
The Dalradian rocks of the central Grampian Highlands of Scotland

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Abstract

The Central Grampian Highlands, as defined here, are bounded to the north-west by the Great Glen Fault, to the south-west by Loch Etive and the Pass of Brander Fault and to the south-east by the main outcrop of the Loch Tay Limestone Formation. The more arbitrary northern boundary runs north-west along the A9 road and westwards to Fort William. The detailed stratigraphy of the Dalradian Supergroup ranges from the uppermost Grampian Group through to the top of the Argyll Group, most notably seen in the two classic areas of Loch Leven-Appin and Schiehallion–Loch Tay; Southern Highland Group strata are preserved only in a small structural inlier south of Glen Lyon.

Major F1 and F2 folds are complicated by co-axial northeast-trending F3 and F4 folding, as well as by locally important north- or NW-trending folds. In the Loch Leven area, nappe-like F1 folds verge to the north-west, whereas to the south-east the major recumbent F1/F2 Tay Nappe verges to the south-east. The trace of the upright Loch Awe Syncline lies between the opposing nappes, but in this region a large mass of late-Caledonian granitic rocks obscures their mutual relationship. Three tectonic 'slides' are identified that are certainly zones of high strain but which in part could be obscuring stratigraphical variations.

The regional metamorphism ranges from greenschist facies on the western seaboard of Argyll to amphibolite facies in most of the remainder of the region. The study of garnets, together with kyanite and staurolite in the Schiehallion area, has enabled a detailed history of the metamorphism and structure to be unravelled.

Stratabound mineralization occurs in the Easdale Subgroup, where there is also evidence of changes of sedimentary environment associated with volcanicity and lithospheric stretching. The region is dissected by a series of NE-trending, dominantly left-lateral, faults, subparallel to the Great Glen Fault, whose movement history is illustrated here by that of the Tyndrum Fault.

1 Introduction

J.E. Treagus

The Central Grampian Highlands, as defined in this special issue, are bounded to the north-west by the Great Glen Fault between Lismore and Fort William, and to the south-east by the main outcrop of the Loch Tay Limestone Formation between the Tyndrum Fault and Pitlochry (Figure 3.1). The south-western and north-eastern boundaries are essentially geographical, rather than geological, but they have been chosen to reflect to a certain extent areas studied by a distinct group of workers. The sites in this region have been selected to illustrate both the stratigraphy and the structure of the Dalradian rocks and, to a lesser extent, aspects of their mineralization and metamorphism.

1.1 Lithostratigraphy and Sedimentary Environments

Most of the formations of the Appin and Argyll groups are represented, many in their type areas, but only the uppermost of the poorly-correlated Grampian Group formations are represented. Although many of the formations of the Appin and Argyll groups show remarkable similarities in facies across the overall outcrop of the Dalradian, there are significant variations in the lowermost formations of both groups within the Central Grampian Highlands (Figure 3.2).

The uppermost formations of the Grampian Group are well represented in the GCR site selection, as is the transition up into the Lochaber Subgroup of the Appin Group. Near the north-western section of the boundary with the Northern Grampian Highlands, the contact between the Grampian Group and the Lochaber Subgroup, previously interpreted as the tectonic Fort William Slide, has been re-interpreted by Glover (1993) as a local unconformity. Although that area is not represented in the GCR site selection, in the *River Leven* GCR site, to the east of Loch Leven, this contact can be shown to be a sedimentary transition, contrary to other suggestions (e.g. Lambert, 1975); the passage from the Eilde Flags into the Eilde Quartzite is continuous, both sedimentologically and structurally (Treagus, 1974). The thick sequence of psammites and semipelites of the Lochaber Subgroup in the type area is described in detail in the reports of several GCR sites around the east and north sides of Loch Leven (*River Leven*, *Nathrach*, *Rubha Cladaidh*, *Tom Meadhoin* and *Doire Ban*, *Stob Ban*), which provide abundant evidence from sedimentary structures, especially cross-bedding, for the shallow-water environment. The lens-like bodies of coarse feldspathic metasandstones of the Eilde and Glen Coe quartzites, seen in the *River Leven* and *Rudbha Cladaich* GCR sites respectively, are entirely local to the Loch Leven area. On the other hand, the clean metasandstones of Binnein-type quartzite, seen in the *River Leven*, *Nathrach*, *Tom Meadhoin* and *Doire Ban* and *Rudbha Cladaich* GCR sites, are widespread; they extend both along strike into the South-west Grampian Highlands as the Maol an Fhithich Quartzite of Islay and across strike as the thin quartzites seen immediately above the Grampian Group psammites in the *River Orchy*, *Allt Druidhe* and *Strath Fionan* GCR sites. Along strike to the north-east, these quartzites are regarded as members of the more dominantly semipelitic Loch Treig Schist and Quartzite Formation of the Glen Spean area (Key *et al.*, 1997) (see Leslie *et al.*, 2013).

