The Dalradian rocks of the northern Grampian Highlands of Scotland

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Abstract

The Northern Grampian Highlands are dominated by the outcrop of the Grampian Group, together with infolds and structural outliers of Appin Group strata and inliers of pre-Dalradian 'basement', consisting of Badenoch Group metasedimentary rocks. The south-eastern limit of this mountainous region corresponds with the regionally continuous Grampian Group-Appin Group boundary, which in the south is marked by a high-strain zone corresponding to the Boundary Slide of some authors. The more arbitrary southern boundary runs north-west from Blair Atholl along the A9 road and then westwards to Fort William.

The Neoproterozoic-age Grampian Group siliciclastic succession accumulated during several transgressive and regressive cycles in multiphase ensialic rift basins. The Badenoch Group constitutes the crystalline floor to those basins and had experienced amphibolite-facies metamorphism, migmatization, gneissification and deformation between *c.* 840–800 Ma, prior to deposition of the Dalradian strata. In contrast, evidence for only 470–450 Ma Caledonian orogenic events is found at higher structural levels in the Grampian and Appin group successions. Locating and understanding the nature of the contact between the basement gneisses and the Dalradian cover sequence has long been a major challenge of Highland geology. Recent research has argued that not only is a rift-basin architecture evident from the patterns of Neoproterozoic stratigraphy, but also that it played a significant role in influencing the geometry of the superimposed Caledonian deformation, with the basin infill buttressed against its margins or intrabasinal 'highs'.

The GCR sites in this region preserve important evidence of cover-basement relationships, patterns of punctuated deposition, and onlapping sequences. The effects of both pre-Caledonian and Caledonian deformation and metamorphic events are also well represented. Despite the deformation and metamorphism, spectacular sedimentary structures are visible at several of the GCR sites and there is evidence of the earliest recorded glacigenic sediments in the Neoproterozoic rocks of the British Isles.

1 Introduction

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The Northern Grampian Highlands are dominated by a widespread and thick succession of Neoproterozoic siliciclastic deposits referred to as the Grampian Group (Figure 5.1). Most interpretations of the regional geological relationships have suggested that the strata were deposited upon an orogenic unconformity, now largely obscured by a zone of ductile shearing at or near the base of the group (Piasecki and van Breemen, 1979b, 1983; Piasecki, 1980; Piasecki and Temperley, 1988a and references therein). These interpretations were based upon structural and metamorphic contrasts recognized between rocks referred to an older 'Moine-like' crystalline basement of probable Grenvillian age and termed the 'Central Highland Division', and a cover sequence referred to as the 'Grampian Division' or Grampian Group. The basement rocks apparently underwent amphibolite-facies migmatization, gneissification and deformation prior to deposition of the cover sequence. While lithologically similar to the Moine Supergroup of the Northern Highlands, and formerly termed the 'Younger Moine', the Grampian Group was included within the Dalradian Supergroup by Harris *et al.* (1978) on the basis of the apparent stratigraphical, structural and metamorphic continuity south-east of the Great Glen Fault in the Grampian Terrane (Harris *et al.*, 1994; Stephenson and Gould, 1995; Strachan *et al.*, 2002). Locating and understanding the nature of the contact between the rocks of the Northern Highlands and Grampian terranes has long been a major challenge of Highland geology.

An alternative model viewed the rocks of the Northern Grampian Highlands as part of a single stratigraphical succession in which a regional metamorphic front separates the supposed basement and cover sequences (Lindsay *et al.,* 1989). Such a model was not however supported by more-recent radiometric studies that confirmed the existence of Neoproterozoic tectonothermal events (*c.* 840–800 Ma) in parts of the Northern Grampian Highlands (Noble *et al.,* 1996; Highton *et al.,* 1999), even though only Caledonian orogenic events (470–450 Ma) are known at higher levels in the Dalradian succession. Such a paradox, whereby comparable studies recognized discrete tectonothermal events in different parts of an apparently continuous stratigraphical succession, but were unable to separate or define the limits of these events, continues to be one of the key problems in Highland geology.

A lithostratigraphical framework has been erected for the Grampian Group in the western and south-western parts of the Northern Grampian Highlands, despite the problems of correlation across major structures, polymetamorphism and the absence of biostratigraphical control (Glover and Winchester, 1989; Glover *et al.,* 1995; Key *et al.,* 1997). Those authors described an evolving depositional basin in which marine and locally terrestrial deposition occurred within multiphase ensialic rift basins, during several transgressive and regressive cycles (Glover *et al.,* 1995; Glover and McKie, 1996). Smith *et al.* (1999) extended the lithostratigraphical approach and integrated detailed mapping with geophysical modelling to define a series of basin-bounding structures in the Northern Grampian Highlands ((Figure 5.2). Current research continues to refine and improve the understanding of this depositional framework (Banks and Winchester, 2004; Banks, 2005; Banks *et al*., 2007).

The Grampian Group sediments were deposited in NE- to SW-trending marine basins formed during a major phase of Neoproterozoic rifting. These basins extended rapidly and accumulated up to 5 km of turbiditic deposits, possibly within 20–30 Ma (Ryan and Soper, 2001). Later thermal subsidence is suggested by the regional development of shallow marine-shelf environments and could have occupied a similar length of time. The margins to these basins are characterized by lateral facies and thickness changes, stratigraphical omission and onlap relationships of both Grampian and Appin group strata onto a basement of predominantly gneissose rocks that records the older, pre-Caledonian tectonothermal history. Stratigraphical relationships are summarized in (Figure 5.3), which is based largely upon Smith *et al.* (1999).

Smith *et al.* (1999) and Robertson and Smith (1999) argued that the basin architecture thus determined is not only reflected in the patterns of Neoproterozoic sedimentation, as would be expected, but also played a significant role in predetermining the geometry of the superimposed orogenic deformation in the Northern Grampian Highlands. For example, the Geal-charn–Ossian Steep Belt has been re-interpreted by those authors to reflect buttressing of basin infill against the architecture of the basin margins or any intrabasinal 'highs'. Such analysis of preserved 'cover-basement' relationships led Smith *et al.* (1999) to propose that a significant stratigraphical and sedimentological break does indeed exist at the base of Grampian Group, much in the manner originally suggested by Piasecki (1980). Although there is presently insufficient structural or metamorphic evidence to prove an orogenic unconformity beyond all reasonable doubt, geochronological data do confirm the presence of Precambrian events in the basement rocks that have not been recognized in the cover. The basement rocks were referred to informally as the Dava and Glen Banchor successions in publications and on Geological Survey maps of the period 1999 to 2010, but have now been united formally as the Badenoch Group, with Dava and Glen Banchor subgroups.

