominance of a singular source was noted for rocks of the Glenshirra, Grampian and Iona groups by previous workers, who suggested that they might be correlatives (Banks *et al.* 2007; McAteer *et al.* 2010*a*, *b*). Here we report, for the first time, that rocks belonging to the Tarskavaig nappe on the Sleat Peninsula of southern Skye also yield the same detrital zircon age spectrum (Fig. 3b; Supplementary material Table S1 Worksheet 1). As highlighted by previous researchers (Marcantonio *et al.* 1988; Daly *et al.* 1991, 1995, 2009; Daly 1996; Daly and Flowerdew 2005), the only rocks in the Scottish–Irish Caledonides from which abundant zircons with the appropriate ages can be sourced are the *c.* 1.8–1.6 Ga Rhinns Complex exposed in four places (Fig. 1): the Inner Hebridean islands of Islay and Colonsay (its northern tip) and, in Ireland, on Inishtrahul off the north coast of Donegal and the Mullet Gneiss of the Annagh Gneiss Complex in County Mayo (Supplementary material Fig. S1). Those rocks are part of a now dismembered Paleoproterozoic Makkovik–Ketilidian orogen of eastern Canada and southern Greenland (Supplementary material Fig. S2); the former also contains *c.* 1.5 Ga igneous rocks that define the Pinwarian event (Gower *et al.* 2008; Augland *et al.* 2015).

Our contribution is to emphasize how stratigraphically and geographically widespread that near-single-temporal-mode distribution is (Fig. 4b), being present in (meta)sedimentary successions from the NW Scottish Highlands to County Mayo, Ireland (Doonamo Formation; McAteer *et al.* 2010*b*). We stress that none of the units typified by this distribution have firm depositional age constraints at present: the only time bounds that

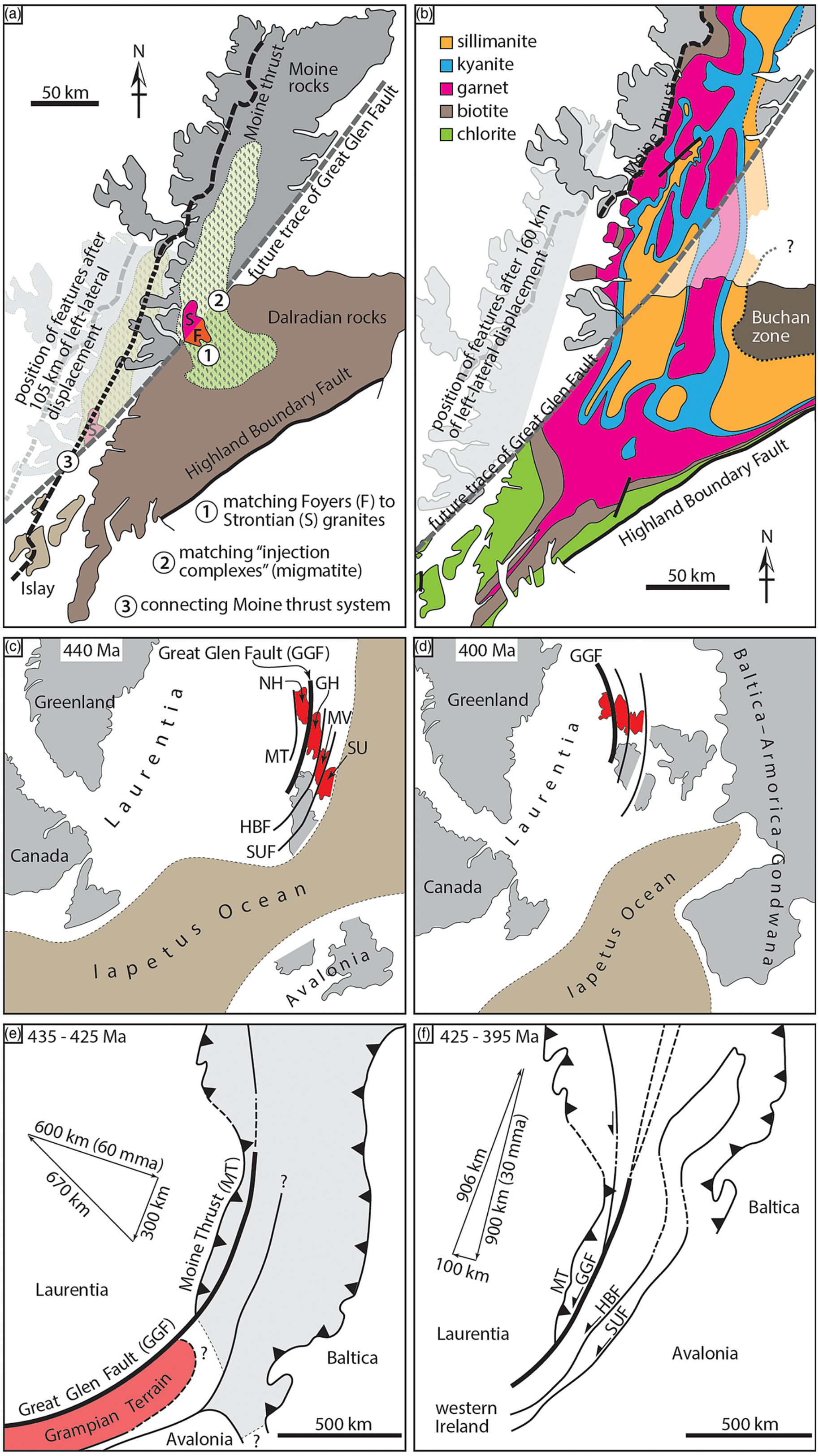

Fig. 2. (**a**, **b**) Earlier reconstructions of the Great Glen Fault system that relied on matching geological features present on the Scottish mainland. Reconstruction of the Great Glen Fault system from postulated plate-tectonic scenarios for the late Silurian to early Devonian (Scottish terranes highlighted in red). (**c**, **d**) Sinistral displacement of several hundred kilometres inferred along the Great Glen Fault. (**e**, **f**) Schematic plate-tectonic terrane diagram inferring 700–1200 km of sinistral displacement along the Great Glen Fault and related fault systems. GGF, Great Glen Fault; GH, Grampian Highlands; HBF, Highland Boundary Fault; MT, Moine Thrust; MV, Midland Valley; NH, Northern Highlands; SUF, Southern Uplands Fault. Source: (a) after Kennedy (1946); (b) after Winchester (1973, 1974); (c, d) after Soper and Hutton (1984); (e, f) after Dewey and Strachan (2003).

exist are that those units must be younger than their youngest detrital zircons (typically *c.* 1.0 Ga) and older than Tonian (*c.* 1.0–0.7 Ga) or Ordovician–Silurian (*c.* 0.5–0.4 Ga) orogenic events during which they were metamorphosed and deformed. Hence, we are not implying that the near-single-mode-bearing units are all temporally correlative; rather, they share derivation from a provenance dominated by rocks spanning a restricted age range (mostly the Statherian Period of the Paleoproterozoic, *c.* 1.8–1.6 Ga).

Despite the lack of age control, what is particularly cogent for providing constraints on assessing original palaeogeographies is that the units dominated by 1.8–1.6 Ga detrital zircons are typified by poor sorting, range in composition from arkosic to feldspathic–quartzitic–lithic wackes and have clasts that are angular to subrounded across all grain sizes, and grain sizes change rapidly (on centimetre to metre scale) from silt–sand mixtures to pebble- and cobble-bearing beds (Figs 5 and 6); most of the units are also several hundred metres thick. Associated sedimentary structures

