Research article

JGS
Journal of the Geological Society

https://doi.org/10.1144/jgs2023-208 | Vol. 181 | 2024 | jgs2023-208

Geometrical restoration of a late Neoproterozoic depositional framework and an intrabasinal unconformity in the Laurentian margin Dalradian Supergroup, Grampian Highlands, Scotland

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Abstract: Restoring primary depositional frameworks from orogenic settings is challenging. To demonstrate a robust determination of original, but now highly deformed, depositional frameworks and their first-order sequence-stratigraphy, we analyse the Dalradian succession of Tyndrum–Glen Lyon (Breadalbane) in the southwestern Grampian Highlands of Scotland. In Breadalbane, several distinctive Appin and Argyll group Dalradian formations are absent. Omission has been attributed to ductile shearing on the Boundary Slide structure, during the Grampian Orogeny (*c.* 470 Ma). Alternatively, we restore and describe a primary depositional framework and widely developed intra-Dalradian basin unconformity in Breadalbane, preserved in the relatively low-strain lower limb of the Grampian D_2 Ben Lui Syncline. On this unconformity, locally distinctive strata of the Easdale Subgroup, and more regionally typical strata of the Crinan Subgroup, were deposited directly on strata of the Lochaber Subgroup. Northeastward loss of strata of the Ballachulish, Blair Atholl and Islay subgroups, observed SW of Tyndrum, contrasts with gradual reappearance of correlative units northeastwards from Glen Lyon. Onlap and/or overstep relationships are well preserved; although strain is enhanced locally along pronounced stratal or rheological contrasts, the stratigraphical framework remains essentially intact. Our Scotland-wide analysis of the Dalradian depositional framework recognizes other probable basin-scale unconformities that locally influenced patterns of superimposed orogenic deformation.

Received 25 November 2023; **revised** 19 February 2024; **accepted** 22 February 2024

The detailed sedimentology and architecture of basins located on evolving continental margins varies greatly in response to differences in amount and duration of extension, sediment supply from the hinterland and magmatic activity, as well as climate and its implications for carbonate production and sea level (Kusznir *et al.* 1991; Lister *et al.* 1991; Manatschal 2004; Manatschal *et al.* 2007; Osmundsen and Ebbing 2008; Peron-Pinvidic *et al.* 2013). The ultimate fate of such continental margin sequences formed during and after continental break-up is, as the Wilson Cycle progresses, to become caught up in ocean closure, orogenesis, uplift and erosion.

Depositional architectures in basins formed on modern continental margins are often best studied by seismic survey and drilling programmes, and where their geometry and character has not been deformed and metamorphosed. In contrast, most ancient continental margin basin sequences can be studied only in outcrop after closure of the ocean that originally accommodated the extended or passive margin, consequent orogenesis and subsequent uplift. Those basin sequences are thus deformed, metamorphosed and variably eroded, creating problems in restoration and interpretation of the primary depositional framework. Significant uncertainty can arise in interpreting contractional fold (and thrust) structures, where those features form by superimposition of ductile deformation upon an already geometrically complex depositional framework.

Robust reconstruction of the depositional framework and stratigraphy of an ancient continental margin basin sequence can, for example, guide exploration for stratabound economic mineralization (e.g. Plant *et al.* 1991), and provide insight into the response of superimposed regional-scale deformation to broad-scale mechanical stratigraphy (rheology) (e.g. Osmundsen and Ebbing 2008). Reconstruction is particularly challenging in regions of pervasive polyphase deformation where primary sedimentology and stratigraphy have been significantly modified, perhaps partially obliterated, by orogenesis and, later still, by erosion. Limited fossil occurrences and resultant poor biostratigraphy in Precambrian successions further hampers recognition of depositional non-sequences. As a consequence, it may be difficult to distinguish between syndepositional extensional detachments (increasingly recognized in modern passive margins; e.g. Reston *et al.* 2004), syndepositional erosional truncations and superimposed orogenic extensional detachments (e.g. Osmundsen and Ebbing 2008). After significant deformation, onlap, offlap and downlap geometries critical to sequence-stratigraphical analysis, and/or syndepositional (listric) normal faults, may be difficult to distinguish from the hanging-wall ramps of thrusts. Equally, the geometries of deformed toplapping depositional relationships may appear similar to those of thrust footwall ramps.

The Scottish sector of the Neoproterozoic–Cambrian Laurentian margin of the Iapetus Ocean is preserved as the Dalradian Supergroup, deformed and metamorphosed within the Caledonian Orogen (Figs 1 and 2). Within this uplifted orogenic setting, numerous otherwise conspicuous formations are apparently ‘missing’. For example, in the mountainous Breadalbane district of Perthshire (between Tyndrum and Glen Lyon), non-appearance, or omission, of a significant part of the more widely recognized lower to mid-Dalradian stratigraphy has been traditionally interpreted as ‘tectonic removal’ (see Harris *et al.* 1994) and the impact of a syn- to post-D_2 ductile high-strain zone: the Boundary Slide of Roberts and Treagus (1977, and see Fig. 2). This and other ‘slides’ proved difficult to place within an evolving contractional–collisional regional structural framework, leading to their interpretation as the result of either (1) late- or post-orogenic extension

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Fig. 1. Simplified pre-Iapetan reconstruction showing the distribution of Late Neoproterozoic ('Dalradian-equivalent') and Cambro-Ordovician shelf sediments on the Eastern Laurentian margin. Source: adapted from Cawood *et al.* (2007), Harland (1997), Peel and Sønderholm (1991) and Smith (2000).

(Hutton and Alsop 1995) or (2) syndepositional intrabasinal extension that somehow excised the 'missing' stratigraphy (Soper and Anderton 1984; Anderton 1988). The alternative examined here, that the missing strata were never deposited in the first place and that stratigraphical 'omission' might instead be the result of non-deposition and significant intrabasinal unconformity, has not previously been proposed or tested.

We present a novel and rigorous method of analysing the depositional framework and first-order sequence-stratigraphical architecture of poly-deformed basin margin sequences. We apply this approach to the Dalradian succession in Scotland, and discuss longstanding issues of regional-scale stratigraphical correlation obscured by superimposed structural complexity. New field data were acquired during 1:10 000-scale remapping of the Breadalbane district of the southern Grampian Highlands between Killin and Dalmally (outline box in Fig. 2; and see BGS 2013*a*, *b*, 2014). These new data encompass the Boundary Slide structure, viewed as one of the most significant markers of syndepositional intrabasinal extension within the recognized Dalradian succession (Roberts and Treagus 1977; Anderton 1988).

General geological setting

Late Neoproterozoic break-up of eastern Rodinia culminated with the formation of the Iapetus Ocean as Baltica and Amazonia separated from Laurentia (Fig. 1; Soper 1994*a*, *b*; Cawood *et al.* 2001, 2003, 2004; Li *et al.* 2008). Break-up and extension along the eastern margin of Laurentia is recorded by widespread igneous activity (Kamo *et al.* 1989, 1995; Aleinikoff *et al.* 1995; McCausland *et al.* 2011; McClellan and Gazel 2014). An evolving record of continental margin sedimentary deposition and oceanic sedimentation lasted from *c.* 800 Ma until the mid-Ordovician at *c.* 477 Ma at least (Fig. 3a). NW Highlands Cambro-Ordovician strata (Ardvreck and Durness groups) and strata of the Grampian Highlands Dalradian Supergroup (Fig. 1) formed two sub-parallel sedimentary belts located along this margin (Figs 1 and 3a; Leslie *et al.* 2008; Prave *et al.* in press); the shelf-carbonate rocks lay on the landward side (NW in present-day coordinates) of the generally deeper water marine lithologies. The apparent total thickness of the Dalradian Supergroup amounts to *c.* 25 km, but is unlikely to ever

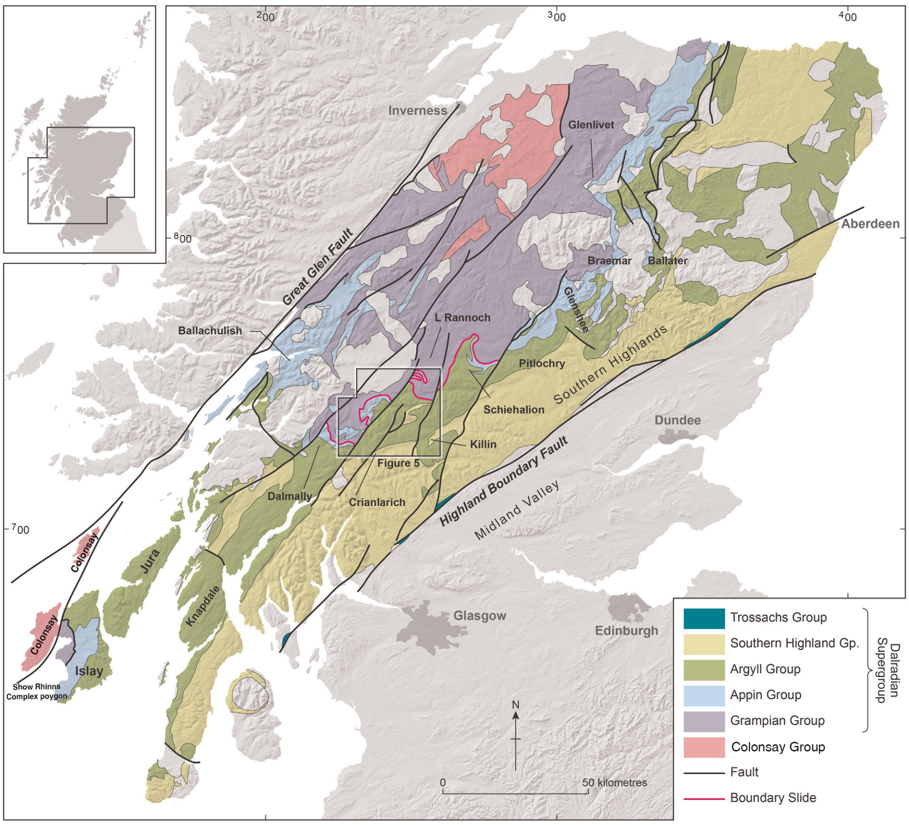

Fig. 2. Simplified geological map of Dalradian Supergroup and basement units in the Grampian Highlands of Scotland. Younger Paleozoic and Mesozoic strata and the Caledonian intrusions are unornamented. Principal late Caledonian faults are superimposed, including the Great Glen and Highland Boundary faults. The boxed outline indicates the location of the map in Figure 5.Soucres: Modified after Stephenson and Gould (1995). Contains BGS Geology 625 000 Data, BGS © UKRI. Hillshading uses NEXTMap Britain elevation data from Intermap Technologies.

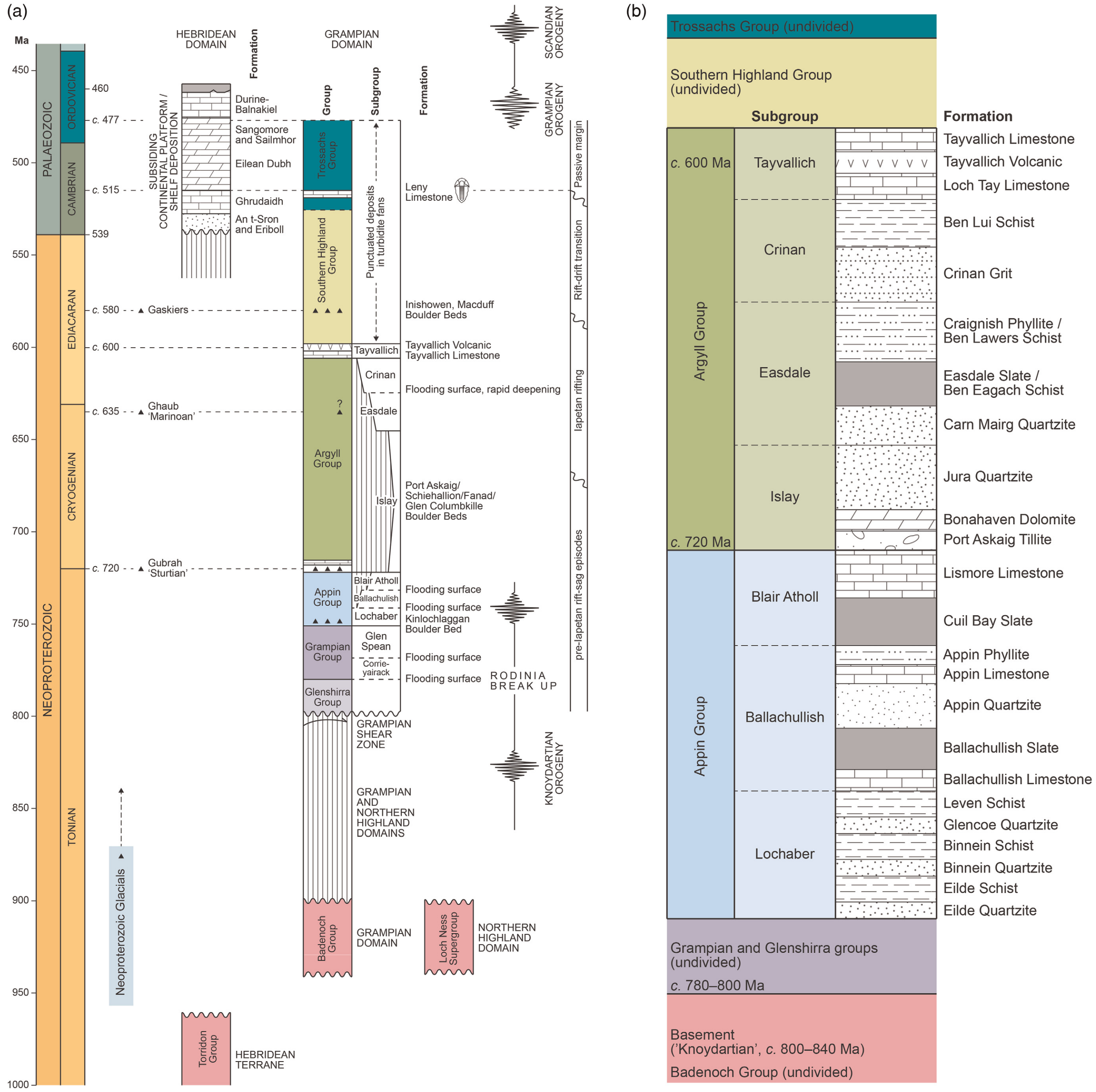

Fig. 3. (**a**) Timing of the Neoproterozoic to Lower Paleozoic Laurentian stratigraphy of Scotland; the 'missing stratigraphy' that is the subject of this paper is shown schematically in grey ornament. Constraints are structured around the dated global record of Neoproterozoic glaciations and a tentative chronologically unconstrained set of basin-wide flooding surfaces suggested by the Neoproterozoic depositional record. Reliable biostratigraphical ages are preserved only in the Leny Limestone Formation (Trossachs Group); topmost Lower Cambrian Paegetia trilobites indicate a *c.* 515 Ma age for the upper parts of Dalradian deposition. The timing of the principal orogenic events is shown schematically; filled triangles indicate glacigenic boulder beds. (**b**) Schematic overview of the principal and widely recognized stratigraphical units of the Dalradian Supergroup in Scotland. (For age constraints see also (**a**). It should be noted that these strata do not anywhere occur together in a single district or recorded succession. Sources: (a) adapted from Leslie *et al.* (2008); Neoproterozoic glaciations from McCay *et al.* (2006) and Prave *et al.* (2016, 2024); *c.* 515 Ma age from Pringle (1940), Tanner (1995) and Tanner and Sutherland (2007). (b) Modified after Harris *et al.* (1994); Trossachs group added after Tanner and Sutherland (2007) and BGS (2008); the age constraints were reviewed by Leslie *et al.* (2008) and Prave *et al.* (2016, in press).

have been deposited as such anywhere in a single continuous succession. A general restoration of lithostratigraphical distribution prior to Ordovician (Grampian) orogenic deformation shows a depocentre that migrated broadly southeastwards with time (Stephenson and Gould 1995). Oceanic crust is presumed to have developed SE of the present Dalradian outcrop, with the youngest Cambrian sediments (the Trossachs Group; Tanner and Sutherland 2007; Stephenson *et al.* 2013) ultimately prograding out onto Iapetan oceanic crust.