The classic localities of the succeeding Ballachulish Subgroup are described in the *St. John's Church*, *Onich* and *Ardsheal Peninsula* GCR site reports and those of the Blair Atholl Subgroup in the *Ardsheal Peninsula* and *Lismore Island* GCR site reports. The type lithologies and sedimentary structures of the shallow-water Appin Group are well illustrated at these GCR sites. Most of these formations can be correlated lithologically with those of the Isle of Islay in the South-western Grampian Highlands (Tanner *et al.*, 2013a), and can be matched virtually formation by formation, with those seen at the *Strath Fionan* GCR site, in the east of the Central Grampian Highlands, discussed below.

There has been controversy concerning the identity of certain formations within the Appin Group in the Loch Leven area, which has considerable implications for the structural interpretation (e.g. Treagus, 1974; Roberts, 1976; Hickman, 1978). Therefore particular attention has been paid in that area to the nature and 'way-up' evidence at the transitional junctions, in order to test the stratigraphical succession established by Bailey (1960). At the *Tom Meadhoin* and *Doire Ban* GCR site, in particular, the description here supports the contention of Roberts (1976) that the quartzite in the core of the Kinlochleven Anticline is the Binnein Quartzite and not the Glen Coe Quartzite as maintained by Bailey (1960) and Hickman (1975). This has considerable implications for the local stratigraphical and structural interpretation.

To the south-west of Loch Leven, in the Benderloch–Loch Creran area, there has also been dispute concerning Bailey's original (1922) stratigraphical attributions (Voll, 1960; Litherland, 1980, 1982). Here the Benderloch Slide, the correlative of the Ballachulish Slide seen within several GCR sites in the Loch Leven area (see below), is seen in the *Camas Nathais* GCR site (Tanner *et al.*, 2013a); it excises most of the Blair Atholl Subgroup and is now considered to have had its origins in syndimentary processes. To the south-east of the slide are formations of the Islay and lower Easdale

subgroups of the Argyll Group. According to Litherland (1980), the latter rocks, some of which were attributed to the Appin Group by Bailey (1922) and Voll (1960), as well as those of the Appin Group to their east, show dramatic changes in thickness and lithology in the Loch Creran area. Only limited representatives of these strata occur at the *Camas Nathais* and *Port Selma* GCR sites, but the latter includes a spectacular limestone metabreccia, containing microfossils (oncolites, catagraphs and possible bryozoans). This facies, part of a submarine slide deposit, is equivalent to the Scarba Conglomerate in the Easdale Subgroup seen on the Isle of Jura (see Tanner et al., 2013a), but is not seen elsewhere in the Central Grampian Highlands.

To the south-east of the Loch Leven area, the Grampian Group rocks are poorly known and much of the ground is occupied by igneous intrusions. In the Dalmally area, the Grampian Group appears to be transitional up into the Appin Group, which is represented only by very abbreviated sequences of part of the Lochaber and Ballachulish subgroups, some of which are seen in the *River Orchy* GCR site. Here, the Boundary Slide, like the Benderloch Slide, brings the abbreviated Ballachulish Subgroup into contact with the pebbly, graphitic facies of the overlying Argyll Group; the Blair Atholl and Islay subgroups are entirely absent. These same relationships extend farther east to the west side of the Schiehallion area (where they are seen in the *Allt Druidhe* GCR site) and continue north-eastwards, but with the gradual appearance and thickening of the missing formations between the Ballachulish Subgroup and the Carn Mairg Quartzite of the Easdale Subgroup (Figure 3.4)a. Thus in the east of the Schiehallion area a complete sequence of the Appin Group is restored, although still abbreviated compared with the type area (Figure 3.2). The total thickness of the group here is about 1 km compared with 5 km at Loch Leven (Treagus, 2000); some of the reduction might be attributed to the higher overall strain in the Schiehallion area, although delicate cross-bedding is still preserved in places.

The Schiehallion area provides transitions from the Appin Group, both down into the Grampian Group (at the *Strath Fionan* GCR site) and upwards (via the *Tempar Burn* GCR site) into a complete Argyll Group succession. To the north of the Schiehallion area the quartzites and psammities of the Glen Spean Subgroup, at the top of the Grampian Group, are well represented in the *A9 and River Garry* and *Creag nan Caisean–Meall Reamhar* GCR sites but correlation with other sequences of the Grampian Group cannot yet be made. The *A9 and River Garry* GCR site provides an unrivalled wealth of sedimentary structures. The *Tempar Burn* GCR site contains the classic section for the famous glaciogenic Port Askaig Tillite (locally known as the Schiehallion Boulder Bed), here much reduced in thickness compared with the type locality at Port Askaig on the Isle of Islay and the *Garvellach Isles* GCR site (Tanner et al., 2013a). Immediately to the east of the *Strath Fionan* GCR site and in the Loch Tummel area, towards the boundary with the North-east Grampian Highlands, the Boundary Slide re-asserts itself. It is not clear to what extent the hiatus attributed to the Boundary Slide is due to sedimentological and/or tectonic factors, although the attenuation or absence of sedimentary structures in formations in which they are normally clear and abundant, adjacent to the slide, indicates the importance of high strains.