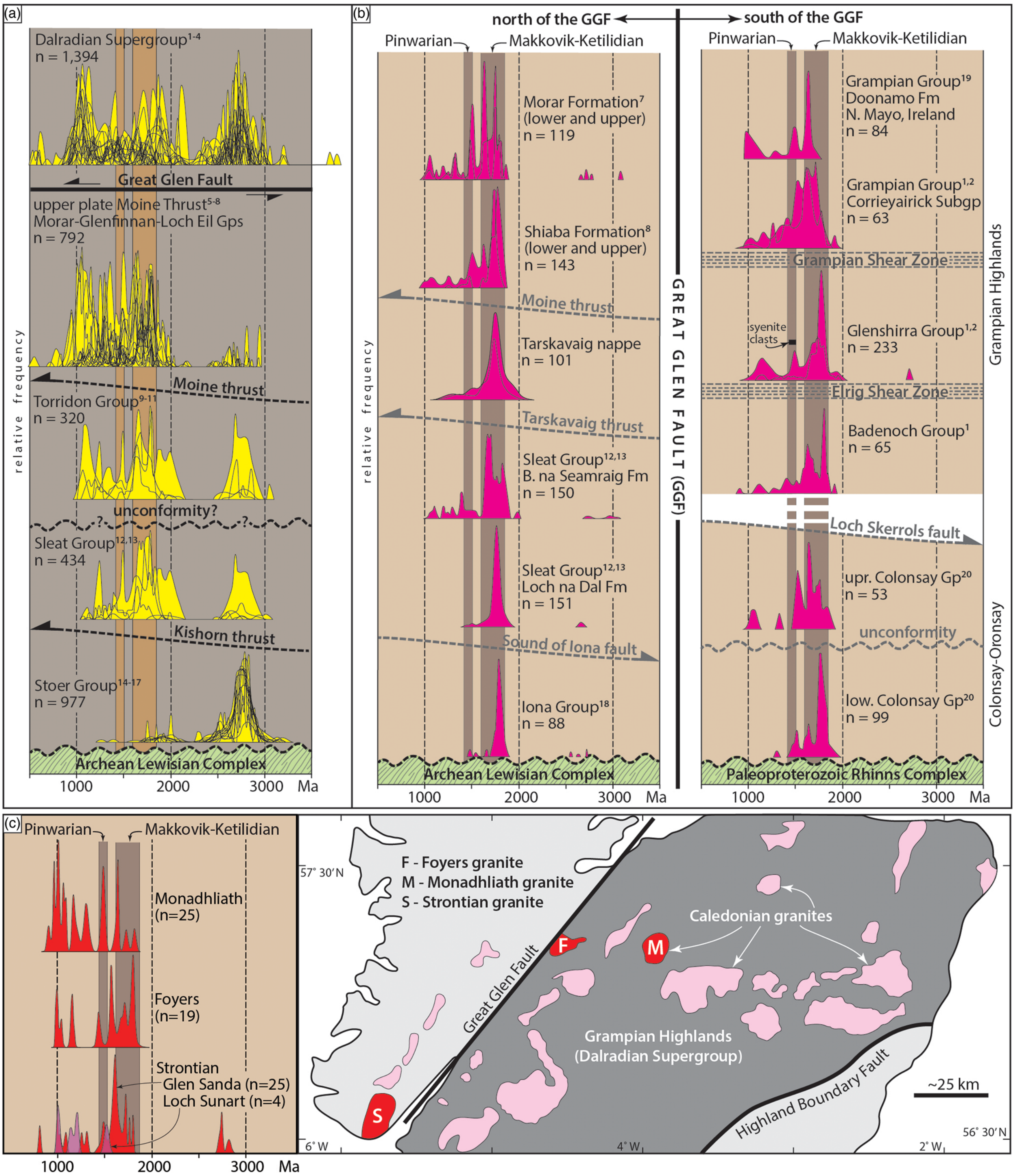

Fig. 3. Detrital zircon age probability density plots. (**a**) Composite plots of the major rock units and their bounding structures; the dark lines are the individual peak traces as depicted in the respective publications. It should be noted that the Kishorn Thrust is part of the Moine Thrust System; the Stoer Group occurs in the footwall of that system and hence is shown occurring beneath that thrust, even though neither occur in geographical proximity to one another. (**b**) Plots of units dominated by 1.8–1.6 Ga grains categorized by location north and south of the Great Glen Fault. Tarskavaig nappe detrital zircon data reported here are new, and are given in Supplementary material Table S1 Worksheets 1 and 2. (**c**) U–Pb age probability density plots for inherited zircons recovered from the Foyers, Monadhliath and Strontian plutons; data are given in Supplementary material Table S2 Worksheet 1. Source: (b) data from (superscript numbers): 1, Cawood *et al.* (2003); 2, Banks *et al.* (2007, 2013); 3, Strachan *et al.* (2013); 4, Johnson *et al.* (2016); 5, Friend *et al.* (2003); 6, Cawood *et al.* (2004); 7, Kirkland *et al.* (2008); 8, Cawood *et al.* (2015); 9, 14, Rainbird *et al.* (2001); 10, 12, 15, Kinnaird *et al.* (2007); 11, 13, Krabbendam *et al.* (2017); 16, Kenny *et al.* (2019); 17, Lebeau *et al.* (2020); 18, McAteer *et al.* (2014); 19, McAteer *et al.* (2010*b*); 20, McAteer *et al.* (2010*a*).

are typically decimetre-thick sets and co-sets of trough and planar cross-bedding, metre-scale multistorey channels and, in places, climbing ripple bed-sets. Palaeocurrent data are broadly unimodal (transport directions mostly towards eastern and northern quadrants) signifying derivation from Laurentian provenances. These facies attributes have led to the conclusion that deposition occurred in alluvial fan-braided fluvial–nearshore marine settings and the textural and compositional immaturity indicates that distance of transport from source to sink was not large (see references and summaries given by Prave *et al.* 2024; Strachan *et al.* 2024). Two exceptions are the turbiditic rocks of the Corrieyairick Subgroup (lower Grampian Group) and the

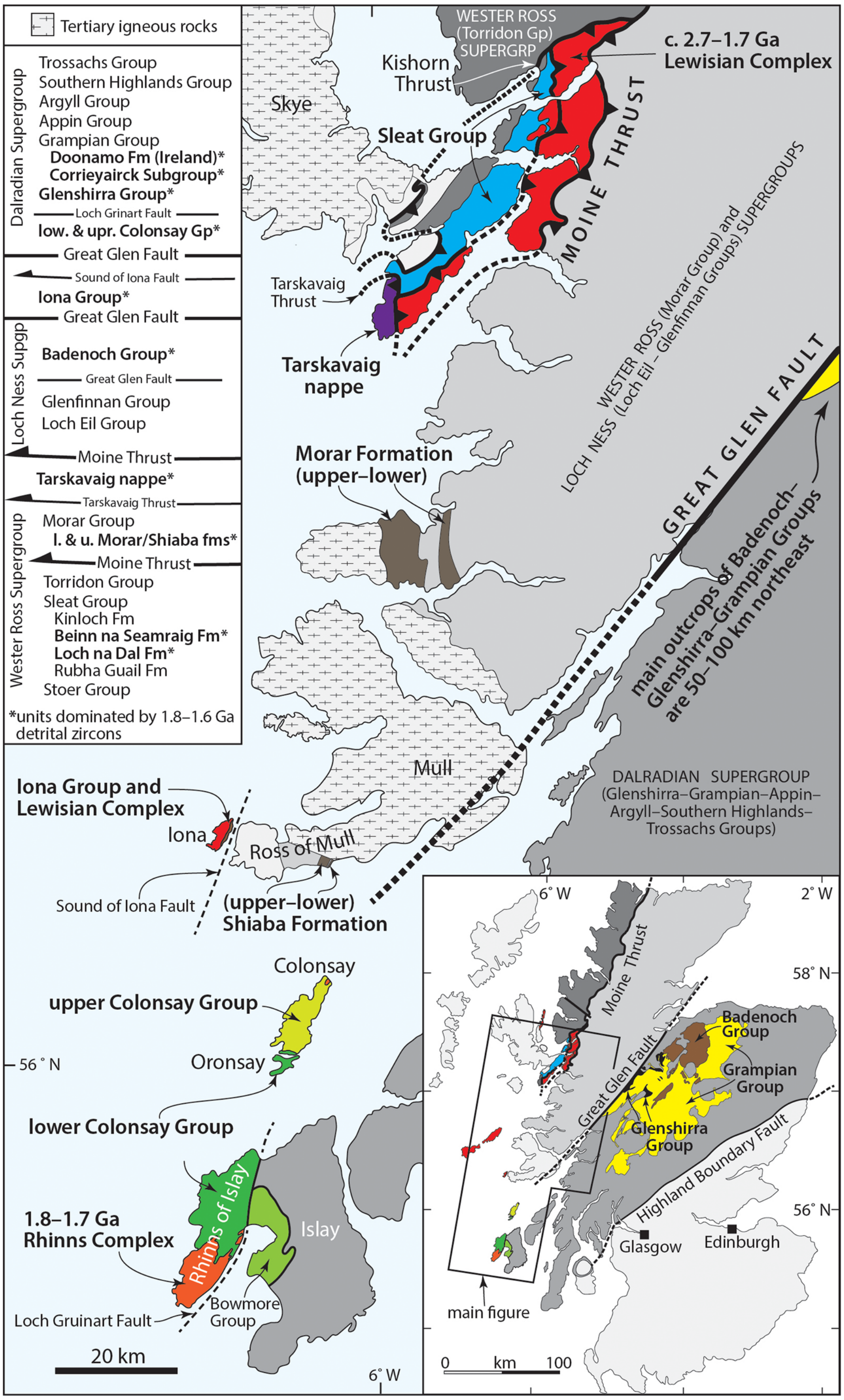

Fig. 4. Generalized geology of the western Highlands of Scotland and Inner Hebrides. Simplified stratigraphic framework is given in the inset; it should be noted that the individual units of the Wester Ross and Loch Ness Supergroup that were sampled are denoted on the map; those two supergroups are mostly Tonian (*c.* 1000–800 Ma) in age whereas the Dalradian Supergroup is late Tonian to early Ordovician in age (*c.* 840–480 Ma). Source: geology from the British Geological Survey's Geology Viewer webpage.

paragneiss of the Badenoch Group, in which original textural features have been obliterated by polyphase deformation and migmatization. Those exceptions aside, the facies attributes indicate that at the time of deposition Makkovik–Ketilidian–Rhinnian crust was exposed and must have been relatively nearby. This, however, poses a conundrum: the nearest exposures of that crust are 150–300 km distant in the Inner Hebrides and west of Ireland yet the coarsest facies, poorly sorted coarse-grained arkosic sandstone of the Tarskavaig nappe and Sleat Group (Fig. 5d–f) and pebbly sandstone and matrix-supported cobble conglomerate of the Glenshirra Group (Fig. 6b and c), are furthest from those exposures.