The GCR sites described within this paper ((Figure 5.1) preserve important evidence from locations where 'cover-basement' relationships, and the pattern of punctuated deposition and onlapping relationships within the Appin Group, are preserved. There are examples of the lithostratigraphical sequence in the Grampian Group and evidence of the earliest recorded glacigenic sediments in the Dalradian succession. Caledonian and pre-Caledonian deformation and metamorphic events are similarly well represented. A broad outline of current thinking and the geological sequence of events is provided below.

1.1 Badenoch Group

Sedimentary structures and way-up criteria are lacking in these metasedimentary gneisses and only the most-recent research has attempted to erect any level of internal stratigraphy (Robertson and Smith, 1999; Smith *et al*., 1999). The Glen Banchor Subgroup is identified in the cores of large-scale antiformal structures in the Glen Banchor and Kincraig districts (Figure 5.1) (see the *An Suidhe* and *Blargie Craig* GCR site reports); comparable strata between Tomatin and Lochindorb are assigned to the Dava Subgroup (see *The Slochd* GCR site report). In broad terms, both the Dava and Glen Banchor subgroups comprise a structurally undivided lower unit of banded psammite, micaceous psammite and subordinate semipelite, and an upper unit of more-varied lithologies including quartzite, siliceous feldspathic psammite, micaceous psammite and schistose banded semipelite. The lithological associations are consistent with deposition in shallow marine environments.

1.1.1 Knoydartian orogenic events

Piasecki (1980) and Piasecki and van Breemen (1979a, 1983) identified a suite of deformed pegmatites emplaced within rocks now assigned to the Badenoch Group and from which they obtained *c*. 750 Ma Rb-Sr muscovite ages (see the *An Suidhe* GCR site report). These pegmatites are located within ductile shear-zones associated with progressive modification and grain-size reduction of gneissose fabrics within the host migmatites. The pegmatites were thought to have formed during, and hence to date, an episode of ductile shearing. They were correlated with *c*. 750 Ma 'older' pegmatites from the Northern Highlands Terrane and were thought to have formed during the Knoydartian Orogeny. However, the Rb-Sr isotope ratios have been variably reset by Caledonian tectonothermal activity (Hyslop and Piasecki, 1999), so that a spectrum of ages from *c*. 700 to 500 Ma has been obtained from the same pegmatites, resulting in ambiguous relationships that frustrate any single unifying interpretative model.

Hyslop (1992) and Hyslop and Piasecki (1999) have confirmed the temporal link between syntectonic metamorphic growth and pegmatite segregation within the ductile shear-zones, while U-Pb analyses of monazites from two large pegmatites at A' Bhuideanaich and Lochindorb have yielded high-precision ages of 808 +11/-9 Ma and 806 ± 3 Ma respectively (Noble *et al*., 1996). Monazites from the matrix of the mylonitic host to the Lochindorb pegmatite yielded an age of 804 +13/–12 Ma. These results confirmed a phase of monazite growth, and by implication pegmatite formation, contemporaneous with metamorphic recrystallization and growth in the host mylonites at *c.* 806 Ma, lending support to the earlier Rb-Sr studies. U-Pb dating of single zircon grains within kyanite-grade migmatites within *The Slochd* GCR site yielded an age of 840 ± 11 Ma and this has been interpreted as dating high-grade metamorphism and migmatization during an orogenic event that can be correlated with the Knoydartian Orogeny (Highton *et al*., 1999).

1.1.2 Basement–cover relationships

A major orogenic break at or near the base of the Grampian Group was first proposed by Piasecki and van Breemen (1979b, 1983), Piasecki (1980), and Piasecki and Temperley (1988a). The original lines of evidence presented by Piasecki and his coworkers centred upon apparent structural and metamorphic contrasts between what is now essentially the Badenoch Group and the Grampian Group. Alternative hypotheses to explain those contrasts have invoked metamorphic fronts (Lindsay *et al.*, 1989) or as yet unrecognized orogenic unconformities in the Appin or Argyll groups (Highton *et al.*, 1999). Previous attempts to test for an orogenic unconformity were hampered by confusion over the significance and regional extent of migmatitic and gneissose rocks in large areas of unmapped ground. With much of the area now resurveyed by the British Geological Survey (BGS), and a coherent stratigraphical framework established, many of the earlier problems are diminished. The distribution and development of gneissose and migmatitic textures is largely compositionally controlled and cannot therefore be used as a discriminant between cover and basement. Semipelite and compositionally suitable psammite of both the Badenoch Group and the Grampian and Appin groups,could have developed such textures during peak metamorphic, upper amphibolite-facies conditions (see the *Lochan Uaine* GCR site report). Any model attempting to explain relationships in the Northern Grampian Highlands should therefore take account of the nature of the stratigraphical framework, the structural and metamorphic evidence for any break, and any evidence for an isotopic break.

1.1.3 Stratigraphical framework

Critical localities in Glen Banchor, Speyside and Lochindorb are largely unaffected by intense Caledonian deformation and preserve unconformable and overstep relationships of Grampian and Appin group rocks onto the Badenoch Group (Smith *et al.*, 1999; Robertson and Smith, 1999), thus providing evidence for a significant stratigraphical break near the base of the Grampian Group. Examples of the nature of these relationships are described under the *An Suidhe*, *Blargie Craig* and *Aonach Beag and Geal-charn* GCR site reports. Since the true base of the Grampian Group has not been identified within the Northern Grampian Highlands, the magnitude of this stratigraphical break is uncertain.

1.1.4 A structural and metamorphic break?

Rocks of the Badenoch Group are intensely recrystallized, preserve no sedimentary structures and commonly contain intrafolial isoclinal folds that deform the first foliation (usually a gneissosity). The overlying Grampian Group rocks are variably recrystallized, structurally less complex and commonly preserve sedimentary structures; the first foliation, usually a schistosity, deforms bedding. Observations such as these imply a structural break, and thus support the original thesis of Piasecki (see the *An Suidhe* GCR site report), but this difference is difficult to detect where both successions are migmatitic or highly deformed. Regional metamorphic studies do not detect a break (Phillips *et al.*, 1999) but this could reflect either the intensity of the Caledonian overprint and/or the likelihood that the Badenoch Group rocks, if already dehydrated during an earlier metamorphic event, would have been essentially unreactive (e.g. Yardley and Valley, 1997).