The remainder of the GCR sites in the central region provide sections through most of the formations of the Argyll Group, many in type localities. From the *Ben Oss* GCR site near Tyndrum, through the *Ben Lawers*, *Slatich* and *Strath Fionan* GCR sites, eastwards to the *Creag an Chanaich to Frenich Burn* GCR site near Aberfeldy, all the Argyll Group formations are represented. Although many of the formations can be readily correlated along strike with those in the South-west and North-east Grampian Highlands, significant variations in the stratigraphy occur in the Easdale Subgroup. Facies and thickness variations are particularly noticeable in the turbiditic pebbly sandstones and graphitic mudstones within the Killiecrankie Schist and Carn Mairg Quartzite formations. The rare exposures of the Farragon Volcanic Formation, as seen in the *Slatich* GCR site, provide the earliest evidence of substantial volcanic activity in this sector of the Grampian highland Terrane which, together with the turbidites, heralds a change to a more unstable sedimentary environment.

Two GCR sites have been chosen to illustrate the stratabound mineralization in the Easdale Subgroup, and also provide evidence of changes of sedimentary environment associated with volcanicity and lithospheric stretching. The GCR site at *Creag an Chanaich to Frenich Burn* contains most of the outcrop of the celebrated ‘Aberfeldy’ baryte/sulphide mineralization at the upper margin of the Ben Eagach Schist Formation. The GCR site at *Auchtertyre*, in the Tyndrum district, contains the rare sulphide mineralization that occurs locally at the upper margin of the Ben Lawers Schist Formation.

The Tayvallich Subgroup is represented in the Central Grampian Highlands by the *Ben Lawers* GCR site. There, it consists dominantly of crystalline metalimestone with only thin amphibolites representing the more substantial volcanic

component seen in the type area around Loch Awe in the South-west Grampian Highlands.

1.2 Structure

The GCR sites of the Central Grampian Highlands exemplify the classic interpretation of the overall structure of the Grampian Terrane, as described by Stephenson et al. (2013a). The refolded, recumbent NW-facing major folds of the Appin–Loch Leven area are particularly well represented in the Schiehallion–Ben Lawers area. Relationships in the area between these NW-facing folds and the SE-facing Tay Nappe are unclear, not least because of large intrusions of late-Caledonian granitic rocks in the Loch Etive–Moor of Rannoch area. In the South-west Grampian Highlands (Tanner et al., 2013a), the upright Loch Awe Syncline fulfils this central role between the SE-facing Tay Nappe and the NW-facing Islay Anticline; Roberts and Treagus (1977c) have attempted to project this fold into the Central Grampian Highlands. Several GCR sites specifically were chosen to examine three major slides of the region, the Benderloch, Ballachulish and Boundary slides. These slides are of particular interest for the debate as to whether they are, wholly or in part, of sedimentological or tectonic origin.

The structural significance of each of the GCR sites is described below, as far as possible in the context of the two classic areas of Appin–Loch Leven and Schiehallion–Ben Lawers.

In the Appin–Loch Leven area, eight GCR sites illustrate the major folds of the two dominant deformation phases ((Figure 3.3)a, b); the descriptions in the text progress essentially from east to west, into areas of decreasing complexity. The descriptions and interpretations in the site reports follow the work of J.L. Roberts and J.E. Treagus, as summarized by Roberts and Treagus (1977a, 1977b, 1977c). This work largely supported the original interpretation of Bailey (1960), but was based primarily on observations of minor structures that were largely ignored by Bailey. These views were challenged in part by Hickman (1978), but Roberts and Treagus (1980) defended their position.

The three major first-phase folds are the Appin Syncline, the Kinlochleven Anticline and the Ballachulish Syncline (Figure 3.3)b; their D1 age is justified from the evidence of minor structures in the individual GCR site reports. However, the Appin Syncline, as seen at the *Ardsheal Peninsula* and *Onich* GCR sites, was interpreted as a D2 structure by Hickman (1978) as was the antiform at the *Tom Meadhoin and Doire Ban* GCR site and the synform between the *Rubha Cladaich* and *Nathrach* GCR sites (the upward- and downward-facing nose of the Kinlochleven Anticline respectively, according to the Roberts and Treagus model preferred here). Hickman also disputed the existence of the Ballachulish Syncline at the *Stob Ban* GCR site, on stratigraphical grounds. The two major second-phase folds are the Stob Ban Synform and the Kinlochleven Antiform (not to be confused with the F1 Kinlochleven Anticline) (Figure 3.3)b; evidence for their existence and relative age, which has not been disputed, is examined in a number of GCR site reports.

