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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 south-western 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 D2 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. North-eastwards loss of strata of the Ballachulish, Blair Atholl and Islay subgroups, observed south-west of Tyndrum, contrasts with gradual reappearance of correlative units north-eastwards from Glen Lyon. Onlap and/or overstep relationships are well-preserved – although strain is enhanced locally along pronounced stratal/rheological contrasts, the stratigraphical framework remains essentially intact.

Our Scotland-wide analysis of the Dalradian depositional framework recognises other probable basin-scale unconformities that locally influenced patterns of superimposed orogenic deformation. [200 words]

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 (Lister *et al.* 1991; Kusznir *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/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 superposition 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 mineralisation (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 syn-depositional extensional detachments (increasingly recognised in modern passive margins, e.g. Reston *et al.* 2004), syn-depositional 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 syn-depositional (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, 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-recognised lower to mid-Dalradian stratigraphy has been traditionally interpreted as 'tectonic removal' (*cf*. Harris *et al.* 1994) and the impact of a syn- to post-D2 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 (i) late/post-orogenic extension (Hutton and Alsop 1995), or (ii) syn-depositional 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 long-standing 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 on Fig. 2; and see BGS 2013a,b; BGS 2014). These new data encompass the Boundary Slide structure – viewed as one of the most significant markers of syn-depositional intrabasinal extension within the recognised 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 1994a,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 (Aleinikoff *et al.* 1995; Kamo *et al.* 1989, 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). Northwest 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.* 2024); the shelf-carbonate rocks lay on the landward side (north-west in present-day co-ordinates) 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 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 south-eastwards with time (Stephenson and Gould 1995). Oceanic crust is presumed to have developed south-east 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 north-western parts of the Republic of Ireland (Figs. 1, 2). The succession is dominated by marine meta-sandstone, siltstone, mudstone, and carbonate rocks (Fig. 3A, Winchester and Glover 1988; Harris *et al.* 1978, 1994; Stephenson and Gould 1995; Smith *et al.* 1999), subdivided into an older Tonian–Cryogenian succession (the Grampian & 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.* 2024). 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 uppermost Tremadocian (*c.* 477 Ma) age (Fig. 3A, Pringle 1940; Tanner & 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; Hyslop and Piasecki 1999; Noble *et al.* 1996). Key to unravelling Dalradian stratigraphy is a number of region-wide events broadly synchronous across Scotland and Ireland that include: (i) transgressive flooding surfaces Stephenson *et al.* (2013), (e.g. the bases of the Ballachulish, Blair Atholl, and Crinan subgroups, Fig. 3A); (ii) Neoproterozoic glaciation events represented by units such as the Port Askaig Tillite Formation (Spencer 1971; McCay *et al.* 2006; Fairchild *et al.* 2018); and (iii) 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 my (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. Glover *et al.* 1995; Smith *et al.* 1999; Litherland 1980; Anderton 1985).

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 D2 deformation phase is the most pervasive of four phases regionally recognised. Megascopic D1 folds do exist (e.g. Krabbendam *et al.* 1997; Treagus 1987, 1999; Crane *et al.* 2002) but have been largely overprinted by pervasive and large-scale D2 structures (Roberts & Treagus 1975; Tanner & Thomas 2010). In the southern and south-eastern Grampian Highlands, the main D2 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 & Thomas 2010). D2 folds face to the south-east and may face downward where deformed by later fold phases; folding was accompanied by pervasive development of the dominant S2 foliation.

Broadly post-peak metamorphic folds assigned to D3 and D4 deformation phases fold and crenulate the main S2 foliation. These later episodes contribute to the complex outcrop patterns that include a number of recognised '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 D3 and D4 deformation resulted only in gentle upward doming such as the Drumochter Dome, (Leslie *et al.* 2006), and the Glen Orchy Dome (Tanner & Thomas 2011).

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 (D1–D4) 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 syn-depositional 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 is well-constrained at regional-scale, and broadly accepted (e.g. Stephenson *et al.* 2013; Prave *et al.* 2024). Issues remain, three of which are considered here.

1) Restrictions of composite stratigraphical columns

No single composite Dalradian stratigraphical column (Fig. 3B, *cf.* Fig. 6, Stephenson *et al.* 2013), or, indeed, *series* of composite columns (Fig. 10, Stephenson and Gould

1995; see also Harris *et al.* 1994), can successfully capture the detailed, laterally variable nature of the regional Dalradian depositional framework. While 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 which 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, *cf*. 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, Figure 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, *cf*. 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: a) syn-depositional faulting separating two sedimentologically distinct units; b) the Easdale Slate onlaps onto the Scarba Conglomerate; c) the Scarba Conglomerate onlaps onto the Easdale Slate; d) the two units interfinger, or grade into, each other. Simplified columns such as those illustrated in Fig. 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, 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 Fig. 4, column 3, albeit labelled as 'tectonically removed' (*cf*. Harris *et* *al.* 1994). In this paper, we address the fact that this stratigraphical gap is even greater locally.

2) 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 cite 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 authors 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 syn-depositional 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 localise lower Argyll Group sedimentation, eventually becoming overstepped by rapidly deposited sub-marine fan deposits of the upper Argyll and Southern Highland Group (see Stephenson and Gould 1995; Stephenson *et al.* 2013).

Much debate has focussed 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 (D2) strain and attenuation, along the boundary zone between the Grampian and Appin groups, from Dalmally to Glen Tilt (Roberts and Treagus 1977; Fig. 2), though 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 tectono-stratigraphical 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 up 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 (S2) 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 F2 folds and, despite carrying younger stratigraphy in the hanging wall, are associated with an overall sense of thrust movement towards the north-west. 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 re-activated in a reverse sense as thrusts during subsequent Grampian orogenic deformation.

3) Possible over-interpretation of the impact of syn-depositional (listric) normal faulting

Previous interpretations that proposed syn-depositional 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 localised 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 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 2013a,b 2014). Table 1 summarises 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 2013a,b, 2014), and see also the generalised descriptive account of Stephenson *et al*. (2013). The map of Fig. 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 3D); on the map these become triple or 'pinch-out points', marked as red circles on Fig. 5.

The Lochaber Subgroup in Breadalbane has been divided into a number of discrete and readily mappable units, in contrast with the more uniformly semipelitic lithology of the Leven Schist Formation in the Appin district west of Breadalbane. The diagnostic characteristics of the relevant formations are summarised in Table 2, including those of the Auch Gleann Psammite Formation (Glen Spean Subgroup) that everywhere precedes the Lochaber Subgroup succession, and those of units only observed in Breadalbane, e.g. 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 F2 Ben Lui Syncline and F4 Ben Lawers Synform (Fig. 5), regional-scale folds that are also recognised in the Schiehallion district further north-east (Treagus 1999, 2000; Fig. 2). In Breadalbane, recumbent, south-facing F2 folds (D2) deform rocks of the Grampian Group and the

Lochaber Subgroup in the north and north-west of the region (Fig. 5; see also Thomas 1980, 1988; Leslie *et al.* 2006; Tanner & 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), *cf.* the new geological map of Fig. 5. The axial surface of the south-facing F2 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 H-H' and section H-H', Fig. 6); further north-east 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 north-east (*cf*. 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 2013a, b 2014).

The maximum omission of type Dalradian stratigraphy can be demonstrated in Glen Lyon, where strata of the Ben Lui Schist Formation overly 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 on Fig. 5, *cf*. Fig. 3A).

The regional NE–SW strike of Dalradian strata is generally regarded as approximately parallel to the Iapetan palaeo-shoreline (Cawood *et al.* 2003; Anderton 1985). 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 D2 Ben Lui Syncline fold to better constrain depositional architecture in that general plane. Individual stratigraphical columns (Fig. 6B) summarise the sequence in each cross-section and highlight variations in the formal (BGS) stratigraphy. All sections reflect the same basic structure in which 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), *cf*. 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 with 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 (*cf*. Table 1).

To the north-east 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 north-eastwards (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 do suffer the same limitations as those published elsewhere (Harris *et al.* 1994; Stephenson and Gould 1995; BGS 2013a, 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 F3 (and F2) folds are ignored while 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 2005, Stephenson *et al.* 2013).