Inherited zircon age distributions and basement of the Grampian Highlands

The basement to the rocks of the Northern Highlands is represented by the Archean Lewisian Gneiss Complex but what underlies the Grampian Highlands is less certain. Magmas that are in large part derived from crustal sources, particularly those forming granitoids, can retain distinctive elemental and isotopic compositions that are indicative of the nature of their source rocks (e.g. Chappell 1984; White *et al.* 2001). Although there are no exposures of Paleoproterozoic Rhinnian rocks on mainland Scotland, the isotopic and geochemical signatures of granites in the Grampian Highlands

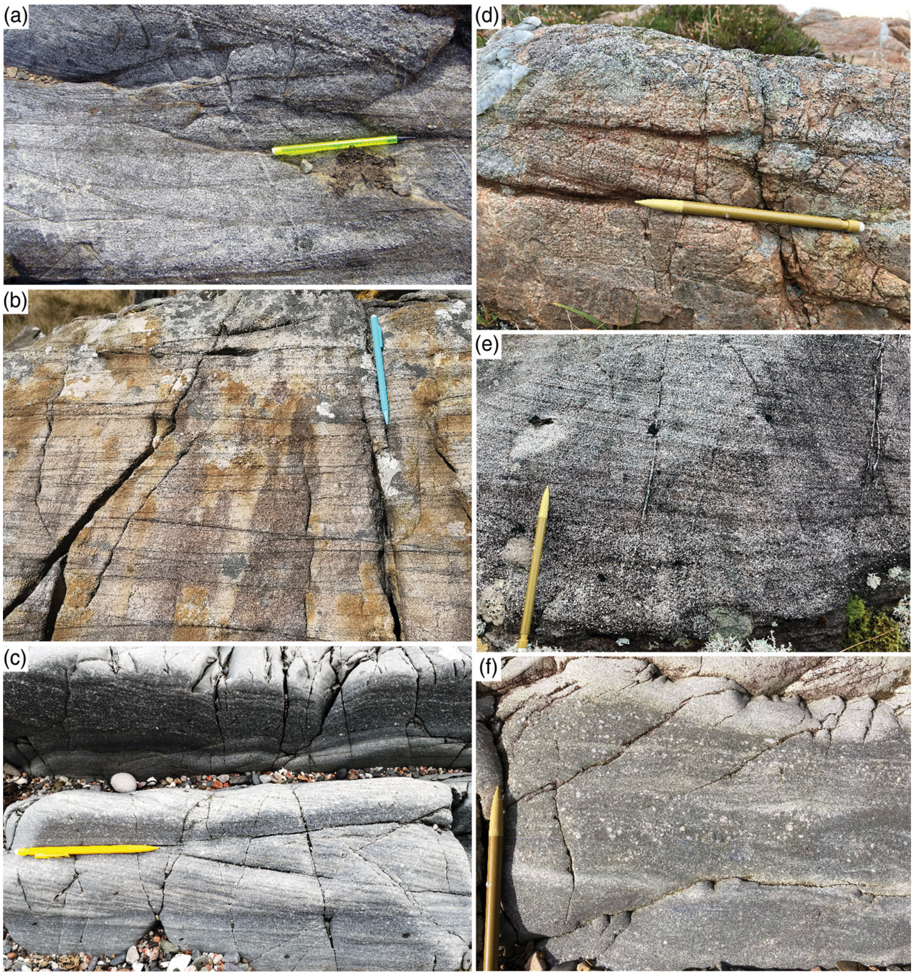

Fig. 5. Representative sandstones of the (meta)sedimentary units north of the Great Glen Fault that are dominated by 1.8–1.6 Ga detrital zircons: (**a**) Lower Morar Group, Ardnamurchan; (**b**) Upper Shiaba Formation (Morar Group), Ross-of-Mull; (**c**) Iona Group, Iona; (**d**) Tarskavaig nappe, Sleat Peninsula; (**e**) Beinn na Seamraig; (**f**) Loch na Dal formations (both part of the Sleat Group), Skye.

indicate that crust containing comparable components occurs at depth (Stephens and Halliday 1984; Halliday *et al.* 1993; Steinhoefel *et al.* 2008). To assess this further, we sampled the Strontian (Loch Sunart granodiorite, Glen Sanda granite), Foyers and Monadhliath plutons for inherited zircons and found that they do indeed contain 1.8–1.5 Ga inherited zircons (Fig. 3c; also Supplementary material Figs S3–S6 and Tables S1 and S2). This supports the inference based on the geochemical data that underlying the Grampian Highlands and Northern Highlands proximal to the Great Glen Fault there is a mid- to late Proterozoic protolith consistent with Rhinnian crust, and that it was prone to melting during Caledonian orogenesis (*c.* 435–405 Ma). Although the number of identified inherited cores is small ($n = 73$), the presence of older zircon cores (*c.* 2.8–2.7 Ga) in the Glen Sanda granite, younger zircons cores (*c.* 1.1–0.9 Ga) in all the sampled granites (particularly Monadhliath pluton) and detrital zircon age spectra for the granites (Supplementary material Fig. S4) similar to those of many of the Neoproterozoic metasedimentary units, together indicate variability in the make-up of the granite source rocks beneath the Grampian Highlands, possibly involving more than a single crustal unit. Analysis of additional plutons would be a good test and refinement of these inferences.

Discussion

Resolving a conundrum: pre-rift North Atlantic realm

Given that every rock type (sedimentary, metasedimentary, igneous) across the Scottish–Irish Highlands is marked by a suite of inherited or detrital zircons derived from Archean to Proterozoic

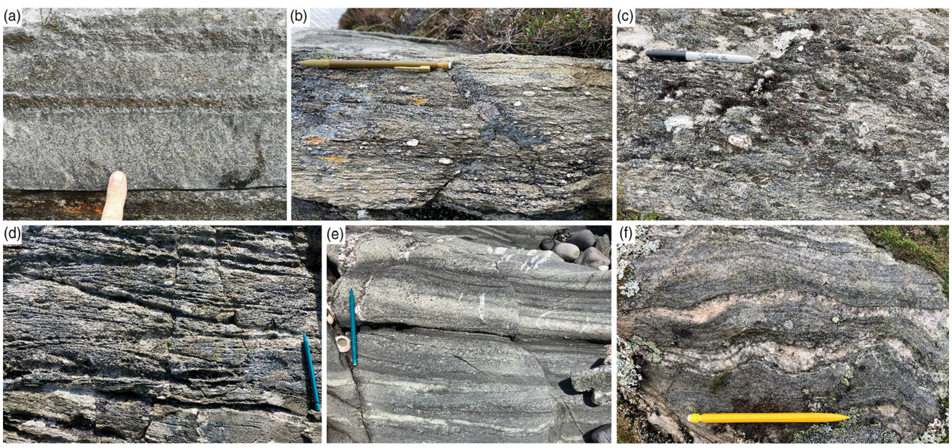

Fig. 6. Representative sandstones of the (meta)sedimentary units south of the Great Glen Fault that are dominated by 1.8–1.6 Ga detrital zircons: (**a**) Loch Laggan Formation (Grampian Group), Loch Laggan; (**b**, **c**) Glenshirra Group, Loch Tarff; (**d**) Dun Gallain Formation (upper Colonsay Group), Colonsay; (**e**) Oronsay Formation (lower Colonsay Group), Oronsay. (**f**) Migmatitic paragneiss of the Badenoch Group, Kincraig.

sources that define multimodal age spectra emphasizes that the essentially single-temporal-mode distribution of *c.* 1.8–1.6 Ga zircons is unique. This fact belies interpretations that it represents derivation from recycled or multicycle sedimentary inheritance processes, which would have contributed zircons of many different ages. Thus, we turned our thoughts to determining a palaeogeography that would satisfy the sedimentological constraints and the geochronological and geochemical data.

Offshore geophysical and coring surveys show that the onshore geological trends and distribution of the Archean Lewisian Complex and Paleoproterozoic Rhinns Complex extend for several hundred kilometres westward across the Scottish and Irish continental shelfs (Fig. 7a): Lewisian rocks underlie the Outer Hebridean shelf and George Bligh Bank whereas the Rockall Bank is underlain by gneissic rocks of the Rhinns Complex (Morton and Taylor 1991; Dickin 1992; Daly *et al.* 1995; Hitchen *et al.* 1997; Hitchen 2004; Holdsworth *et al.* 2019). The clearly defined boundary between those areas leaves little doubt that it is a fundamental crustal feature, being coincident with the present-day Anton Dohrn Transfer Zone (Dickin 1992; Doré *et al.* 1997; Corfield *et al.* 1999), that separates areas of differential syn- to post-Cretaceous exhumation across Britain and Ireland (Rateau and Chew 2020). Based on reconstructions of the North Atlantic prior to early Tertiary separation of North America and Europe (Barnett-Moore *et al.* 2016; Ady and Whittaker 2019; MacMahon *et al.* 2020), a Laurentian parentage for the Lewisian–Rhinnian crustal blocks is assured whereby the Scottish–Irish Highlands and their continental shelfs join to Archean and Makkovik–Ketilidian crust of eastern Canada and southernmost Greenland (Fig. 7b). There are no exposures or drill-core data to constrain the northeastern extent beyond the Scottish mainland of the postulated Makkovik–Ketilidian–Rhinns crustal fragment (i.e. Laurentian crust). However, geophysical modelling suggests that the Laurentia–Baltica crustal boundary occurs no more than a few tens of kilometres offshore of NE Scotland (Lyngsie and Thybo 2007, fig. 11b) thereby providing an approximate termination of the proposed Makkovik–Ketilidian–Rhinns crustal block (Fig. 7a).

Using the knowledge that Rhinnian crust occurs at depth beneath the Grampian Highlands, the reconstituted tectonic framework for the North Atlantic realm (Fig. 7b) shows a Makkovik–Ketilidian–Rhinns crustal fragment extending for more than 1500 km from eastern Canada to Ireland. However, at the location of the Great Glen Fault, the consistently east–west-trending boundary between Paleoproterozoic and Archean crust is disrupted by an abrupt change in trend and apparent sinistral offset. If the Grampian Highlands block (i.e. Makkovik–Ketilidian–Rhinns crustal block) is shifted SW by 250–300 km along the Great Glen Fault, it slots into a position that compensates that disruption and realigns the linear trend of the crustal boundary separating Archean from Paleoproterozoic rocks (Fig. 7c). That shift also resolves the sedimentological conundrum highlighted above. Marine geophysical surveys indicate that the Great Glen Fault projects between the Irish continental margin and Rockall Bank (Riddihough and Max 1976; Bailey *et al.* 1977; Max and Barker 1978; Dickin 1992). Using that projection as an offshore guide, placing the Grampian Highlands in the position that realigns the crustal blocks juxtaposes the texturally and compositionally immature sedimentary units dominated by 1.8–1.6 Ga detrital zircons adjacent to Makkovik–Ketilidian–Rhinns crust. This satisfies the lithofacies attributes (e.g. poor sorting, coarse-grained, angular clasts across all grain sizes) that suggest source areas must have been relatively nearby and, based on palaeocurrent data, located to the west and SW.