The F1 Appin Syncline, which faces steeply up to the north-west, epitomizes the structural style of the westernmost part of the Central Grampian Highlands. The north-west limb is well represented in the *Ardsheal Peninsula* GCR site and the core and south-east limb in the *Onich* GCR sites. Relationships of the F1 minor folds and cleavage to the major fold are exceptionally well seen, as is the growth of chlorite (at Ardsheal) and of biotite (at Onich) in the stretching direction on the S1 cleavage planes. These observations support those of Bailey (1960) and Treagus and Treagus (1971) but contradict both those of Hickman (1978) and those of Bowes and Wright (1967) who suggested that the fold is a product of a third generation of deformation, associated with retrograde metamorphism. These GCR sites also provide evidence of the beginning of the D2 deformation, which increases in intensity eastwards towards the major F2 Stob Ban Synform. The *Lismore Island* GCR site, at a higher level in the Appin Syncline, although less well known with respect to the D1 history, illustrates the style of D2 particularly well, with large-scale folds that verge in sympathy with the Stob Ban Synform (Hickman, 1978).

The *Tom Meadhoin and Doire Ban* GCR site gives an unrivalled view of the upward-facing core of the F1 Kinlochleven Anticline, with associated minor structures. In its northern part, it illustrates relatively large-scale F2 folds on the north-west limb of the most significant major fold of that age, the Stob Ban Synform, which is fully exposed to the north-east at the *Stob Ban* GCR site. The *Rubha Cladaich* and *Nathrach* GCR sites illustrate the downward facing of the D1 structures on the north-west and south-east limbs respectively of the F1 major fold, the Kinlochleven Anticline. Lying on the south-east limb of the Stob Ban Synform, these two sites display D2 minor structures sympathetic to the major fold

and syn-D2 growth of garnet is well seen. The south-east limb of the complementary F2 Kinlochleven Antiform, to the east of the Stob Ban Synform, is represented by the *River Leven* GCR site, although the D1 facing here is not well documented.

The *St John's Church* GCR site has been chosen to illustrate the Ballachulish Slide, a major dislocation, also seen in the *Tom Meadhoin and Doire Ban* GCR site, which removes part of the succession on the common limb between the Kinlochleven Anticline and the next highest major F1 fold, the Ballachulish Syncline. This structure was originally a low-angle syn-D1 normal fault according to Bailey (1960), but it has been suggested by Soper and Anderton (1984) that it had a syn-sedimentation origin. According to Roberts and Treagus (1977a, 1977c), the Ballachulish Syncline is the correlative of the Loch Awe Syncline of the South-west Grampian Highlands. The documented stratigraphical evidence for the existence of the Ballachulish Syncline (Roberts, 1976) is given in the *Stob Ban* GCR site report; however, this evidence and evidence for the age of the Ballachulish Slide at that site clearly need re-examination. The *Rubha Cladaich* and *Nathrach* GCR sites also provide evidence for a set of structures that, according to Treagus (1974), are associated with the major post-D2 swing in strike of the earlier structures across Loch Leven (Figure 3.3)a.

In the Schiehallion–Loch Tay area ((Figure 3.4)a, b), the site descriptions and interpretations follow the work of Nell (1984) and Treagus (1987, 2000), but differ substantially from the earlier views of Bailey and McCallien (1937) and of Rast (1958). Three GCR sites (*Creag nan Caisean–Meall Reamhar*, *A9 and River Garry* and *Strath Fionan*,) illustrate aspects of the structure of the Schiehallion district, where major F1 folds on the lower limb of the SE-facing Tay Nappe are folded by major F2 folds. The *Allt Druidhe* GCR site has been chosen to illustrate the high strains associated with the Boundary Slide in this area and that at *Meall Dail-chealach* demonstrates the style of major late kink folds. To the south of Schiehallion, minor structures at the *Slatich* GCR site in Glen Lyon can be used to demonstrate the D2 age of a major fold, the Ruskich Antiform, which can be traced laterally to the south-west into the Ben Lui Fold; these F2 folds are major components of the architecture of the Grampian Terrane, at the north-western margin of the Tay Nappe. The *Slatich* and *Ben Lawers* GCR sites also exemplify D3 minor structures superimposed on those of the D1 and D2 phases. These sites also provide a structural link between the Schiehallion district and the Flat Belt, part of the inverted limb of the Tay Nappe, which dominates the structure of the south-eastern Dalradian. The *Ben Lawers* GCR site in particular contains the hinge-zone of one of the major post-D2 folds that affect the Flat Belt, the F4 Ben Lawers Synform.