Neoproterozoic to Early Paleozoic Dalradian sedimentation (*c.* 800–*c.* 477 Ma)

The Dalradian Supergroup comprises a continental margin sedimentary succession that can be traced across the Scottish Grampian Highlands, as well as Northern Ireland, and the northwestern parts of the Republic of Ireland (Figs 1 and 2). The succession is dominated by marine meta-sandstone, siltstone, mudstone and carbonate rocks (Fig. 3a; Harris *et al.* 1978, 1994; Winchester and Glover 1988;

Stephenson and Gould 1995; Smith *et al.* 1999), subdivided into an older Tonian–Cryogenian succession (the Grampian and Appin groups, and the glacigenic lower part of the Islay Subgroup at the base of the Argyll Group), and an overlying Cryogenian–mid-Cambrian succession comprising the remainder of the Argyll Group, along with the Southern Highland Group (Prave *et al.* in press). The partially dismembered strata assigned to the Trossachs Group are locally in undisturbed stratigraphical contact with the youngest strata of the Southern Highland Group and are of early Cambrian to latest Tremadocian (*c.* 477 Ma) age (Fig. 3a; Pringle 1940; Tanner and Sutherland 2007; Ethington 2008).

The Grampian Group must be younger (<800 Ma) than the pegmatites contained within successions of the basement Badenoch Group (Hyslop 1992; Noble *et al.* 1996; Hyslop and Piasecki 1999). Key to unravelling Dalradian stratigraphy is a number of region-wide events broadly synchronous across Scotland and Ireland that include the following: (1) transgressive flooding surfaces (Stephenson *et al.* 2013) (e.g. the bases of the Ballachulish, Blair Atholl and Crinan subgroups; Fig. 3a); (2) Neoproterozoic glaciation events represented by units such as the Port Askaig Tillite Formation (Spencer 1971; McCay *et al.* 2006; Fairchild *et al.* 2018); (3) rift-related magmatism as represented by A2-group granitoids and large volumes of basic volcanic rocks in the Argyll Group such as the Ben Vuirich Granite Pluton (Rogers *et al.* 1989; Pidgeon and Compston 1992; Tanner and Leslie 1994; Tanner *et al.* 2006) and the Tayvallich Volcanic Formation (Dempster *et al.* 2002). These events help constrain correlation in a stretching pericontinental environment over a period of *c.* 300–320 myr (Fig. 3a). Fluctuations in water depth accompanied active stretching and the development of second- and third-order sub-basins during continental margin break-up (e.g. Litherland 1980; Anderton 1985; Glover *et al.* 1995; Smith *et al.* 1999).

Post-deposition Grampian orogenic deformation (*c.* 470–*c.* 440 Ma)

Dalradian strata were progressively and pervasively deformed during the mid-Ordovician Grampian Orogeny (*c.* 470–460 Ma). The syn-peak metamorphic D_2 deformation phase is the most pervasive of four phases regionally recognized. Megascopic D_1 folds do exist (e.g. Treagus 1987, 1999; Krabbendam *et al.* 1997; Crane *et al.* 2002) but have been largely overprinted by pervasive and large-scale D_2 structures (Roberts and Treagus 1975; Tanner and Thomas 2010). In the southern and southeastern Grampian Highlands, the main D_2 deformation phase produced a number of large-scale recumbent 'fold-nappes', and large areas (>1000 km^2) of structurally inverted strata (Bailey 1922; Shackleton 1958; Krabbendam *et al.* 1997; Leslie *et al.* 2006; Tanner and Thomas 2010). D_2 folds face to the SE and may face downward where deformed by later fold phases; folding was accompanied by pervasive development of the dominant S_2 foliation.

Broadly post-peak metamorphic folds assigned to D_3 and D_4 deformation phases fold and crenulate the main S_2 foliation. These later episodes contribute to the complex outcrop patterns that include a number of recognized 'steep belts' such as the Tummel Steep Belt of the Schiehallion district (Treagus 1987, 1999; Fig. 2), as well as the Highland Border Downbend structure (Shackleton 1958). In large parts of the Grampian Highlands, however, the D_3 and D_4 deformation resulted only in gentle upward doming such as the Drumochter Dome (Leslie *et al.* 2006) and the Glen Orchy Dome (Tanner and Thomas 2010).

Late Caledonian faults

Large-scale NE–SW-trending faults such as the Bridge of Balgie, Garabal Hill and Tyndrum faults clearly cross-cut and disrupt all of the major (D_1–D_4) ductile Grampian fold structures (Fig. 2). As such, these structures have no direct relationship to the Dalradian basin architecture and could not have influenced basin evolution. The observed NE–SW trend of these faults is, however, (sub-) parallel to the syndepositional discontinuities in the (margin-parallel) faulting models promoted by Litherland (1980) and Anderton (1985). It is possible that the present traces of these late-stage Caledonian faults may be at least partially constrained through inheritance from a pre-existing intrabasinal fault architecture within the subsiding–stretching Laurentian margin.

Challenges when restoring a deformed stratigraphical architecture

The stratigraphical framework, age range and setting of the Dalradian Supergroup are well constrained at regional scale, and broadly accepted (e.g. Stephenson *et al.* 2013; Prave *et al.* in press). Issues remain, three of which are considered here.

Restrictions of composite stratigraphical columns

No single composite Dalradian stratigraphical column (Fig. 3b; compare fig. 6 of Stephenson *et al.* 2013), or, indeed, series of composite columns (see fig. 10 of Stephenson and Gould 1995; see also Harris *et al.* 1994), can successfully capture the detailed, laterally variable nature of the regional Dalradian depositional framework. Although representative, individual columns are drawn from separate successions identified in different regions of the Highlands and then compared to provide broad-scale patterns of change. A more comprehensive depositional framework that seeks to portray lateral variation more realistically within accumulated lithostratigraphy, whilst integrating local gaps or breaks in the stratigraphical record, has not yet been published for Dalradian strata, compared with examples from the Browse Basin, NW Australian margin (Jablonski and Saitta (2004), or the Alberta Plains, Canada (AGS 2019).

As an example (see column 2, Fig. 4), Harris *et al.* (1994) placed the Craignish Phyllite Formation (Easdale Group) above the Cuil Bay Slate Formation (Blair Atholl Subgroup). However, that relationship is not recorded in any single mappable succession (Harris *et al.* 1994), and derives only as a result of amalgamating two sequences recorded from different locations some 60 km apart (Loch Craignish and Duror, Loch Leven).

Juxtaposition of composite columns does not explain how differences between them should be interpreted. The Scarba Conglomerate and Easdale Slate formations occur at a similar stratigraphical level (columns 1 and 2 of Fig. 4; see Harris *et al.* 1994). However, the overlying Port Ellen Phyllite–Craignish Phyllite formations, and underlying Jura Quartzite Formation, are lithostratigraphically continuous at this scale, showing that lateral (facies) change must exist at Easdale Slate–Scarba Conglomerate formational level. At least four interpretations are possible: (1) syndepositional faulting separates two sedimentologically distinct units; (2) the Easdale Slate onlaps onto the Scarba Conglomerate; (3) the Scarba Conglomerate onlaps onto the Easdale Slate; (4) the two units interfinger, or grade into, each other. Simplified columns such as those illustrated in Figure 4 give no indication of the author's preferred interpretation.

Finally, lithostratigraphical columns tend to 'fill gaps', aiming to portray stratigraphy as completely as possible. Gaps in the (litho) stratigraphical record are under-represented, and the significance of breaks in successions may be unaccounted for in the overall evolution of the basin and in any future response to deformation. For example, a gap is shown between the Ballachulish Limestone and Carn Mairg Quartzite formations in Figure 4, column 3, albeit labelled as 'tectonically removed' (see Harris *et al.* 1994). In this

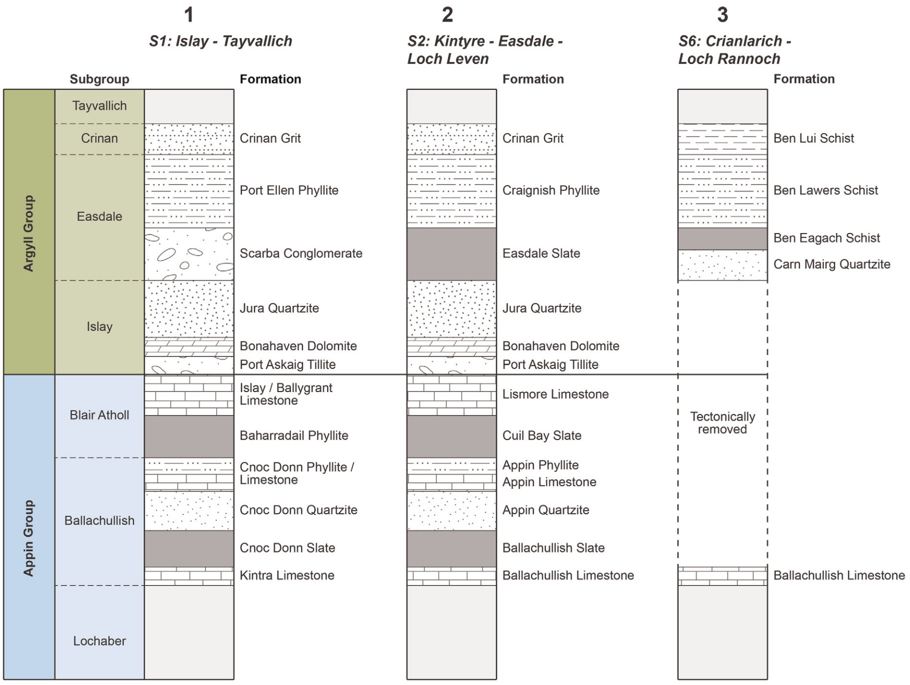

Fig. 4. Excerpts of parts of columns S1, S2 and S6 from the original figure 14, as columns 1, 2 and 3 respectively, each showing composite Appin and Argyll group stratigraphy. Source: figure 14 of Harris *et al.* (1994).

paper, we address the fact that this stratigraphical gap is even greater locally.

The Boundary Slide and excision of stratigraphy

Several studies have addressed Dalradian basin architecture and its possible influence on the evolution and overall geometry of some regional-scale folds. Glover *et al.* (1995), Goodman *et al.* (1997), Smith *et al.* (1999) and Robertson and Smith (1999) all cited lateral thickness and facies changes and examples of overstep onto older strata within the Grampian Group and lower parts of the Appin Group; features that those researchers associated with proposed basin margin structures and Dalradian depositional frameworks (but see also Prave 1999; Prave *et al.* 2023). Knill (1963), Borradaile (1979), Litherland (1980) and Anderton (1985) all identified very rapid and pronounced lateral facies and thickness changes in the Appin Group and lower parts of the Argyll Group, which they associated with syndepositional faulting and generation of accommodation space. Anderton (1985) argued for a series of NW-dipping fault blocks bounded by listric faults that delimited individual sub-basins. Such faults might also have acted to localize lower Argyll Group sedimentation, eventually becoming overstepped by rapidly deposited submarine fan deposits of the upper Argyll and Southern Highland Group (see Stephenson and Gould 1995; Stephenson *et al.* 2013).

Much debate has focused on the ‘Boundary Slide’ structure in the Grampian Highlands, a concept introduced by Bailey (1922). This structure has been traced almost continuously, as a zone of high (D_2) strain and attenuation, along the boundary zone between the Grampian and Appin groups, from Dalmally to Glen Tilt (Roberts and Treagus 1977; Fig. 2), although with less certainty and intermittently in the eastern Grampian Highlands (Upton 1986; Stephenson and Gould 1995).

Bailey (1922) originally interpreted the Boundary Slide as a major dislocation separating the two major tectonostratigraphical units, but its significance in that sense has diminished in more recent reviews (Stephenson *et al.* 2013; Treagus *et al.* 2013). The Boundary Slide does not present as a single or discrete shear zone *sensu stricto*. Treagus (1987) described an arrangement of sub-parallel high-strain features comprising highly schistose or platy rocks that straddle the Grampian–Appin Group boundary, with that zone ranging in thickness from a only few metres to 2000 m. Those features are coincident with a change from psammitic and quarzitic strata of the Grampian Group and lower parts of the Appin Group to more heterolithic overlying strata, potentially acting as a locus for high strain, with or without localized shearing and displacement. The strong platy or schistose fabric marking the slide was regarded by Treagus (1987) as an intense development of the main regional schistosity (S_2) developed during nappe formation. Local planes of dislocation within the slide-zone have been argued to result in a total displacement of possibly several kilometres (Treagus 1987).

Where identified within the Dalradian outcrop (e.g. Crane *et al.* 2002), most of these slides attenuate the short limbs of F_2 folds and, despite carrying younger stratigraphy in the hanging wall, are associated with an overall sense of thrust movement towards the NW. That fact is clearly contrary to the earlier concept of the dislocations as ‘extensional slides’ or ‘lags’ placing younger stratigraphy over older (Bailey 1922), and led to the proposal that they were initiated as extensional structures during basin development (Soper and Anderton 1984; Anderton 1988), or during the formation of the primary nappes (Thomas 1980), and were then reactivated in a reverse sense as thrusts during subsequent Grampian orogenic deformation.

Possible over-interpretation of the impact of syndepositional (listric) normal faulting

Previous interpretations that proposed syndepositional normal faulting to account for the extensional ‘lags’ in the Grampian Highlands attempted to ‘look through’ Grampian deformation (e.g. Soper and Anderton 1984; Anderton 1985, 1988; Glover *et al.* 1995), did not *a priori* assume a layer-cake stratigraphy and attempted to reconstruct a pre-orogenic basin structure. The Scarba Transfer Fault remains one of the best examples of such basin-scale extension in Scottish Dalradian strata, along with the somewhat cryptic succession of the Easdale–Tayvallich Subgroup preserved in the Cabrach area of west Aberdeenshire (Fettes *et al.* 1991, 2011; MacDonald *et al.* 2005). Such basin-scale extension during deposition of the mid-Dalradian does appear localized, however, and should not perhaps be over-played. It is possible that the balance has swung too far towards over-interpretation in this regard and that

