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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 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 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 be have had its origins in synsedimentary 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 4a). 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 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 psammites 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 glacigenic 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 (Figures 3a, 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 3b); 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 3b); 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 3a).

In the Schiehallion–Loch Tay area (Figure 4a, 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 porphroblasts 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 helecitic 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 Fionan* GCR site.

2 RIVER LEVEN SECTION (NN 191 619–NN 205 189)

J.E. Treagus

2.1 Introduction

The River Leven, east of Kinlochleven, provides a virtually continuous section, from the uppermost formation of the Grampian Group (the Eilde Flag Formation) through the three lowest members of the Loch Treig Schist and Quartzite Formation at the base of the Appin Group (the Eilde Quartzite, the Eilde Schists, and the Binnein Quartzite) (Figure 5). Its importance lies in the fact that a sedimentary transition between the Grampian and Appin groups can be clearly demonstrated. In addition, structural information from these rocks, in conjunction with that from other GCR sites around Loch Leven to the west, enables the large-scale tectonic picture of the western Grampian fold-belt to be understood. The exposures in the present-day bed and banks of the river are complemented in the east by those in an old course of the river and in the west by exposures adjacent to a pipeline.

The stratigraphical succession and the broad structural relationships of the Kinlochleven area have been described by Bailey (1960), with detailed structural data relating to the two regional phases of deformation being provided by Treagus (1974). A description of the GCR site was included in a guide to the Loch Leven area by Roberts and Treagus (1977b). A different interpretation of the structure was proposed by Hickman (1978), but this was refuted by Roberts and Treagus (1980).

2.2 Description

The GCR site extends from the youngest rocks at 1910 6186, just west of the old bridge across the River Leven at Kinlochleven, east to the oldest at 2047 6088, some 1.7 km upstream (Figure 5). At the former location, and for some 400 m upstream, are excellent exposures of the well-bedded, pure white, Binnein Quartzite with plentiful cross-bedding that youngs consistently to the west in vertical rocks (Figure 6). Characteristic rusty spots, a few millimetres in length are seen elongated parallel to a steep west-dipping cleavage in interbedded pelites. The transitional junction with the Eilde Schists is exposed in the river at about 1950 6173; younging in quartzite ribs immediately east of the junction is to the west.

The Eilde Schists are dark-grey pelites and semipelites with ribs of quartzite and feldspathic psammite, particularly near the top and bottom transitional beds, where carbonaceous and calcareous beds are also more common. Much of the accessible outcrop is in the flat limbs of folds, which are knee-shaped and tens of metres in wavelength; these folds verge north-west with an axial-planar, steep NW-dipping, intensely-developed, crenulation cleavage. The junction of the Eilde Schists with the Eilde Quartzite is exposed at about 2006 6150, on the vertical limb (some 50 m wide and striking 037°) of a major fold; to the east a flat limb, some 100 m wide is exposed at waterfalls, where inverted cross-bedding and slump-folds are excellently displayed in the feldspathic quartzites. The dip then gradually increases to the east across a major fold hinge, to return to vertical at about 2025 6606; some good exposures are seen in the old river course which runs north-west from here. Associated with this major fold are small-scale folds in thin quartzite beds and a steep axial-planar crenulation cleavage in the pelites.

The junction with the Eilde Flags at the top of the Grampian Group is easily identified at the point where an overflow channel from the pipeline to the south joins the river at 2026 6598. Thin-ribbed psammites and semipelites occur to the east of the reddened quartzites of the Eilde Quartzite, with typical Grampian Group thicker-bedded feldspathic psammites coming in immediately east of a porphyritic microdiorite dyke. Westward-younging cross-beds and slump-folds in the steep east-dipping rocks are well-seen throughout, but one 5 m-wide unit, between two waterfalls on the north bank, displays 10 cm- to 1 m-thick beds of slump folds particularly well, together with 50 cm-thick beds of unusually pebbly psammites. Pebbles in the latter are strongly elongated, up to a length of 4 cm, in the plane of the dominant, steep west-dipping, crenulation cleavage. Cleavage/bedding intersections are sub-horizontal (e.g. 5° to 062°).