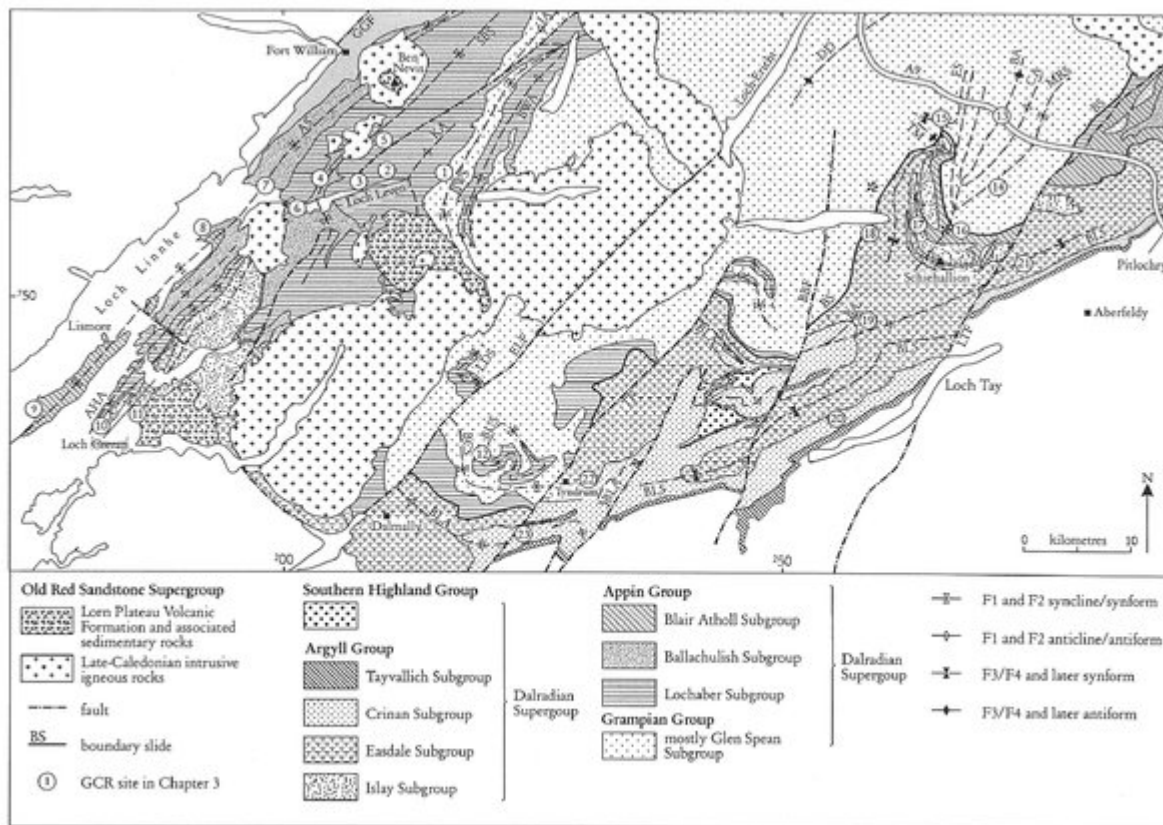
In the Tyndrum area the *River Orchy* GCR site, in a comparable position and along strike to the south-west of the *A9 and River Garry* GCR site, contains the hinge-zone of a major SE-facing early fold, the presumed D1 age of which has recently been shown to be D2 (Tanner and Thomas, 2010). The nearby *Ben Oss* GCR site, uniquely in this special issue, has been chosen to illustrate the history of movement and mineralization on a major fault, the NE-trending Tyndrum Fault, which is one of several that cause major displacements within the Grampian Terrane.