Discussion

Postulated pairings: the Great Glen and Leannan faults and the Donegal–Argyll granitic suites

Our findings that explain the detrital zircon age spectra and sedimentology of the rocks yielding those spectra prompted another curiosity. Our proposed 250–300 km sinistral offset is comparable

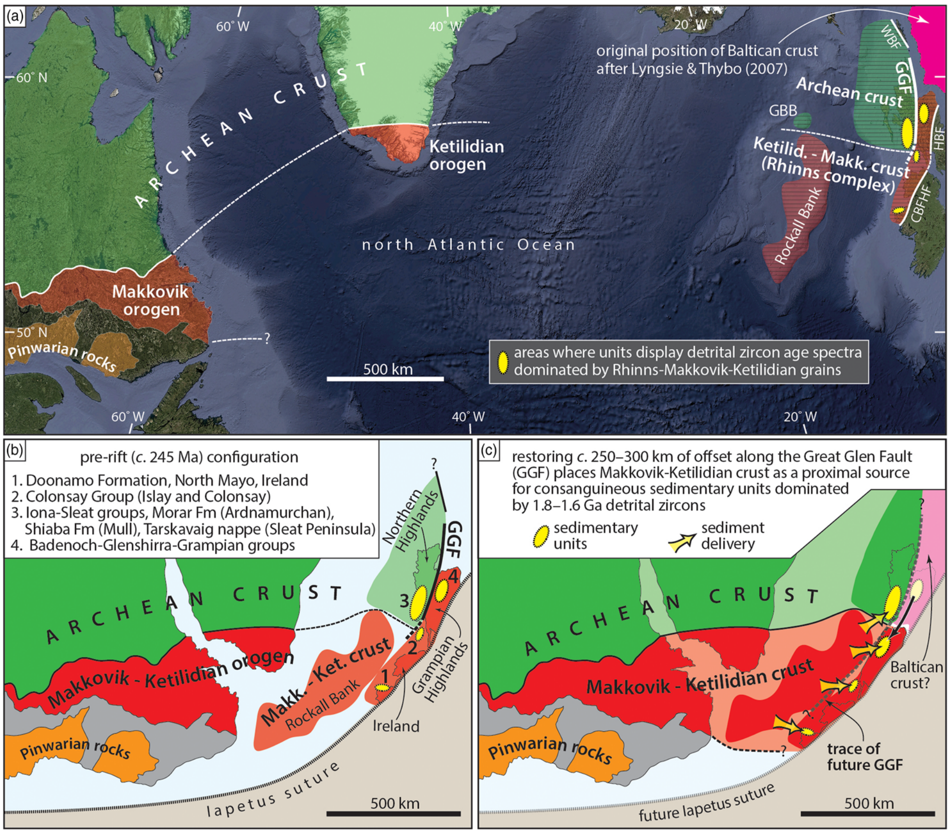

Fig. 7. (**a**) Present-day North Atlantic geography. (**b**) Pre-rift reconstruction of the North Atlantic. (**c**) Reconstruction by restoring 250–300 km of sinistral offset along Great Glen Fault (GGF). CBFHF, Clew Bay–Fair Head Fault; GBB, George Bligh Bank; HBF, Highland Boundary Fault; WBF, Walls Boundary Fault. It should be noted that the Anton Dohrn Transfer Zone coincides approximately with the Archean–Paleoproterozoic crustal boundary shown in the Atlantic Ocean offshore Britain and Ireland. Source: (b) after Ady and Whittaker 2019; location of the edge of Baltican crust adjacent to the Scottish mainland is after Lyngsie and Thybo (2007). Source: (a) Google Earth image (IBACO, Landsat/Copernicus and USGS).

with the earlier estimates of Kennedy (1946) and Winchester (1973). Although the evidence for those estimates is now refuted, this nevertheless led us to think about the matching of other geological features that might inform on ways to assess or even test the magnitude of displacement along the Great Glen Fault. A wealth of data exists about the timing, geochemistry and composition of Caledonian plutons and related intrusive rocks that pepper the Scottish–Irish Highlands (Pitcher and Berger 1972; Wright and Bowes 1979; Hutton 1982; Halliday and Stephens 1984; Stephens and Halliday 1984; Chappell and Stephens 1988; Canning *et al.* 1996, 1998; Atherton and Ghani 2002; Ghani and Atherton 2006; Fowler *et al.* 2008; Neilson *et al.* 2009; Murphy *et al.* 2019; Murphy 2020; Archibald *et al.* 2021, 2022). From such data, Stephens and Halliday (1984) defined three major suites of Scottish granites: the Argyll and Cairngorm suites in the Grampian Highlands and the South of Scotland suite in the Southern Highlands, Midland Valley and Southern Uplands (plutons in the northern Highlands did not readily classify as suites). Of those, the Argyll suite and Donegal plutons share some key geochemical traits (Fig. 8). We are, however, circumspect in the use of such data. The Strontian and Foyers plutons also share Argyll-suite characteristics but differ in whole-rock rare earth element abundances (Pankhurst 1979), which invalidated the conjecture that they were the same pluton displaced by the Great Glen Fault. Nevertheless, it is striking what additional traits are shared between the Argyll suite plutons in the region centred on Glen Coe and the Donegal plutons in Ireland (Fig. 9): both have diverse petrological characteristics commonly with nested zoning patterns; both were emplaced between 430 and 405 Ma (summarized geochronology data were given by Archibald *et al.* 2022); both are associated with two of the most concentrated and well-developed occurrences anywhere in the Scottish–Irish Caledonides of Silurian appinite bodies and Tonian–Ediacaran metadolerite/gabbro intrusions (this aspect was highlighted as early as the 1960s; e.g. Pitcher and Shackleton 1966); and both intrude garnet-bearing upper greenschist–amphibolite-facies Dalradian rocks (Winchester 1973, 1974; Yardley 1976; Fettes 1979). Given these similarities and shared traits, the question we asked was: is it plausible that the Donegal–Argyll plutons and associated intrusive rocks were once more closely aligned?

The Leannan Fault in Donegal, Ireland (Fig. 1), like the Great Glen Fault, occupies a strikingly narrow, linear valley and has been postulated to be an extension of the left-lateral Great Glen Fault system (e.g. Dowling *et al.* 1954; Pitcher *et al.* 1964; Max and Barker 1978). Two observations have been used to deduce that its magnitude of displacement is limited to a few tens of kilometres. The first is based on presumed offsets of facies trends in Argyll Group strata (Pitcher *et al.* 1964; Alsop and Hutton 1990). This, however, is fraught with difficulties because facies changes in the Argyll Group are abrupt and trends cannot be followed for more than a few kilometres (e.g. Litherland 1980; Anderton 1988). Consequently, the utility of such features as pierce points for the Leannan Fault is equivocal. The second observation is a 30 km offset of the Lough Foyle synform (Fig. 9a), a structure that folds local D_1–D_3 features on the east side of the fault (Alsop 1992). In contrast, on the western side of the fault later structural overprinting and/or higher metamorphic grade, or later structural overprinting along the Main Donegal Granite Shear Zone, has masked those relationships (I. Alsop, pers. comm., 2024). This indicates that the fold and, hence, its offset formed during the later stages of strike-slip movement. Thus, that offset is a minimum, not a maximum, measure of displacement along the Leannan Fault. Consequently, we postulate that the Leannan and Great Glen faults are indeed a linked structure and that the commonalities shared by the Donegal and Argyll-suite plutons support the idea that they were once closer together.

Under that postulate, restoring 250–300 km of left-lateral offset along a combined Leannan–Great Glen fault juxtaposes both plutonic suites in a manner that is compatible with their allied