1.1.5 An isotopic break?

Evidence for a Neoproterozoic (Knoydartian) tectonothermal event has so far only been reported from within the Badenoch Group; rocks assigned to the Grampian Group do not record this event. In addition, as yet unpublished BGS data draw a further distinction between the Grampian Group and the Badenoch Group in as much as the latter contain complex monazite populations whose ages span c. 1200–450 Ma, while Grampian Group rocks contain relatively simple monazites that record only Caledonian (470–450 Ma) events.

Taken all together, the above lines of evidence indicate a significant break in sedimentation near the base of the Grampian Group in the Northern Grampian Highlands. The rocks of the Badenoch Group are therefore thought to form a ‘Moine like’ metasedimentary basement, which was affected by a ‘Knoydartian’ event prior to the deposition of the overlying Grampian Group. The possibility that it is the Badenoch Group, rather than the Grampian Group that might more easily share affinities with the Moine Supergroup and thus establish linkages across the Great Glen Fault, requires further geochemical, provenance and structural studies.

1.2 Grampian Group lithostratigraphy and basin evolution

Flaggy psammitic metasedimentary rocks older than the Appin Group were originally regarded as ‘Younger Moine’ (Johnstone, 1975) and were known by such local names as the Struan Flags in Perthshire, the Eilde Flags in Argyllshire and the Central Highland ‘Granulites’ over much of the Northern Grampian Highlands. Based upon apparent stratigraphical, structural and metamorphic continuity in the Grampian Terrane, Harris *et al.* (1978) extended the then tripartite Dalradian Supergroup downwards to include such lithologies, which were all assigned to a new Grampian Group. A number of constituent subgroups and formations were proposed by Winchester and Glover (1988) and the lithostratigraphical relationships were synthesized by Harris *et al.* (1994) and Stephenson and Gould (1995).

Since then, application of the techniques of basin analysis to the lithostratigraphy of the Northern Grampian Highlands has made important contributions to an evolutionary model for the Grampian and Appin group depocentre in that region (Glover *et al*., 1995; Smith *et al*., 1999; Robertson and Smith, 1999). Three main lithofacies associations have been recognized and interpreted as representing distinct phases of early- and syn-rift extension followed by a protracted period of post-rift thermal subsidence. Modelling of basin subsidence curves, using the method developed by Ryan and Soper (2001), has indicated that both the syn-rift and post-rift phases might each have lasted *c.* 30 Ma. Thus defined, the Grampian Group is believed to record the initiation of late-Neoproterozoic extension and basin development. However Prave (1999), in contrast, has re-interpreted the Grampian Group as detritus that was shed, post-806 Ma, from a Knoydartian orogenic terrane as molasse or flysch deposits.

The timing of deposition of the Grampian and Appin groups is not well constrained and is the subject of some current debate; the general consensus is that the base of the Grampian Group is unlikely to be older than *c.* 750 Ma. That consensus is supported by chemostratigraphical data derived from Grampian and Appin group metalimestones, all of which have $^{87}Sr/^{86}Sr$ isotope ratios greater than 0.7064 (Thomas *et al*., 2004). Comparing that data with the calibration of chemostratigraphy for global Neoproterozoic carbonates (Melezhik *et al*., 2001) implies that precipitation of the original carbonate must have occurred less than *c.* 750 Ma ago and possibly even from as little as 670 Ma ago.

The lithostratigraphy of the Grampian Group that forms the basis for the following outline is known in detail only for the area now referred to as the Corrieyairack Basin ((Figure 5.2) Smith *et al*., 1999). The true base of the Grampian Group is not exposed; the oldest unit is the Glenshirra Subgroup (Figure 5.3), which has never been found in undisturbed primary contact with rocks of the underlying Badenoch Group.

1.2.1 Glenshirra Subgroup

The Glenshirra Subgroup comprises stacked thinning-upward sequences of immature feldspathic psammite and beds of metaconglomerate, the latter increasing in abundance up section and up dip towards the Great Glen Fault. The type locality is in the inlier formed by the Glenshirra Dome, around the upper reaches of the River Spey (Haselock *et al.*, 1982; Okonkwo, 1988; Banks and Winchester, 2004). There it is represented by the Garva Bridge Psammite Formation, locally with a distinctive Gairbeinn Pebbly Psammite Member in its upper part (see the *Garva Bridge* GCR site report). Closer to the Great Glen Fault, the subgroup is represented by the Glen Buck Pebbly Psammite Formation in several smaller inliers, such as the one traversed by the *River E* GCR site. The faulted inlier between Loch Lochy and Fort Augustus exposes a succession of psammites and metaconglomerates over 2000 m thick, which includes minor dolomitic metalimestone and graphitic pelite (Parson, 1982; May and Highton, 1997). This inlier is separated from the overlying Corrieyairack Subgroup by the Eilrig Shear-zone, a zone of mylonites up to 1.0 km thick (Phillips *et al.*, 1993), and high-strain zones are also seen elsewhere at that junction, as in the *Lochan Uaine* GCR site.

In this subgroup, abundant sedimentary structures, including convolute lamination, trough cross-bedding and ripple lamination, together with rare hummocky cross-stratification indicate deposition by traction currents in shallow marine environments subject to storms. Parts of the subgroup might represent fluviatile deposits, and Banks and Winchester (2004) interpreted the whole association as alluvial fan and shallow water sediments deposited within a SE-thinning fan–delta clastic wedge. They considered the sedimentary environment to be so different from the overlying sub-marine slope setting of the overlying Corrieyairack Subgroup to warrant elevation of the Glenshirra Subgroup to group status. However, this suggestion has not become generally accepted and has not been adopted in this special issue.

Seams of magnetic heavy minerals are common. Progressive thickening and coarsening of the strata westwards, combined with the pebble compositions (mainly granite and vein-quartz with rare amphibolite, psammite and quartzite), imply the presence of a basin margin to the west or north-west, with an exposed hinterland of mature crust beyond, perhaps composed of older Proterozoic rocks similar to parts of the Rhinns Complex of Islay.