2.3 Interpretation

The section in the River Leven is so unbroken and the way-up indicators are so unambiguous, that there can be no doubt that it provides a continuous stratigraphical section from the Eilde Flags (oldest), at the top of the Grampian Group, through the Eilde Quartzite and the Eilde Schists into the Binnein Quartzite, the lowest members of the Loch Treig Schist and Quartzite Formation at the base of the Lochaber Subgroup in the Appin Group. Most importantly, the attitude and style of the minor structures is consistent throughout the section and there is no evidence for a tectonic or metamorphic break at the junction between the Grampian and Appin group rocks. This observation became important with the assertion by Piasecki and van Breeman (1983) that rocks near Aviemore, which they assigned to the lower part of the Grampian Group, share a structural and tectonic event, then dated at 750 Ma, with underlying migmatitic rocks. Since there is no evidence in the Appin Group of events of this age, it appeared at that time that there must be a tectonic and/or metamorphic break within, or at the top of, the Grampian Group. However, since all of the rocks with evidence of a 750 Ma or older event (the date has subsequently been revised to c. 800 Ma) are now regarded as part of the pre-Grampian Group Badenoch Group (see Leslie et al., 2013), such an interpretation is no longer necessary.

The Grampian–Appin group junction exposed in the River Leven had been proposed as a possible site of a major tectonic boundary on the basis of the change in sedimentary environment (Lambert, 1975). However, the change in the nature of the metasedimentary lithologies at this junction does not mark a dramatic alteration in the original sedimentary environment. The major change is from the more-feldspathic (K-feldspar rich in thin section) Eilde Flags and their unusually coarse pebble beds into the cleaner Eilde Quartzite (plagioclase rich in thin section); however, psammites with mixtures of both feldspars occur in both the Eilde Quartzite and Eilde Schists, as well as in the Glen Coe Quartzite to the west of the GCR site, and the 'background' semipelite and pelite in all units remains of a consistent nature. The scale and nature of the cross-bedding and slump-folds also remains consistent across the junction.

Throughout the section, the minor- and intermediate-scale folds, with their associated cleavage, consistently verge north-west in a series of step-like folds. The cleavage in the pelites is very intensely developed and might be mistaken for a first cleavage, but in thin section it is clearly a crenulation of an earlier penetrative cleavage (Treagus, 1974). In fact in some locations it is possible to see an angle between bedding and this earlier penetrative cleavage, but the plunge of their apparent intersection and their vergence relationship is so variable as to render these observations of no use in the determination of facing of the first structures. The folds and dominant cleavage belong to the regional D2 phase of Treagus (1974); the intermediate-scale folds are on the eastern limb of the major F2 Kinlochleven Anitiform (which can be seen clearly from the western part of the GCR site in the hills to the north of Kinlochleven). Minor F2 folds and cleavage on the western limb of this fold are seen in the *Nathrach* GCR site. At Nathrach, D1 structures face downwards and, according to the regional structural interpretation of Treagus (1974), the Kinlochleven Antiform would be responsible for a change in the facing of D1 structures to steeply upward-facing on its eastern limb; this facing has not been confirmed in the rocks exposed in the River Leven GCR site, but should be a subject of future research. Bailey (1960), by contrast, considered that the rocks of this GCR site lie in the hinge area of a major recumbent F1 syncline, facing towards the west, a view that was shared by Hickman (1978). In the latter view, minor F1 folds and their axial planar cleavage would be recumbent, but the minor structure evidence presented here does not conform with that interpretation.