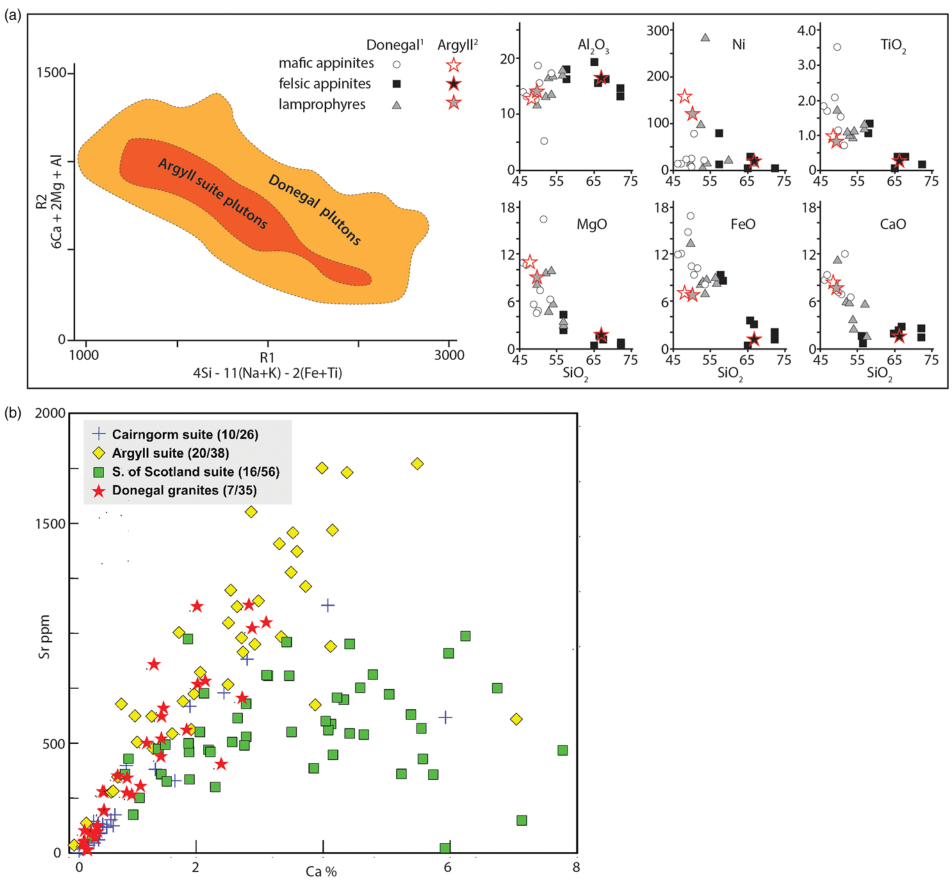

Fig. 8. (**a**) Chemical variation plot of the Donegal and Argyll suite plutons that shows the latter enveloped entirely within the former, and Harker plots of major oxide compositions of the appinite suites in Donegal, Ireland, and SW Grampian Highlands region of Scotland. (**b**) Ca–Sr cross plot of the Donegal plutons showing their chemical affinity with the Argyll suite granites of Scotland. Cairngorm suite and South of Scotland suite granites are also shown for comparison. *x*/*y* in the key indicates the number of discrete granite bodies (mostly plutons) and the total number of samples in each cluster. Source: (a) Neilson *et al.* (2009); data from (superscript numbers): 1, Murphy *et al.* (2019); 2, Wright and Bowes (1979). (b) Data sources: Archibald *et al.* (2022) for the Donegal plutons; Stephens and Halliday (1984) for the Scottish granite suites.

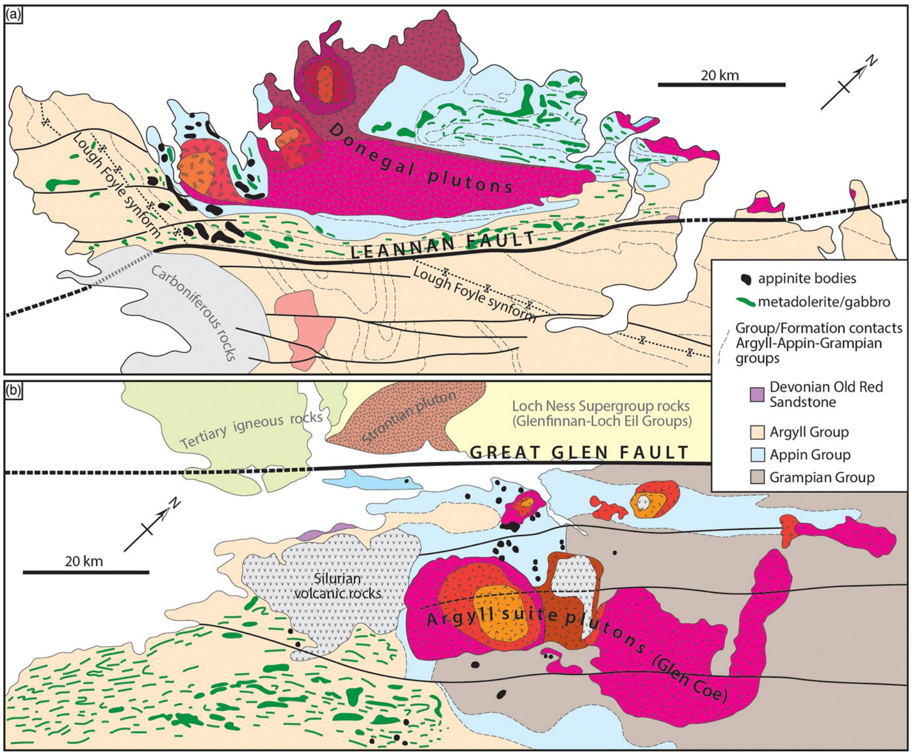

Fig. 9. Highly simplified geology of (**a**) Donegal and (**b**) Glen Coe regions. Source: (a) geology from the Geological Survey of Ireland's spatial resources webpage; (b) geology from the British Geological Survey's Geology Viewer webpage.

features (Fig. 10): it brings into conjunction two of the largest, geochemically compatible and similar-aged suites of plutonic bodies in the Scottish–Irish Caledonides, it pairs the exceptional concentrations of appinite and metadolerite/gabbro intrusions and it matches similar metamorphic facies in the Dalradian rocks that encase the plutons. This proposed amount of restoration also corresponds to that required for aligning the trend of the boundary between Archean (Lewisian) and Paleoproterozoic (Rhinns–Makkovik–Ketilidian) crustal blocks and placement of compositionally and texturally immature sedimentary units against Rhinnian crust as a source of 1.8–1.6 Ga detrital zircons (Fig. 7c). One aspect that is different between the matched Argyll suite in Glen Coe and the plutons in Donegal is the presence of extensive volcanic rocks in the former and their absence in the latter. A plausible explanation is that the *c.* 1 km of downthrow on the SE side of the Great Glen Fault relative to its NW side has resulted in preserving extrusive units of the Argyll suite. It is noteworthy that the latest movement documented along the Great Glen Fault has been dextral transtensional and is as young as early Cretaceous (e.g. Tamas *et al.* 2023, and references therein). The amount of dextral reactivation, though, is limited to several tens of kilometres and, thus, does not severely affect our postulated reconstruction.

We have not included the Walls Boundary Fault in Shetland (Fig. 7a) in this reconstruction. Although often linked to the Great Glen Fault, it records early sinistral ductile fabrics that are overprinted by later brittle dextral movement (Watts *et al.* 2007). The 440 Ma Graven Complex (Lancaster *et al.* 2017) plausibly intrudes the earlier ductile fabrics and, if so, the left-lateral offset along the Walls Boundary fault predates the *c.* 430–400 Ma timing of sinistral motion along the Great Glen Fault. Given these uncertainties, how the Walls Boundary Fault fits within the sinistral Caledonian fault system(s) remains to be determined.

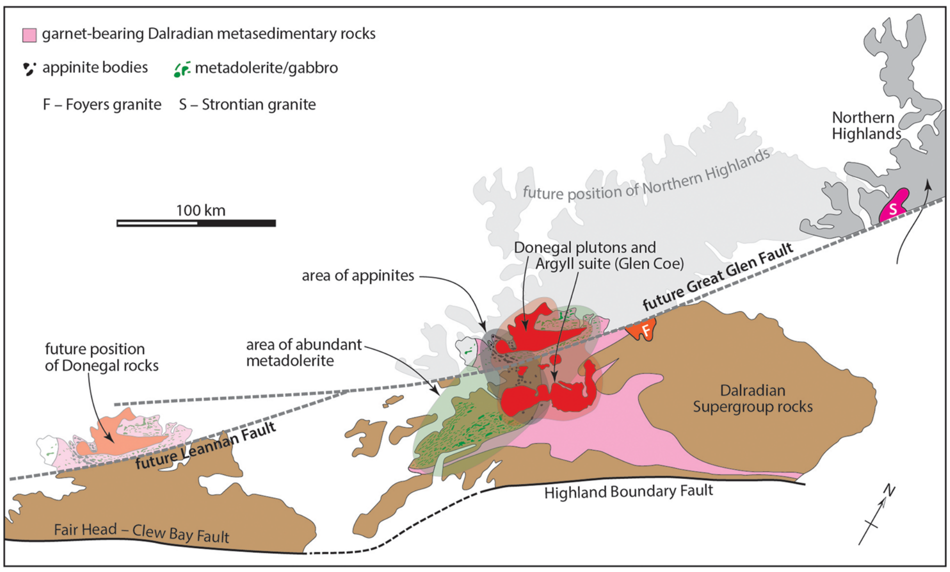

Fig. 10. Postulated pre-strike-slip configuration of the Donegal plutons and zones of exceptionally concentrated appinite and metadolerite with their proposed counterparts in the Argyll suite in the Glen Coe area. This reconstruction results from restoring 250–300 km of sinistral displacement along a combined Great Glen–Leannan fault system.

Summary

Ideas about the magnitude of displacement along the Great Glen Fault system and its role in the Caledonian Orogeny have oscillated between interpreting it as a sinistral transcurrent structural element in the tectonic framework of the Scottish–Irish Caledonides with displacements of 100–200 km (Kennedy 1946; Winchester 1973) to its role as a major tectonic boundary along which as much as 1000 km or more of displacement occurred (e.g. van der Voo and Scotese 1981). The geological evidence upon which those end-member models were constructed has been subsequently disproven, but debate continues, as evident by the concept of the Great Glen Fault having relatively small displacements being resurrected by Searle (2021) in his revised model of Caledonian orogenesis that contrasts with the 700 km or more of tectonic translation envisaged by Dewey and Strachan (2003).

Our contribution in this debate is based on integrating sedimentology with igneous geochemistry, and detrital and inherited zircon age data. The near-single-mode peak of 1.8–1.6 Ga zircons sourced from Rhinns–Makkovik–Ketilidian crust that characterizes compositionally and texturally immature sandstone-dominated units geographically widespread across the Scottish–Irish Highlands, and its presence as inheritance in the Caledonian granites, requires explanation. The Rhinns–Makkovik–Ketilidian orogen, when reconstructed into a pre-North-Atlantic-rift configuration, defines a 1500 km long linear belt along which the only disruption to that trend coincides with the Great Glen Fault. Restoring 250–300 km of sinistral displacement along a combined Great Glen and Leannan fault system re-establishes the linear trend of the orogen and, in so doing, explains sedimentological features indicative of deposition occurring proximal to source areas composed of Rhinns–Makkovik–Ketilidian crust. It also unites into a single coherent assemblage several otherwise widely separated yet comparable geological features: the compositionally and temporally compatible Donegal–Argyll granitic suites and the concentrated zones of Caledonian peri-batholitic appinite intrusions and Tonian–Ediacaran metadolerite/gabbro bodies.