1.3 Metamorphism

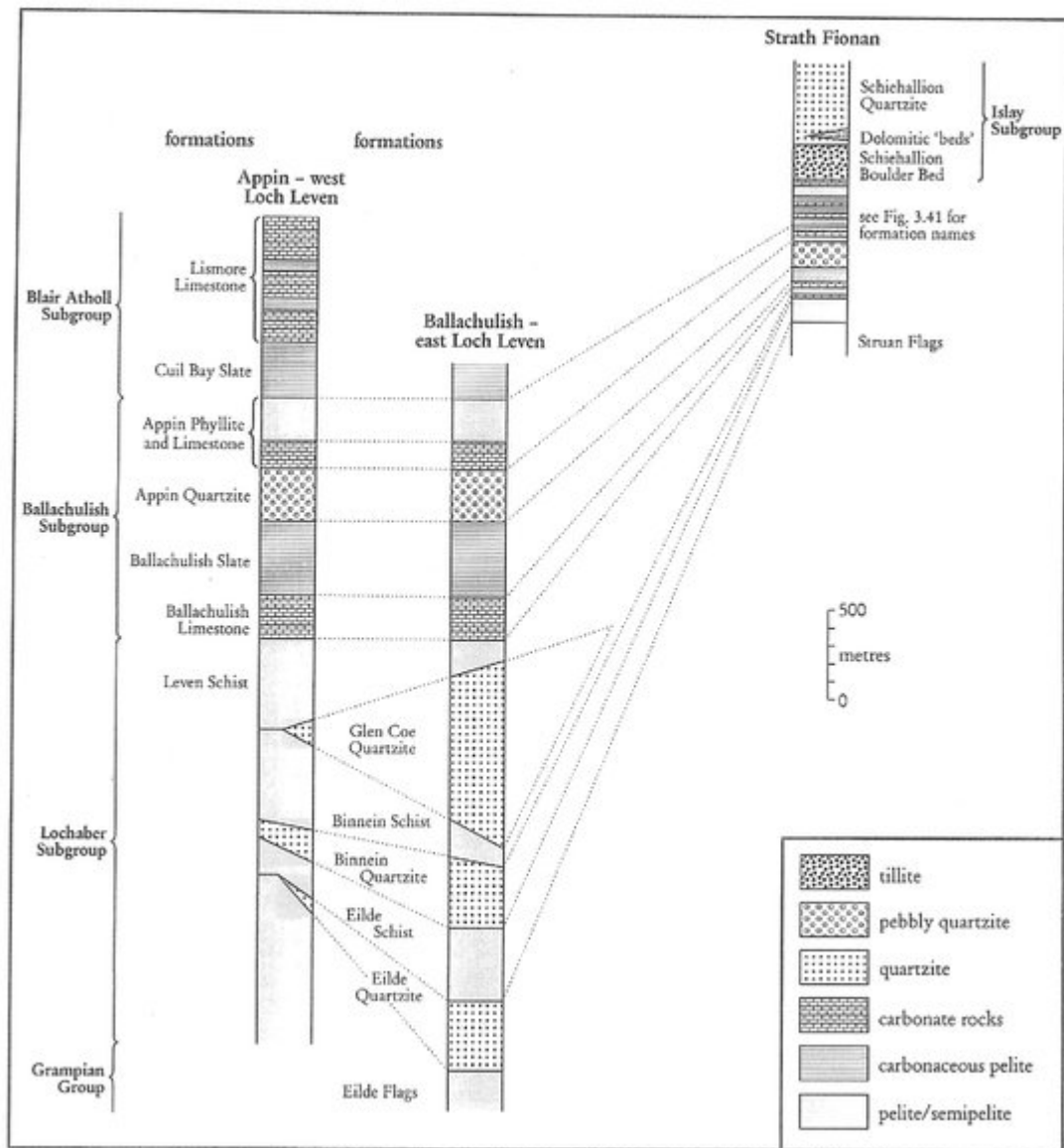
The selected GCR sites encompass rocks in both the greenschist and amphibolite facies. The greenschist-facies rocks are characteristic of the western seaboard of Argyll and of the Highland Border region; the remainder of the region is occupied by amphibolite-facies rocks. The *Ardsheal Peninsula* and *Onich* GCR sites exemplify, particularly well, low-grade slaty and phyllitic rocks. Chlorite-muscovite stacks at the former site and biotite crystals, up to 10 mm long at the latter site, are visibly elongated in the stretching direction on the S1 cleavage surfaces. To the east of these two GCR sites, the rocks pass into the lower amphibolite facies, coincident with the onset of the D2 deformation. Garnet and K-feldspar porphyroblasts are especially prominent in the Binnein Schist at the *Rubha Cladaich* GCR site; there it can be seen that these porphyroblasts are wrapped by the dominant S2 schistosity and include the S1 fabric.