Grampian D2 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 D2 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 & Huber 1983; Ramsay *et al.* 1987). The geological relationships displayed on the published (BGS) geological maps are projected down dip in each sector, generally to the south, to portray the depositional geometry, focussing on locations where individual units are 'pinched out'; for comparison, the map of Fig. 5 can be viewed upside down!

Each pinch-out triple point is labelled (red circles on 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 the 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 north-east, 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 localised 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, 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) D2 shear (Harris *et al.* 1978; Nell 1986; Bradbury *et al.* 1979; Krabbendam *et al.* 1997; Rose & Harris 2000, Treagus 2000; *cf*. Mendum & Thomas 1997; Tanner 2014, 2016).

Due to the strong three-dimensional variability in both amount and vorticity (the component of simple shear with respect to pure shear) of D2 shear strain (Krabbendam *et al.* 1997; Treagus 1999; Tanner & 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 & 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 Fig. 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 Fig. 7B, the minor (parasitic) F2 folds identified in the upper, inverted limb in Glen Lochay (Fig. 7A) are accounted for and removed. Note that the Ben Lawers Schist is prominent in the (inverted) upper limb of the simplified fold structure (Area B, Glen Lochay), whilst absent in the hinge zone around Glen Lyon and in the right-way-up limb of the fold structure (Area A). In Fig. 7C, the major F2 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-D2 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 Psammite Formation) are succeeded by those of the Beinn a' Chaisteil Quartzite Formation, 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 on the Fig. 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 south-west 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 & K on 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 recognised 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 north-east (see Fig. 2), through the restoration for the Breadalbane district, to Islay in the south-west; this regional-scale schematic framework is illustrated in the upper and lower panels of Fig. 8, *cf*. Fig. 6C. As in the method for construction of Fig. 6C described above, we apply a first-order restoration of the superimposed deformation, undoing the major D2, D3 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 Fig. 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, D2 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 south-west (Argyllshire), to Glenlivet (Aberdeenshire) in the north-east.

The south-westernmost (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 recognised 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 syn-depositional faults (e.g. the Scarba Transfer Fault) are included in this part of the transect.

There is a marked change in stratigraphy north-eastwards 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 south-east into the plane of the Fig. 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 south-westward continuation of such an intrabasinal (fault-bound?) structural high separated these areas of post-Grampian Group deposition, at least as far south-west 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 north-eastwards 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 recognised 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 north-eastwards (upper panel) and regional-scale correlations are readily established at subgroup level with that of the type Loch Leven succession in the south-west.

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). South-west 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. While 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 north-east of the transect onlaps south-westwards onto strata of the Lochaber Subgroup from Schiehallion towards Loch Rannoch and Breadalbane (Fig. 8, upper panel and Fig. 6C) Volcanic rocks assigned to, or correlated with, the Farragon Volcanic Formation are more sporadically developed and represent localised volcanic outpourings that accumulated as basin instability increased (Stephenson *et al.* 2013).

All of that intrabasinal variability is submerged in Crinan Subgroup time; mud-dominated deposits of the Ben Lui Schist Formation are recognised across much of the transect of Fig. 8 (including Breadalbane) but change progressively south-westwards to the more sand-dominated Crinan Grit Formation assigned to this subgroup in the south-west (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 south-west, 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 four-kilometre-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 Fig. 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 decrease in relative sea level (RSL), leading to sediment reworking (winnowing). Strata of the Beinn a’ Chaisteil Quartzite Formation are succeeded by an essentially muddying-upwards 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 south-west end of the transect around Ben Lui records relatively uniform accumulation of muddy (pelitic and semipelitic) strata that comprise the Leven Schist Formation (DALS/DAIN).

The restored geometry of these formations and their pinch-out points (i.e. points B, C and D on 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 sees more localised accumulation/preservation of strata that comprise the Beinn Dorain Semipelite Formation with possible offlap relationships recorded in the Meggernie sector (pinch-out points A, B on Figs. 5, 6C) and locally north-west of Beinn a’ Chaisteil (pinch-out point P on Figs. 5, 6C). Erosion is also possible at this time; strata of 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 on 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, B on 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 localised 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 high stand 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 Fig. 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 with the preceding and continuous succession of the Lochaber Subgroup, south-westwards into the Breadalbane district from Schiehallion. This suggests that sediment supply is likely to have been much more continuous in this sector north-east 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 simplistic 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 (*cf.* (Roberts and Treagus 1977; Treagus 1987). Such interpretations have always suffered from 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 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 recognised 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. Catuneanu 2022; Embry 2009; Van Wagoner *et al.* 1988). Overall, the stratigraphy of the Lochaber Subgroup of the Breadalbane district records a muddying upwards 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, whilst greater accommodation space was being generated to the north-east and south-west 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 (Cawood *et al*. 2003; Anderton 1985) and that context is assumed for the reconstructions of Fig. 9.

At end-Grampian Group times (Fig. 9, block A), 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 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 south-eastern flank of the (proto-)Ericht-Laiden Fault (Fig. 9, block A), 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. 9, block B), 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 & 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 localised 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 south-eastern 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 relative sea level (RSL) increased and transgression occurred (Fig. 9, block C). Consequently, the stratigraphical boundary marking the upwards 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-upwards facies succession recorded by the upwards 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. 9, block C) 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 compartmentalise 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 north-west (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. 9, block C). 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. 9, uppermost unit of block C). We suggest a reducing rate of RSL rise by this time thus stabilising depositional environments in the larger scale basin and permitting the 'type' Appin Group stratigraphy seen in south-west and north-east Scotland. The top of this unit would mark a Maximum Transgressive Surface. Localised uplift on the south-eastern 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 on 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. 9, block D). 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 localised and limited intrabasinal uplift, would have resulted in a net reduction in relative sea level and progradation of the shelf from the north. The fall in sea level will have destabilised the basin shelf, cascading reworked sediment down into the deeper setting as frequent turbidite flows. North-east of Tyndrum (Fig. 5), and on either side of the trace of the Tyndrum Fault, the Carn Mairg Quartzite Formation probably represents localised incursion of channelised(?) 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. 9, blocks D–F).

In upper Easdale Subgroup times (Fig. 9, block E), it seems likely that relative sea level and basin-wide sediment supply had stabilised, 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, 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, 2024).

By latest Easdale Subgroup times (Fig. 9, block E), 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 north-east (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. 9, uppermost unit of block E). 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. 9, block F).

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 localised 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 re-interpreted. 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 focussed 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 methodology 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 recognised and interpreted in a first-order sequence-stratigraphical framework. [Main text: 10327 words]

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Figure and Table Captions: Figures 1–9 and Tables 1 & 2:

Figure 1:

Simplified pre-Iapetan reconstruction showing the distribution of Late-Neoproterozoic ('Dalradian-equivalent') and Cambro-Ordovician shelf sediments on the Eastern Laurentian margin. ES = Eastern Svalbard, WS = West Svalbard. Adapted from Cawood *et al*. (2007); Harland (1997); Peel & Sønderholm (1991); Smith (2000).

Figure 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. Modified after Stephenson & Gould (1995). The boxed outline indicates the location of the map in Figure 5. Contains BGS Geology 625 000 Data, BGS © UKRI. Hillshading uses NEXTMap Britain elevation data from Intermap Technologies.

Figure 3A:

Timing of the Neoproterozoic to Lower Paleozoic Laurentian stratigraphy of Scotland (adapted from Leslie et al. 2008), 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 (McCay *et al*. 2006; Prave *et al*. 2016, 2024) and a tentative chronologically unconstrained set of basin-wide flooding surfaces (*f*) suggested by the Neoproterozoic depositional record. Reliable biostratigraphical ages are only preserved in the 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 (Pringle 1940; Tanner 1995; Tanner and Sutherland 2007).The timing of the principal orogenic events is shown schematically; ▲ indicates glacigenic boulder beds.

Figure 3B:

Schematic overview of the principal and widely recognized stratigraphical units of the Dalradian Supergroup in Scotland. Modified after Harris *et al*. (1994); Trossachs group added after Tanner and Sutherland (2007 and BGS (2008). The age constraints are reviewed by Leslie *et al*. (2008) and Prave *et al.* (2016, 2024), see also Fig. 3A). Note that these strata do not anywhere occur together in a single district or recorded succession.