2.4 Conclusions

The River Leven Section GCR site is of national importance in demonstrating the continuity of sedimentation and the similarity of structural features across the boundary between the Grampian and Appin groups of the Dalradian succession. It is therefore not a candidate for the location of a major break in the history of geological events in the Scottish Highlands, as had once been suggested. The site provides a unique continuous section across the topmost formation of the Grampian Group into the loweest formation of the Appin Group and is rich in structures that provide evidence both for the sedimentary environment of these rocks and for their deformation history. The small-scale deformational structures (folds and cleavages) are important in the reconstruction of the largest-scale folds, many kilometres in length, that make up this western part of the Grampian Mountain Belt; the site will be important for further research in this respect.

3 NATHRACH
(NN 164 624)

J.E. Treagus

3.1 Introduction

The Nathrach GCR site, which is on a well-exposed hillside above the main road on the north side of Loch Leven west of Kinlochleven, has both stratigraphical and structural importance. Firstly, it contains fine exposures of the Binnein Schist and Binnein Quartzite members of the Loch Treig Schist and Quartzite Formation (Lochaber Subgroup) and of their transitional junction (Figure 7). The exposures of quartzite are rich in sedimentary structures. Secondly, the interbedded thin quartzites and pelites of the transitional beds contain minor structures, unrivalled for their clarity (Figure 8), which give important information on both the geometry and position of major folds of two deformation phases. The locality is therefore critical, together with other GCR sites

(*River Leven, Rubha Cladaich, St John's Church, Tom Meadhoin and Doire Ban* and *Stob Ban*) to the interpretation of the large-scale recumbent refolded folds which characterize the Loch Leven–Ballachulish area.

The stratigraphy and the structure of the GCR site have been described by Bailey (1960) and Treagus (1974). A description of the site is also included in a geological field guide to the Loch Leven area by Roberts and Treagus (1977b).

3.2 Description

There are three areas of interest in this GCR site. The principal interest is in the structure of the Binnein Schists, as displayed in a series of prominent NW-facing exposures about 50 m long at around 1656 6235 (Figure 7, locality A). The member here comprises finely bedded pelite and semipelite with some interbedded centimetre- to 0.5 metre-thick white quartzite beds. Cross-bedding in these pure quartzites, which are of a similar facies to the Binnein Quartzite, youngs to the north-west in the near-vertical NE-striking beds. The exposures provide numerous examples of tight folds (F2 in the interpretation below) with centimetre- to metre-scale amplitude and wavelength (Figure 8). At the south-western end of the crags, the plunge of these folds is at steep angles (70–80°) to the south-west, but towards the north-eastern end they plunge steeply to the north-east. The penetrative fabric of the pelite, which is subparallel to the bedding, has been affected by a tight crenulation cleavage (S2), which is near vertical, NE-striking and axial planar to the folds; the penetrative fabric in the semipelite is tightly folded together with the bedding. The vergence geometry of the folds and of the bedding in relation to the crenulation cleavage is of an 'S' type (assuming an average vertical plunge). In certain exposures it is possible to see that earlier folds (F1) are deformed by this main set; neither the vergence nor the plunge of these early folds is easily measured, but the nature of the interference patterns shows that they are not precisely co-axial with the later set. The earlier folds have the penetrative cleavage (S1) in the semipelite parallel to their axial surfaces. A weaker, NNE-trending, crenulation cleavage associated with more-open folds is developed locally; this is the third set of structures more fully described at locality C, below.

The second area of interest is the structure of the Binnein Quartzite, best seen in prominent crags centred about 1640 6237, some 10–50 m west of a sharp change of slope which marks the Binnein Quartzite–Binnein Schist junction (Figure 7, locality B). Here, the member consists of white quartzite, well bedded (10–90 cm-thick beds) with rare semipelite and pelite units. Cross-bedding, not easily seen near the junction with the Binnein Schists, is seen to young consistently to the south-east in the near-vertical NE-striking beds. Of particular interest are thin (10 cm) beds of quartzite, interbedded with the pelite and semipelite, which commonly display well-developed tight folds. These asymmetric folds, with a short limb length of some 10–20 cm, plunge at 30–50° to 070°, have a 'Z' geometry and have a penetrative schistosity in the semipelite parallel to their axial-surfaces, as noted in the F1 folds at locality A (Figure 9). In the adjacent pelites, a crenulation cleavage (of the type noted above related to the later F2 folds) is developed, which transects the F1 folds; folds related to this cleavage are not developed here, although they are seen, with the characteristic 'S' geometry, in more schistose lithologies nearer to the junction with the Binnein Schists. Similar relationships can be observed elsewhere near this junction (Figure 7).