Our postulated pairing of the Donegal and Argyll suite plutons offers a model that could be tested by additional detailed isotope and REE geochemistry coupled with high-precision and high-accuracy U–Pb geochronology. However, the striking feature that has been highlighted as central in discussions about the Great Glen Fault is the presence of Scandian-age (Silurian) deformational fabrics in the rocks of the Northern Highlands north of the fault and their absence in the rocks of the Grampian Highlands south of the fault. Although the 250–300 km of offset we propose for the Great Glen Fault falls short of the minimum of 400 km postulated by Dewey and Ryan (2022) to explain that relationship, we note that similarly scaled shear zones elsewhere, such as the Puros and Okahandja shear zones in Namibia as well as numerous others formed during the pan-African assembly of Gondwana (Schmitt *et al.* 2023), juxtapose disparate tectonothermal terranes not unlike the geological differences between the Northern and Grampian Highlands. Thus, given uncertainties in exact geometries of plate boundaries during the Scandian phase of the Caledonian Orogeny, it is possible that the magnitude of offset we suggest could account for the Scandian event in the Northern Highlands and the lack of deformational fabrics related to that event in the Grampian Highlands. In essence, our postulate offers a model of the Great Glen–Leannan fault system that can be tested. To do so requires forming collaborations that will stimulate joint research into Irish and Scottish geology to find shared ways to deepen knowledge about and further understanding of the Caledonian Orogeny.

Scientific editing by Sarah Boulton

Acknowledgements We thank many colleagues over our many shared years of working in the Scottish and Irish Highlands. We also acknowledge the careful and thorough reviews of A. Bird, P. Cawood and B. Holdsworth that much improved the paper. Special thanks go to R. Strachan for freely sharing his ideas and deep knowledge of Scottish and Irish geology.

Author contributions **ARP**: conceptualization (lead), writing – original draft (lead), writing – review & editing (lead); **WES**: conceptualization (supporting), formal analysis (supporting), writing – original draft (supporting), writing – review & editing (supporting); **AEF**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **IW**: formal analysis (supporting), writing – original draft (supporting), writing – review & editing (supporting); **KK**: formal analysis (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Funding This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability All data generated or analysed during this study are included in this published article and its supplementary information files.

References

Ady, B.E. and Whittaker, R.C. 2019. Examining the influence of tectonic inheritance on the evolution of the North Atlantic using a palinspastic deformable plate reconstruction. *Geological Society, London, Special Publications*, **470**, 245–263, https://doi.org/10.1144/SP470.9

Alsop, G.I. 1992. Late Caledonian strike-slip displacement across the Leannan Fault system, northwest Ireland. *Geological Journal*, **27**, 119–125, https://doi.org/10.1002/gj.3350270203

Alsop, G.I. and Hutton, D.H.W. 1990. A review and revision of Dalradian stratigraphy in central and southern Donegal, Ireland. *Irish Journal of Earth Sciences*, **10**, 181–198.

Anderton, R. 1988. Dalradian slides and basin development: a radical interpretation of stratigraphy and structure in the SW and Central Highlands of Scotland. *Journal of the Geological Society, London*, **145**, 669–678, https://doi.org/10.1144/gsjgs.145.4.0669

Archibald, D.B., Macquarrie, L.M.G. *et al.* 2021. The construction of the Donegal composite batholith, Irish Caledonides: temporal constraints from U–Pb dating of zircon and titanite. *Geological Society of America Bulletin*, **133**, 2335–2354, https://doi.org/10.1130/2021.2554(15)

Archibald, D.B., Murphy, J.B., Fowler, M., Strachan, R.A. and Hildebrand, R.S. 2022. Testing petrogenetic models for contemporaneous mafic and felsic to intermediate magmatism within the 'Newer Granite' suite of the Scottish and Irish Caledonides. *Geological Society of America, Special Papers*, **554**, 375–399.

Atherton, M.P. and Ghani, A.A. 2002. Slab breakoff: a model for Caledonian late granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos*, **62**, 65–85, https://doi.org/10.1016/S0024-4937(02)00111-1

Augland, L.E., Moukhsil, A., Solgadi, F. and Indares, A. 2015. Pinwarian to Grenvillian magmatic evolution in the central Grenville Province: new constraints from ID-TIMS U–Pb ages and coupled Lu–Hf S-MC-ICP-MS data. *Canadian Journal of Earth Sciences*, **52**, 701–721, https://doi.org/10.1139/cjes-2014-0232

Bailey, R.J., Jackson, P.D. and Bennell, J.D. 1977. Marine geology of Slyne Ridge. *Journal of the Geological Society, London*, **133**, 165–172, https://doi.org/10.1144/gsjgs.133.2.0165

Banks, C.J., Smith, M., Winchester, J.A., Horstwood, M.S.A., Noble, S.R. and Ottley, C.J. 2007. Provenance of intra-Rodinian basin-fills: the lower Dalradian Supergroup, Scotland. *Precambrian Research*, **153**, 46–64, https://doi.org/10.1016/j.precamres.2006.11.004

Banks, C.J., Peters, D.P., Winchester, J.A., Noble, S.R. and Horstwood, M.S.A. 2013. Basement palaeogeography of late Neoproterozoic Scotland: constraints from exotic clasts within the lower Dalradian Supergroup. *Scottish Journal of Geology*, **49**, 81–92, https://doi.org/10.1144/sjg2011-449

Barnett-Moore, N., Müller, D.R., Williams, S., Skogseid, J. and Seton, M. 2016. A reconstruction of the North Atlantic since the earliest Jurassic. *Basin Research*, **30**, 160–185, https://doi.org/10.1111/bre.12214

Briden, J.C., Turnell, H.B. and Watts, D.R. 1984. British paleomagnetism, Iapetus Ocean, and the Great Glen Fault. *Geology*, **12**, 428–431, https://doi.org/10.1130/0091-7613(1984)12<428:BPIOAT>2.0.CO;2

Canning, J.C., Henney, P., Morrison, M. and Gaskarth, J. 1996. Geochemistry of late Caledonian minettes from northern Britain: implications for the Caledonian sub-continental lithospheric mantle. *Mineralogical Magazine*, **60**, 221–236, https://doi.org/10.1180/minmag.1996.060.398.15

Canning, J.C., Henney, P.J., Morrison, M.A., Van Calsteren, P.W.C., Gaskarth, J.W. and Swarbrick, A. 1998. The Great Glen fault: a major vertical lithospheric boundary. *Journal of the Geological Society, London*, **155**, 425–428, https://doi.org/10.1144/gsjgs.155.3.0425

Cawood, P.A., Nemchin, A.A., Smith, M. and Loewy, S. 2003. Source of the Dalradian Supergroup constrained by U–Pb dating of detrital zircon and implications for the East Laurentian margin. *Journal of the Geological Society, London*, **160**, 231–246, https://doi.org/10.1144/0016-764902-039

Cawood, P.A., Nemchin, A.A., Strachan, R.A., Kinny, P.D. and Loewy, S. 2004. Laurentian provenance and an intracratonic tectonic setting for the Moine Supergroup, Scotland, constrained by detrital zircons from the Loch Eil and Glen Urquhart successions. *Journal of the Geological Society, London*, **161**, 861–874, https://doi.org/10.1144/16-764903-117

Cawood, P.A., Nemchin, A.A., Strachan, R., Prave, A.R. and Krabbendam, M. 2007. Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia. *Journal of the Geological Society, London*, **164**, 257–275, https://doi.org/10.1144/0016-76492006-115

Cawood, P.A., Strachan, R.A. *et al.* 2015. Neoproterozoic to early Paleozoic extensional and compressional history of East Laurentian margin sequences: the Moine Supergroup, Scottish Caledonides. *Geological Society of America Bulletin*, **127**, 349–371, https://doi.org/10.1130/B31068.1

Chappell, B.W. 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London, Series A*, **310**, 693–707, https://doi.org/10.1098/rsta.1984.0015

Chappell, B.W. and Stephens, W.E. 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **79**, 71–86, https://doi.org/10.1017/S0263593300014139

Chew, D.M. and Strachan, R.A. 2014. The Laurentian Caledonides of Scotland and Ireland. *Geological Society, London, Special Publications*, **390**, 45–91, https://doi.org/10.1144/390.16

Corfield, S., Murphy, N. and Parker, S. 1999. The structural and stratigraphic framework of the Irish Rockall Trough. *Geological Society, London, Petroleum Geology Conference Series*, **5**, 407–420, https://doi.org/10.1144/0050407

Dallmeyer, R.D., Strachan, R.A., Rogers, G., Watt, G.R. and Friend, C.R.L. 2001. Dating deformation and cooling in the Caledonian thrust nappes of north Sutherland, Scotland: insights from $^{40}Ar/^{39}Ar$ and Rb–Sr chronology. *Journal of the Geological Society, London*, **158**, 501–512, https://doi.org/10.1144/jgs.158.3.501

Daly, J.S. 1996. Pre-Caledonian history of the Annagh Gneiss Complex, northwestern Ireland, and correlation with Laurentia–Baltica. *Irish Journal of Earth Sciences*, **15**, 5–18.

Daly, J.S. and Flowerdew, M.J. 2005. Grampian and late Grenville events recorded by mineral geochronology near a basement–cover contact in north Mayo, Ireland. *Journal of the Geological Society, London*, **162**, 163–174, https://doi.org/10.1144/0016-764903-150

Daly, J.S., Muir, R.J. and Cliff, R.A. 1991. A precise U–Pb zircon age for the Inishtrahull syenitic gneiss, County Donegal, Ireland. *Journal of the Geological Society, London*, **148**, 639–642, https://doi.org/10.1144/gsjgs.148.4.0639

Daly, J.S., Heaman, L.M., Fitzgerald, R.C., Menuge, J.F., Brewer, T.S. and Morton, A.C. 1995. Age and crustal evolution of crystalline basement in western Ireland and Rockall. *Geological Society, London, Special Publications*, **93**, 433–434, https://doi.org/10.1144/GSL.SP.1995.093.01.34

Daly, J.S., Flowerdew, M.J., McAteer, C., Horstwood, M.S.A., Whitehouse, M.J. and Chew, D.M. 2009. Palaeoproterozoic orthogneiss on Colonsay, SW Scotland. Abstracts of the 52nd Annual Irish Geological Research Meeting, 20–22 February, Trinity College Dublin.