Figure 4:

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

Figure 5:

Simplified geological map of Tyndrum – Glen Lyon (Breadalbane) district, modified after BGS (2013a, b, 2014). The uncoloured polygons adjacent to the southern end of the Bridge of Balgie Fault represent a microgranite intrusion. The section lines of Fig. 6A (A–A' to H–H') and Fig. 7 (J– J') are superimposed, their various alignments reflect the sinuous nature of the trace of the D2 Ben Lui Syncline fold in this region. Red circles identified by letter (A–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 3D. 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). Contains BGS 50k data, BGS © UKRI. Hillshading uses NEXTMap Britain elevation data from Intermap Technologies.

Figure 6:

A) Simplified cross-sections A–A' to H–H', (locations on Figure 5) in order to help reconstruct depositional architecture across the region. Data for section H-H' – Ben Lui after Tanner & Thomas, (2010). B) Individual stratigraphical columns summarising the strata identified in each of the sections in A) above. 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 of Fig. 6A. Minor F3 (and F2) folds are ignored while major ones are restored (as described in the text). See also discussion in text of relative X and Y scales adopted for this figure. The Loch Tay Limestone is chosen as a palaeo-horizontal for this transect, as it represents basin-wide flooding event.

Figure 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). In Figure B), the minor (parasitic) F2 folds are removed. In Figure 7C), the major F2 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-D2 continuity with right-way-up rock rocks in the lower (upright) limb of the Ben Lui Syncline.

Figure 8:

Schematic section constructed along regional strike to illustrate the Dalradian depositional framework from south-west to north-east Scotland, constrained by projection of published regional geological mapping across Scotland, supported by local transverse cross-section constructions similar to our reconstruction of Fig. 6C. Minor F3 (and F2) folds are ignored while major ones are restored in the manner described in the text for Fig. 7. See discussion in text of relative X and Y scales adopted for this figure. The Loch Tay Limestone is chosen as a palaeo-horizontal for this regional-scale transect, the depositional framework is described in the text.

Figure 9:

Schematic 3D illustrations (blocks A-F) 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. Note 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 (Cawood *et al*. 2003; Anderton 1985) and is assumed as the context for these reconstructions. Note that the vertical scale is exaggerated with respect to the horizontal in order to display the necessary detail. Individual formation colours used here are exactly as those for the preceding Figs. 5–7. See discussion of sedimentological evolution in main text.

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 generalised descriptive account of Stephenson et al. (2013). The stratigraphic nomenclature (of Table 1 group/subgroup etc.) encompasses all of the individual units depicted in Figs. 5–7.

Table 2:

Descriptions of previously unrecognised Dalradian lithostratigraphical units in the Breadalbane district between Glen Orchy and Glen Lyon, south-west Grampian Highlands of Scotland. These units are placed within the overall stratigraphical succession for the region in shown in the map of Fig. **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 Figs. 5–8.

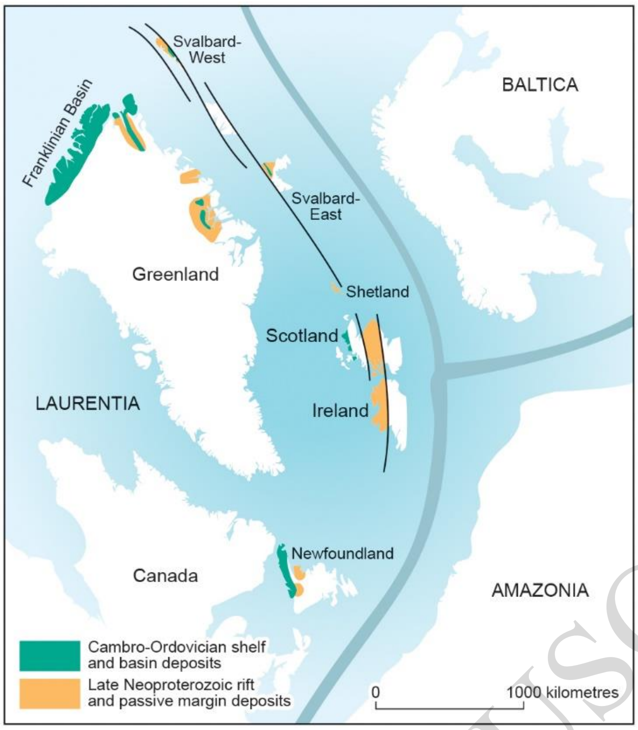
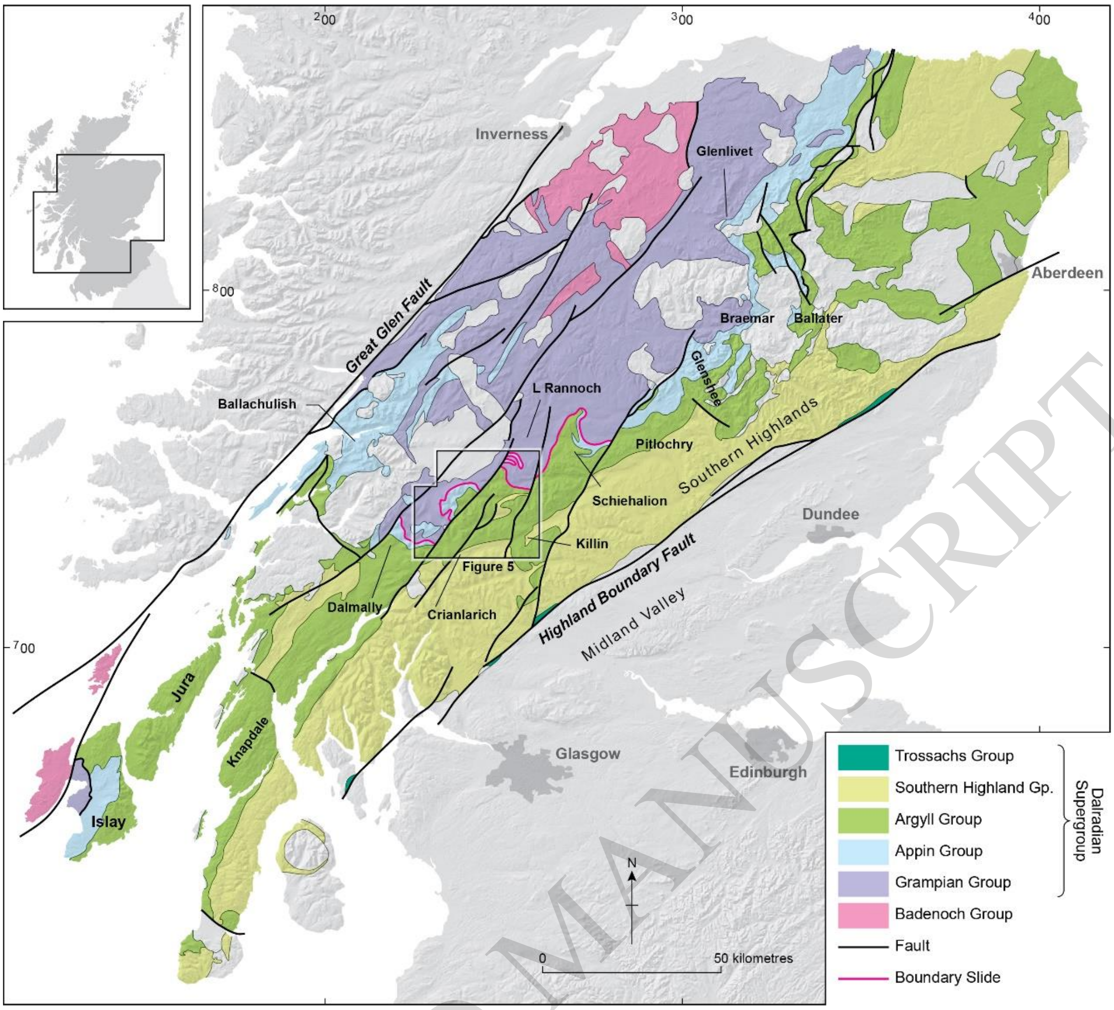
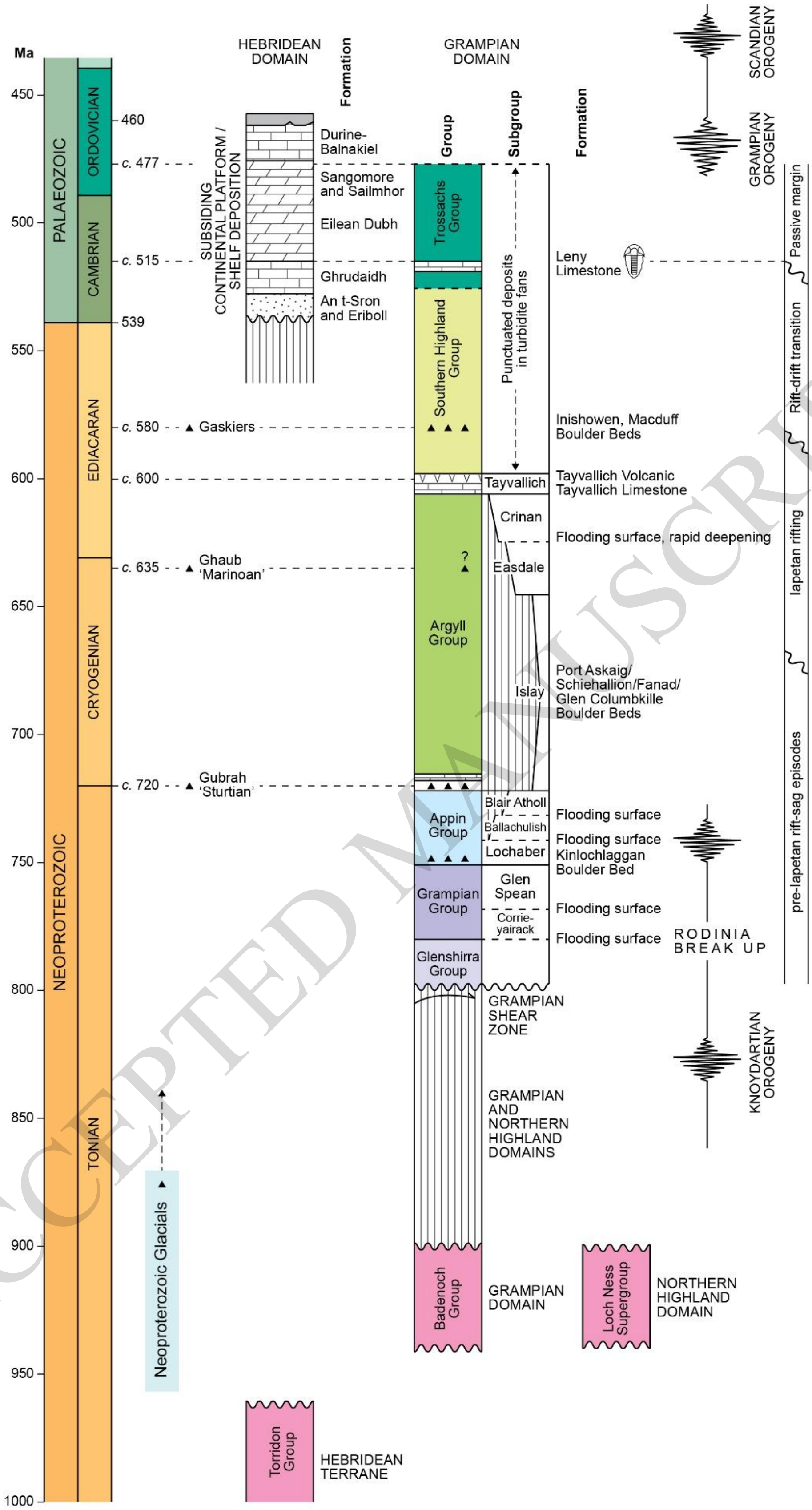