1.2.2 Corrieyairack Subgroup

The base of the overlying Corrieyairack Subgroup is marked by a distinctive and regionally widespread succession of semipelite and striped semipelite and psammite, which corresponds to basin-wide flooding and the start of widespread subsidence and rift-related extension. Locally, as at Kincraig, a heterogeneous succession of muscovite-rich semipelites interbedded with calcsilicate rocks, thin quartzites and metacarbonate rocks marks the base of the subgroup (see the *An Suidhe* GCR site report). Such rocks probably represent a condensed basin-margin facies reflecting deposition on, or adjacent to, an uplifting high.

A near-complete sequence through the main rift cycle is preserved within the western part of the basin, around Loch Laggan and in Glen Roy ((Figure 5.3); Smith *et al*., 1999; Banks, 2005). The basal semipelitic facies (the Coire nan Laogh Semipelite Formation) is overlain by *c.* 4 km of siliciclastic strata (the Loch Laggan Psammite Formation), deposited by prograding turbidite complexes (see the *Rubha Magach* GCR site report). Variations in sediment supply and source area and the depositional processes are best documented for the Loch Laggan–Glen Roy area (Glover and Winchester, 1989; Key *et al*., 1997). Bouma sequences are well represented within the main depocentre around Loch Laggan and Glen Doe, while graded bedding is reflected as 'saw-tooth' bed profiles over most of the outcrop. Inferred bottom structures are extremely rare but there is no lack of way-up criteria.

The overlying Ardair Semipelite Formation records a reduction in sand-grade sediment supply and development of shelf conditions along the basin margins. Turbidite deposition apparently continued unabated in the putative basin centre, while lateral facies changes into striped semipelite and psammite indicate more marginal settings. A return to sand-dominated turbidites (the Creag Meagaidh Psammite Formation) marks deposition in extensive turbidite fan-lobe systems, derived from the north-west and extending southwards and eastwards into shelf environments in the Glen Roy and Drumochter areas (Glover *et al*., 1995). Rapid local facies variations and thickness variations indicate active tectonism at this time and, together with progressive overstep onto an interbasin high in the Glen Banchor area (see the *Blargie Craig* and *Aonach Beag and Geal-charn* GCR site reports), permit the tracing of outlines of former basin margins (Glover *et al*., 1995; Robertson and Smith, 1999).

1.2.3 Glen Spean Subgroup

The turbiditic rocks in the upper part of the Corrieyairack Subgroup are overlain conformably by lithological associations with well-preserved sedimentary structures that indicate deposition in shallow marine environments. Such shelf areas were subjected to tidal influences and sea-level fluctuations that resulted in intensive sediment recycling and winnowing of the underlying turbiditic rocks. The successions reflect reduced subsidence and relative tectonic stability, which have been interpreted as indicative of a post-rift thermal subsidence phase at this time (Glover *et al.*, 1995).

On the south-western and south-eastern margins of the Corrieyairack Basin, sediments prograded into the basin from the north-west and south-east and complex diachronous and lateral facies relationships are common (Key *et al*., 1997). The *Allt Mhainisteir* and *Aonach Beag and Geal-charn* GCR sites both lie on the south-eastern margin, within the Geal-charn–Ossian Steep Belt, and contain Glen Spean Subgroup strata. The northern part of the Strath Tummel Basin is dominated by the Gaick Psammite Formation, which was 1–2 km thick before deformation and has been repeated by a stack of recumbent F2 folds (Leslie *et al*., 2006). It must contribute significantly to the great thickness of Grampian Group strata in this basin revealed by geophysical modelling (Smith *et al*., 1999). The southern part of the Strath Tummel Basin is covered by GCR sites described by Treagus et al. (2013). Farther north, in the Cromdale Basin, psammites and quartzites of the Glen Spean Subgroup are well represented. There, the top part of the subgroup is dominated by thick quartzite formations, originally channel-dominated quartz-rich sands, which extend from the Hills of Cromdale to the Banff coast near Cullen, where they form the western end of the *Cullen to Troup Head* GCR site (see Stephenson et al., 2013b).

1.3 Appin Group lithostratigraphy and overstep

The Appin Group is characterized generally by consistency of sediment supply into low-energy (open to lagoonal) marine environments; many of its constituent formations can be correlated along some 280 km of strike length, despite significant lateral facies and thickness variations and local unconformable relationships. Sedimentation occurred in a régime of progressive lithospheric stretching in which listric synsedimentary growth faults apparently constrain the architecture of NE-trending basins (Hickman, 1975; Litherland, 1980; Anderton, 1985; see Stephenson et al., 2013a). In the Northern Grampian Highlands, Appin Group rocks record progressive overstep and onlap onto a substrate of rifted

Grampian Group rocks as stretching and subsidence proceeded.

1.3.1 Lochaber Subgroup

The basal Lochaber Subgroup conformably succeeds the Grampian Group in the Central and Northern Grampian Highlands as alternating successions of siliceous psammite and quartzite with minor semipelite, pelite and rare metacarbonate units (Glover *et al.*, 1995; Key *et al.*, 1997). Such strata record the persistence of relatively shallow marine environments from Grampian Group times; the geometry of the basin architecture established earlier continued to exert a strong influence (Robertson and Smith, 1999; Smith *et al.*, 1999). A general pattern for the Lochaber district in the Central Grampian Highlands has offshore sediments interbedded with tidally dominated quartzites that thicken to the south-west. The nearshore sediments are interpreted as extending away from a coastline to the north and are a reflection of periodic basin shoaling events (Glover and McKie, 1996). To the north-east, around Loch Laggan, comparable sediments in the Geal-charn–Ossian Steep Belt underlie the glacigenic Kinlochlaggan Boulder Bed (Treagus, 1969, 1981; Evans and Tanner, 1996).

Upper parts of the Lochaber Subgroup record a period of renewed rifting with gradual deepening and widespread marine transgression, as is represented by the Leven Schist Formation. Laminated pale-grey schistose pelites account for up to 1200 m of strata in the Central Grampian Highlands (Harris *et al*., 1994) but elsewhere this formation is absent or is represented by thin local correlatives (see the *Aonach Beag and Geal-charn* and *Allt Mhanisteir* GCR site reports). Such dramatic variations have been attributed to significant intrabasinal footwall uplift, reflecting continuing basin development (Glover *et al*., 1995; Robertson and Smith, 1999).