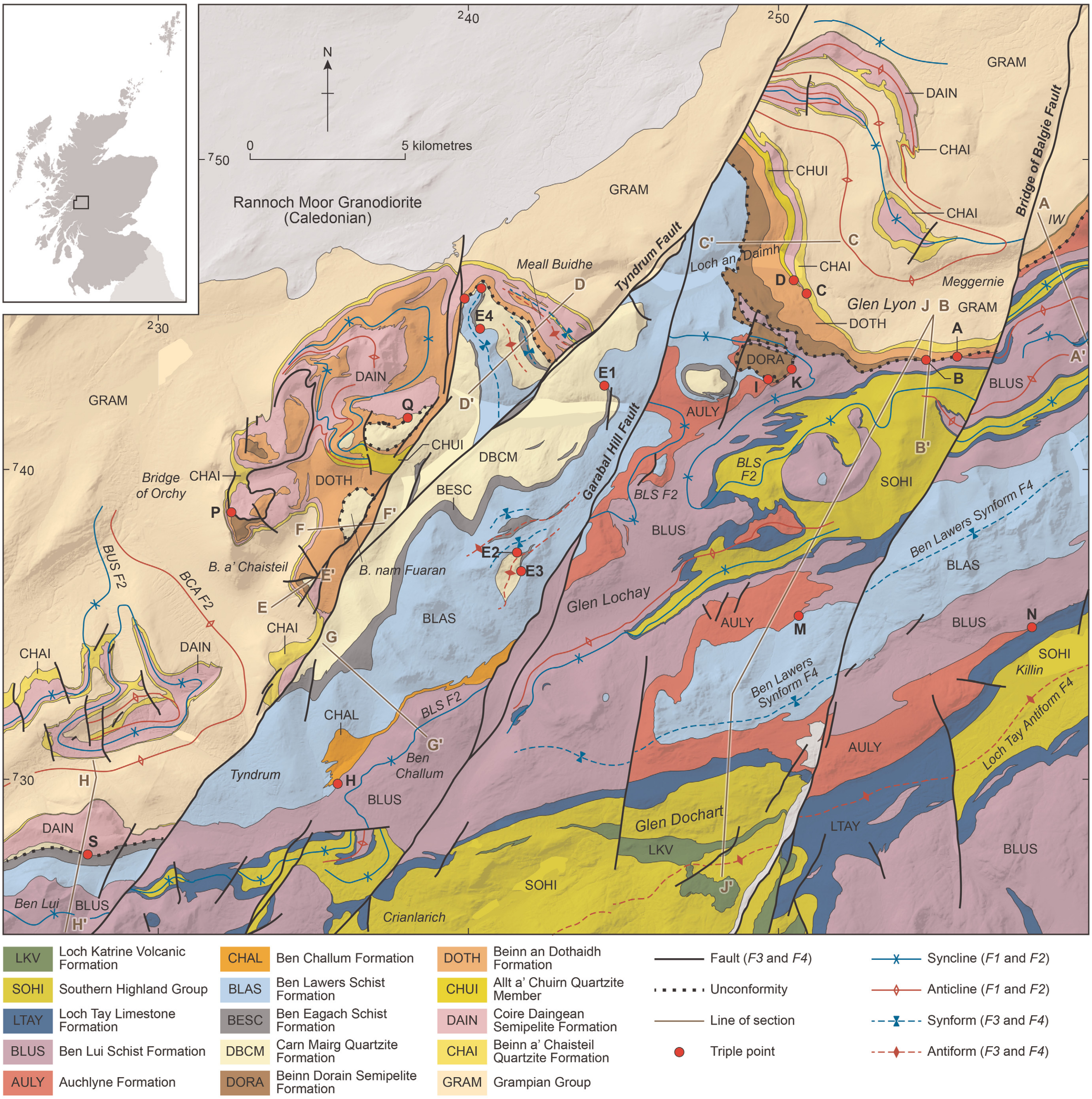

Fig. 5. Simplified geological map of Tyndrum–Glen Lyon (Breadalbane) district. The uncoloured polygons adjacent to the southern end of the Bridge of Balgie Fault represent a microgranite intrusion. The section lines of Figure 6a (A–A’ to H–H’) and Figure 7 (J–J’) are superimposed; their various alignments reflect the sinuous nature of the trace of the D_2 Ben Lui Syncline fold in this region. Red circles identified by letters between A and S locate positions (‘pinch-out triple points’) where older stratigraphical units are overstepped by younger strata. Points E1–E4 all lie along the same pinch-out line in three dimensions. All four-letter (caps) unit abbreviations used here and in subsequent figures are consistent with the nomenclature of the *BGS Lexicon of Named Rock Units*. GRAM, Grampian Group includes the Auch Gleann Formation of Breadalbane (AUGL, Table 2). Sources: modified after BGS (2013*a*, *b*, 2014). Contains BGS 50 k data, BGS © UKRI. Hillshading uses NEXTMap Britain elevation data from Intermap Technologies.

other aspects of the sedimentary depositional framework should be considered.

The Dalradian succession of the Breadalbane district

We focus here on the Tyndrum to Glen Lyon tract of the Dalradian Supergroup in Breadalbane, where our new mapping demonstrates that much of the classic succession of the Dalradian Ballachulish Subgroup to lower Easdale Subgroup (locally all of the latter) is absent (BGS 2013*a*, *b*, 2014). Table 1 summarizes key aspects of the lithostratigraphy of the Appin–Argyll Group observed in that re-mapping; more detail is presented in the Generalized Vertical Section (GVS) columns of the published geological maps (BGS 2013*a*, *b*, 2014), and in the generalized descriptive account of Stephenson *et al.* (2013). The map of Figure 5 shows the distribution of lithostratigraphical units, along with the traces of major folds and faults. Stratigraphical onlaps and/or oversteps should result in ‘pinch-out lines’ (in three dimensions); on the map these become triple or ‘pinch-out points’, marked as red circles in Figure 5.

The Lochaber Subgroup in Breadalbane has been divided into a number of discrete and readily mappable units, in contrast to the more uniformly semipelitic lithology of the Leven Schist Formation

Table 1. Summary of the lithostratigraphy of the Breadalbane district of the southern Grampian Highlands, highlighting recorded variations in the Lochaber and Easdale subgroup successions (see also BGS (2013a, b, 2014) and the generalized descriptive account of Stephenson et al. (2013))

		Area of interest		
		Tyndrum–Dalmally	Tyndrum–Loch Lyon	Glen Lyon–Killin
Group	Subgroup	Formation present		
Southern Highland		Pitlochry Schist Formation	Pitlochry Schist Formation	Pitlochry Schist Formation
	Tayvallich Subgroup	Loch Tay Limestone Formation	Loch Tay Limestone Formation	Loch Tay Limestone Formation
	Crinan Subgroup	Ben Lui Schist Formation	Ben Lui Schist Formation	Ben Lui Schist Formation
Argyll Group		Ardrishaig Phyllite Formation	Ben Challum–Auchlyne formations	Farragon Volcanic–Auchlyne formations
			Ben Lawers Schist Formation	Ben Lawers Schist Formation
	Easdale Subgroup	Ben Eagach Schist Formation	Ben Eagach Schist Formation	Ben Eagach Schist Formation
		Carn Mairg Quartzite Formation	Carn Mairg Quartzite Formation	Carn Mairg Quartzite Formation
		Unconformity		
Appin Group	Lochaber Subgroup	Leven Schist Formation	Beinn Dorain Semipelite Formation	Beinn Dorain Semipelite Formation
			Beinn an Dothaidh Formation (including Allt a' Chuirn Quartzite Member)	Beinn an Dothaidh Formation (quartzite member absent)
			Coire Daingean Semipelite Formation	Absent
		Beinn Udlaidh Quartzite Formation	Beinn a' Chaisteil Quartzite Formation	Beinn a' Chaisteil Quartzite Formation
Grampian Group	Glen Spean Subgroup	Auch Gleann Psammite Formation	Auch Gleann Psammite Formation	Auch Gleann Psammite Formation

The stratigraphic nomenclature of Table 1 (group, subgroup, etc.) encompasses all of the individual units depicted in Figures 5–7.

in the Appin district west of Breadalbane. The diagnostic characteristics of the relevant formations are summarized in Table 2, including those of the Auch Gleann Psammite Formation (Glen Spean Subgroup), which everywhere precedes the Lochaber Subgroup succession, and those of units observed only in Breadalbane; for example, the Ben Challum and Auchlyne formations (Easdale Subgroup).

Restoration of the Dalradian depositional framework in Breadalbane

Restoration of the Dalradian depositional framework for Breadalbane is achieved by using the mapped geometry of lithostratigraphical units as the basis for 'subtracting', as far as is possible, the effects of subsequent orogenic deformation.

The structural geology of Breadalbane is dominated by the F_2 Ben Lui Syncline and F_4 Ben Lawers Synform (Fig. 5), regional-scale folds that are also recognized in the Schiehallion district further NE (Treagus 1999, 2000; Fig. 2). In Breadalbane, recumbent, south-facing F_2 folds (D_2) deform rocks of the Grampian Group and the Lochaber Subgroup in the north and NW of the region (Fig. 5; see also Thomas 1980, 1988; Leslie *et al.* 2006; Tanner and Thomas 2010). In contrast, however, to the Schiehallion district, the Dalradian succession between the upper part of the Grampian Group and the Ben Lawers Schist Formation occurs within a relatively low-strain, right-way-up panel of strata in Breadalbane, in which earlier relationships are readily observed (Fig. 6). This panel includes the previously reported trace of the 'Boundary Slide' structure (Fig. 2) (see the new geological map of Fig. 5). The axial surface of the south-facing F_2 Ben Lui Syncline lies structurally above this right-way-up panel (e.g. sections A–A', B–B', G–G' and H–H' of Fig. 6), and the upper limb of this recumbent fold passes upwards (and SSE-wards) into the regionally inverted 'flat-belt' of the Tay Nappe fold (Krabbendam *et al.* 1997; Treagus 1999; Rose and Harris 2000; Tanner *et al.* 2013). Strata of the Ben Lui Schist Formation dominate the hinge region of the Ben Lui Syncline in the Tyndrum area (Fig. 5 and column and section H–H', Fig. 6); further NE in Glen Lyon, the hinge region contains strata of the Southern Highland Group and the low-strain right-way-up panel includes the Loch Tay Limestone Formation in these youngest units (Fig. 5 and column and section B–B', Fig. 6).

The impacts of ductile deformation are less complex that those evident in the Schiehallion or Glen Shee sectors further to the NE (see Treagus 2000; Crane *et al.* 2002) but the Breadalbane district is transected by a number of (N)NE–(S)SW-trending sinistral oblique-slip faults that significantly disrupt lithostratigraphy; the Ericht–Laidon, Tyndrum, Garabal Hill, Bridge of Balgie and Loch Tay faults (Fig. 5) are each associated with kilometre-scale late Caledonian displacements (Treagus 1991; BGS 2013*a*, *b*, 2014).

The maximum omission of type Dalradian stratigraphy can be demonstrated in Glen Lyon, where strata of the Ben Lui Schist Formation overlie those of the Beinn an Dothaidh Formation; strata representative of the entire Easdale, Islay, Blair Atholl and Ballachulish subgroups are absent (between triple points A and B in Fig. 5; see Fig. 3a).

The regional NE–SW strike of Dalradian strata is generally regarded as approximately parallel to the Iapetan palaeo-shoreline (Anderton 1985; Cawood *et al.* 2003). A (schematic) along-strike section can restore the depositional framework of a panel aligned broadly parallel to that palaeo-shoreline, whereas across-strike sections would represent panels aligned broadly perpendicular to that palaeo-shoreline.

Restoration of upright lower limb of Ben Lui Syncline

Figure 6a illustrates simplified cross-sections constructed broadly perpendicular to the trace of the D_2 Ben Lui Syncline fold to better constrain depositional architecture in that general plane. Individual stratigraphical columns (Fig. 6b) summarize the sequence in each cross-section and highlight variations in the formal (BGS) stratigraphy. All sections reflect the same basic structure in which

Table 2. Descriptions of previously unrecognized Dalradian lithostratigraphical units in the Breadalbane district between Glen Orchy and Glen Lyon, SW Grampian Highlands of Scotland

Lithostratigraphy			Lithology	Thickness
Argyll Group	Easdale Subgroup	Ben Challum Fm (CHAL)	Occurs west of the Garabal Hill Fault, BGS (2013*b*): 5–10 cm-scale bedded pale brown quartzite to quartzose psammite with subsidiary (30%) centimetre-scale layers of schistose quartz–muscovite ± biotite semipelitic schist interbeds at the same scale. Hornblende-bearing schist layers (30–40 cm thick) are conspicuous. Upward change from Ben Lawers Schist Formation calcareous 'pitted' psammite and semipelite is sharp with a marked decrease (from 50% or more) in semipelite content. The upper boundary with the Ben Lui Schist Formation is sharp and oversteps the southwestward disappearance of quartzite	*c.* 20 m
		Auchlyne Fm (AULY)	Occurs east of the Garabal Hill Fault, BGS (2013*b*): 5–20 cm thick layers of interbedded psammite, micaceous psammite, garnet–mica schist and quartz–garnet–mica schist; small millimetre-sized garnets are conspicuous in semipelite to pelite. Subsidiary, thin (*c.* 2 cm) layers of calc-silicate rock, calcareous mica schist, with 5–10 cm thick garnet–hornblende schist layers locally; latter contain psammite streaks, suggesting a meta-volcanic or meta-volcaniclastic origin. The basal contact is a transition over 5–10 m of succession, represented by the upward loss of the calcareous mica schist and calc-silicate rock typical of the underlying Ben Lawers Schist Formation	*c.* 700 m
			Unconformity	
Appin Group	Lochaber Subgroup	Beinn Dorain Semipelite Fm (DORA)	Predominantly massive, poorly bedded garnet–mica schist and muscovite–quartz schist, biotite-poor, with abundant quartz sweats. Characteristic large (3–4 mm diameter) garnets always appear fresh (dark red) compared with frequently chloritized garnets found in the Coire Daingean Semipelite. Weathers dark grey, typically steely grey on 'knotted' (after garnet) fresh surfaces. Top of formation is not seen	*c.* 70–90 m preserved
		Beinn an Dothaidh Fm (DOTH)	Heterolithic formation, comprising units of muscovite-rich semipelite, with interbedded units of psammite and quartzite. Locally, where Allt a' Chuirn Quartzite Member absent, calcareous semipelite or tremolite-bearing calc-silicate at the base (up to 5 m thick) indicates a transitional boundary with the massive garnet–mica schist below. Thin, possibly volcaniclastic, amphibolite units common throughout; more massive (ortho?) amphibolite occurs locally	180–200 m, typically thickened by folding
		Allt a' Chuirn Quartzite Mbr (CHUI)	Quartzite, often ribbed in appearance, with up to 10% of interbedded muscovite pelite; this member only locally identified at the base of the Beinn an Dothaidh Formation (channels?). Units of quartzite pass gradationally up into semipelite over a few metres	<10 m
		Coire Daingean Semipelite Fm (DAIN)	Predominantly massive, poorly bedded garnet–mica schist and muscovite–quartz schist, biotite-poor, with abundant quartz sweats. Muscovite-wrapped garnets of 1–2 mm in diameter are typical. Grey colour. Weathers grey–brown to brown. A lower calcareous semipelite unit with characteristic pitted weathering surfaces is interbedded with massive garnet–mica schist; graphitic pelite occurs locally at the top of the formation	*c.* 70 m overall, lower calcareous unit 0–30 m
		Beinn a' Chaisteil Quartzite Fm (CHAI)	Stacked sheet-like beds (0.1–1 m thick) of internally massive grey to pinkish-brown quartzose psammite and quartzite; limited semipelite layers up to 0.05 m thick. Low-strain clean exposures reveal low-amplitude (<0.01 m) apparently symmetrical, straight crested and occasionally bifurcating ripples (λ *c.* 0.1 m). Uppermost 5–10 m of the formation is more thinly bedded (3–5 cm), frequently flaggy. Basal contact with underlying Auch Gleann Psammite Formation is sharp and readily traced	*c.* 90 m
Grampian Group (GRAM)	Glen Spean Subgroup	Auch Gleann Psammite Fm (AUGL)	'Salt and pepper' textured, biotite-bearing psammite and siliceous psammite is typical. Sands, parallel-bedded sands, undulose-bedded sands incorporating hummocky cross stratification (HCS) and minor muds stack in a single sand-dominated (psammite) lithofacies association. Bed forms commonly on 10–40 cm scale; millimetre-scale internal lamination reflects minor composition changes (mica *v.* quartz and feldspar). Trough cross-bedding locally seen, then only in upper parts of units of micaceous psammite. Metre-scale lenticular bedforms and metre-scale interleaving herringbone bed sets observed in a few places. Uppermost 50–90 m of formation overall has thinner bedded (3–5 cm) mixed sequences of biotite-bearing psammite, biotite–muscovite semipelite and dark biotite-rich psammite	*c.* 1–2 km thick overall

These units are placed within the overall stratigraphical succession for the region as shown in the map of Figure 5. All four-letter (caps) unit abbreviations used here are consistent with the nomenclature of the *BGS Lexicon of Named Rock Units*. The Auch Gleann Formation (AUGL) is included with the wider Grampian Group (GRAM) in Figures 5–8.