Svalbard-
West
BALTICA
Franklinian Basin
Svalbard-
East
Greenland
Shetland
Scotland
LAURENTIA
Ireland
Newfoundland
Canada
AMAZONIA
Cambro-Ordovician shelf
and basin deposits
Late Neoproterozoic rift
and passive margin deposits
0
1000 kilometres

Figure 1



2 00
3 00
4 00
8 00
7 00
Inverness
Glenlivet
Aberdeen
Great Glen Fault
Braemar
Ballater
Glenshee
L Rannoch
Ballachulish
Pitlochry
Southern Highlands
Schiehalion
Dundee
Killin
Figure 5
Highland Boundary Fault
Dalmally
Crianlarich
Midland Valley
Jura
Knapdale
Glasgow
Edinburgh
Islay
N
0
50 kilometres
Trossachs Group
Southern Highland Gp.
Argyll Group
Appin Group
Grampian Group
Badenoch Group
Fault
Boundary Slide
Dalradian Supergroup

Figure 2



Ma
HEBRIDEAN DOMAIN
Formation
GRAMPIAN DOMAIN
Group
Subgroup
Formation
SCANDIAN OROGENY
GRAMPIAN OROGENY
PALAEOZOIC
ORDOVICIAN
CAMBRIAN
NEOPROTEROZOIC
EDIACARAN
CRYOGENIAN
TONIAN
450
500
550
600
650
700
750
800
850
900
950
1000
460
c. 477
c. 515
539
c. 580
c. 600
c. 635
c. 720
SUBSIDING CONTINENTAL PLATFORM / SHELF DEPOSITION
Durine-Balnakiel
Sangomore and Sailmhor
Eilean Dubh
Ghrudaidh
An t-Sron and Eriboll
Gaskiers
Ghaub 'Marinoan'
Gubrah 'Sturtian'
Trossachs Group
Southern Highland Group
Punctuated deposits in turbidite fans
Leny Limestone
Inishowen, Macduff Boulder Beds
Tayvallich
Tayvallich Volcanic
Tayvallich Limestone
Crinan
Flooding surface, rapid deepening
Easdale
Argyll Group
Islay
Port Askaig/ Schiehallion/Fanad/ Glen Columbkille Boulder Beds
Appin Group
Blair Atholl
Ballachulish
Lochaber
Flooding surface
Flooding surface
Kinlochlaggan Boulder Bed
Grampian Group
Glen Spean
Corrie-yairack
Flooding surface
Flooding surface
Glenshirra Group
RODINIA BREAK UP
GRAMPIAN SHEAR ZONE
GRAMPIAN AND NORTHERN HIGHLAND DOMAINS
KNOYDARTIAN OROGENY
Passive margin
Rift-drift transition
Iapetan rifting
pre-Iapetan rift-sag episodes
Neoproterozoic Glacials
Badenoch Group
GRAMPIAN DOMAIN
Loch Ness Supergroup
NORTHERN HIGHLAND DOMAIN
Torridon Group
HEBRIDEAN TERRANE

Figure 3A

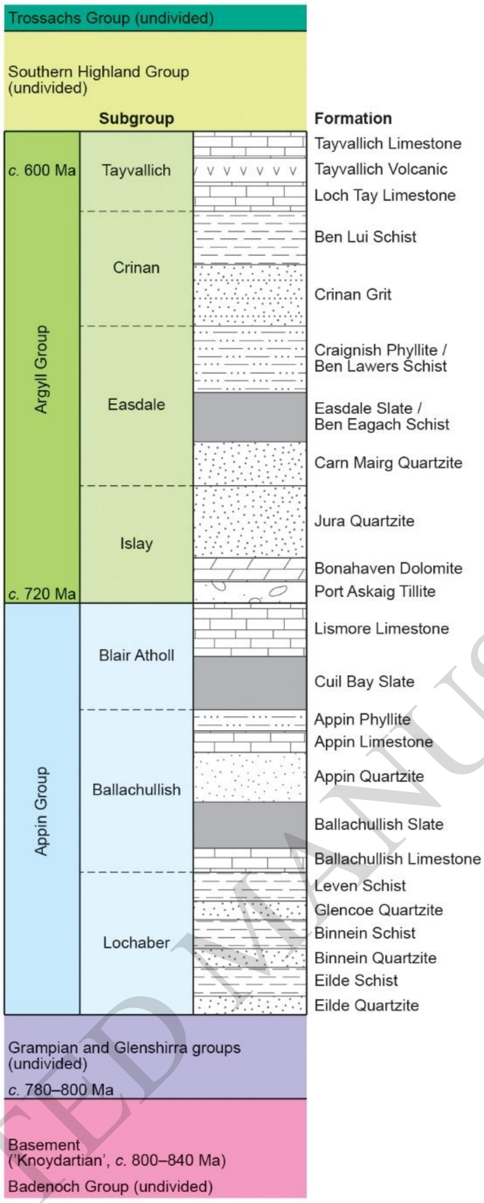

Trossachs Group (undivided)
Southern Highland Group (undivided)
Subgroup
Formation
c. 600 Ma
Tayvallich
Tayvallich Limestone
Tayvallich Volcanic
Loch Tay Limestone
Crinan
Ben Lui Schist
Crinan Grit
Argyll Group
Easdale
Craignish Phyllite / Ben Lawers Schist
Easdale Slate / Ben Eagach Schist
Carn Mairg Quartzite
Islay
Jura Quartzite
Bonahaven Dolomite
Port Askaig Tillite
c. 720 Ma
Blair Atholl
Lismore Limestone
Cuil Bay Slate
Appin Group
Ballachullish
Appin Phyllite
Appin Limestone
Appin Quartzite
Ballachullish Slate
Ballachullish Limestone
Lochaber
Leven Schist
Glencoe Quartzite
Binnein Schist
Binnein Quartzite
Eilde Schist
Eilde Quartzite
Grampian and Glenshirra groups (undivided)
c. 780–800 Ma
Basement ('Knoydartian', c. 800–840 Ma)
Badenoch Group (undivided)