1.3.2 Ballachulish Subgroup

Metasedimentary rocks of the overlying Ballachulish Subgroup record the further effects of major marine transgression and widespread thermally driven subsidence. There is a progressive development of shallow shelf, tidally influenced sedimentation and anoxic lagoonal environments in the Northern Grampian Highlands as elsewhere across the Dalradian outcrop (Anderton, 1985). The regional pattern of widespread stability and relatively uniform subsidence for the lower formations of the subgroup is interrupted locally by stratigraphical excision and the more sporadic distribution of the upward-coarsening, deltaically influenced Appin Quartzite (Litherland, 1980). A return to interbedded semipelite, calcsilicate rock and metalimestone (the Appin Phyllite and Limestone Formation) indicates renewed transgression and deepening. In the Geal-charn-Ossian Steep Belt, the distinctive Appin Quartzite Formation is absent; correlatives of the Appin Phyllite and Limestone Formation overstep onto underlying Lochaber Subgroup lithologies, and across the entire Grampian Group, to rest directly on the Glen Banchor Subgroup (see the *Blargie Craig* and *Aonach Beag and Geal-charn* GCR site reports). This overstep has been attributed to a combination of non-deposition and erosion on a long-standing intrabasinal ‘high’ (Robertson and Smith, 1999).

1.4 Caledonian deformation

The mushroom-like structure resulting from the divergent facing of the major folds in the South-western and Central Grampian Highlands encouraged the idea of a fundamental ‘root-zone’ beneath the Loch Awe Syncline in early structural models (Sturt, 1961; Rast, 1963). Various geometries and locations for the extension of this root-zone into the Northern Grampian Highlands have been debated (Harris, 1963; Roberts and Treagus, 1979; Bradbury *et al*., 1979), with attention focussed latterly on the the Geal-charn-Ossian Steep Belt. Thomas (1979, 1980) interpreted this fold-complex as a ‘root-zone’ for the emergence of the SE-facing structures of the Atholl Nappe that lies beneath the Boundary Slide. The NW-facing nappes identified in Lochaber formed a similar architecture emerging to the north-west during the earlier phases of Caledonian compression. Other workers, whilst recognizing the existence of the steep belts, regarded them as late developments in the deformation sequence and rejected any connection with a primary or fundamental root-zone (Hall in Fettes *et al*., 1986; Krabbendam *et al*., 1997). Smith *et al.* (1999) and Robertson and Smith (1999) made a genetic link between the location of the major Caledonian structural features in the Northern Grampian Highlands and the pre-existing architecture of the Dalradian depositional basins.

Despite the differences in overall models to explain the distribution of the major fold-complexes in the Northern Grampian Highlands and the debate surrounding pre-Caledonian orogenesis in the Badenoch Group, there is a general consensus with regard to the pattern of Caledonian fabric development and metamorphism (Thomas, 1979; Smith *et al*., 1999). The Caledonian metamorphic peak is broadly coincident with the second fabric or foliation, that typically being a crenulation of a pre-existing schistosity or cleavage that has affected the bedding. There is however more debate with regard to the development of the later third or fourth fabrics, which are commonly more localized in the intensity of their development.

1.4.1 Folds beneath the Boundary Slide: the Atholl Nappe

Along the A9 road section, which forms the southern boundary of the Northern Grampian Highlands as described in this special issue, Thomas (1979, 1980) argued that the Grampian Group strata are disposed in a large-scale, isoclinal F1 fold termed the Atholl Nappe. This structure lies beneath the Boundary Slide and the Tay Nappe, is disposed in the form of a broad arch called the Drumochter Dome (see the *A9 and River Garry* GCR site report in Treagus et al., 2013). However, Treagus (1987) has suggested that there is no need to invoke a separate Atholl Nappe below the Tay Nappe and hence that there is no need to invoke considerable movement on the Boundary Slide in order to excise an intervening right way-up limb.

The nature of the Drumochter Dome has also been the subject of some controversy. Thomas (1979, 1980) argued that it is an early structure but the work of Lindsay *et al.* (1989) has shown that D2 axial planes and cleavages are folded across the dome, which is consequently now generally accepted as a later structure, possibly D4. Over most of the dome the strata were originally represented as flat-lying and inverted; however, a recent BGS survey across the Gaick region in the north-eastern part of the dome has shown that bedding is generally right-way-up in a SSE-facing system of F2 recumbent folds, geometrically similar to the original concept of the Atholl Nappe (Leslie *et al*., 2006).

1.4.2 The Geal-Charn–Ossian Steep Belt

To the north-west of the Drumochter Dome, a 4 km-wide zone in which all the fold limbs and axial planes are near vertical, forms a complex of upward-facing isoclines ((Figure 5.4) (see the *Aonach Beag and Geal-charn* GCR site report). This is the Geal-charn–Ossian Steep Belt of Thomas (1979), which can be traced for some 40 km from south-west of Loch Ossian, through Aonach Beag and Geal-charn, to Kinloch Laggan. In the Aonach Beag–Geal-charn area, three major slide-zones are recognized, which commonly form steep boundaries between Grampian Group and Appin Group strata. The steep belt includes, on its north-west side, the Kinlochlaggan Syncline which has long been regarded as a major isoclinal primary fold (Anderson, 1947b, 1956; Smith, 1968; Treagus, 1969).