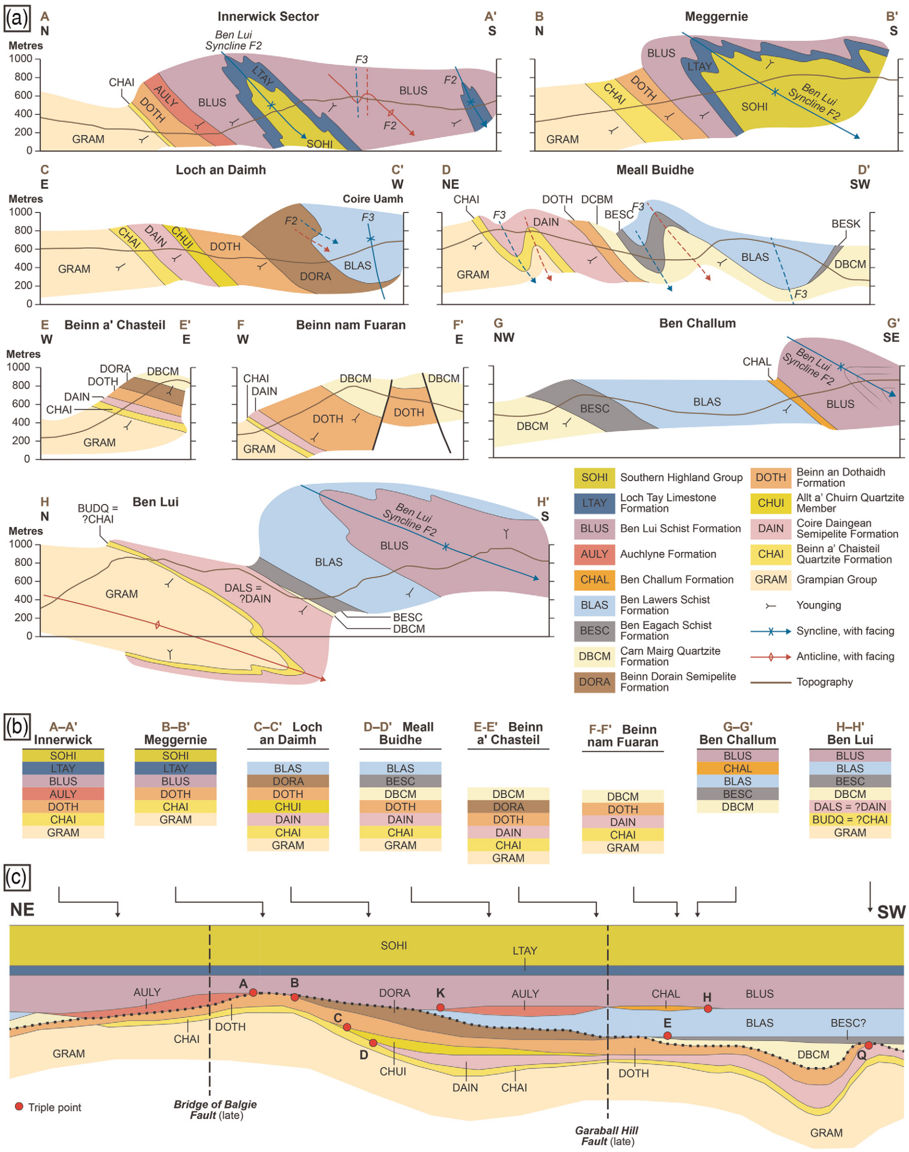

Fig. 6. (**a**) Simplified cross-sections A–A' to H–H' (locations are shown in Fig. 5) to help reconstruct depositional architecture across the region. (**b**) Individual stratigraphical columns summarizing the strata identified in each of the sections in (**a**). (**c**) Schematic section constructed along regional strike to illustrate the Dalradian depositional framework in Breadalbane, constrained by projection of the published geological mapping, and supported by the transverse cross-section constructions in (**a**). Minor F_3 (and F_2) folds are ignored whereas major ones are restored. The Loch Tay Limestone is chosen as a palaeo-horizontal for this transect, as it represents a basin-wide flooding event. Source: (a) data for section H-H', Ben Lui, are after Tanner and Thomas (2010).

the hinge zone (axial surface) of the Ben Lui Syncline is underlain by a panel of right-way-up strata assigned to units ranging from the Pitlochry Schist Formation (Southern Highland Group) down into the Auch Gleann Psammite Formation (Grampian Group). No strata belonging to the Ballachulish, Blair Atholl or Islay subgroups occur in any of these transects. Instead, strata of the Lochaber Subgroup are succeeded by those belonging to formations of the Easdale or Crinan subgroups.

Starting in the east in the Innerwick sector, east of the Bridge of Balgie Fault (section and column A–A', Fig. 6), strata of the Beinn an Dothaidh Formation (DOTH) are overlain by strata of the Auchlyne Formation (AULY) succeeded by strata of the Ben Lui Schist Formation (BLUS) (see Table 1). Near Meggernie Castle (section and column B–B', Fig. 6), strata of the Beinn an Dothaidh Formation (Lochaber Subgroup) are directly overlain by an unusually thin (but not highly strained) unit of strata of the Ben Lui Schist Formation, succeeded by the distinctive carbonate rocks of the Loch Tay Limestone Formation (LTAY). This sector shows the greatest omission of strata within the Breadalbane district. The distribution of the individual units of the Lochaber Subgroup in this region (Fig. 5) suggests that strata of the Beinn Dorain Semipelite Formation (DORA) locally have an offlap relationship to the strata of older formations in the subgroup. The Beinn a' Chaisteil Quartzite Formation (CHAI) is always present at the base of the Lochaber Subgroup, succeeding strata of the Grampian group; the Beinn an Dothaidh Formation is the most continuously developed of the succeeding units in the subgroup.

Further west in the Loch an Daimh, Meall Buidhe, Beinn a' Chaisteil and Beinn nam Fuaran sectors (sections and columns C–C', D–D', E–E' and F–F', Fig. 6), the stratigraphical interval of the 'Leven schist' (Lochaber Subgroup) that succeeds the Auch Gleann Psammite Formation (Grampian Group) can now be subdivided. The Beinn a' Chaisteil Quartzite, Coire Daingean Semipelite, Beinn an Dothaidh and Beinn Dorain Semipelite formations (CHAI–DORA) are lithologically distinct (Table 2) and readily mapped. Locally, either of the two youngest of these formations are abruptly overlain (overstepped) by strata of the Carn Mairg Quartzite Formation (DBCM, Easdale Subgroup).

In the Ben Lui sector (section and column H–H', Fig. 6) a single unit of strata assigned to the Leven Schist Formation (DALS) is overlain in turn by strata of the Carn Mairg Quartzite, Ben Eagach Schist and Ben Lawers Schist (DBCM–BLAS) formations, and finally by strata of the Ben Lui Schist Formation (BLUS).

From east to west therefore, the strata of the Lochaber Subgroup are respectively overlain by those of the Ben Lui Schist Formation of the Crinan Subgroup (A–A' and B–B'), the Ben Lawers Schist Formation (BLAS; D–D') and the Carn Mairg Quartzite Formation (DBCM) of the Easdale Subgroup (E–E' and F–F'). Onlapping of progressively younger strata onto older Lochaber Subgroup strata is evident (see Table 1).

To the NE of Meggernie Castle, thin successions of Lochaber and Ballachulish subgroup reappear around the apex of the Schiehallion fold complex and mark the progressive return of a 'complete' succession from Schiehallion–Glen Tilt northeastwards (Treagus and King 1978; Roberts and Treagus 1979; Treagus 1987, 1999; BGS 2000). Units are thus present in one sector but absent in another.

The stratigraphical columns in Figure 6b are affected by the same limitations as those published elsewhere (Harris *et al.* 1994; Stephenson and Gould 1995; BGS 2013*a*, *b*, 2014); lateral relationships are not fully resolved. These limitations are mitigated here by constructing a schematic along-strike section focused upon the Dalradian depositional framework, as constrained by our geological mapping and the transverse cross-sections. In this schematic section (Fig. 6c), minor F_3 (and F_2) folds are ignored whereas major ones are restored. The Loch Tay Limestone Formation is a palaeo-horizontal for this transect as it represents a basin-wide flooding and depositional event (Stephenson and Gould 1995; Stephenson *et al.* 2013).

Grampian D_2 deformation was dominated by SSE-directed tectonic transport at a high angle to the regional Dalradian strike and can, at the large scale, be approximated as plane strain. As a result, the horizontal scale of this along-strike cross-section (Fig. 6c), in essence the y strain axis, is approximately true-scale. However, the vertical scale (z strain axis) must lie within the shortening field of the regional D_2 strain, which is spatially highly variable. Therefore, the vertical axis in this section is much less well constrained and more broadly schematic than in the y axis. Our projection method is essentially that adopted when constructing a down-plunge projection (e.g. Ramsay and Huber 1983; Ramsay *et al.* 1987). The geological relationships displayed on the published (BGS) geological maps are projected downdip in each sector, generally to the south, to portray the depositional geometry, focusing on locations where individual units are 'pinched out'; for comparison, the map of Figure 5 can be viewed upside down!

Each pinch-out triple point is labelled (red circles in Fig. 5). Thus, at triple point A, the Auchlyne Formation pinches out westwards such that strata of the Ben Lui Schist Formation overstep and occur in direct contact with those of the Beinn an Dothaidh Formation; at point B, strata of the Beinn Dorain Semipelite Formation pinch out eastwards and are overstepped by those of the Ben Lui Schist Formation. Strata of the Coire Daingean Semipelite Formation and succeeding Allt a' Chuirn Quartzite Member (of the Beinn an Dothaidh Formation) pinch out eastwards at points C and D respectively and do not reappear further east.

At points E1, E2 and E3 west of the (later) Garabal Hill Fault, strata of the Ben Lawers Schist Formation overstep those of the Ben Eagach Schist Formation to rest directly on the Carn Mairg Quartzite Formation; at point H strata of the Ben Challum Formation pinch out westwards such that strata of the Ben Lui Schist Formation are in direct contact with those of the older Ben Lawers Schist Formation (see also section G–G', Fig. 6). East of the Garabal Hill Fault, strata of the distinctive volcaniclastic Auchlyne Formation replace the Ben Challum Formation at this stratigraphical level, overstepping strata of the Ben Lawers Schist Formation to rest directly on those of the Beinn Dorain Semipelite Formation (point I). Slightly further NE, strata of the Auchlyne Formation are themselves overstepped by those of the Ben Lui Schist Formation (point K). At points M and N, west and east of the Bridge of Balgie Fault trace respectively, strata assigned to the Auchlyne Formation first appear between strata of the Ben Lawers Schist and Ben Lui Schist formations, thickening westwards and southwards to replace those of the Ben Lui Schist Formation around the hinge of the Ben Lawers Synform (Fig. 5), thinning again eastwards forming a wedge-shaped localized facies development within the Ben Lawers–Ben Lui Schist formations.

West of the Tyndrum Fault, strata of the Beinn Dorain Semipelite Formation are limited to two small areas around point P; strata of the Carn Mairg Quartzite Formation overstep (and locally downcut across) the boundary between the Coire Daingean Semipelite and Beinn Dothaidh formations (point Q), probably removing any strata that would otherwise be assigned to the Beinn Dorain Semipelite Formation. Strata of the Ben Lawers Schist Formation overstep limited occurrences of strata of the Ben Eagach Schist Formation near point E4. Finally, north of Ben Lui (point S), strata of the Ben Eagach Schist Formation overstep the Carn Mairg Quartzite Formation to rest directly upon strata of the Lochaber Subgroup (DAIN).

Restoration of the upper inverted limb of Ben Lui Syncline

Reconstruction must also incorporate strata now disposed within the overturned, upper limb of the Ben Lui Syncline (Figs 5 and 6a); to this end, the Ben Lui Syncline must be restored, and a qualitative (i.e. without scale) restoration is presented here (Fig. 7). In the absence of reliable strain indicators, a quantitative restoration cannot be achieved. Most recent models for the generation of the Tay Nappe accept that the lower, overturned limb of that structure has experienced some form of progressive top-to-the-(S)SE rotation and translation during regional-scale top-to-the-ESE (or east) D_2 shear (Harris *et al.* 1978; Bradbury *et al.* 1979; Nell 1986; Krabbendam *et al.* 1997; Rose and Harris 2000; Treagus 2000; see Mendum and Thomas 1997; Tanner 2014, 2016).

Owing to the strong 3D variability in both amount and vorticity (the component of simple shear with respect to pure shear) of D_2 shear strain (Krabbendam *et al.* 1997; Treagus 1999; Tanner and Thomas 2011), the true horizontal (x) and vertical (z) scale of any restoration are uncertain. Rheological properties will vary considerably within this heterolithic Dalradian succession and variations in layer thickness of over an order of magnitude from limb to hinge are known (Tanner and Thomas 2011). Nevertheless, a schematic, scale-less cross-section demonstrates the essential stratigraphical relationships (Fig. 7), including the relative locations of the pinch-out triple points. The reconstruction of Figure 7 is aligned approximately at right angles to the probable orientation of the original passive margin.

Figure 7a is the true-scale present-day cross-section across the Ben Lui–Tay Nappe fold structure from Glen Lyon in the north to Glen Dochart to the south (section J–J', Fig. 5). In Figure 7b, the minor (parasitic) F_2 folds identified in the upper, inverted limb in Glen Lochay (Fig. 7a) are accounted for and removed. It should be noted that the Ben Lawers Schist is prominent in the (inverted) upper limb of the simplified fold structure (area B, Glen Lochay) but absent in the hinge zone around Glen Lyon and in the right-way-up limb of the fold structure (area A). In Figure 7c, the major F_2 Ben Lui fold is restored, bringing the inverted rocks in the upper limb of the Ben Lui fold (lower limb of the Tay Nappe) northward into pre-D_2 continuity with right-way-up rocks in the lower (upright) limb of the Ben Lui Syncline.

The major result of this portrayal of the stratigraphical architecture prior to Grampian orogenic deformation is that strata of area B (Glen Lochay) are restored to a more northerly position with respect to those of area A (Glen Lyon) (Fig. 7). In area B the stratigraphical succession is Ben Lawers Schist Formation, succeeded by Auchlyne Formation, Ben Lui Schist Formation, Loch Tay Limestone Formation, and finally by strata of the Southern Highland Group. The Auchlyne Formation partially or wholly replaces the Ben Lui Schist Formation in this succession and the two restored lower and upper pinching-out points are shown (see also Fig. 5). In contrast, in area A (Glen Lyon district, now restored to be to the south) strata of the Grampian Group (Auch Gleann

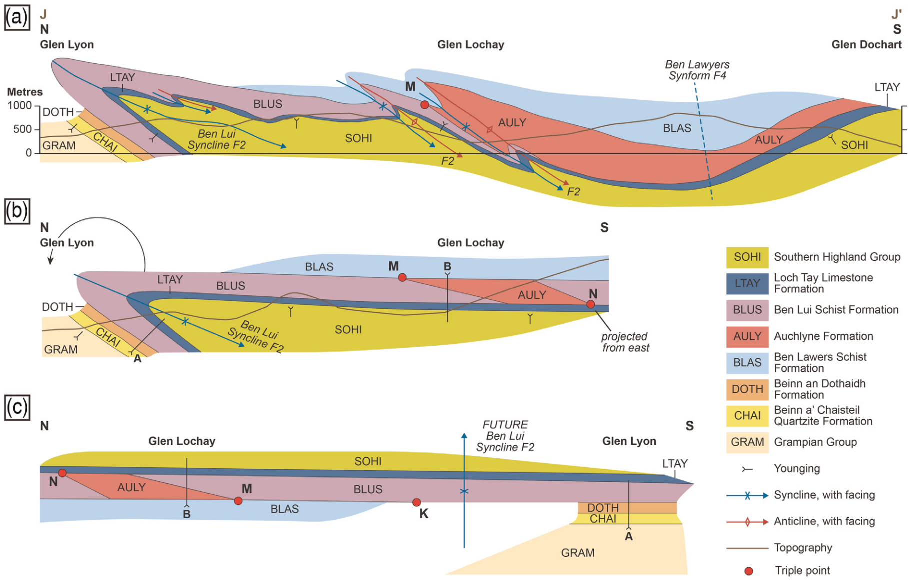

Fig. 7. (**a**) True-scale present-day cross-section (J–J'), constructed across the Ben Lui–Tay Nappe fold structure from Glen Lyon in the north to Glen Dochart in the south (see Fig. 5 for location). (**b**) The minor (parasitic) F_2 folds are removed. (**c**) The major F_2 Ben Lui fold is restored, bringing the inverted rocks in the lower limb of the Tay Nappe (= the upper limb Ben Lui fold) into pre-D_2 continuity with right-way-up rock rocks in the lower (upright) limb of the Ben Lui Syncline.