Dewey, J.F. and Ryan, P.D. 2022. Discussion of Searle, 'Tectonic evolution of the Caledonian orogeny in Scotland: a review based on the timing of magmatism, metamorphism and deformation'. *Geological Magazine*, **159**, 1833–1836, https://doi.org/10.1017/S0016756822000553

Dewey, J.F. and Strachan, R.A. 2003. Changing Silurian–Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society, London*, **160**, 219–229, https://doi.org/10.1144/0016-764902-085

Dickin, A.P. 1992. Evidence for an Early Proterozoic crustal province in the North Atlantic region. *Journal of the Geological Society, London*, **149**, 483–486, https://doi.org/10.1144/gsjgs.149.4.0483

Doré, A.G., Lundin, E.R., Fichler, C. and Olesen, O. 1997. Patterns of basement structure and reactivation along the NE Atlantic margin. *Journal of the Geological Society, London*, **154**, 85–92, https://doi.org/10.1144/gsjgs.154.1.0085

Dowling, J.W.F., Shackleton, R.W., Pitcher, W.S., Cheesman, R.L. and Read, H.H. 1954. The Great Glen Fault, Donegal. *Geological Magazine*, **91**, 519–520, https://doi.org/10.1017/S001675680006636X

Fettes, D.J. 1979. A metamorphic map of the British and Irish Caledonides. *Geological Society, London, Special Publications*, **8**, 305–321, https://doi.org/10.1144/GSL.SP.1979.008.01.35

Fowler, M.B., Kocks, H., Darbyshire, D.P.F. and Greenwood, P.B. 2008. Petrogenesis of high Ba–Sr plutons from the Northern Highlands terrane of the British Caledonian Province. *Lithos*, **105**, 129–148, https://doi.org/10.1016/j.lithos.2008.03.003

Freeman, S.R., Butler, R.W.H., Cliff, R.A. and Rex, D.C. 1998. Direct dating of mylonite evolution; a multi-disciplinary geochronological study from the Moine thrust zone, NW Scotland. *Journal of the Geological Society, London*, **155**, 745–758, https://doi.org/10.1144/gsjgs.155.5.0745

Friend, C.R.L., Strachan, R.A., Kinny, P.D. and Watt, G.R. 2003. Provenance of the Moine Supergroup of NW Scotland: evidence from geochronology of detrital and inherited zircons from (meta) sedimentary rocks, granites and migmatites. *Journal of the Geological Society, London*, **160**, 247–257, https://doi.org/10.1144/0016-764901-161

Ghani, A.A. and Atherton, M.P. 2006. The chemical character of the late Caledonian Donegal granites, Ireland, with comments on their genesis. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **97**, 437–454, https://doi.org/10.1017/S0263593300001553

Gower, C.F., Kamo, S.L., Kwok, K. and Krogh, T.E. 2008. Proterozoic southward accretion and Grenvillian orogenesis in the interior Grenville Province in eastern Labrador: evidence from U–Pb geochronological investigations. *Precambrian Research*, **165**, 61–95, https://doi.org/10.1016/j.precamres.2008.06.007

Halliday, A.N. and Stephens, W.E. 1984. Crustal controls on the genesis of the 400 Ma old Caledonian granites. *Physics of the Earth and Planetary Interiors*, **35**, 89–104, https://doi.org/10.1016/0031-9201(84)90036-0

Halliday, A.N., Dickin, A.P., Hunter, R.N., Davies, G.R., Dempster, T.J., Hamilton, P.J. and Upton, B.G. 1993. Formation and composition of the lower continental crust: evidence from Scottish xenolith suites. *Journal of Geophysical Research*, **98**, 581–607, https://doi.org/10.1029/92JB02276

Hitchen, K. 2004. The geology of the UK Hatton–Rockall margin. *Marine and Petroleum Geology*, **21**, 993–1012, https://doi.org/10.1016/j.marpetgeo.2004.05.004

Hitchen, K., Morton, A.C., Mearns, E.W., Whitehouse, M. and Stoker, M.S. 1997. Geological implications from geochemical and isotopic studies of Upper Cretaceous and Lower Tertiary igneous rocks around the northern Rockall Trough. *Journal of the Geological Society, London*, **154**, 517–521, https://doi.org/10.1144/gsjgs.154.3.0517

Holdsworth, R.E., Morton, A. *et al.* 2019. The nature and significance of the Faroe–Shetland Terrane: linking Archaean basement blocks across the North Atlantic. *Precambrian Research*, **321**, 154–171, https://doi.org/10.1016/j.precamres.2018.12.004

Hutton, D.H.W. 1982. A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Journal of the Geological Society, London*, **139**, 615–631, https://doi.org/10.1144/gsjgs.139.5.0615

Johnson, T.E., Kirkland, C.L., Reddy, S.M., Evans, N.J. and McDonald, B.J. 2016. The source of Dalradian detritus in the Buchan Block, NE Scotland: application of new tools to detrital datasets. *Journal of the Geological Society, London*, **173**, 773–782, https://doi.org/10.1144/jgs2016-019

Kennedy, W.Q. 1946. The Great Glen Fault. *Quarterly Journal of the Geological Society*, **102**, 41–76, https://doi.org/10.1144/GSL.JGS..1946.102.01-04.04

Kenny, G.G., O'Sullivan, G.J., Alexander, S., Simms, M.J., Chew, D.M. and Kamber, B.S. 2019. On the track of a Scottish impact structure: a detrital zircon and apatite provenance study of the Stac Fada Member and wider Stoer Group of NW Scotland. *Geological Magazine*, **156**, 1863–1876, https://doi.org/10.1017/S0016756819000220

Kinnaird, T.C., Prave, A.R., Kirkland, C.L., Horstwood, M., Parrish, R. and Batchelor, R.A. 2007. The late Mesoproterozoic–Early Neoproterozoic tectonostratigraphic evolution of Northwest Scotland: the Torridonian revisited. *Journal of the Geological Society, London*, **164**, 541–551, https://doi.org/10.1144/0016-76492005-096

Kinny, P.D., Strachan, R.A., Friend, C.R.L., Kocks, H., Rogers, G. and Paterson, B.A. 2003. U–Pb geochronology of deformed metagranites in central Sutherland, Scotland: evidence for widespread late Silurian metamorphism and ductile deformation of the Moine Supergroup during the Caledonian orogeny. *Journal of the Geological Society, London*, **160**, 259–269, https://doi.org/10.1144/0016-764901-087

Kirkland, C.L., Strachan, R.A. and Prave, A.R. 2008. Detrital signature of the Moine Supergroup, Scotland: Contrasts and comparisons with other Neoproterozoic successions within the circum-North Atlantic region. *Precambrian Research*, **163**, 332–350, https://doi.org/10.1016/j.precamres.2008.01.003

Krabbendam, M., Bonsor, H., Horstwood, M.S.A. and Rivers, T. 2017. Tracking the evolution of the Grenvillian foreland basin: constraints from sedimentology and detrital zircon and rutile in the Sleat and Torridon groups, Scotland. *Precambrian Research*, **295**, 67–89, https://doi.org/10.1016/j.precamres.2017.04.027

Krabbendam, M., Strachan, R. and Prave, T. 2022. A new stratigraphic framework for the early Neoproterozoic successions of Scotland. *Journal of the Geological Society, London*, **179**, https://doi.org/10.1144/jgs2021-054

Lancaster, P.J., Strachan, R.A., Bullen, D., Fowler, M., Jaramillo, M. and Saldarriaga, A.M. 2017. U–Pb zircon geochronology and geodynamic significance of 'Newer Granite' plutons in Shetland, northernmost Scottish Caledonides. *Journal of the Geological Society, London*, **174**, 486–497, https://doi.org/10.1144/jgs2016-106

Lebeau, L.E., Ielpi, A., Krabbendam, M. and Davis, W.J. 2020. Detrital-zircon provenance of a Torridonian fluvial–aeolian sandstone: the 1.2 Ga Meall Dearg Formation, Stoer Group (Scotland). *Precambrian Research*, **346**, 105822, https://doi.org/10.1016/j.precamres.2020.105822

Litherland, M. 1980. The stratigraphy of the Dalradian rocks around Loch Creran, Argyll. *Scottish Journal of Geology*, **16**, 105–123, https://doi.org/10.1144/sjg16020105

Lyngsie, S.B. and Thybo, H. 2007. A new tectonic model for the Laurentia–Avalonia–Baltica sutures in the North sea: a case study along MONA LISA profile 3. *Tectonophysics*, **429**, 201–227, https://doi.org/10.1016/j.tecto.2006.09.017

MacMahon, H., Welford, J.K., Sandoval, L. and Pearce, A.L. 2020. The Rockall and the Orphan Basins of the Southern North Atlantic Ocean: determining continuous basins across conjugate margins. *Geosciences*, **10**, https://doi.org/10.3390/geosciences10050178

Marcantonio, F., Dickin, A.P., McNutt, R.H. and Heaman, L.M. 1988. A 1,800-million year-old Proterozoic gneiss terrane in Islay with implications for the crustal structure and evolution of Britain. *Nature*, **335**, 62–64, https://doi.org/10.1038/335062a0

Max, M.D. and Barker, P.L. 1978. The westward continuation of the Leannan Fault of Donegal and its bearing on the Great Glen Fault system. *Geological Magazine*, **115**, 215–218, https://doi.org/10.1017/S0016756800036918