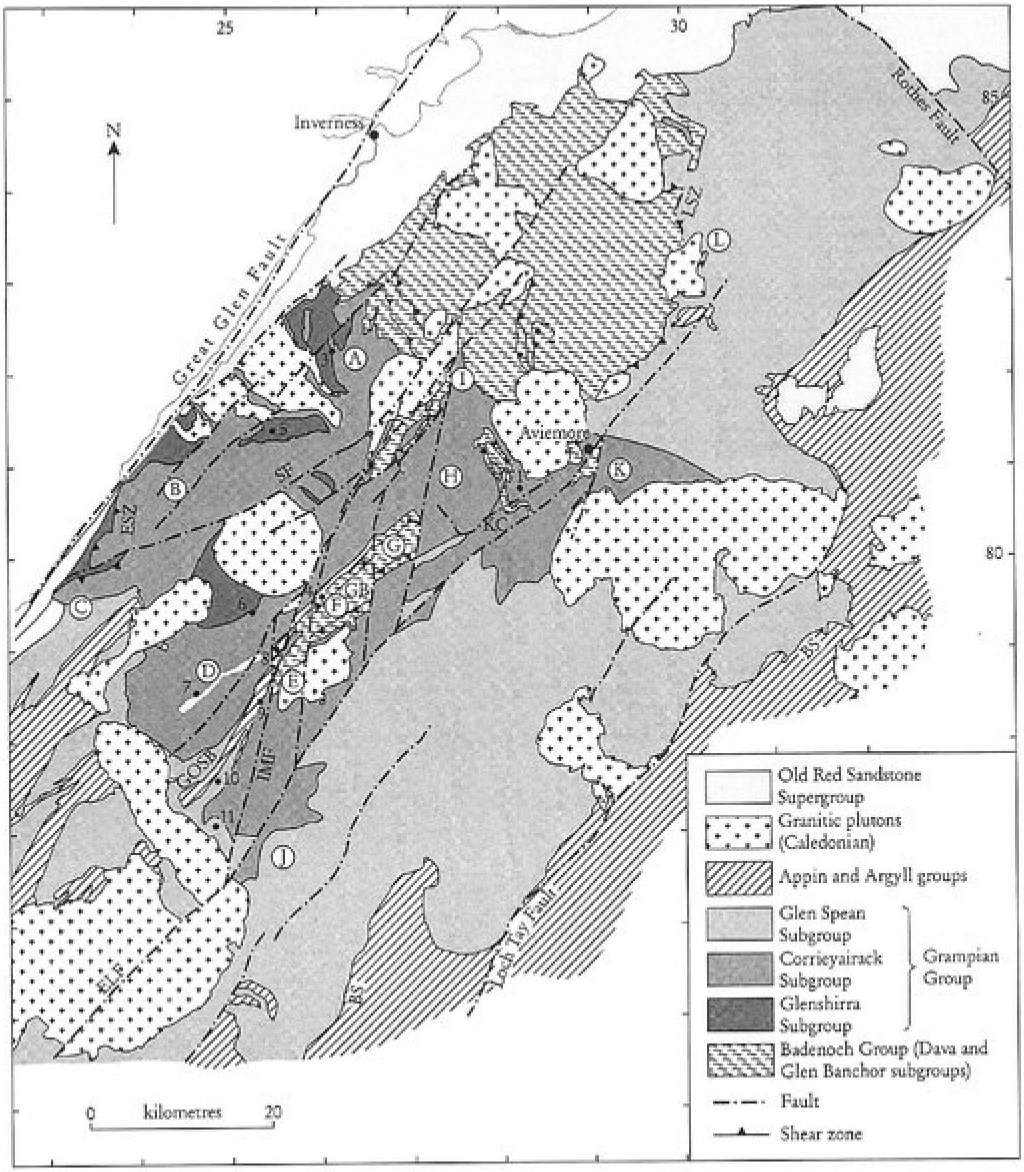
To the south-west, the Geal-charn-Ossian Steep Belt may be aligned approximately with the axial plane trace of the F1 Loch Awe Syncline, although the Rannoch Moor and Etive granitic plutons intervene, making direct correlation difficult. Both structures appear to mark a fundamental structural divide between NW-facing F1 folds on one side (i.e. the Islay Anticline and other primary structures such as the Appin Syncline) and SE-facing F1 folds on the other (i.e. the Atholl, Glen Orchy and Tay nappes). Consequently, Thomas (1979) proposed that the Geal-charn-Ossian Steep Belt constitutes a root-zone, lying directly below the Loch Awe Syncline, from which all of the fundamental F1 nappes of the Grampian Highlands have diverged (see the *Ben Alder* GCR site report).

1.4.3 Strathspey and the Monadhliath mountains

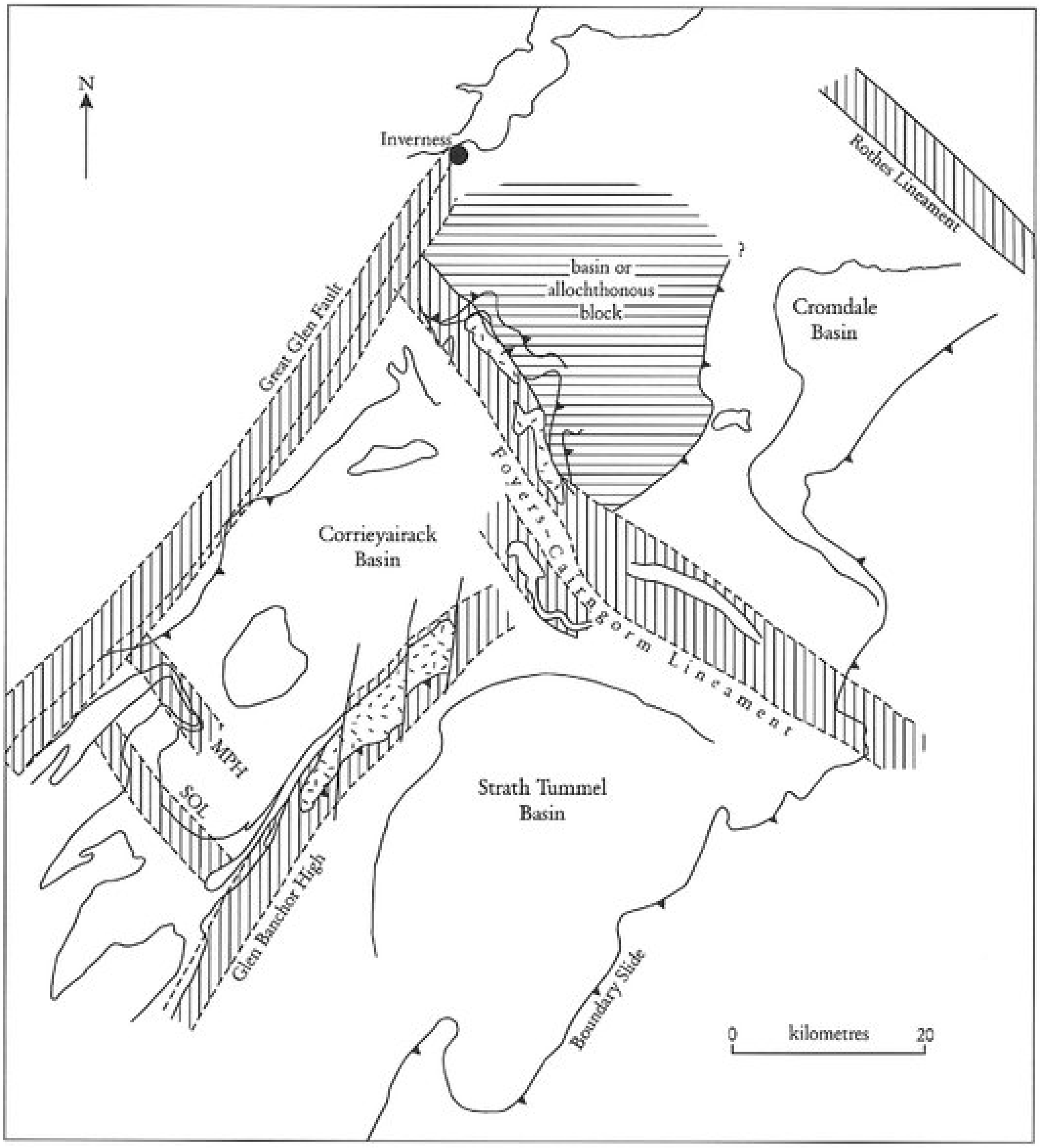
The phases of Caledonian deformation in this region are broadly comparable to those established to the south and south-west in fold-complexes that affect the higher structural and stratigraphical levels of the Grampian Terrane. A detailed study of the area around Kincraig, coupled with reconnaissance mapping and traversing over much of the Monadhliath area between Lochindorb and Kingussie, led to the first detailed comparison of structures and the development of ideas, promoting a ‘basement-cover’ relationship and the presence of an orogenic unconformity (Piasecki and van Breemen, 1979b; Piasecki, 1980).