Garnet is prominently displayed in schistose rocks across the central part of the area, and is well seen at the *River Orchy*, *Strath Fionan* and *Tempar Burn* GCR sites, here too with clear wrapping by the dominant S2 fabric; curved leucitic inclusion trails of S1 can also be seen in the field within the porphyroblasts. Amphibole (syn- to post-D2) is well developed in the Farragon Volcanic Formation at the *Slatich* and *Ben Lawers* GCR sites, and in the concordant amphibolites at the *Strath Fionan* GCR site. The Ben Lawers Schist Formation at the *Creag an Chanaich to Frenich Burn* GCR site displays coarse crystals of amphibole but within the Ben Lawers Synform (in the *Ben Lawers* GCR site) the formation is in the greenschist facies. Both staurolite (syn-D2) and kyanite (cross-cutting S2) are seen at the *Strath*

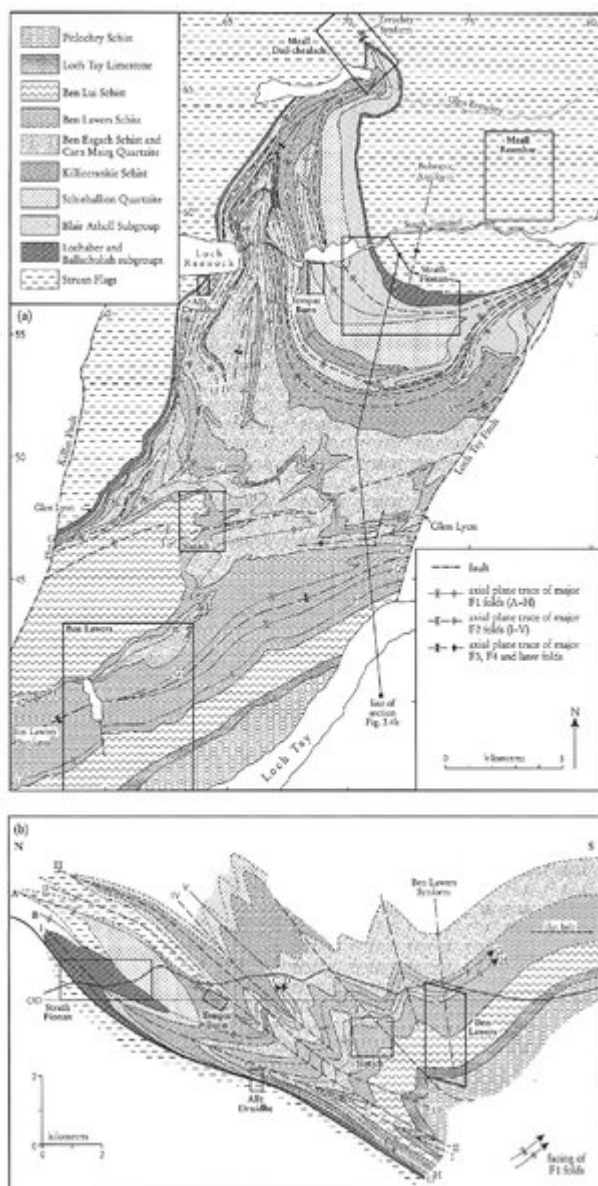
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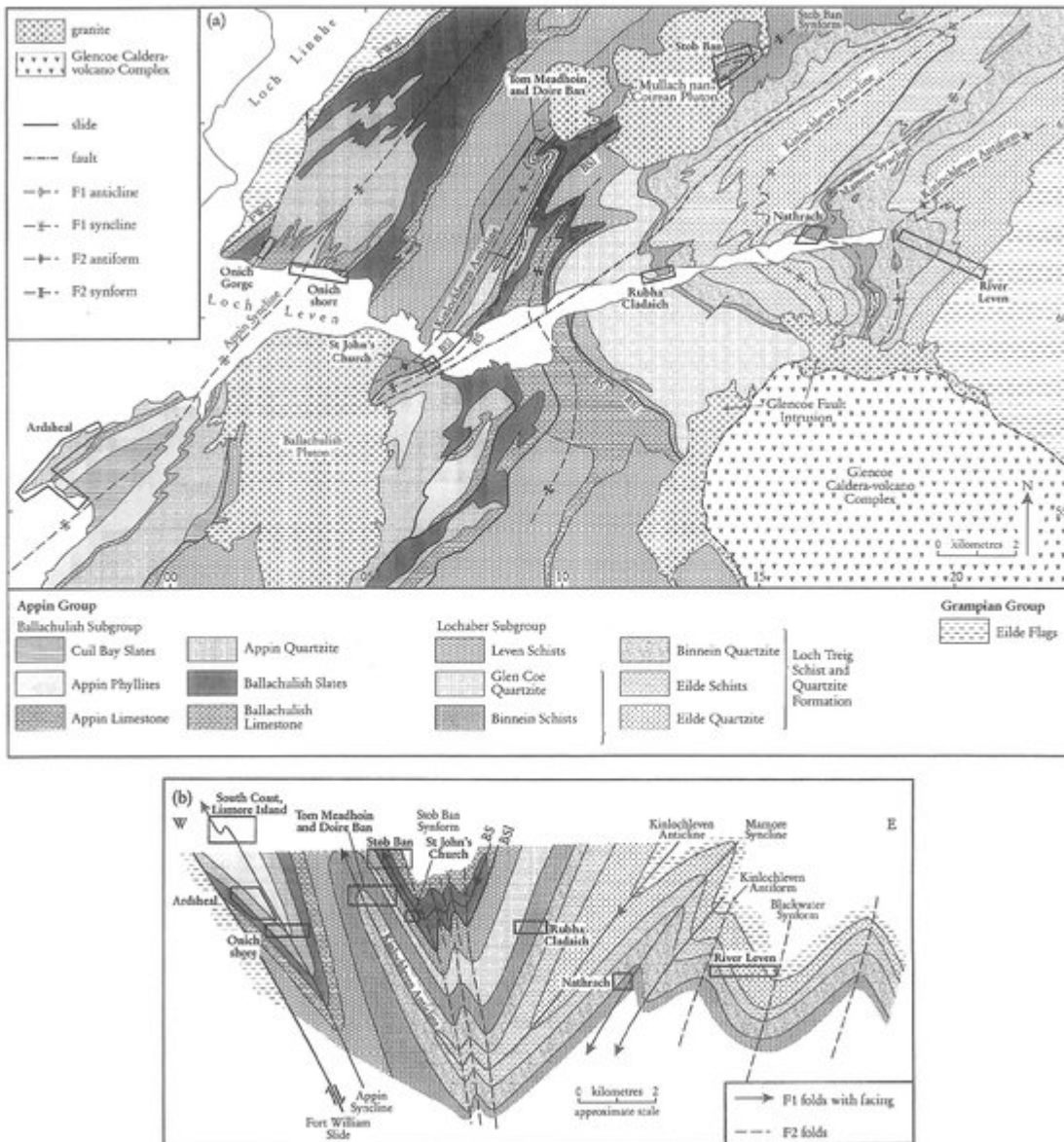
(Figure 3.1) Map of the Central Grampian Highlands, showing Dalradian subgroups, major structures including the Boundary Slide and locations of GCR sites. Only areas described in Chapter 3 are ornamented. * On the limbs of the late Errochty Synform, to the north of Schiehallion, highly attenuated condensed sequences of the Lochaber and Ballachulish subgroups, too thin to be shown at this scale, are present in the Boundary Slide-zone. GCR sites: 1, River Leven Section, 2 Nathrach, 3 Rubha Cladaich, 4 Tom Meadhoin and Doire Ban, 5 Stob Ban, 6 St John's Church, Loch Leven, 7 Onich Dry River Gorge and Onich Shore Section, 8 Ardsheal Peninsula, 9 South Coast, Lismore Island, 10 Camas Nathais, 11 Port Selma, Ardmucknish, 12 River Orchy, 13 A9 