The third area is a series of crags at the top of a small hill near the road at 1630 6205 (Figure 7, locality C), which exposes Binnein Schists of the type described at locality A, and in a similar structural position. Metre-thick quartzites, north striking and near vertical, display excellent cross-sets younging to the west. The quartzites are affected by open folds, and the interbedded pelites display the development of an axial-planar, wide-spaced (1 cm), crenulation affecting the two earlier cleavages described above. The axial surfaces of these crenulations strike east-north-east and are near vertical; the plunge of this third set of folds is approximately vertical.

3.3 Interpretation

The Nathrach GCR site is located across the transitional junction between the Binnein Quartzite and the Binnein Schists and, although a totally continuous section is not exposed, the abundant easterly-younging cross-bedding in the quartzites at locality B leaves no doubt that the schists are the younger member. In a regional context, this junction is on the western, sub-vertical, limb of a tight, upright, antiform which closes to the north-east on Sgor an Fharain (180 640) (Figure 3a). The same transitional junction on the eastern limb of the fold can be examined east of the Nathrach Burn around 170 627 where cross-bedding youngs to the west (Figure 7). Bailey (1960), from stratigraphical considerations, proposed that this fold (named the Mamore Syncline by Treagus, 1974) is a downward-facing D1 structure, a major subsidiary fold on the eastern limb of the regional Kinlochleven Anticline. This proposal is consistent with the minor structures observed in the western area of the GCR site at locality B, which show that the rocks face downwards on the first penetrative cleavage, related to minor folds that must lie on the western limb of a major syncline (see also Treagus, 1974). These observations are complemented by those at the *Rubha Cladaich* GCR site, which lie on the western limb of the downward-facing F1 Kinlochleven Anticline.

To the east of the junction of the Binnein Quartzite and Binnein Schists, at locality A, interbedded quartzites within the Binnein Schists young towards the west. Since the crenulation cleavage and related minor folds (D2 of the regional structure) have the same vergence here as in locality B, the fold between the two localities must either be a subsidiary F1 fold related to the Mamore Syncline or the major fold itself. The importance of these observations is to show that the major reversals of younging in the area are the product of the downward-facing D1 folding and not of the D2 phase. Similarly, the consistent vergence of the D2 structures here and in the *Rubha Cladaich* GCR site, on the opposing limb of the

Kinlochleven Anticline, can be used to demonstrate the D1 age of that fold.

Locality C exhibits examples of a third generation of minor folds (F3), and a related E–W-trending crenulation cleavage (S3). Both are geometrically associated with the major swing in strike, to a south-east direction, of all earlier structures across Loch Leven (Figure 3,3a). Treagus (1974) suggested that this change in strike (the Loch Leven Fold) on the south side of the loch might be the result of the intrusions of the Glen Coe Caldera-volcano Complex of late-Silurian age. The re-interpretation of this volcanism in a NW-orientated graben, resulting from regional NE-directed tension or from a transtensional scenario (Moore and Kokelaar, 1997), might account for such a deflection in the adjacent Dalradian rocks.