However, Lindsay *et al.* (1989) summarized structural studies that strengthened belief in common elements of a Caledonian structural history traced with some confidence from the Boundary Slide at Blair Atholl, along the A9 road section and across the Drumochter Dome to Strathspey. In the latter area, stratigraphical way-up evidence becomes less reliable as tectonic strain and the degree of migmatization intensify. However, tectonic fabric relationships have been traced north and south-west from Aviemore into Strathnairn and the Corrieyairack area, and comparable fabrics are recognized both in the Grampian Group and in the structurally underlying, highly migmatized rocks that are now assigned to the Badenoch Group. As previously discussed, current structural, metamorphic and isotope data are still insufficient to prove the existence of any orogenic unconformity beyond doubt, but recent detailed mapping in the region by the British Geological Survey has confirmed the existence of a significant stratigraphical and sedimentological break between the two sequences (Smith *et al*., 1999).

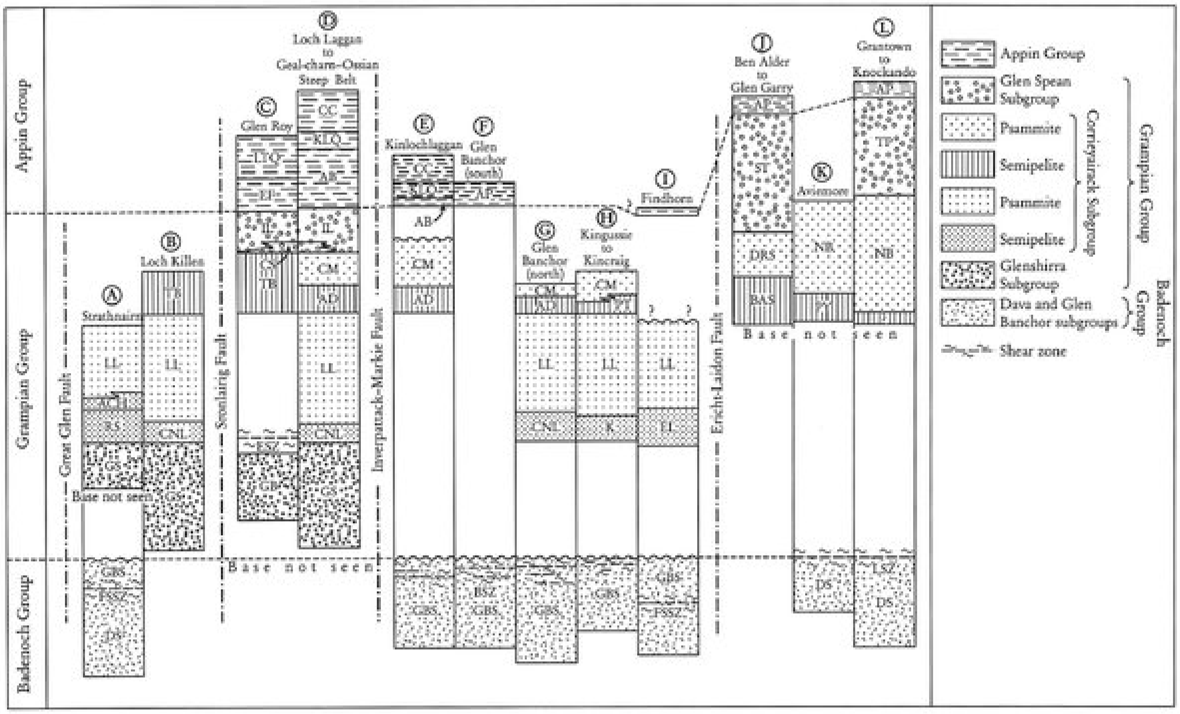
References



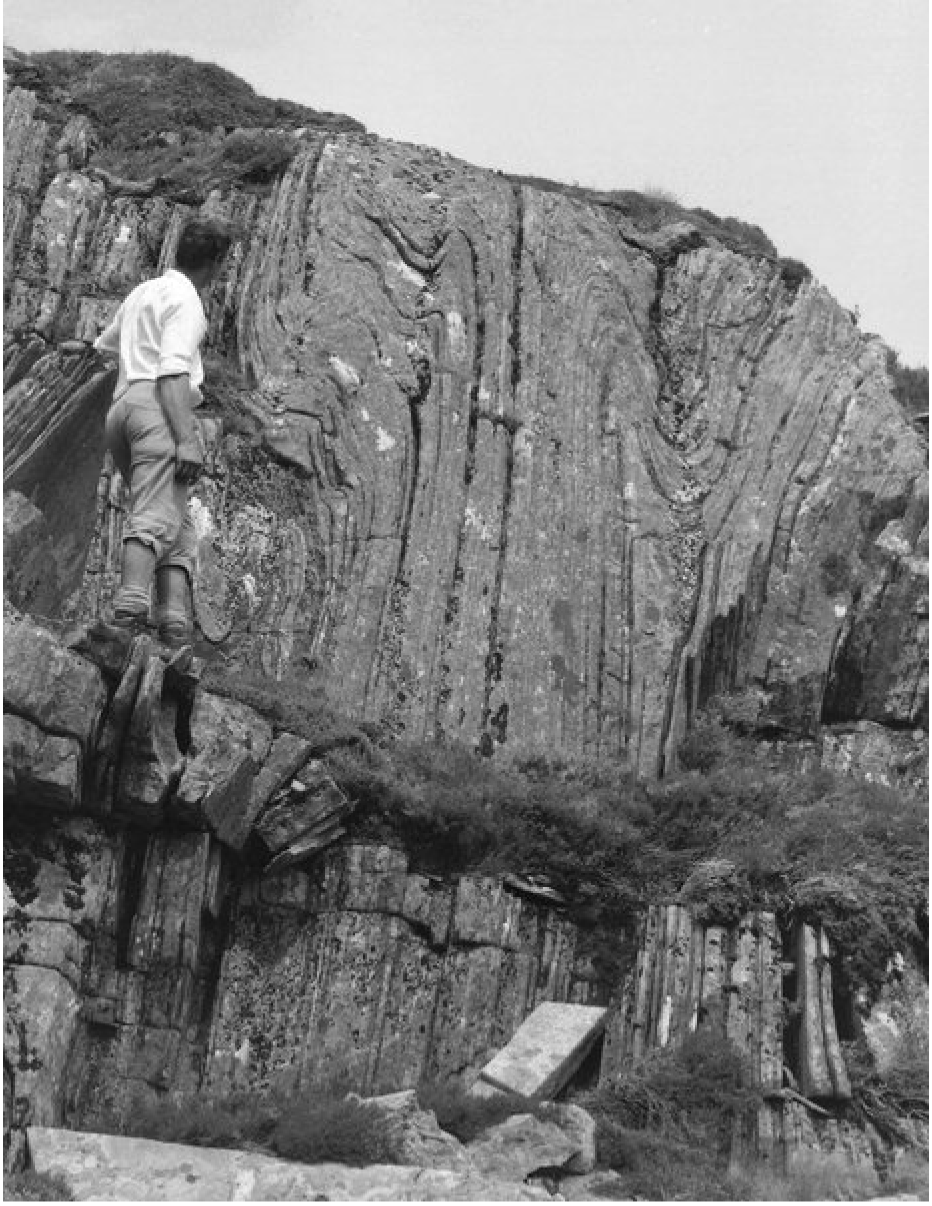
(Figure 5.1) Map of the Northern Grampian Highlands showing distribution of subgroups (after Smith et al., 1999). Circled letters on the map refer to stratigraphical columns in (Figure 5.3). GCR Sites: 1 An Suidhe, Kincraig 2 The Slochd, 3 Lochan Uaine, 4 Blargie Craig, 5 River E, 6 Garva Bridge, 7 Rubha na Magach, 8 Kinloch Laggan Road A86, 9 Allt Mhainisteir, 10 Aonach Beag and Geal-charn, 11 Ben Alder. Abbreviations: BS Boundary Slide, ESZ Eilrig Shear-zone, ELF Ericht–Laidon Fault, FSSZ Flichity–Slochd Shear-zone, GB Glen Banchor, GOSB Geal-charn–Ossian Steep Belt, IMF Inverpattack–Markie Fault, KC Kincraig, LSZ Lochindorb Shear-zone, SF Sronlairig Fault.