Road Cuttings and River Garry Gorge, 14 Creag nan Caisean–Meall Reamhar, 15 Meall Dail Chealach, 16 Strath Fionan, 17 Tempair Burn, 18 Allt Druidhe, 19 Slatich, 20 Ben Lawers, 21 Craig an Chanaich to Frenich Burn, 22 Auchtertyre, 23 Ben Oss. Faults: BBF Bridge of Balgie Fault, ELF Ericht–Laidon Fault, GGF Great Glen Fault, LTF Loch Tay Fault, TF Tyndrum Fault. F1 and F2 folds: AS Appin/Cuil Bay Syncline, AHA Airds Hill Anticline, BCS Beinn Chuirn Synform, BDS Beinn Donn Syncline, BLA Ben Lui Antiform, BSA Beinn Sgùich Anticline, BUS Beinn Udlaidh Syncline, BWA Blackwater Antiform/Treig Syncline, BWS Blackwater Synform, CA Clunes Antiform, IA Inverlair Antiform, KA Kinlochleven Antiform, LDS Loch Dochard Syncline, MRS Meall Reamhar Synform, RA Ruskich Antiform, SBS Stob Ban Synform. F3, F4 and later folds: BA Bohespic Antiform, BLS Ben Lawers Synform, DD Drumochter Dome, ES Errochty Synform, TM Trinafour Monoform.



(Figure 3.2) Comparison of Dalradian successions in the Loch Leven and Schiehallion (Strath Fionan) areas.



(Figure 3.4) (a) Map of the Schiehallion–Loch Tay area, showing outcrops of the main stratigraphical units, major structures and locations of GCR sites. (b) Cross-section of the Schiehallion–Loch Tay area, showing positions of GCR sites. Key, abbreviations and horizontal scale as in (a).



(Figure 3.3) (a) Map of the Loch Leven area, showing outcrops of the main stratigraphical units, major structures and locations of GCR sites. BS Ballachulish Syncline, BaSl Ballachulish Slide, FWSI Fort William Slide (b) Diagrammatic profile of the area shown in (a), looking up-plunge of F1 folds and showing position of GCR sites. Key, abbreviations and horizontal scale as in (a).