Figure 3B

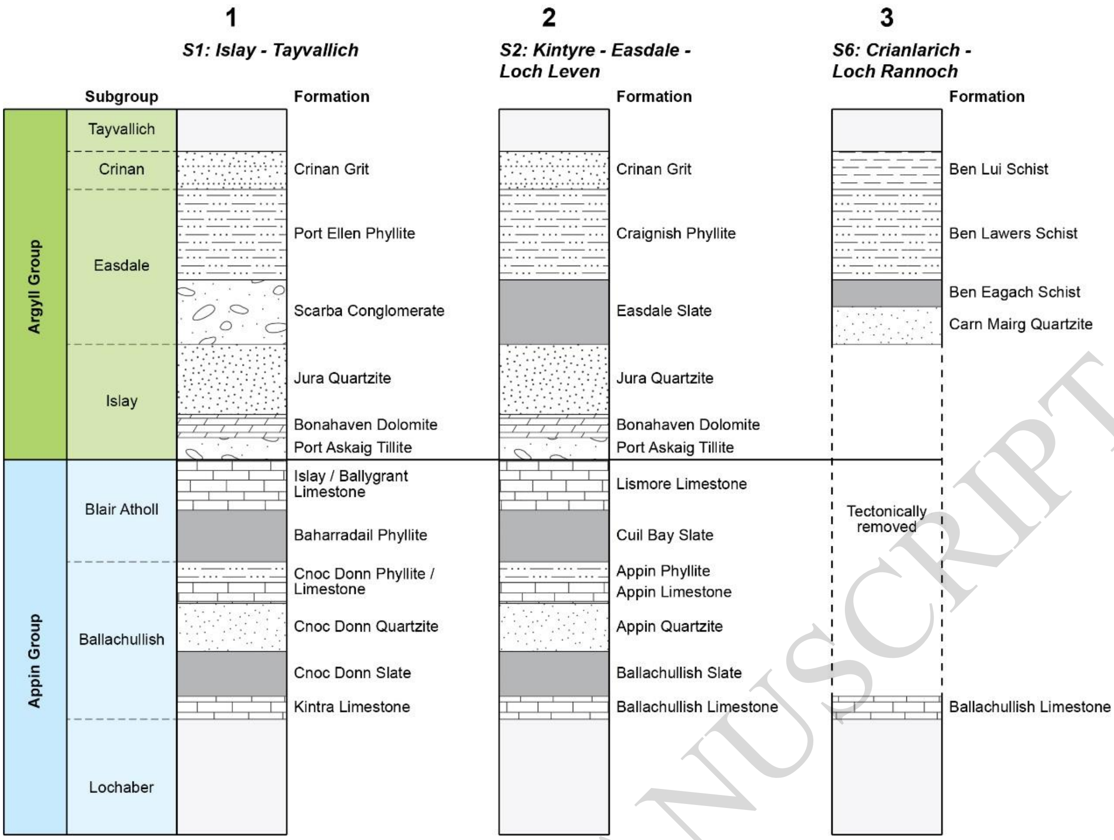

1
S1: Islay - Tayvallich
2
S2: Kintyre - Easdale - Loch Leven
3
S6: Crianlarich - Loch Rannoch
Subgroup
Formation
Formation
Formation
Argyll Group
Appin Group
Tayvallich
Crinan
Easdale
Islay
Blair Atholl
Ballachullish
Lochaber
Crinan Grit
Port Ellen Phyllite
Scarba Conglomerate
Jura Quartzite
Bonahaven Dolomite
Port Askaig Tillite
Islay / Ballygrant Limestone
Baharradail Phyllite
Cnoc Donn Phyllite / Limestone
Cnoc Donn Quartzite
Cnoc Donn Slate
Kintra Limestone
Crinan Grit
Craignish Phyllite
Easdale Slate
Jura Quartzite
Bonahaven Dolomite
Port Askaig Tillite
Lismore Limestone
Cuil Bay Slate
Appin Phyllite
Appin Limestone
Appin Quartzite
Ballachullish Slate
Ballachullish Limestone
Ben Lui Schist
Ben Lawers Schist
Ben Eagach Schist
Carn Mairg Quartzite
Tectonically removed
Ballachullish Limestone