(Figure 5.2) Rift basins and their bounding lineaments in the Northern Grampian Highlands (after Smith et al., 1999). Based on a simplified geological map after restoration and removal of major faults and intrusions. Solid linework shows the outline of the main subgroups (see (Figure 5.1)). Abbreviations: MPH Meall Ptarmigan High, SOL Strath Ossian Lineament.



(Figure 5.3) Stratigraphical correlations in the Northern Grampian Highlands (after Smith et al., 1999) for the areas shown by circled letters in (Figure 5.1). Thicknesses are relative but not to scale. Blank areas in columns indicate stratigraphical breaks. Abbreviations: AB Aonach Beag Semipelite Fm, ACH Achneim Striped Psammite Fm, AD Ardair Semipelite Fm, AP Appin Group, undivided, BAS Ben Alder succession, BSZ Blargie Shear-zone, CC Coire Cheap Semipelite Fm, CM Creag Meagaidh Psammite Fm, CNL Coire nan Laogh Semipelite Fm, CS Clachaig Semipelite Fm, DRS Drumochter succession, DS Dava Subgroup, EF Eilde Flag Formation, EL Elrick Formation, ESZ Eilrig Shear-zone, FSSZ Flichity–Slochd Shear-zone, GB Glen Buck Psammite Fm, GBS Glen Banchor Subgroup, GS Glenshirra Subgroup (undivided), IL Inverlair Psammite Fm, K Kincraig Formation, KLQ Kinlochlaggan Quartzite Fm, LL Loch Laggan Psammite Fm, LSZ Lochindorb Shear-zone, LTQ Loch Treig Schist and Quartzite Fm, NB Nethybridge Fm, PT Pitmain Semipelite Fm, PY Pityoulish Semipelite Fm, RS Ruthven Semipelite Fm, STS Strathtummel succession, TB Tarff Banded Semipelite Fm, TP Tormore Psammite Fm.



(Figure 5.4) Opposed verging fold-pairs separated by a vertical high-strain zone in psammites of the Glen Spean Subgroup in the Geal-charn–Ossian Steep Belt. North-east of Loch a'Bhealaich Leamhain, Ardverikie Forest [NN 5060 7960], 5 km north-east of the Aonach Beag and Geal-charn GCR site). S. Robertson provides a scale. (Photo: BGS No. P 508351, reproduced with the permission of the Director, British Geological Survey, © NERC.)