3.4 Conclusions

The importance of the Nathrach GCR site lies in its wealth of sedimentary structures across the junction between two members of the Loch Treig Schist and Quartzite Formation (Lochaber Subgroup) and in its abundant minor tectonic structures (folds and cleavages) of unrivalled clarity. Taken together, these structures demonstrate that the earliest major folds, of many kilometres amplitude and originally probably flat-lying, have been bent by later forces to assume remarkable, totally downward-facing (i.e. upside-down) attitudes. Even later forces have twisted the earlier folds yet again through 90° to change the whole grain of the country rock for several tens of kilometres, which may be related to the tensional opening of the crust associated with development of the Glen Coe Caldera-volcano to the south.

4 RUBHA CLADAICH (NN 120 610–NN 133 613)

J.E. Treagus

4.1 Introduction

The Rubha Cladaich GCR site, adjacent to the main road on the north shore of Loch Leven, provides important sedimentological and structural information in a section across three members of the Loch Treig Schist and Quartzite Formation in the Ballachulish Subgroup of the Appin Group. The sedimentary make-up of the three members (Glen Coe Quartzite, Binnein Schist and Binnein Quarzite), their transitional facies and their sedimentary structures can be seen clearly on clean glaciated surfaces. In addition, the evidence from minor structures supports the relative ages and geometry of the three principal phases of deformation in the region. Together with complementary information from the *Nathrach* GCR site, these structures can be used to demonstrate the D1 age of the dominant major fold in the area, the Kinlochleven Anticline. The rocks at this site are exceptionally rich in porphyroblasts both of garnet and of plagioclase, which can be related to the structural history.

The principal features of the GCR site have been described by Bailey (1960), Treagus (1974), and in a field guide to the Loch Leven area by Roberts and Treagus (1977b).

4.2 Description

This GCR site provides both sedimentological and structural information from the base of the Glen Coe Quartzite, down through the Binnein Schists into the top of the Binnein Quartzite in a series of shoreline exposures, complemented by road-cuttings (Figure 10). At the western margin of these exposures (NN 1216 6098 to 1228 6098), the peninsula of Rubha Cladaich exposes glaciated surfaces of the thick-bedded (0.5–2 m) feldspathic Glen Coe Quartzite. The western edge of the exposure is part of a steep N-dipping 'short' limb of a major steeply-plunging fold, the long limb of which, dipping at 48–72° to the west-north-west, occupies the remainder of the exposure to the east. Cross-bedding, in 30 cm-thick sets younging to the south, is particularly well seen on the short limb, by the mouth of a small burn. Other sedimentary features that are seen in the quartzites on both limbs include ripple cross-lamination, slump folds and mud-flakes that are associated with thin pelitic beds (centimetres thick). The latter contain thin string-like concentrations of feldspar clasts up to 2 cm long.

The hinge area of the major fold, which is exposed on the main promontory to the east of the burn, has a vertical penetrative axial plane schistosity that strikes 072°. Calculated plunges of minor folds within the hinge are variable from steep (e.g. 80° to the south-west), through vertical, to 44° to 020°; the latter are presumed to be more typical of the regional plunge of the major folds (Treagus, 1976). The NNE-striking long limb of the fold is corrugated by metre-wavelength, open folds with axial-surfaces trending east-north-east that are locally associated with a widely spaced crenulation cleavage.

To the east of the main promontory the next exposures, around 1233 6098, contain the Glen Coe Quartzite–Binnein Schist junction, showing a transition from metre-thick quartzites in semipelite into garnetiferous pelites with only thin (10 cm) beds of quartzite. The latter quartzites exhibit cross-bedding and channel structures that indicate younging to the west. In the Binnein Schists, porphyroblasts both of plagioclase feldspar and of garnet are common in the pelites. Both are wrapped by a dominant, near-vertical, crenulation cleavage (e.g. 070°/86°NW) that crosses the bedding (e.g. 020°/70°W) in a clockwise sense; minor folds related to the cleavage show consistent 'S' vergence and plunge to the south-west (e.g. 40° to 335°). Of particular importance, seen in the middle of this exposure, are several 10–20 cm-wavelength isoclinal folds (F1 in the interpretation below) that are clearly folded or are cross-cut by the dominant crenulation cleavage (S2) and its associated minor folds (F2) (Figure 11). These earlier folds, which have a penetrative schistosity (S1) parallel to their axial-surfaces, plunge steeply to the north-east and have an 'S' vergence. Particularly clear patterns produced by the interference of the two sets of folds are seen at the extreme edge of this exposure at about NN 1249 6101. Similar relationships can be seen on a steep glaciated surface farther east at NN 1262 6004. Locally, open folds (F3) with E-W-trending axial surfaces and a coarse crenulation cleavage, deform the earlier cleavages.