Figure 4

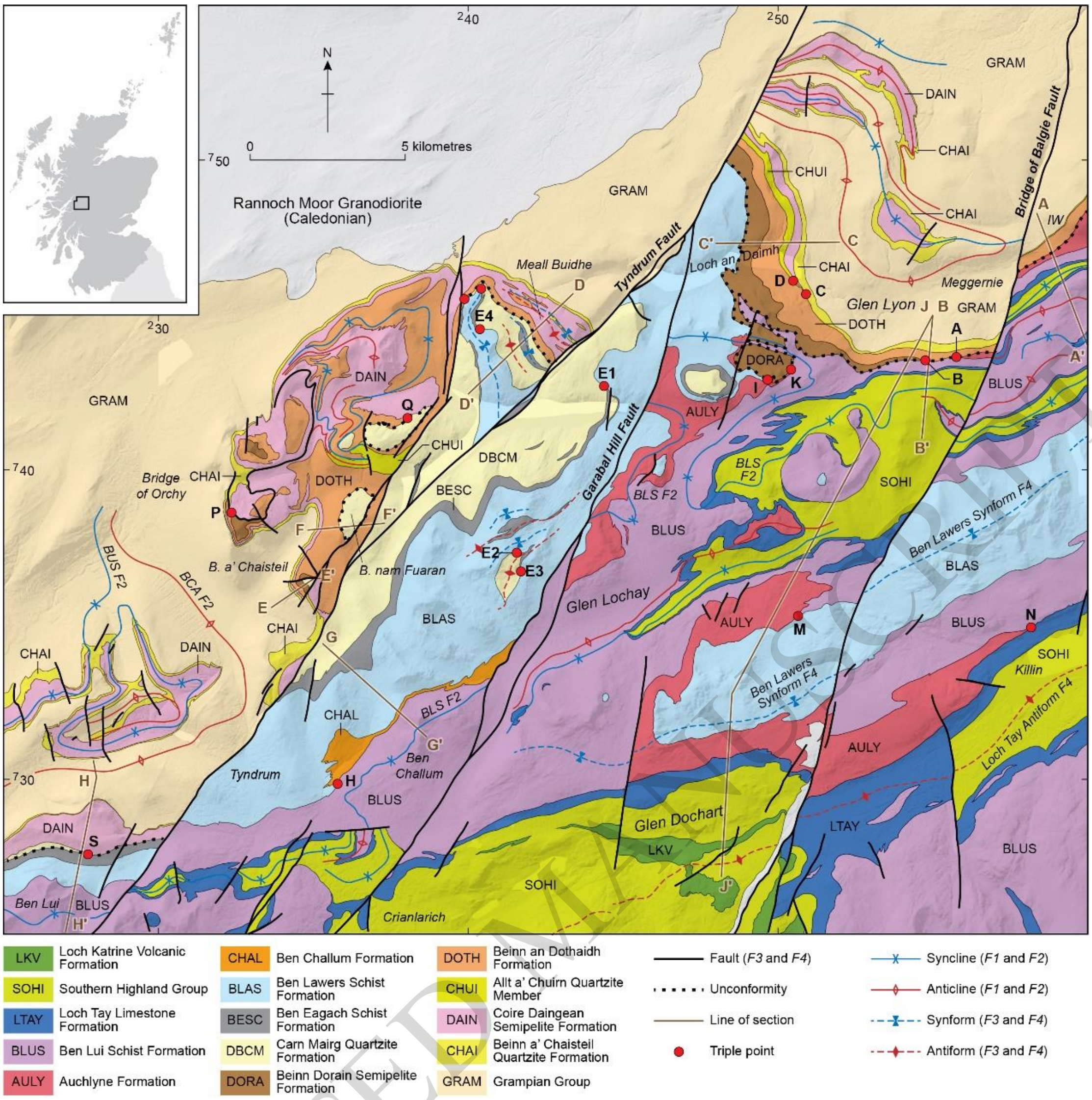
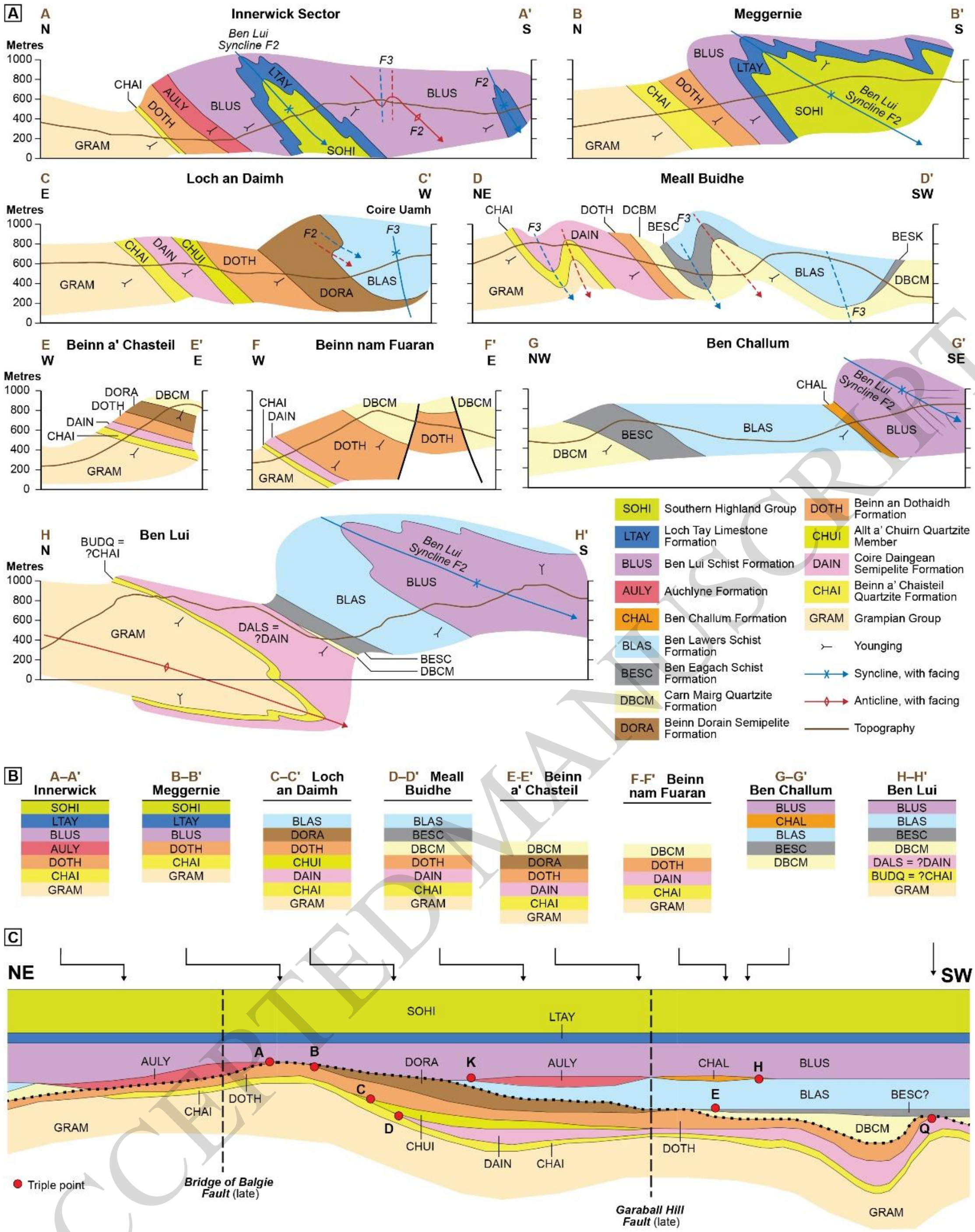

Rannoch Moor Granodiorite
(Caledonian)
N
0
5 kilometres
GRAM
Tyndrum Fault
Garabal Hill Fault
Bridge of Balgie Fault
Meall Buidhe
Loch an Daimh
Glen Lyon
Meggernie
Bridge of Orchy
B. a' Chaisteil
B. nam Fuaran
Glen Lochay
Ben Lawers Synform F4
Loch Tay Antiform F4
Tyndrum
Ben Challum
Glen Dochart
Crianlarich
Killin
Ben Lui
BUS F2
BCA F2
BLS F2
LKV Loch Katrine Volcanic Formation
SOHI Southern Highland Group
LTAY Loch Tay Limestone Formation
BLUS Ben Lui Schist Formation
AULY Auchlyne Formation
CHAL Ben Challum Formation
BLAS Ben Lawers Schist Formation
BESC Ben Eagach Schist Formation
DBCM Carn Mairg Quartzite Formation
DORA Beinn Dorain Semipelite Formation
DOTH Beinn an Dothaidh Formation
CHUI Allt a' Chuirn Quartzite Member
DAIN Coire Daingean Semipelite Formation
CHAI Beinn a' Chaisteil Quartzite Formation
GRAM Grampian Group
Fault (F3 and F4)
Unconformity
Line of section
Triple point
Syncline (F1 and F2)
Anticline (F1 and F2)
Synform (F3 and F4)
Antiform (F3 and F4)

Figure 5



A
Innerwick Sector
Meggernie
Loch an Daimh
Meall Buidhe
Beinn a' Chasteil
Beinn nam Fuaran
Ben Challum
Ben Lui
Ben Lui Syncline F2
Metres
Coire Uamh
SOHI Southern Highland Group
LTAY Loch Tay Limestone Formation
BLUS Ben Lui Schist Formation
AULY Auchlyne Formation
CHAL Ben Challum Formation
BLAS Ben Lawers Schist Formation
BESC Ben Eagach Schist Formation
DBCM Carn Mairg Quartzite Formation
DORA Beinn Dorain Semipelite Formation
DOTH Beinn an Dothaidh Formation
CHUI Allt a' Chuirn Quartzite Member
DAIN Coire Daingean Semipelite Formation
CHAI Beinn a' Chaisteil Quartzite Formation
GRAM Grampian Group
Younging
Syncline, with facing
Anticline, with facing
Topography
B
C
NE
SW
Triple point
Bridge of Balgie Fault (late)
Garaball Hill Fault (late)
BUDQ = ?CHAI
DALS = ?DAIN
BESC?