Psammite Formation) are succeeded by those of the Beinn a' Chaisteil Quartzite Formation and the Beinn an Dothaidh Formation, and then overstepped, with no evidence of superimposed high strain, by strata of the Ben Lui Schist Formation, Loch Tay Limestone Formation and Southern Highland Group. The lateral changes that must exist below the level of the Ben Lui Schist have been eroded and so cannot be definitively incorporated into the restored section. This restoration does not reveal whether the stratigraphical changes are the result of sedimentary or structural processes.

Key features of the Breadalbane stratigraphical framework: summary

No strata from the Ballachulish, Blair Atholl or Islay subgroups are present in the Figure 6c transect for Breadalbane. Instead, strata of the Lochaber Subgroup are succeeded by strata of the Carn Mairg Quartzite Formation (Easdale Subgroup) in the west and SW with little evidence of an actively down-cutting relationship. Strata of progressively younger formations succeed strata of the Lochaber Subgroup eastwards towards the Meggernie sector.

Examination of the geology in Upper Glen Lyon around Loch an Daimh (locations C, D, I and K in Fig. 5) shows that strata of the Ben Lawers Schist Formation (Easdale Subgroup) were deposited directly onto strata of the Lochaber Subgroup, and are themselves overstepped progressively eastwards by strata of the Auchlyne and Ben Lui Schist formations. Strata of successively younger formations of the (upper) Argyll Group succeed strata of the Lochaber Subgroup (lowest Appin Group). Although it has been possible to map out stratigraphical overstep, onlap, etc., the degree of tectono-metamorphic change affecting the mapped stratigraphy does, however, mean that we cannot confidently assess the nature of any subtle lateral change around the 'pinch-out' triple points identified in the stratigraphical framework presented here.

When traced in the field in the Breadalbane district (Figs 5 and, 6a), none of the member–formation–subgroup–group-level boundaries included in this transect are associated with any mappable evidence of significant attenuation or other ductile high strain. Across good levels of exposure in mountainous relief, the low-strain state overall argues instead that the mapped boundaries represent the pre-Grampian deformation depositional framework. The relationship is most simply explained by an unconformity, possibly one where limited erosion of already accumulated strata of the Lochaber Subgroup has emphasized the stratigraphical omission that has occurred in this sector. Similar stratigraphical frameworks are recognized, for example, in modern Atlantic margins (Peron-Pinvidic *et al.* 2013).

In this setting, the base of the succession that includes the Argyll Group can be interpreted as a regionally significant intrabasinal unconformity, where deposition of strata of the Easdale Subgroup is finally recorded in a region that had previously accumulated little or no sediment since the end of Lochaber Subgroup time, precluding the development of successions typical of the Ballachulish–Blair Atholl–Islay subgroups recorded elsewhere in the basin. A model for such a setting is proposed and described in the Discussion below.

Extending the concept: an along-strike Dalradian section for the Grampian Highlands

Building on the above, we expand analysis of the Dalradian schematic framework along-strike from Glenlivet in the NE (see Fig. 2), through the restoration for the Breadalbane district, to Islay in the SW; this regional-scale schematic framework is illustrated in the upper and lower panels of Figure 8 (see Fig. 6c). As in the method for construction of Figure 6c described above, we apply a first-order restoration of the superimposed deformation, undoing the major D_2, D_3 episodes of folding and large-scale faults, and view the map-face distribution of mappable lithostratigraphical units in an along-strike transect perpendicular to the regional dip. As in Figure 6c, the horizontal scale of this regional-scale along-strike cross-section, in essence the y strain axis, is approximately true-scale. The vertical scale (z strain axis) lies within the shortening field of regional, but spatially highly variable, D_2 strain and is much less well constrained. The stratigraphical framework represented here is therefore more broadly schematic in the z axis than in the y axis. Figure 8 is a proposed depositional framework for Grampian–Appin–Argyll–Southern Highland Group Dalradian stratigraphy, extending from Islay, Knapdale and Breadalbane in the SW (Argyllshire), to Glenlivet (Aberdeenshire) in the NE.

The southwesternmost (Islay–Knapdale, lower panel right) part of the transect lies generally along-strike from the 'classical Dalradian' succession of the Appin–Ballachulish region; successions of the Ballachulish and Blair Atholl subgroups recognized and correlated with that area are incorporated here. Previous studies (e.g. Litherland 1980; Anderton 1985; Fairchild *et al.* 2018) have demonstrated significant and rapid lateral thickness and facies changes that affect the successions of the Blair Atholl and Islay–Easdale subgroups in this region. Putative locations of important

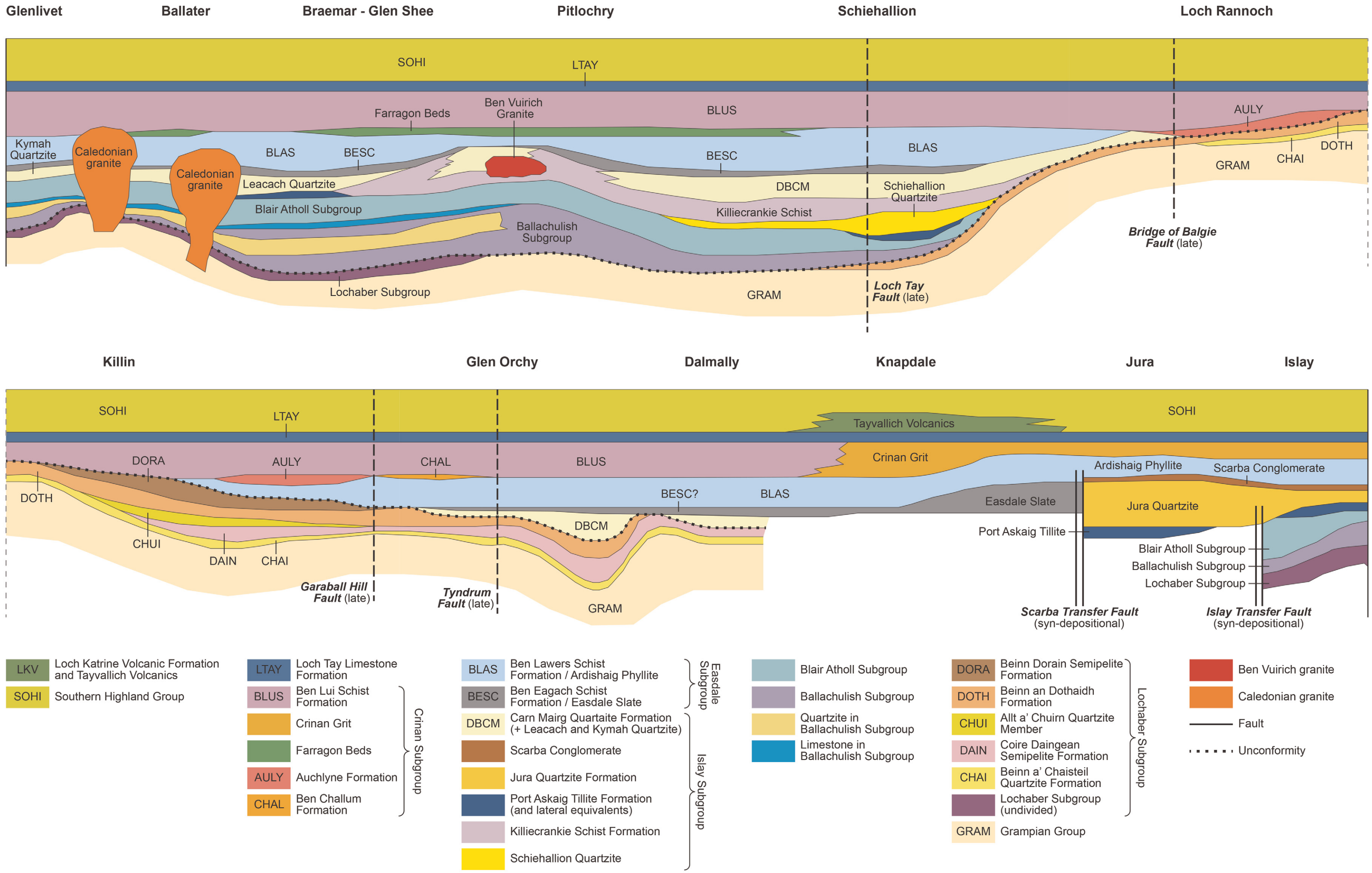

Fig. 8. Schematic section constructed along regional strike to illustrate the Dalradian depositional framework from SW to NE Scotland, constrained by projection of published regional geological mapping across Scotland, supported by local transverse cross-section constructions similar to our reconstruction of Figure 6c. Minor F_3 (and F_2) folds are ignored whereas major ones are restored as in Figure 7. The Loch Tay Limestone is chosen as a palaeo-horizontal for this regional-scale transect.

syndepositional faults (e.g. the Scarba Transfer Fault) are included in this part of the transect.

There is a marked change in stratigraphy northeastwards across the Knapdale sector of the transect. Strata of the Easdale Subgroup absent in the Breadalbane district are present in the Dalmally–Glen Orchy area and apparently thicken towards the SE into the plane of the Figure 8 restoration (see Litherland 1980). However, it is not clear that equivalent strata were ever present in the Knapdale sector, beneath the laterally continuous strata of the Ardrishaig Phyllite–Ben Lawers Schist and younger formations. This area lies along-strike from the outcrops of strata of the structurally high Badenoch Group separating the Grampian Group Strath Tummel and Corrieyairack basins (Robertson and Smith 1999; Smith *et al.* 1999). It is possible that a southwestward continuation of such an intrabasinal (fault-bound?) structural high separated these areas of post-Grampian Group deposition, at least as far SW as the area transected by the NW–SE-trending Cruachan Lineament (Graham 1986).

Strata of the Grampian Group underlie the entire strike length of the transect northeastwards from Knapdale to Glenlivet (lower and upper panels). Units of mature quartzose psammite become prominent in the uppermost parts of the Grampian Group (Stephenson *et al.* 2013). Traditionally, the lithostratigraphical base of the Lochaber Subgroup is marked by a named quartzite formation occurring at the same level as the Beinn a' Chaisteil Quartzite Formation now recognized in the Tyndrum–Schiehallion sector of this work. That qualification aside, this implies a significant degree of connectivity within the depositional framework, at a time when separately developing sub-basins have been proposed (Smith *et al.* 1999). The succession of the Appin–Argyll–Southern Highland Group is well developed from Loch Rannoch northeastwards (upper panel) and regional-scale correlations are readily established at subgroup level with the type Loch Leven succession in the SW.

Strata of the Blair Atholl Subgroup do locally show more evidence of lateral facies variation than those of the preceding Ballachulish Subgroup (Goodman *et al.* 1997; Crane *et al.* 2002). At a higher stratigraphical level, the succession of the Islay Subgroup in the Braemar–Glen Shee sector is dominated by strata of the Creag Leacach Quartzite Formation (Fig. 8, upper panel). SW of the locus of the Ben Vuirich Granite pluton (Fig. 8, upper panel, centre) and towards the Pitlochry sector, this quartzite is apparently replaced entirely by pelitic, locally graphitic, rocks assigned to the Killiecrankie Schist Formation. Although some of that substitution may be due in part to the structural complexity that affects the Gleann Fearnach Transfer Zone (Crane *et al.* 2002), this lateral change shows strata of the Killiecrankie Schist Formation sandwiched between those of the Schiehallion Quartzite Formation below and Carn Mairg Quartzite Formation above. These lateral variations in stratigraphy possibly reflect a significant change in intrabasinal geometry and sediment-routing in the Gleann Fearnach region. The absence (or non-preservation) of any 'Boulder Bed' (Islay Subgroup) deposits succeeding strata of the Blair Atholl Subgroup may also be significant in this context (Crane *et al.* 2002).

All of the stratigraphy of the Islay–Easdale subgroups in the NE of the transect onlaps southwestwards onto strata of the Lochaber Subgroup from Schiehallion towards Loch Rannoch and Breadalbane (Fig. 6c and Fig. 8, upper panel) Volcanic rocks assigned to, or correlated with, the Farragon Volcanic Formation are more sporadically developed and represent localized volcanic outpourings that accumulated as basin instability increased (Stephenson *et al.* 2013).

All of that intrabasinal variability was submerged in Crinan Subgroup time; mud-dominated deposits of the Ben Lui Schist Formation are recognized across much of the transect of Figure 8 (including Breadalbane) but change progressively southwestwards to the more sand-dominated Crinan Grit Formation assigned to this subgroup in the SW (lower panel). These units are interpreted as turbiditic deposits (Anderton 1985; Stephenson *et al.* 2013) signalling the onset of rift–drift transition along the Iapetan margin. The Loch Tay Limestone Formation (also turbiditic in part) is present throughout and, in the SW, is accompanied by the thick extrusive mafic volcanic rocks and subvolcanic sills (Tayvallich Volcanic Formation, lower panel) with U–Pb zircon ages of 601 ± 4 Ma (Dempster *et al.* 2002) that mark, perhaps for the first time, rupture of the continental crust during Iapetan rifting. At the highest stratigraphical level represented in this transect, units of the Southern Highland Group mark the onset of accumulation of an approximately 4 km thick pile of siliciclastic and volcaniclastic turbiditic deposits, probably laid down in slope apron or ramp settings in deep-water submarine fans; basin deepening stayed ahead of sedimentary and volcanic infill (Burt 2002).

Sedimentology of the new depositional framework for Breadalbane

We interpret the sedimentology of the lithological units in the restored Figure 6c depositional framework for Breadalbane as follows. Grampian Group sandstone units deposited on a shallow marine shelf (Banks 2005), are consistently overlain by the mineralogically much more mature regressive strata of the Beinn a' Chaisteil Quartzite Formation (CHAI). Deposition of these mature sandstone units marks a fall in relative sea level (RSL), leading to sediment reworking (winnowing). Strata of the Beinn a' Chaisteil Quartzite Formation are succeeded by an essentially muddying-upward succession (comprising the three further formations (DAIN–DORA) in the remainder of the Lochaber Subgroup recorded in this transect. Strata of these separate formations record a continuing overall rise in relative sea level, albeit fluctuating, and with conditions of variable sediment supply. Contemporaneously, the SW end of the transect around Ben Lui records relatively uniform accumulation of muddy (pelitic and semipelitic) strata that form the Leven Schist Formation (DALS–DAIN).

The restored geometry of these formations and their pinch-out points (i.e. points B, C and D in Fig. 6c) strongly suggests that individual units onlap onto strata of the 'basal' Beinn a' Chaisteil Quartzite Formation, possibly indicating that the Meggernie–Innerwick sector received limited sediment input at this time compared with the Loch an Daimh to Beinn a' Chaisteil–Tyndrum sector adjacent to it. Around Ben Lui, the more uniformly muddy nature of the Leven Schists in that region may indicate deeper water or calmer conditions; in essence, sandy heterolithic (locally carbonate-bearing) sediments become confined to only the more proximal areas of the shelf and more distal deeper basinal areas accumulate dominantly muddy deposits over the same extended period of time. Initial pulses of locally enhanced sediment supply, possibly in channels (Table 2), are preserved as strata of the Allt a' Chuirn Quartzite Member. These are overstepped by deposition of strata belonging to the Beinn an Dothaidh Formation, including those within the previously poorly supplied Meggernie–Innerwick sector. The final stages of deposition of the succession of the Lochaber Subgroup in Breadalbane see more localized accumulation or preservation of strata that form the Beinn Dorain Semipelite Formation with possible offlap relationships recorded in the Meggernie sector (pinch-out points A and B in Figs 5 and 6c) and locally NW of Beinn a' Chaisteil (pinch-out point P in Figs 5 and 6c). Erosion is also possible at this time; strata of the Carn Mairg Quartzite Formation rest directly on strata of the Beinn an Dothaidh Formation in the Beinn nam Fuaran sector (section F–F' of Fig. 6a; and see also around pinch-out Q in Fig. 5). However, the preserved mud-on-mud succession observed in the Meggernie sector (Beinn an Dothaidh Formation succeeded by Ben Lui Schist Formation, around pinch-out points A and B in Fig. 6c) does not suggest active down-cutting when coarser clastic (basal) deposits might be expected above any such depositional hiatus.