The junction of the Binnein Schists with the Binnein Quartzite is exposed in a road-cutting at NN 1267 6017, where there is a transition over a distance of a metre from the typical Binnein Schist lithology, described above, into thinly-bedded (centimetre-thick) pure quartzite. The quartzite, which dips at about 50° to the west, becomes thicker-bedded eastwards, with 30 cm-thick units and clear cross-sets younging to the west that are best displayed near the end of the roadcut (NN 1284 6027), but also seen on the foreshore at NN 1279 6020. Also seen are folds of a metre wavelength, with a similar geometry to the dominant F2 set in the previous exposures, which plunge moderately to steeply to the south-west with an 'S' vergence.

4.3 Interpretation

The almost continuous exposure across the two boundaries between the three members gives an exceptionally compact section in which the nature of this sedimentary succession, the detail of its sedimentary structures and its way-up can be studied.

Structurally, the importance of the site lies in the clear superimposition of the three regional phases of deformation. The folds and cleavage in the Glen Coe Quartzite are identifed as D1, as no earlier structure can be observed; their plunge and vergence are compatible with their position on the upper limb of the major downward-facing F1 Kinlochleven Anticline, which lies in the outcrops of Eilde Quartzite and Eilde Schist between here and the *Nathrach* GCR site to the east. In the adjacent Binnein Schists, the S1 schistosity is intensely crenulated by the dominant S2 cleavage, but clear examples of F1 folds are also preserved (Figure 11). The D2 minor folds complement those seen at the same stratigraphical boundary in the *Nathrach* GCR site. Their plunge and vergence demonstrate that the Kinlochleven Anticline is cross-cut by the D2 structures and also support the interpretation of the geometry and position of the major F2 Stob Ban Synform to the west (see also the *Stob Ban* and *Tom Meadhoin and Doire Ban* GCR site reports). The growth of the garnet and plagioclase porphyroblasts can be seen to be associated with the development of the S2 cleavage that wraps them, both in thin section and in hand specimen (Treagus, 1974).

The third generation of minor structures is seen in the open folds of the Glen Coe Quartzite exposures and as the coarse ENE-striking crenulation cleavage in the Binnein Schists. These structures are related to the regional F3 Loch Leven Antiform, which is responsible for the deflection of the regional north-east strike into the south-east strike on the S side of Loch Leven (Treagus, 1974; Figure 3a; see also the *Nathrach* GCR site report).

The interpretation of the D1 and D3 major structures given here agrees with the interpretation of Bailey (1960), which was supported by the minor structural data given by Treagus (1974). The latter author used the minor structures to propose the present three-phase history. However, Hickman (1976) refuted that the downward-closing fold between the present site and that at Nathrach is the closure of the F1 Kinlochleven Anticline, attributing it to a secondary phase, although he did not present any specific data to support this interpretation. His main argument, from the NW-striking exposures on the south side of Loch Leven, appeared to be that minor F1 folds plunge to the south-east on the south-west limb and to the north-west on the north-east limb and thus must be folded around the major closure. However, the data presented here and in the *Nathrach* GCR site report show that F1 minor folds exhibit a considerable variation in plunge from steep to the south-west, through vertical to gentle NE-plunging attitudes. Allowing for the late swing of strike across Loch Leven, this variation in fold geometry is similar to that recorded by Hickman, but here it can be seen within a single F1 major fold limb. Furthermore, there is no evidence from post-D1 minor structures to support the existence of a major secondary synform to the east of the Rubha Cladaich GCR site.