Figure 6

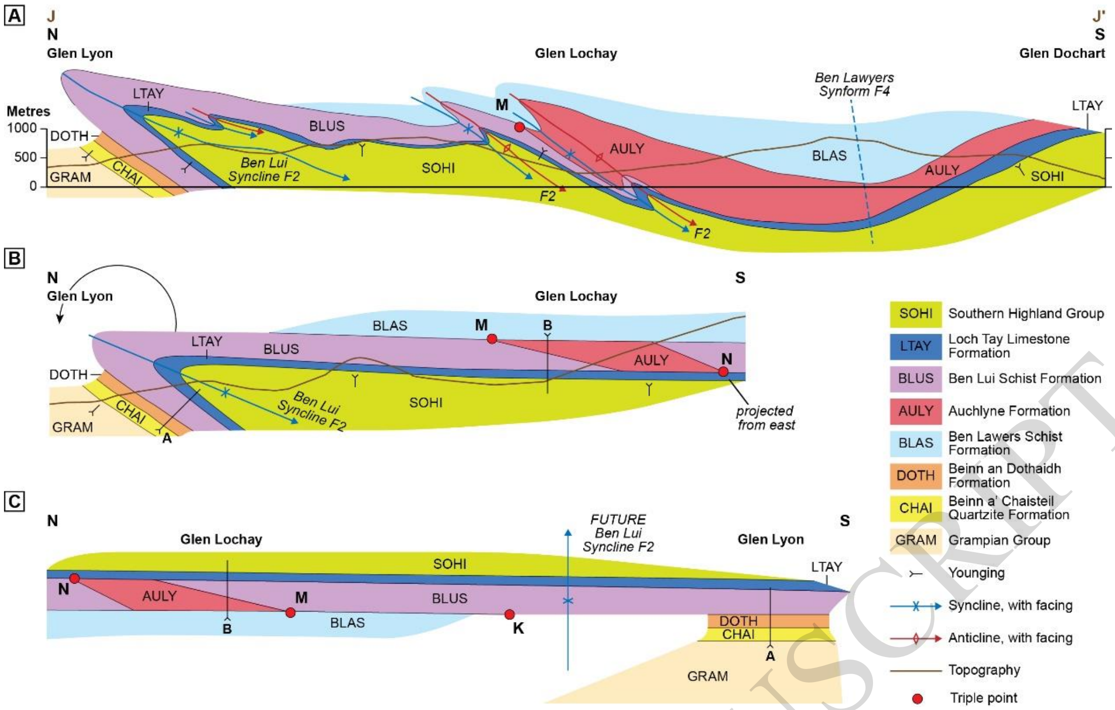
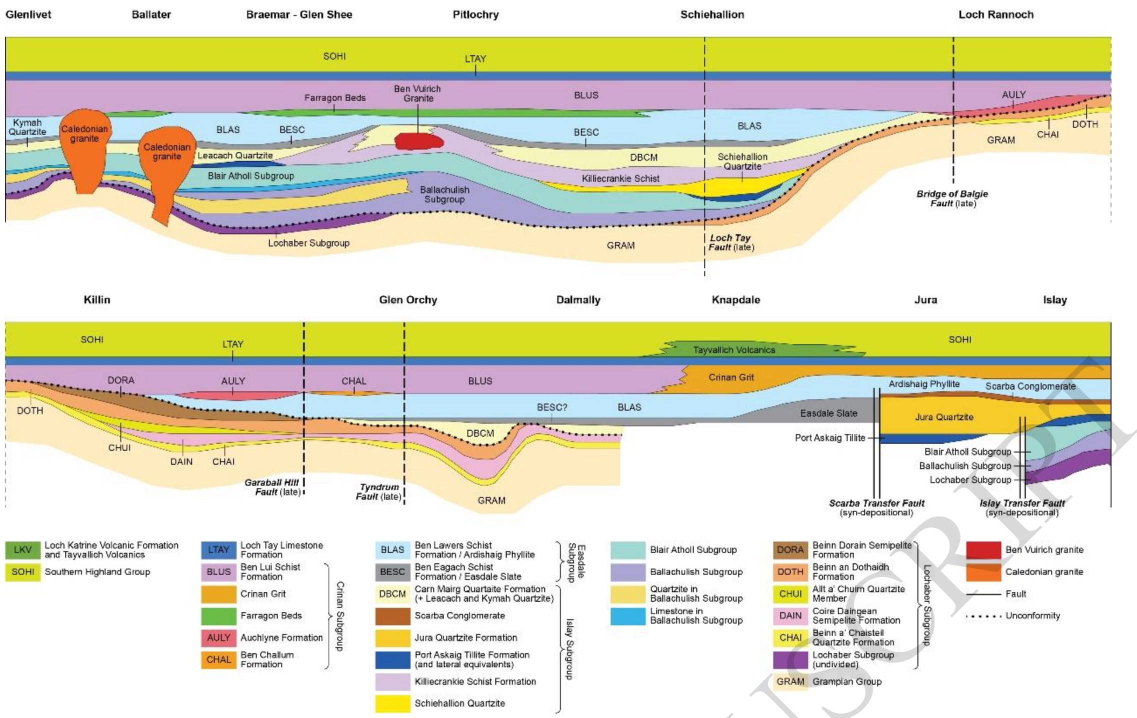

A
J
J'
N
S
Glen Lyon
Glen Lochay
Glen Dochart
Metres
1000
500
0
DOTH
GRAM
CHAI
LTAY
BLUS
Ben Lui Syncline F2
SOHI
M
AULY
F2
Ben Lawyers Synform F4
BLAS
AULY
SOHI
LTAY
B
N
S
Glen Lyon
Glen Lochay
LTAY
BLUS
BLAS
M
B
AULY
N
DOTH
GRAM
CHAI
A
Ben Lui Syncline F2
SOHI
projected from east
C
N
S
Glen Lochay
FUTURE Ben Lui Syncline F2
Glen Lyon
SOHI
LTAY
N
AULY
M
BLUS
BLAS
K
B
DOTH
CHAI
A
GRAM
SOHI Southern Highland Group
LTAY Loch Tay Limestone Formation
BLUS Ben Lui Schist Formation
AULY Auchlyne Formation
BLAS Ben Lawers Schist Formation
DOTH Beinn an Dothaidh Formation
CHAI Beinn a' Chaisteil Quartzite Formation
GRAM Grampian Group
Younging
Syncline, with facing
Anticline, with facing
Topography
Triple point

Figure 7



Glenlivet
Ballater
Braemar - Glen Shee
Pitlochry
Schiehallion
Loch Rannoch
SOHI
LTAY
Ben Vuirich Granite
Farragon Beds
BLUS
AULY
Kymah Quartzite
Caledonian granite
Caledonian granite
BLAS
BESC
BESC
BLAS
GRAM
CHAI
DOTH
Leacach Quartzite
DBCM
Schiehallion Quartzite
Blair Atholl Subgroup
Killiecrankie Schist
Ballachulish Subgroup
Bridge of Balgie Fault (late)
Lochaber Subgroup
GRAM
Loch Tay Fault (late)
Killin
Glen Orchy
Dalmally
Knapdale
Jura
Islay
SOHI
LTAY
Tayvallich Volcanics
SOHI
DORA
AULY
CHAL
BLUS
Crinan Grit
Ardishaig Phyllite
Scarba Conglomerate
DOTH
BESC?
BLAS
Easdale Slate
Jura Quartzite
DBCM
Port Askaig Tillite
CHUI
DAIN
CHAI
Blair Atholl Subgroup
Ballachulish Subgroup
Lochaber Subgroup
Garaball Hill Fault (late)
Tyndrum Fault (late)
GRAM
Scarba Transfer Fault (syn-depositional)
Islay Transfer Fault (syn-depositional)
LKV Loch Katrine Volcanic Formation and Tayvallich Volcanics
SOHI Southern Highland Group
LTAY Loch Tay Limestone Formation
BLUS Ben Lui Schist Formation
Crinan Grit
Farragon Beds
AULY Auchlyne Formation
CHAL Ben Challum Formation
Crinan Subgroup
BLAS Ben Lawers Schist Formation / Ardishaig Phyllite
BESC Ben Eagach Schist Formation / Easdale Slate
Easdale Subgroup
DBCM Carn Mairg Quartaite Formation (+ Leacach and Kymah Quartzite)
Scarba Conglomerate
Jura Quartzite Formation
Port Askaig Tillite Formation (and lateral equivalents)
Killiecrankie Schist Formation
Schiehallion Quartzite
Islay Subgroup
Blair Atholl Subgroup
Ballachulish Subgroup
Quartzite in Ballachulish Subgroup
Limestone in Ballachulish Subgroup
DORA Beinn Dorain Semipelite Formation
DOTH Beinn an Dothaidh Formation
CHUI Allt a' Chuim Quartzite Member
DAIN Coire Daingean Semipelite Formation
CHAI Beinn a' Chaisteil Quartzite Formation
Lochaber Subgroup (undivided)
Lochaber Subgroup
GRAM Grampian Group
Ben Vuirich granite
Caledonian granite
Fault
Unconformity