Unconformable deposition of the Carn Mairg Quartzite Formation can be interpreted as marking the end of a long period of much-reduced sediment supply or even bypass. The eastward thinning Carn Mairg Quartzite Formation here represents apparently localized incursion of turbidites into an otherwise pelagic background of strata of the Ben Eagach Schist Formation. The overall muddy succession from the Ben Eagach to Ben Lawers Schist formations thus records subsequent relative sea-level rise or highstand conditions. The Meggernie sector remains a region of limited, if any, sediment accumulation at this stage and is still apparently a relative intrabasinal high.

Volcanic and volcaniclastic deposits recorded locally by the Auchlyne and Farragon Volcanic formations indicate a discrete period of increased (tectonic) instability affecting this part of the Dalradian basin before renewed deepening everywhere (and now including the Meggernie sector) accommodates deposition of the dominantly muddy Ben Lui Schist Formation. Finally, and preceding more rapid deepening, the carbonate rocks of the Loch Tay Limestone Formation are recorded all across this transect, succeeded by the turbiditic deposits of the Southern Highland Group.

The restoration of Figure 8 (upper panel) reveals that strata of the Appin and Argyll groups succeeding the characteristic and readily correlated quartzite and limestone formations of the Ballachulish Subgroup apparently have a progressive onlap relationship to the preceding and continuous succession of the Lochaber Subgroup, southwestwards into the Breadalbane district from Schiehallion. This suggests that sediment supply is likely to have been much more continuous in this sector NE of Breadalbane than in the comparatively sediment-starved area now represented by the limited stratigraphy recorded between Loch Rannoch and Glen Orchy (Fig. 8, lower panel).

Discussion

Viewed in a simplified layer-cake stratigraphical framework, comparison with the 'classical' Dalradian type-stratigraphy (Harris *et al.* 1994; Stephenson and Gould 1995; Stephenson *et al.* 2013) implies that all of the strata of the Ballachulish, Blair Atholl and Islay subgroups, and those of the lower part of the Easdale Subgroup, are missing in the Breadalbane district, and that a tectonic break or attenuation (e.g. the 'Boundary Slide') might be required (see Roberts and Treagus 1977; Treagus 1987). Such interpretations have always been subject to the challenge that tectonic breaks that excise stratigraphy are normally extensional detachments; thrusts repeat stratigraphy. Extensional detachments are known from sedimentary basins, but mainly on extremely attenuated continental margins (e.g. Manatschal *et al.* 2007; Osmundsen and Ebbing 2008), which is patently not the early Dalradian basin setting.

The Breadalbane Dalradian stratigraphical framework reported here is derived from rigorous mapping of the distribution of lithostratigraphical units and their pattern of terminations (pinch-outs) across a broad region; key boundaries are not obscured by superimposed ductile (or brittle) deformation. A more dynamic depositional framework permits an alternative explanation, one that does not require a tectonic removal of strata. The Dalradian succession in Breadalbane can be regarded as essentially as deposited and complete, albeit attenuated locally (Treagus *et al.* 2013); zones of variably intense ductile deformation are superimposed on a primary stratigraphical geometry.

The missing stratigraphy and temporal changes

Non-deposition of the 'missing' Dalradian stratigraphy on an intrabasinal high or bulge can explain the stratal patterns observed, even when the superimposed ductile strain is accounted for. Large sections of strata belonging to the more regionally recognized mid-Dalradian succession (Appin and Argyll groups) are absent in the Breadalbane district and most probably were never deposited. In this scenario, the boundary between the heterolithic units of the Lochaber Subgroup and strata of the Carn Mairg Quartzite, Ben Lawers Schist and Ben Lui Schist formations in the Breadalbane district represents an intrabasinal unconformity (disconformity). The degree of actual uplift in this region is considered to have been limited, as mud-on-mud deposition seems unlikely on an active block uplift where down-cutting erosional processes, sediment reworking and preferential deposition of sand-rich sediment are more likely to occur. Sediment routing and supply are thought to be the dominant controls on depositional processes in this region of the Dalradian basin at this time.

Changes in relative sea level (RSL) and accommodation space can explain the observed lithostratigraphical succession. During rapidly increasing RSL and transgression succeeding Grampian Group deposition, the rate of sea-level rise quickly outpaced that of sediment supply, causing retrogradation of proximal sandy facies that became confined to only the most proximal areas of the shelf. More basinal areas became sediment starved and record protracted periods of time in comparatively thin mud-dominated strata (e.g. Van Wagoner *et al.* 1988; Embry 2009; Catuneanu 2022). Overall, the stratigraphy of the Lochaber Subgroup of the Breadalbane district records a muddying-upward succession indicating reduction of depositional energy, low sediment accumulation rates and retrogradation of facies belts during relative sea-level rise. This sector also appears to record long-term tectonic stability, whereas greater accommodation space was being generated to the NE and SW where sediment accumulation rates were maintained, generating 'complete' (classical) Dalradian successions in those regions.

A depositional model

Schematic 3D representations (Fig. 9) illustrate the accumulation of stratigraphical units and their depositional setting for the Breadalbane Dalradian, from end-Grampian Group times through the Lochaber Subgroup (Appin Group), into the latter stages of the Argyll Group and deposition of the Loch Tay Limestone Formation. We acknowledge that these diagrams cannot readily or fully capture the true scale (horizontal or vertical) of any intrabasinal relief that existed during deposition (e.g. Robertson and Smith 1999; Smith *et al.* 1999; but see Prave *et al.* 2023). Likewise, it is challenging to do more than schematically account for the thickness of strata accumulating. The 'driving' mechanisms assumed to have generated the stratal surfaces of onlap, offlap and hiatuses are global in scale. Furthermore, the implied longevity of these highs is uncertain in such a poorly age-constrained succession as the Dalradian Supergroup. The regional NE–SW strike of Dalradian strata is generally regarded as approximately parallel to the Iapetan palaeo-shoreline (Anderton 1985; Cawood *et al.* 2003) and that context is assumed for the reconstructions of Figure 9.

At end-Grampian Group times (Fig. 9a), shallow-marine shoreface sediments prograded generally south-(east)ward into a generally stable basin. A shallow nearshore shelfal environment that experienced periodic inundation with sediment under oscillatory currents is likely. The area of the model is represented by a lower shoreface below Fair Weather Wave Base (FWWB). Distinct lithofacies (sands, parallel-bedded sands, undulose-bedded sands incorporating hummocky cross stratification (HCS) and minor muds stack up to form a single sand-dominated (psammite) lithofacies association (see Table 2). This association suggests an agitated water–sediment column consistently above Storm Weather Wave Base (SWWB). Limited periods of calm water allowed only

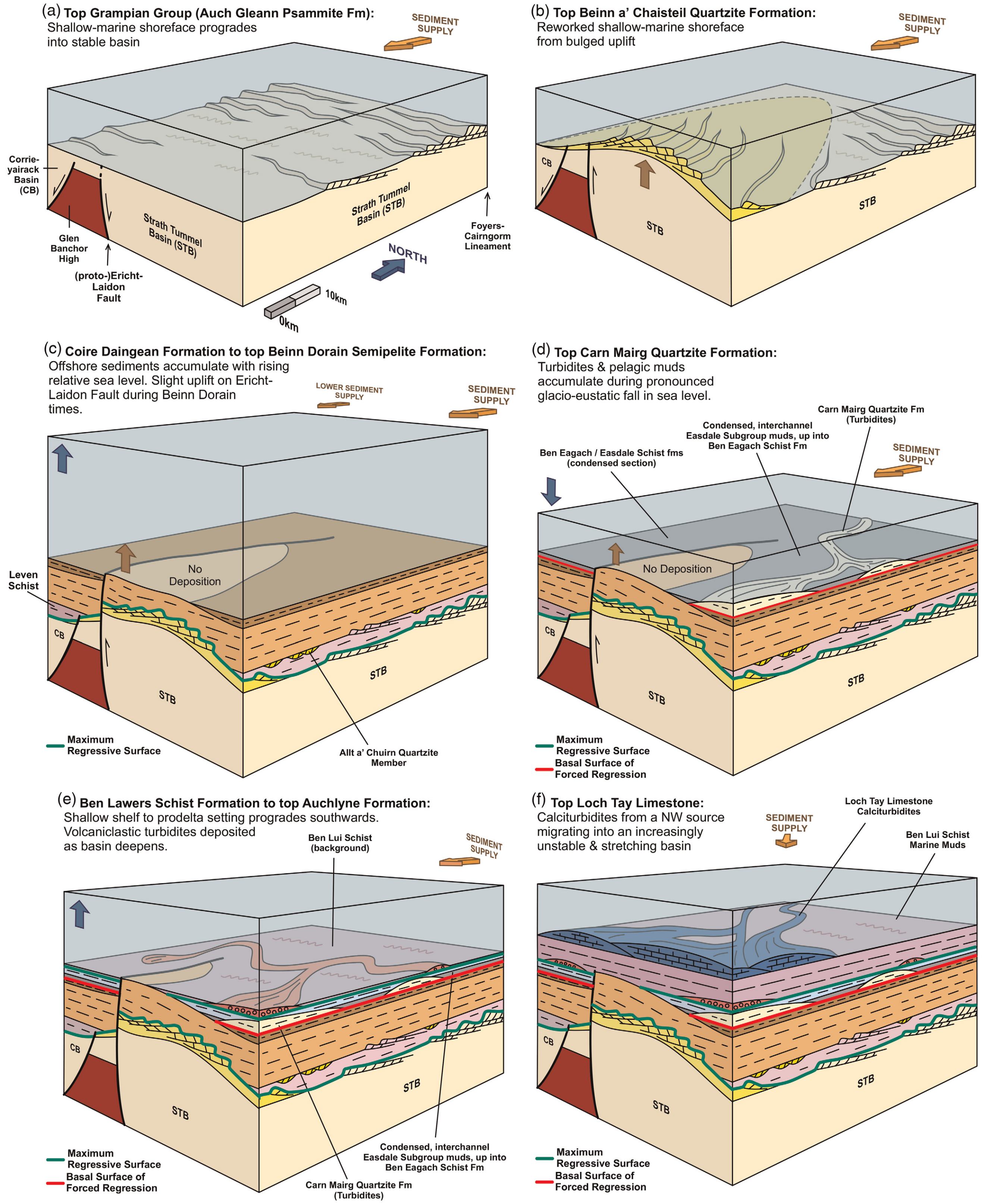

Fig. 9. (**a**–**f**) Schematic 3D illustrations of the accumulation of mapped stratigraphical units and their setting within the depositional framework for the Breadalbane district Dalradian, from end-Grampian Group time through the Lochaber Subgroup (Appin Group), into the latter stages of the Argyll Group Argyll and deposition of the Loch Tay Limestone Formation. It should be noted that these diagrams cannot readily or fully capture the true scale (horizontal or vertical) of any intrabasinal relief that existed during deposition, and that could thus account for the thickness of strata accumulating; the implied longevity of these highs is uncertain in such a poorly age-constrained succession as the Dalradian Supergroup. The regional NE–SW strike of Dalradian strata is generally regarded as approximately parallel to the Iapetan palaeo-shoreline and is assumed as the context for these reconstructions. It should be noted that the vertical scale is exaggerated with respect to the horizontal to display the necessary detail. Individual formation colours used here are the same as those for Figures 5–7. Sources: regional Dalradian strike from Anderton (1985) and Cawood *et al.* (2003).

minimal accumulation of muddy sediment from suspension. The lack of any significant pattern of vertical facies change within strata of the Auch Glenn Psammite Formation indicates that the balance between the creation of accommodation space and sediment infill was maintained for long periods in Breadalbane. Overall, strata of the Grampian Group recorded long-term basin shallowing, a reduction in accommodation space and progradation of proximal facies belts, resulting from sediment infill and normal regression (Smith *et al.* 1999; Banks *et al.* 2007; Leslie *et al.* 2008).

Youngest sediments of the Grampian Group in the Breadalbane district on the southeastern flank of the (proto-)Ericht–Laiden Fault (Fig. 9a) are proposed to have been raised above SWWB, and possibly above FWWB. This long-lived shoreface was capped by strata of the Beinn a' Chaisteil Quartzite Formation (Lochaber Subgroup) (Fig. 9b), the most mineralogically mature and depositionally shallowest sediment recorded within this shoreface succession. As such, the strata of this formation suggest repeated sediment reworking and winnowing of fines. The formation preserves low-amplitude straight-crested bifurcating ripples (see Table 2), typically observed in upper shoreface settings (above FWWB). This is the culmination of the Grampian Group to early Lochaber regression as recorded by previous workers (Glover *et al.* 1995; Glover and McKie 1996; Banks 2005).

Mapped stratal relationships between the shelf succession of the Grampian Group–Beinn a' Chaisteil Quartzite Formation and overlying units imply an onlap relationship and require a positive basin floor topography (warp or bulge) in late Grampian to Beinn a' Chaisteil times, most obviously in the Meggernie region where stratigraphical omission is highest. We propose that tectonic activity coinciding with the end of Grampian Group deposition generated a localized uplift or 'bulge' against pre-existing intrabasinal discontinuities that are now perhaps reflected in regional-scale late Caledonian fault traces, such as the Ericht–Laidon Fault delineating the southeastern flank of the Glen Banchor High (Robertson and Smith 1999; Smith *et al.* 1999; but see Prave *et al.* 2023). Such tectonic activity may indicate a response to the *c.* 720–700 Ma phase of break-up of eastern Rodinia (Aleinikoff *et al.* 1995; Kamo *et al.* 1995; McClellan and Gazel 2014).

The top of the Beinn a' Chaisteil Quartzite Formation represents the maximum regressive surface (*sensu* Catuneanu 2022), overstepped by an early Appin Group succession as RSL rose and transgression occurred (Fig. 9c). Consequently, the stratigraphical boundary marking the upward change from strata of the Beinn a' Chaisteil Quartzite Formation into those of the rest of the Lochaber Subgroup can be considered a sequence boundary (*sensu* Galloway 1989), separating dominantly regressive Grampian Group facies belts (perhaps indicative of a shelf margin systems tract) and the onset of dominantly transgressive Appin Group successions. This boundary is followed by a muddying-upward facies succession recorded by the upward transition from quartzite at the base of the Lochaber Subgroup into heterolithic mudstone, with thin psammite and quartzite ribs interpreted as continued transgression and retrogradation of the preserved facies belts from shoreface sands (above FWWB) to offshore muds and sands (below FWWB). Despite a long-standing lithostratigraphical attribution of quartzite formations at this level in the Dalradian succession to the Lochaber Subgroup, we argue that the Beinn a' Chaisteil Quartzite is better regarded as a genetic continuation of a typical Grampian Group lithofacies association.

A rapid rise in RSL (Fig. 9c) followed the earlier tectonically driven intrabasinal bulge and possible inversion on a (proto-) Ericht–Laiden fault structure. Such a structure may have created differential topography sufficient to compartmentalize sediment supply in different parts of the basin. Rates of sea-level rise exceeded rates of uplift to produce net deepening and promoted deposition of the offshore or lower shoreface into deeper water sediments of the Coire Daingean Semipelite Formation (mud and ripple-laminated sand). Assuming that sediment supply was still broadly from the north or NW (i.e. from the Laurentian continental margin), the area west of the (proto-)Ericht–Laiden Fault apparently received considerably less sediment than that to the east, with sediment starvation generally resulting in suspension sedimentation (Leven Schist Formation). Sediments of the Coire Daingean Semipelite Formation onlapped the southern and eastern edges of the 'bulge', and the bulge itself recorded no deposition (or an extremely condensed section).