McAteer, C.A., Daly, J.S., Flowerdew, M.J., Connelly, J.N., Housh, T.B. and Whitehouse, M.J. 2010a. Detrital zircon, detrital titanite and igneous clast U–Pb geochronology and basement–cover relationships of the Colonsay Group, SW Scotland: Laurentian provenance and correlation with the Neoproterozoic Dalradian Supergroup. *Precambrian Research*, **181**, 21–42, https://doi.org/10.1016/j.precamres.2010.05.013

McAteer, A., Daly, J.S., Flowerdew, M.J., Whitehouse, M.J. and Kirkland, C.L. 2010b. A Laurentian provenance for the Dalradian rocks of north Mayo, Ireland, and evidence of an original basement cover contact with the underlying Annagh Gneiss Complex. *Journal of the Geological Society, London*, **167**, 1033–1048, https://doi.org/10.1144/0016-76492009-147

McAteer, C.A., Daly, S.J., Flowerdew, M.J., Whitehouse, M.J. and Monaghan, N.M. 2014. Sedimentary provenance, age and possible correlation of the Ione Group, SW Scotland. *Scottish Journal of Geology*, **50**, 143–158, https://doi.org/10.1144/sjg2013-019

Morton, A.C. and Taylor, P.N. 1991. Geochemical and isotopic constraints on the nature and age of basement rocks from Rockall Bank, NE Atlantic. *Journal of the Geological Society, London*, **148**, 631–634, https://doi.org/10.1144/gsjgs.148.4.0631

Murphy, J.B. 2020. Appinite suites and their genetic relationship with coeval voluminous granitoid batholiths. *International Geology Review*, **62**, 683–713, https://doi.org/10.1080/00206814.2019.1630859

Murphy, J., Nance, R., Gabler, L., Martell, A. and Archibald, D. 2019. Age, geochemistry and origin of the Ardara appinite plutons, northwest Donegal, Ireland. *Geoscience Canada*, **46**, 31–48, https://doi.org/10.12789/geocanj.2019.46.144

Neilson, J.C., Kokelaar, B.P. and Crowley, Q.G. 2009. Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian terrane, Scotland. *Journal of the Geological Society, London*, **166**, 545–561, https://doi.org/10.1144/0016-76492008-069

Pankhurst, R.J. 1979. Isotope and trace element evidence for the origin and evolution of Caledonian granites in the Scottish Highlands. *In*: Atherton, M.P. and Tarney, J. (eds) *Origin of Granite Batholiths*. Birkhäuser, Boston, 18–33, https://doi.org/10.1007/978-1-4684-0570-5_3

Pitcher, W.S. and Berger, A.R. 1972. *The Geology of Donegal: A Study of Granite Emplacement and Unroofing*. Wiley, Chichester.

Pitcher, W.S. and Shackleton, R.M. 1966. On the correlation of certain lower Dalradian successions in northwest Donegal. *Geological Journal*, **5**, 149–156, https://doi.org/10.1002/gj.3350050112

Pitcher, W.S., Elwell, R.W.D., Tozer, C.F. and Cambry, F.W. 1964. The Leannan Fault. *Quarterly Journal of the Geological Society*, **120**, 241–273, https://doi.org/10.1144/gsjgs.120.1.0241

Prave, A.R., Fallick, A.E., Strachan, R.A., Krabbendam, M. and Leslie, A.G. 2024. Late Tonian to early Ordovician: from Rodinia to Iapetus. *In*: Smith, M. and Strachan, R.A. (eds) *The Geology of Scotland*, 5th edn. Geological Society, London.

Rainbird, R.H., Hamilton, M.A. and Young, G.M. 2001. Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *Journal of the Geological Society, London*, **158**, 15–27, https://doi.org/10.1144/jgs.158.1.15

Rateau, R. and Chew, D. 2020. The multi-scale control of crustal structures on the exhumation of the British–Irish Isles, revealed by 40 years of AFT studies. Abstract and Poster, Thermo2020 Conference, Santa Fe, New Mexico.

Riddihough, R.P. and Max, M.D. 1976. A geological framework for the continental margin to the west of Ireland. *Geological Journal*, **11**, 109–120, https://doi.org/10.1002/gj.3350110202

Schmitt, R.S., Trouw, R.A.J., Da Silva, E.A., Mendes de Jesus, J.V., da Costa, L.F.M. and Passarelli, C.R. 2023. The role of crustal-scale shear zones in SW Gondwana consolidation – transatlantic correlation. *Geological Society, London, Special Publications*, **531**, 149–187, https://doi.org/10.1144/SP531-2022-278

Searle, M.P. 2021. Tectonic evolution of the Caledonian orogeny in Scotland: a review based on the timing of magmatism, metamorphism and deformation. *Geological Magazine*, **159**, 124–152, https://doi.org/10.1017/S0016756821000947

Sherlock, S.C., Kelley, S.P., Zalasiewicz, J.A., Schofield, D.I., Evans, J.A., Merriman, R.J. and Kemp, S.J. 2003. Precise dating of low-temperature deformation: strain-fringe analysis by ^{40}Ar/^{39}Ar laser microprobe. *Geology*, **31**, 219–222, https://doi.org/10.1130/0091-7613(2003)031<0219:PDOLTD>2.0.CO;2

Smith, D.I. and Watson, J. 1983. Scale and movements on the Great Glen fault, Scotland. *Geology*, **11**, 523–526, https://doi.org/10.1130/0091-7613(1983)11<523:SATOMO>2.0.CO;2

Soper, N.J. and Hutton, D.H.W. 1984. Late Caledonian sinistral displacements in Britain: implications for a three-plate collision model. *Tectonics*, **3**, 781–794, https://doi.org/10.1029/TC003i007p00781

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A. and Greiling, R.O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London*, **149**, 871–880, https://doi.org/10.1144/gsjgs.149.6.0871

Steinhoefel, G., Hegner, E. and Oliver, G.J.H. 2008. Chemical and Nd isotope constraints on granitoid sources involved in the Caledonian Orogeny in Scotland. *Journal of the Geological Society, London*, **165**, 817–827, https://doi.org/10.1144/0016-76492007-107

Stephens, W.E. and Halliday, A.N. 1984. Geochemical contrasts between late Caledonian granitoid plutons of northern, central and southern Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 259–273, https://doi.org/10.1017/S0263593300013894

Stewart, M., Strachan, R.A. and Holdsworth, R.E. 1999. Structure and early kinematic history of the Great Glen Fault Zone, Scotland. *Tectonics*, **18**, 326–342, https://doi.org/10.1029/1998TC900033

Strachan, R.A., Prave, A.R., Kirkland, C.L. and Storey, C.D. 2013. U–Pb detrital zircon geochronology of the Dalradian Supergroup, Shetland Islands, Scotland: implications for regional correlations and Neoproterozoic–Palaeozoic basin development. *Journal of the Geological Society, London*, **170**, 905–916, https://doi.org/10.1144/jgs2013-057

Strachan, R.A., Prave, T., Krabbendam, M. and Smith, M. 2024. Late Mesoproterozoic to early Proterozoic sedimentation and orogeny. *In*: Smith, M. and Strachan, R.A. (eds) *The Geology of Scotland*, 5th edn. Geological Society, London.

Tamas, A., Holdsworth, R.E. *et al.* 2023. Older than you think: using U–Pb calcite geochronology to better constrain basin-bounding fault reactivation, Inner Moray Firth Basin, western North Sea. *Journal of the Geological Society, London*, **180**, jgs2022-166, https://doi.org/10.1144/jgs2022-166

Thirlwall, M.F. 1989. Movement on proposed terrane boundaries in northern Britain: constraints from Ordovician–Devonian igneous rocks. *Journal of the Geological Society, London*, **146**, 373–376, https://doi.org/10.1144/gsjgs.146.3.0373

van der Voo, R. and Scotese, C. 1981. Paleomagnetic evidence for a large (~2,00 km) sinistral offset along the Great Glen fault during Carboniferous time. *Geology*, **9**, 583–589, https://doi.org/10.1130/0091-7613(1981)9<583:PEFALK>2.0.CO;2

Watts, L.M., Holdsworth, R.E., Sleight, J.A., Strachan, R.A. and Smith, S.A.F. 2007. The movement history and fault rock evolution of a reactivated crustal-scale strike-slip fault: the Walls Boundary Fault Zone, Shetland. *Journal of the Geological Society, London*, **164**, 1037–1058, https://doi.org/10.1144/0016-76492006-156

White, A.J.R., Allen, C.M. *et al.* 2001. Granite suites and supersuites of Australia. *Australian Journal of Earth Sciences*, **48**, 515–530, https://doi.org/10.1046/j.1440-0952.2001.00874.x

Wilson, J.T. 1962. Cabot Fault, an Appalachian equivalent of the San Andreas and Great Glen faults and some implications for continental displacement. *Nature*, **195**, 135–138, https://doi.org/10.1038/195135a0

Winchester, J.A. 1973. Pattern of regional metamorphism suggests a sinistral displacement of 160 km along the Great Glen Fault. *Nature*, **246**, 81–84.

Winchester, J.A. 1974. The zonal pattern of regional metamorphism in the Scottish Caledonides. *Journal of the Geological Society, London*, **130**, 509–524, https://doi.org/10.1144/gsjgs.130.6.0509

Wright, A.E. and Bowes, D.R. 1979. Geochemistry of the appinite suite. *Geological Society, London, Special Publications*, **8**, 699–704, https://doi.org/10.1144/GSL.SP.1979.008.01.84

Yardley, B.W.D. 1976. Deformation and metamorphism of Dalradian rocks and the evolution of the Connemara cordillera. *Journal of the Geological Society, London*, **132**, 521–542, https://doi.org/10.1144/gsjgs.132.5.0521