Figure 8

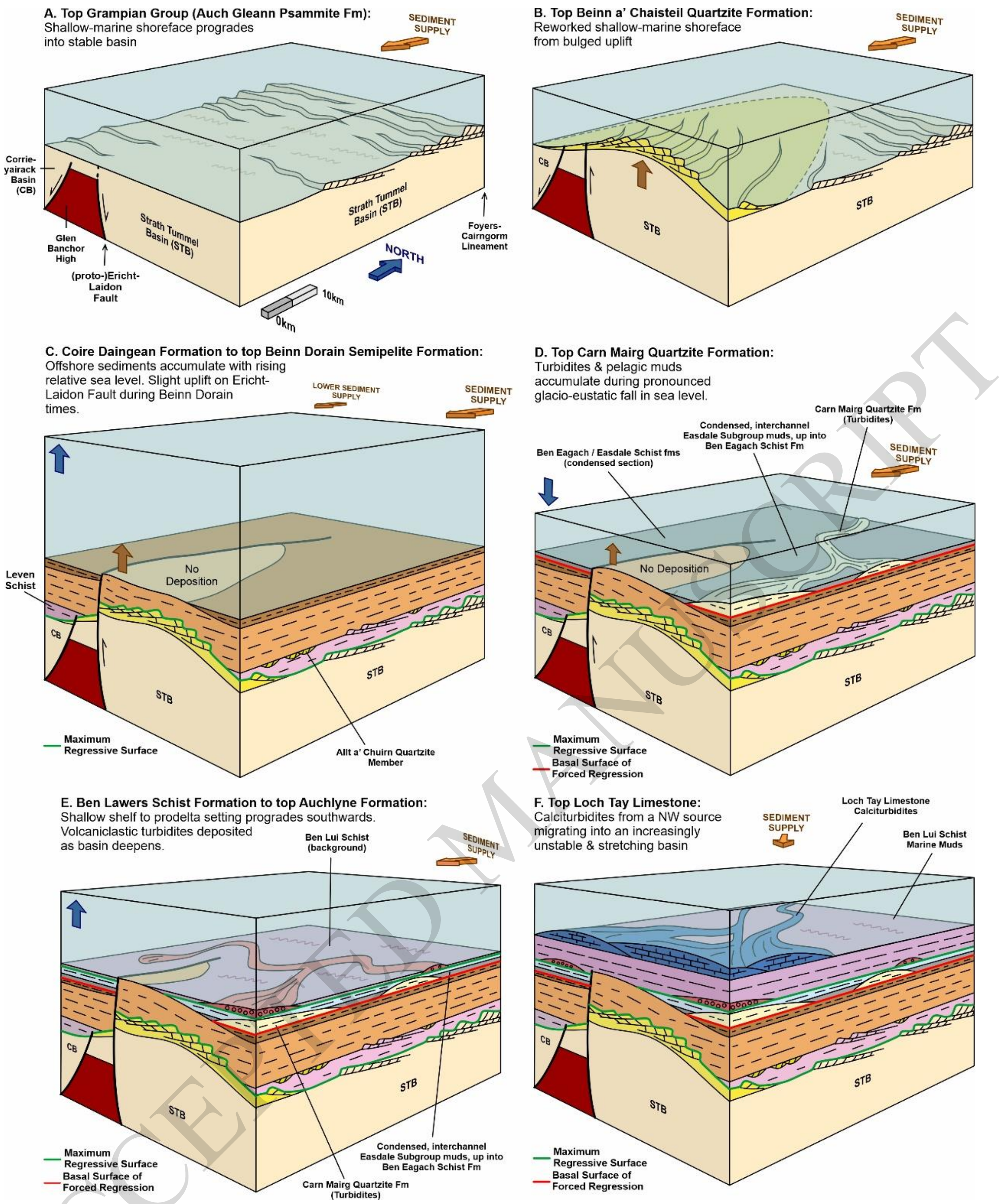

A. Top Grampian Group (Auch Gleann Psammite Fm):
Shallow-marine shoreface progrades into stable basin
SEDIMENT SUPPLY
Corrie-yairack Basin (CB)
Glen Banchor High
(proto-)Ericht-Laidon Fault
Strath Tummel Basin (STB)
Strath Tummel Basin (STB)
Foyers-Cairngorm Lineament
NORTH
0km
10km
B. Top Beinn a' Chaisteil Quartzite Formation:
Reworked shallow-marine shoreface from bulged uplift
SEDIMENT SUPPLY
CB
STB
STB
C. Coire Daingean Formation to top Beinn Dorain Semipelite Formation:
Offshore sediments accumulate with rising relative sea level. Slight uplift on Ericht-Laidon Fault during Beinn Dorain times.
LOWER SEDIMENT SUPPLY
SEDIMENT SUPPLY
Leven Schist
No Deposition
CB
STB
STB
Maximum Regressive Surface
Allt a' Chuirn Quartzite Member
D. Top Carn Mairg Quartzite Formation:
Turbidites & pelagic muds accumulate during pronounced glacio-eustatic fall in sea level.
Carn Mairg Quartzite Fm (Turbidites)
Condensed, interchannel Easdale Subgroup muds, up into Ben Eagach Schist Fm
Ben Eagach / Easdale Schist fms (condensed section)
SEDIMENT SUPPLY
No Deposition
CB
STB
STB
Maximum Regressive Surface
Basal Surface of Forced Regression
E. Ben Lawers Schist Formation to top Auchlyne Formation:
Shallow shelf to prodelta setting progrades southwards. Volcaniclastic turbidites deposited as basin deepens.
Ben Lui Schist (background)
SEDIMENT SUPPLY
CB
STB
STB
Maximum Regressive Surface
Basal Surface of Forced Regression
Condensed, interchannel Easdale Subgroup muds, up into Ben Eagach Schist Fm
Carn Mairg Quartzite Fm (Turbidites)
F. Top Loch Tay Limestone:
Calciturbidites from a NW source migrating into an increasingly unstable & stretching basin
SEDIMENT SUPPLY
Loch Tay Limestone Calciturbidites
Ben Lui Schist Marine Muds
CB
STB
STB
Maximum Regressive Surface
Basal Surface of Forced Regression

Figure 9

Table 1

Group	Subgroup	Area of interest: Tyndrum–Dalmally	Area of interest: Tyndrum–Loch Lyon	Area of interest: Glen Lyon–Killin
Group	**Subgroup**	**Formation present**		
Southern Highland		Pitlochry Schist Formation	Pitlochry Schist Formation	Pitlochry Schist Formation
Argyll Group	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
	Easdale Subgroup	Ardrishaig Phyllite Formation	Ben Challum/ Auchlyne formations	Farragon Volcanic/ Auchlyne formations
			Ben Lawers Schist Formation	Ben Lawers Schist Formation
		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 (*incl. 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

Table 2

Lithostratigraphy			**Lithology**	**Thickness**
Argyll Group	**Easdale Subgroup**	*Ben Challum Formation [CHAL]*	Occurs west of the Garabal Hill Fault, BGS (2013b): 5–10 cm-scale bedded pale brown quartzite to quartzose psammite with subsidiary (30%) cm-scale layers of schistose quartz-muscovite +/- biotite semipelitic schist interbeds at the same scale. Hornblende-bearing schist layers (30–40 cm thick) are conspicuous. Upwards change from Ben Lawers Schist Formation calcareous ‘pitted’ psammite and semipelite is sharp with a marked decrease (from 50% or more) semipelite content. The upper boundary with the Ben Lui Schist Formation is sharp and oversteps the south-westwards disappearance of quartzite.	*c.* 20 m
		Auchlyne Formation [AULY]	Occurs east of the Garabal Hill Fault, BGS (2013b): 5–20 cm thick layers of interbedded psammite, micaceous psammite, garnet-mica schist, and quartz-garnet-mica schist; small mm-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 upwards 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 dia.) garnets always appear fresh (dark red) compared to frequently chloritised 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. 1–2 mm in diameter muscovite-wrapped garnets are typical. Grey colour Weathers grey/brown to brown. A lower calcareous semipelite unit with characteristic pitted	*c.* 70 m overall, lower calc. unit 0–30 m

			weathering surfaces is interbedded with massive garnet-mica schist; graphitic pelite occurs locally at the top of the formation.	
		Beinn a' Chaisteil Quartzite Fm. [CHAI]	0.1–1 m thick stacked sheet-like beds 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 Formation [AUGL]*	'Salt & 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, mm-scale internal lamination reflects minor composition changes (mica versus 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 herring-bone 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