A continued rise in RSL, and some regional (compactional?) subsidence, maintained the 'offshore to deeper water' conditions (muds and ripple-laminated sands) throughout Beinn an Dothaidh times (Fig. 9c). These deposits draped and eventually buried the 'bulge', with little or no topographical expression remaining on the sea floor. The banded or ribbed Allt a' Chuirn Quartzite Member (with up to 10% interbedded pelite) may represent turbidite or contourite sands deposited in channels. This unit is only locally identified (typically <10 m thick) at the base of the Beinn an Dothaidh Formation and passes gradationally upwards into strata of the host formation over a few metres of section.

Deposition of the locally graphitic Beinn Dorain Semipelite Formation occurred in slightly deeper water (locally euxinic) conditions (Fig. 9c, uppermost unit). We suggest a reducing rate of RSL rise by this time, thus stabilizing depositional environments in the larger scale basin and permitting the 'type' Appin Group stratigraphy seen in SW and NE Scotland. The top of this unit would mark a Maximum Transgressive Surface. Localized uplift on the southeastern flank of the (proto-)Ericht–Laiden Fault at this time may be responsible for the more spatially restricted occurrences of sediment belonging to the Beinn Dorain Semipelite Formation in the west of the region around Beinn Dorain and Beinn nam Fuaran (locations P and Q respectively in Fig. 5; see also Fig. 6).

No sediment accumulated, or at least none was preserved on, or in the vicinity of, this intrabasinal 'bulge' until early Easdale Subgroup times saw deposition of sediments belonging to the Carn Mairg Quartzite Formation (Fig. 9d). There is no evidence for a major tectonic break in the outcrops examined; consequently, the succeeding strata of the Easdale Subgroup can be considered as being in stratigraphical and sedimentological (typically mud-on-mud) continuum with the underlying heterolithic units of the Appin Group (Lochaber Subgroup), albeit unconformable. This period overlaps the globally significant *c.* 700 Ma Sturtian glaciation (Fairchild *et al.* 2018). We propose that a pronounced sea-level fall, along with any localized and limited intrabasinal uplift, would have resulted in a net fall in relative sea level and progradation of the shelf from the north. The fall in sea level will have destabilized the basin shelf, cascading reworked sediment down into the deeper setting as frequent turbidite flows. NE of Tyndrum (Fig. 5), and on either side of the trace of the Tyndrum Fault, the Carn Mairg Quartzite Formation probably represents localized incursion of channelized (?) immature turbidite sands across the basin floor. Consequently, the top of the Beinn Dorain Semipelite Formation (or a level somewhere in the early Carn Mairg Quartzite Formation) could be viewed as a Basal Surface of Forced Regression (Fig. 9d–f).

In upper Easdale Subgroup times (Fig. 9e), it seems likely that relative sea level and basin-wide sediment supply had stabilized, coincident with deposition and accumulation of the Ben Lawers Schist Formation. The 'bulge' affecting the stratigraphy of the Breadalbane district remained a positive intrabasinal feature with no accumulation of Ben Lawers sediments on its crest, and we propose that a calcareous shallow shelf prograded southward to deposit prodelta muds and ripple-laminated sands. Low RSL would drive normal regression and development of a Maximum Regressive Surface at the top (or in the uppermost part) of the succession of the Ben Lawers Schist Formation, potentially coincident with *c.*

635 Ma Marinoan glaciation (McCay *et al.* 2006; Prave *et al.* 2016, in press).

By latest Easdale Subgroup times (Fig. 9e), Auchlyne Formation volcaniclastic turbidite strata were deposited as relative sea level rose again and the basin deepened in response to stretching–rifting preceding eastern Rodinia break-up at *c.* 600 Ma. These volcaniclastic turbidites may have entered the Breadalbane sector of the basin from the Farragon–Pitlochry area to the NE (see Figs 2 and 8), where volcanic rocks are conspicuous in the Dalradian succession (e.g. the Farragon Volcanic Formation). The 'bulge' had become increasingly inundated such that any residual uplift no longer countered sediment supply. Input of volcaniclastic detritus gave way to the more typically siliciclastic detritus of the Ben Lui Schist Formation (Crinan Subgroup) with these turbiditic flows finally submerging the intrabasinal 'bulge' in the Breadalbane district (Fig. 9e, uppermost unit). Lastly in this model, by Tayvallich Subgroup times, and prior to foundering of the Iapetan margin and the protracted deposition of Southern Highland Group turbidite flows, relative sea level changed little but the basin margin remained unstable. Calciturbidite flows entered the basin depositing sediments of the Loch Tay Limestone Formation (Fig. 9f).

The majority of lateral changes mapped out preserve onlap–downlap relationships and thus indicate a response to the larger-scale controls of relative sea level, sediment supply and sediment routing. Such changes become more profound within strata of the Islay–Easdale subgroups, probably influenced by distinct changes in sediment supply coincident with localized volcanic activity. Deposits of the Crinan Subgroup overstep all this variability, presumably as more uniform (and increasing) subsidence rates take over on a broader scale, promoting turbiditic deposits all along this part of the continental margin.

Conclusions

We present a geometrical restoration of parts of the late Neoproterozoic primary depositional framework for the Dalradian Supergroup in Scotland that now includes recognition of a significant intrabasinal unconformity.

Construction of robust and restorable cross-strike sections through the relatively low-strain, albeit poly-deformed, Dalradian Supergroup in the Breadalbane district of the Scottish Highlands allows the context of the Boundary Slide structure to be reinterpreted. Hitherto considered responsible for structural excision of significant elements of 'classical' Dalradian stratigraphy, we are now able to interpret the absence of that stratigraphy as a consequence of the development of that intrabasinal unconformity, even when superimposed ductile strain is allowed for.

The absence of a large tract of 'classical' Dalradian stratigraphy in the Breadalbane district of the Grampian Highlands cannot be explained by syn-orogenic thrusting, or by a syn- or post-depositional (but pre-orogenic) extensional detachment. The Boundary Slide does not, in fact, represent a particularly high-strain zone in Breadalbane; the stratigraphical 'omission' is best explained as the result of non-deposition and development of an intrabasinal unconformity over a long-lived structural high. The resultant stratigraphical framework was later modified to only a limited extent by focused strain during Grampian orogenic deformation.

The 'missing units' were never deposited in the places where they do not now occur in Breadalbane, and the original Dalradian depositional framework is preserved, albeit modified.

Our approach relies upon robust outcrop mapping and rigorous interpretation of restorable sections. As such, it is readily applicable across the wider regional Dalradian basin in Scotland, and to any other similar continental basin margin sequences that have undergone polyphase deformation during collisional orogenesis. Via this approach, main depocentres, shelfal regions, and sediment-starved sectors and dispositional stratigraphy can be recognized and interpreted in a first-order sequence-stratigraphical framework.

Scientific editing by Sarah Boulton

Acknowledgements C. Woodward, BGS, greatly improved original drafts of a number of key figures. R. Palamakumbura is thanked for an insightful review of the paper for the BGS, prior to submission. A. Prave and I. Fairchild each provided very encouraging, insightful and constructive reviews for the Geological Society, London. Together, those reviews have greatly improved this account. This paper is published with the permission of the Executive Director, BGS (UK Research and Innovation).

Author contributions **AGL**: conceptualization (equal), formal analysis (supporting), investigation (equal), methodology (supporting), visualization (supporting), writing – original draft (lead), writing – review & editing (lead); **MK**: conceptualization (equal), formal analysis (lead), investigation (equal), methodology (lead), visualization (lead), writing – original draft (supporting), writing – review & editing (supporting); **CWT**: conceptualization (supporting), formal analysis (supporting), investigation (equal), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting); **CJB**: formal analysis (supporting), investigation (supporting), methodology (supporting), writing – original draft (supporting), writing – review & editing (supporting); **SMC**: conceptualization (supporting), formal analysis (supporting), methodology (supporting), visualization (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 relevant data generated or analysed during this study are included in this published article. In addition, references are provided for the new 1:50 000 scale geological maps published by BGS, the new mapping for which includes the data analysed for this research.

References

Alberta Geological Survey 2019. *Alberta Table of Formations*. Alberta Energy Regulator.

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T. and Burton, W.C. 1995. U–Pb ages of metarhyolites Catoctin and Mount Rogers formations, Central and Southern Appalachians; evidence for two pulses of Iapetan rifting. *American Journal of Science*, **295**, 428–454, https://doi.org/10.2475/ajs.295.4.428

Anderton, R. 1985. Sedimentation and tectonics in the Scottish Dalradian. *Scottish Journal of Geology*, **21**, 407–436, https://doi.org/10.1144/sjg21040407

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

Bailey, E.B. 1922. The structure of the South West Highlands of Scotland. *Quarterly Journal of the Geological Society*, **78**, 82–131, https://doi.org/10.1144/GSL.JGS.1922.078.01-04.03

Banks, C.J. 2005. *Neoproterozoic Basin Analysis: A Combined Sedimentological and Provenance Study in the Grampian Group, Central Highlands, Scotland*. PhD thesis, University of Keele.

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

BGS 2000. *Schiehallion. Scotland Sheet 55W. Solid Geology. 1:50 000*. British Geological Survey, Keyworth, Nottingham.

BGS 2008. *Dunoon and Millport. Scotland Sheet 29E, with part of 21E. Bedrock Geology. 1:50 000 Geology Series*. British Geological Survey, Keyworth, Nottingham.

BGS 2013*a*. *Crianlarich. Scotland Sheet 46W. Bedrock Geology. 1:50 000 Geology Series*. British Geological Survey, Keyworth, Nottingham.

BGS 2013*b*. *Killin. Scotland Sheet 46E. Bedrock Geology. 1:50 000 Geology Series*. British Geological Survey, Keyworth, Nottingham.

BGS 2014. *Loch Rannoch. Scotland Sheet 54E. Bedrock Geology. 1:50 000 Geology Series*. British Geological Survey, Keyworth, Nottingham.

Borradaile, G.J. 1979. Pre-tectonic reconstruction of the Islay anticline: implications for the depositional history of Dalradian rocks in the SW Highlands. *Geological Society, London, Special Publications*, **8**, 229–238, https://doi.org/10/.1144/GSL.SP.1979.008.01.23

Bradbury, H.J., Harris, A.L. and Smith, R.A. 1979. Geometry and emplacement of nappes in the Central Scottish Highlands. *Geological Society, London, Special Publications*, **8**, 213–220, https://doi.org/10/.1144/GSL.SP.1979.008.01.21

Burt, C.E. 2002. *Sedimentary Environments and Basin Evolution of the Upper Dalradian: Tayvallich Subgroup and Southern Highland Group*. PhD thesis, Kingston University.

Catuneanu, O. 2022. *Principles of Sequence Stratigraphy*, 2nd edn. Elsevier.

Cawood, P.A., McCausland, P.J.A. and Dunning, G.R. 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. *Geological Society of America Bulletin*, **113**, 443–453, https://doi.org/10.1130/0016-7606(2001)113<0443:OICFTL>2.0.CO;2

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 upper 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. and Strachan, R. 2007. Provenance record of Laurentian passive margin strata in the northern Caledonides: implications for paleodrainage and paleogeography. *Geological Society of America Bulletin*, **119**, 993–1003, https://doi.org/10.1130/B26152.1

Crane, A., Goodman, S., Krabbendam, M., Leslie, A.G., Paterson, I.B., Robertson, S. and Rollin, K.E. 2002. *Geology of the Glen Shee District. Memoir of the British Geological Survey. Sheet 56W with parts of sheets 55E, 65W and 64E (Scotland)*. British Geological Survey, Keyworth, Nottingham.

Dempster, T.J., Rogers, G. *et al.* 2002. Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U–Pb zircon ages. *Journal of the Geological Society, London*, **159**, 83–94, https://doi.org/10.1144/0016-764901061

Embry, A.F. 2009. *Practical Sequence Stratigraphy*. Canadian Society of Petroleum Geologists, Calgary, AB.

Ethington, R.L. 2008. Conodonts from the Margie Limestone in the Highland Border Complex, River North Esk, Scotland. *Scottish Journal of Geology*, **44**, 75–82, https://doi.org/10.1144/sjg44010075

Fairchild, I.J., Spencer, A.M. *et al.* 2018. Tonian–Cryogenian boundary sections Argyll, Scotland. *Precambrian Research*, **319**, 37–64, https://doi.org/10.1016/j.precamres.2017.09.020

Fettes, D.J., Leslie, A.G., Stephenson, D. and Kimbell, S.F. 1991. Disruption of Dalradian stratigraphy along the Portsoy Lineament from new geological and magnetic surveys. *Scottish Journal of Geology*, **27**, 57–73, https://doi.org/10.1144/sjg27010057

Fettes, D.J., MacDonald, R., Fitton, J.G., Stephenson, D. and Cooper, M.R. 2011. Geochemical evolution of Dalradian metavolcanic rocks: implications for the break-up of the Rodinia supercontinent. *Journal of the Geological Society, London*, **168**, 1133–1146, https://doi.org/10.1144/0016-76492010-161

Galloway, W.E. 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. *AAPG Bulletin*, **73**, 125–142.

Glover, B.W. and McKie, T. 1996. A sequence stratigraphical approach to the understanding of basin history in orogenic Neoproterozoic successions: an example from the central Highlands of Scotland. *Geological Society, London, Special Publications*, **103**, 257–269, https://doi.org/10.1144/GSL.SP.1996.103.01.15

Glover, B.W., Key, R.M., May, F., Clark, G.C., Phillips, E.R. and Chacksfield, B.C. 1995. A Neoproterozoic multi-phase rift sequence: the Grampian and Appin groups of the southwestern Monadhliath Mountains of Scotland. *Journal of the Geological Society, London*, **152**, 391–406, https://doi.org/10.1144/gsjgs.152.2.0391

Goodman, S., Crane, A., Krabbendam, M. and Leslie, A.G. 1997. Correlation of lithostratigraphic sequences in a structurally complex area: Gleann Fearnach to Glen Shee, Scotland. *Transactions of the Royal Society of Edinburgh*, **87**, 503–513, https://doi.org/10.1017/S0263593300018162

Graham, C.M. 1986. The role of the Cruachan Lineament during Dalradian evolution. *Scottish Journal of Geology*, **22**, 257–270, https://doi.org/10.1144/sjg22020257

Harland, W.B. 1997. *The Geology of Svalbard*. Geological Society of London, Memoirs, **17**, https://doi.org/10.1144/GSL.MEM.1997.017.01.26

Harris, A.L., Baldwin, C.T., Bradbury, H.J., Johnson, H.D. and Smith, R.A. 1978. Ensialic basin sedimentation: the Dalradian Supergroup. *Geological Journal*, Special Issue, **10**, 115–138.

Harris, A.L., Haselock, P.J., Kennedy, M.J., Mendum, J.R., Long, J.A., Winchester, J.A. and Tanner, P.W.G. 1994. The Dalradian Supergroup in Scotland, Shetland, and Ireland. *In*: Gibbons, W. and Harris, A.L. (eds) *A Revised Correlation of the Precambrian Rocks of the British Isles*. Geological Society, London, Special Reports, **22**, 33–53.

Hutton, D.H. and Alsop, G.I. 1995. Extensional geometries as a result of regional scale thrusting: tectonic slides of the Dunlewy–NW Donegal area, Ireland. *Journal of Structural Geology*, **17**, 1279–1292, https://doi.org/10.1016/0191-8141(95)00031-8

Hyslop, E.K. 1992. *Strain-Induced Metamorphism and Pegmatite Development in the Moine Rocks of Scotland*. PhD thesis, University of Hull.

Hyslop, E.K. and Piasecki, M.A.J. 1999. Mineralogy, geochemistry and the development of ductile shear zones in the Grampian Slide Zone of the Scottish Central Highlands. *Journal of the Geological Society, London*, **156**, 577–590, https://doi.org/10.1144/gsjgs.156.3.0577

Jablonski, D. and Saitta, A.J. 2004. Permian to Lower Cretaceous plate tectonics and its impact on the tectono-stratigraphic development of the Western Australian margin. *APPEA Journal*, **44**, 287–328, https://doi.org/10.1071/AJ03011

Kamo, S.L., Gower, C.F. and Krogh, T.E. 1989. Birthdate for the lapetus Ocean? A precise U–Pb zircon and baddeleyite age for the Long Range dikes, southeast Labrador. *Geology*, **17**, 602–605, https://doi.org/10.1130/0091-7613(1989)017<0602:BFTLOA>2.3.CO;2

Kamo, S.L., Krogh, T.E. and Kumarapeli, P.S. 1995. Age of the Grenville dyke swarm, Ontario–Quebec: implications for the timing of Iapetan rifting. *Canadian Journal of Earth Sciences*, **32**, 273–280, https://doi.org/10.1139/e95-022

Knill, J.L. 1963. A sedimentary history of the Dalradian Series. *In*: Johnson, M.R.W. and Stewart, F.H. (eds) *The British Caledonides*. Oliver and Boyd, Edinburgh, 99–121.

Krabbendam, M., Leslie, A.G., Crane, A. and Goodman, S. 1997. Generation of the Tay Nappe, Scotland, by large-scale SE-directed shearing. *Journal of the Geological Society, London*, **154**, 15–24, https://doi.org/10.1144/gsjgs.154.1.0015

Kusznir, N.J., Marshden, G. and Egan, S.S. 1991. A flexural cantilever simple shear/pure shear model of continental lithosphere extension: applications to the Jeanne d'Arc basin, Grand Banks, and the Viking Graben, North Sea. *Geological Society, London, Special Publications*, **56**, 41–60, https://doi.org/10.1144/GSL.SP.1991.056.01.04

Leslie, A.G., Krabbendam, M. and Smith, R.A. 2006. The Gaick Fold Complex: large-scale recumbent folds and their implications for Caledonian structural architecture in the Central Grampian Highlands. *Scottish Journal of Geology*, **42**, 149–160, https://doi.org/10.1144/sjg42020149

Leslie, A.G., Smith, M. and Soper, N.J. 2008. Laurentian margin evolution and the Caledonian orogeny – a template for Scotland and East Greenland. *Geological Society of America, Memoirs*, **202**, 307–343.

Li, Z.X., Bogdanova, S.V. *et al.* 2008. Assembly, configuration, break-up history of Rodinia: a synthesis. *Precambrian Research*, **160**, 179–210, https://doi.org/10.1016/j.precamres.2007.04.021

Lister, G.S., Etheridge, M.A. and Symonds, P.A. 1991. Detachment models for the formation of passive continental margins. *Tectonics*, **10**, 1038–1064, https://doi.org/10.1029/90TC01007

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

MacDonald, R., Fettes, D.J., Stephenson, D. and Graham, C.M. 2005. Basic and ultrabasic volcanic rocks from the Argyll Group (Dalradian) of NE Scotland. *Scottish Journal of Geology*, **41**, 159–174, https://doi.org/10.1144/sjg41020159

Manatschal, G. 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. *International Journal of Earth Sciences*, **93**, 432–466, https://doi.org/10.1007/s00531-004-0394-7

Manatschal, G., Müntener, O., Lavier, L., Minshull, T.A. and Peron-Pinvidic, G. 2007. Observations from the Alpine Tethys and Iberia–Newfoundland margins pertinent to the interpretation of continental breakup. *Geological Society, London, Special Publications*, **282**, 291–324, https://doi.org/10.1144/SP282.14

McCausland, P.J.A., Hankard, F., Van der Voo, R. and Hall, C.M. 2011. Ediacaran paleogeography of Laurentia: paleomagnetism and ^{40}Ar–^{39}Ar geochronology of the 583 Ma Baie des Moutons syenite, Quebec. *Precambrian Research*, **187**, 58–78, https://doi.org/10.1016/j.precamres.2011.02.004

McCay, G.A., Prave, A.R., Alsop, G.I. and Fallick, A.E. 2006. Glacial trinity: Neoproterozoic Earth history within the British–Irish Caledonides. *Geology*, **34**, 909–912, https://doi.org/10.1130/G22694A.1

McClellan, E. and Gazel, E. 2014. The Cryogenian intra-continental rifting of Rodinia: evidence from the Laurentian margin in eastern North America. *Lithos*, **206**, 321–327, https://doi.org/10.1016/j.lithos.2014.08.006

Mendum, J.R. and Thomas, C.W. 1997. Discussion on the generation of the Tay Nappe, Scotland, by large-scale SE-directed shearing. *Journal of the Geological Society, London*, **154**, 581–583, https://doi.org/10.1144/gsjgs.154.3.0581

Nell, P.A.R. 1986. Discussion on the Caledonian metamorphic core: an Alpine model. *Journal of the Geological Society, London*, **143**, 723–728, https://doi.org/10.1144/gsjgs.143.4.0723

Noble, S.R., Hyslop, E.K. and Highton, A.J. 1996. High-precision U–Pb monazite geochronology of the *c.* 806 Ma Grampian Shear Zone and the implications for evolution of the Central Highlands of Scotland. *Journal of the Geological Society, London*, **153**, 511–514, https://doi.org/10.1144/gsjgs.153.4.0511

Osmundsen, P.T. and Ebbing, J. 2008. Styles of extension offshore mid-Norway and implications for mechanisms of crustal thinning at passive margins. *Tectonics*, **27**, TC6016, https://doi.org/10.1029/2007TC002242

Peel, J.S. and Sønderholm, M. 1991. *Sedimentary Basins of North Greenland*. Bulletin Grønlands Geologiske Undersøgelse, **161**.

Peron-Pinvidic, G., Manatschal, G. and Osmundsen, P.T. 2013. Structural comparison of archetypal Atlantic rifted margins: a review of observations and concepts. *Marine and Petroleum Geology*, **43**, 21–47, https://doi.org/10.1016/j.marpetgeo.2013.02.002

Pidgeon, R.T. and Compston, W. 1992. A Shrimp ion microprobe study of inherited and magmatic zircon from Scottish Caledonian granites. *Transactions of the Royal Society, Edinburgh: Earth Sciences*, **83**, 473–483, https://doi.org/10.1017/S0263593300008142

Plant, J.A., Cooper, D.C., Green, P.M., Reedman, A.J. and Simpson, P.R. 1991. Regional distribution of As, Sb and Bi in the Grampian Highlands of Scotland and English Lake District: implication for gold metallogeny. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Science)*, **100**, 135–147.

Prave, A.R. 1999. The Neoproterozoic Dalradian Supergroup of Scotland: an alternative hypothesis. *Geological Magazine*, **136**, 609–617, https://doi.org/10.1017/S0016756899003155

Prave, A.R., Fallick, A.E. and Kirsimäe, K. 2023. Evidence, or not, for late Tonian break-up of Rodinia? The Dalradian Supergroup, Scotland. *Journal of the Geological Society, London*, **180**, https://doi.org/10.1144/jgs2022-134

Prave, A.R., Condon, D.J., Hoffmann, K.H., Tapster, S. and Fallick, A.E. 2016. Duration and nature of end-Cryogenian (Marinoan) glaciation. *Geology*, **44**, 631–634, https://doi.org/10.1130/G38089.1

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

Pringle, J. 1940. The discovery of Cambrian trilobites in the Highland Border rocks near Callander, Perthshire (Scotland). *British Association for the Advancement of Science: Annual Report for 1939–40*, **1**, 252.

Ramsay, J.G. and Huber, M.I. 1983. *The Techniques of Modern Structural Geology: Strain Analysis*, **1**. Academic Press, New York.

Ramsay, J.G., Huber, M.I. and Lisle, R.J. 1987. *The Techniques of Modern Structural Geology: Folds and Fractures*, **2**. Academic Press, New York.

Reston, T.J., Gaw, V., Pennel, J., Klaeschen, D., Stubenrauch, A. and Walker, I. 2004. Extreme crustal thinning in the south Porcupine Basin and the nature of the Porcupine median high; implications for the formation of non-volcanic rifted margins. *Journal of the Geological Society, London*, **161**, 783–798, https://doi.org/10.1144/0016-764903-036

Roberts, J.L. and Treagus, J.E. 1975. The structure of the Moine and Dalradian rocks in the Dalmally district of Argyllshire, Scotland. *Geological Journal*, **10**, 59–74, https://doi.org/10.1002/gj.3350100105

Roberts, J.L. and Treagus, J.E. 1977. Polyphase generation of nappe structures in the Dalradian rocks of the Southwest Highlands of Scotland. *Scottish Journal of Geology*, **13**, 237–254, https://doi.org/10.1144/sjg13030237

Roberts, J.L. and Treagus, J.E. 1979. Stratigraphical and structural correlation between the Dalradian rocks of the SW and Central Highlands of Scotland. *Geological Society, London, Special Publications*, **8**, 199–204, https://doi.org/10.1144/GSL.SP.1979.008.01.19

Robertson, S. and Smith, M. 1999. The significance of the Geal Charn–Ossian Steep Belt in basin development in the Central Scottish Highlands. *Journal of the Geological Society, London*, **156**, 1175–1182, https://doi.org/10.1144/gsjgs.156.6.1175

Rogers, G., Dempster, T.J., Bluck, B.J. and Tanner, P.W.G. 1989. A high precision U–Pb age for the Ben Vuirich Granite: implications for the evolution of the Scottish Dalradian Supergroup. *Journal of the Geological Society, London*, **146**, 789–798, https://doi.org/10.1144/gsjgs.146.5.0789

Rose, P.T.S. and Harris, A.L. 2000. Evidence for the Lower Palaeozoic age of the Tay Nappe; the timing and nature of Grampian events in the Scottish Highland sector of the Laurentian margin. *Journal of the Geological Society, London*, **157**, 381–391, https://doi.org/10.1144/jgs.157.2.381

Shackleton, R.M. 1958. Downward-facing structures of the Highland Border. *Quarterly Journal of the Geological Society*, **113**, 361–392, https://doi.org/10.1144/GSL.JGS.1957.113.01-04.15

Smith, M.P. 2000. Cambro-Ordovician stratigraphy of Bjørnøya and North Greenland: constraints on tectonic models for the Arctic Caledonides and the Tertiary opening of the Greenland Sea. *Journal of the Geological Society, London*, **157**, 459–470, https://doi.org/10.1144/jgs.157.2.459

Smith, M., Robertson, S. and Rollin, K.E. 1999. Rift basin architecture and stratigraphical implications for basement–cover relationships in the Neoproterozoic Grampian Group of the Scottish Caledonides. *Journal of the Geological Society, London*, **156**, 1163–1173, https://doi.org/10.1144/gsjgs.156.6.1163

Soper, N.J. 1994*a*. Was Scotland a Vendian RRR junction? *Journal of the Geological Society, London*, **151**, 579–582, https://doi.org/10.1144/gsjgs.151.4.0579

Soper, N.J. 1994*b*. Neoproterozoic sedimentation on the northeast margin of Laurentia and the opening of Iapetus. *Geological Magazine*, **131**, 291–299, https://doi.org/10.1017/S0016756800011067

Soper, N.J. and Anderton, R. 1984. Did the Dalradian slides originate as extensional faults? *Nature, London*, **307**, 357–360, https://doi.org/10.1038/307357a0

Spencer, A.M. 1971. *Late Pre-Cambrian Glaciation in Scotland*. Geological Society, London, Memoirs, **6**.

Stephenson, D. and Gould, D. 1995. *British Regional Geology: The Grampian Highlands*, 4th edn. HMSO for the British Geological Survey, London.

Stephenson, D., Mendum, J.R., Fettes, D.J. and Leslie, A.G. 2013. The Dalradian rocks of Scotland: an introduction. *Proceedings of the Geologists' Association*, **124**, 3–82, https://doi.org/10.1016/j.pgeola.2012.06.002

Tanner, P.W.G. 1995. New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex. *Geological Magazine*, **132**, 473–483, https://doi.org/10.1017/S0016756800021142

Tanner, P.W.G. 2014. A kinematic model for the Grampian Orogeny, Scotland. *Geological Society, London, Special Publications*, **390**, 467–511, https://doi.org/10.1144/SP390.23

Tanner, P.W.G. 2016. A new model for the formation of a spaced crenulation (shear band) cleavage in the Dalradian rocks of the Tay Nappe, SW Highlands, Scotland. *Journal of Structural Geology*, **84**, 120–141, https://doi.org/10.1016/j.jsg.2015.11.007

Tanner, P.W.G. and Leslie, A.G. 1994. A pre-D_2 age for the 590 Ma Ben Vuirich Granite in the Dalradian of Scotland. *Journal of the Geological Society, London*, **151**, 209–212, https://doi.org/10.1144/gsjgs.151.2.0209

Tanner, P.W.G. and Sutherland, S. 2007. The Highland Border Complex, Scotland: a paradox resolved. *Journal of the Geological Society, London*, **164**, 111–116, https://doi.org/10.1144/0016-76492005-188

Tanner, P.W.G. and Thomas, P.R. 2010. Major nappe-like D2 folds in the Dalradian rocks of the Beinn Udlaidh area, Central Highlands, Scotland. *Transactions of the Royal Society of Edinburgh: Earth and Environmental Science*, **100**, 371–389, https://doi.org/10.1017/S1755691009009098

Tanner, P.W.G., Leslie, A.G. and Gillespie, M.R. 2006. Structural setting and petrogenesis of a rift-related intrusion: the Ben Vuirich Granite of the Grampian Highlands, Scotland. *Scottish Journal of Geology*, **42**, 113–136, https://doi.org/10.1144/sjg42020113

Tanner, P.W.G., Thomas, C.W., Harris, A.L., Gould, D., Harte, B., Treagus, J.E. and Stephenson, D. 2013. The Dalradian rocks of the Highland Border region of Scotland. *Proceedings of the Geologists' Association*, **124**, 215–262, https://doi.org/10.1016/j.pgeola.2012.07.013

Thomas, P.R. 1980. The stratigraphy and structure of the Moine rocks north of the Schiehallion Complex, Scotland. *Journal of the Geological Society, London*, **137**, 469–482, https://doi.org/10.1144/gsjgs.137.4.0469

Thomas, P.R. 1988. A9 road section Blair Atholl to Newtonmore. *In*: Allison, I., May, F. and Strachan, R.A. (eds) *An Excursion Guide to the Moine Geology of the Scottish Highlands*. Scottish Academic Press for Edinburgh Geological Society and Geological Society of Glasgow, Edinburgh, 39–50.

Treagus, J.E. 1987. The structural evolution of the Dalradian of the Central Highlands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **78**, 1–15, https://doi.org/10.1017/S0263593300010919

Treagus, J.E. 1991. Fault displacements in the Dalradian of the Central Highlands. *Scottish Journal of Geology*, **27**, 135–145, https://doi.org/10.1144/sjg27020135

Treagus, J.E. 1999. A structural reinterpretation of the Tummel Belt and a transpressional model of evolution of the Tay Nappe in the Central Highlands of Scotland. *Geological Magazine*, **136**, 643–660, https://doi.org/10.1017/S0016756899003143

Treagus, J.E. 2000. *The Solid Geology of the Schiehallion District*. Memoir of the British Geological Survey. Sheet 55W (Scotland). HMSO, London.

Treagus, J.E. and King, G. 1978. A complete Lower Dalradian succession in the Schiehallion district, central Perthshire. *Scottish Journal of Geology*, **14**, 157–166, https://doi.org/10.1144/sjg14020157

Treagus, J.E., Tanner, P.W.G., Thomas, P.R., Scott, R.A. and Stephenson, D. 2013. The Dalradian rocks of the Central Grampian Highlands of Scotland. *Proceedings of the Geologists' Association*, **124**, 148–214, https://doi.org/10.1016/j.pgeola.2012.07.009

Upton, P.S. 1986. A structural cross-section of the Moine and Dalradian rocks of the Braemar area. *Report of the British Geological Survey*, **17**, 9–19.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J. 1988. *An overview of the fundamentals of sequence stratigraphy and key definitions*. SEPM Special Publications, **42**. https://doi.org/10.2110/pec.88.01.0039

Winchester, J.A. and Glover, B.W. 1988. The Grampian Group, Scotland. *In:* Winchester, J.A. (ed.) *Later Proterozoic Stratigraphy of the Northern Atlantic Region*. Blackie, Glasgow, 146–161.