4.4 Conclusions

The Rubha Cladaich GCR site provides both essential sedimentological and structural information for the interpretation of the Dalradian of the western side of the Grampian mountain belt. Firstly, it allows the establishment of the stratigraphical succession of the lower part of the Appin Group (the Glen Coe Quartzite, Binnein Schist and Binnein Quartzite members of the Loch Treig Schist and Quartzite Formation) in an unusually compact and continuous shore section. Sedimentary structures, which give information concerning the conditions of sedimentation, as well as the way-up of the succession, are particularly well preserved on clean glaciated surfaces. Similarly, these surfaces provide clear evidence of minor tectonic structures (folds and cleavages) of three generations. Study of these structures, particularly in the context of adjacent GCR sites allows the geometry and relative age of major folds of the three generations to be understood.

This site complements the *Nathrach* GCR site in demonstrating the dramatic large-scale closure of the Kinlochleven Anticline, the most important of the early regional folds in the area, which is here totally inverted by the second phase of deformation. It also exhibits still later folds, with their associated cleavage, which are essential to the understanding of the regional swing in the trend of the beds and earlier structures through 90° across the eastern end of Loch Leven.

5 TOM MHEADHOIN AND DOIRE BAN
(NN 071 610–NN 091 631 AND NN 097 634–NN 089 645)

J.E. Treagus

5.1 Introduction

The GCR site at Tom Meadhoin and Doire Ban occupies a summit ridge between Loch Leven and Gleann Righ to the north (Figure 12). It is important for the placing of major folds into the regional deformational picture, establishing in particular the Tom Meadhoin Antiform as the closure of the major F1 Kinlochleven Anticline, which is here upward facing as a result of refolding by D2 structures. Information from this site has also allowed a revision of the stratigraphical identity of lithological units on the north side of Loch Leven, which in turn has lead to a refinement of the structural interpretation. One of the major dislocations of the area, the Ballachulish Slide, which separates the Kinlochleven Anticline from the structurally overlying Ballachulish Syncline, is also exposed.

The rocks were described in some detail by Bailey (1960), who identified the Tom Meadhoin Antiform as an 'early' structure, but a stratigraphical revision was made by Roberts (1976) who also provided the structural detail reported here.

5.2 Description

The stratigraphical succession of this site (Figure 12) is in the Appin Group. It progresses from the Binnein Quartzite (oldest) through the Binnein Schists and the Glen Coe Quartzite into the Leven Schists (all Lochaber Subgroup) and then across the Ballachulish Slide into the abbreviated Ballachulish Limestone and Ballachulish Slates of the Ballachulish Subgroup. The Binnein Quartzite is the best-seen unit, being prominently exposed on the crags of Tom Mheadhoin, where it forms the core of a doubly-plunging antiform, the Tom Meadhoin Antiiform (Bailey, 1960) The rock is a well-bedded, pure-white quartzite in which the dip can be readily measured to demonstrate the north-easterly and south-westerly plunges at its north-eastern and south-western ends respectively. The craggy outcrops between NN 099 629 and NN 084 620 exhibit many examples of cross-bedding, unambiguously younging up towards the boundary with the surrounding schists.

The transitional facies from the Binnein Quartzite to the Binnein Schists consists of impure quartzites (commonly cross-bedded) and dark pelite and semipelite (commonly graded), as seen in the *Rubha Cladaich* GCR site. These lithologies are well seen at the north-eastern end of the antiform (NN 095 637), and on both limbs of its south-western closure at NN 620 088 and NN 083 620. At these three exposures the angular relations between the steep NW-dipping penetrative cleavage and the shallower dipping bedding clearly shows that the cleavage is axial-planar to the major fold. The cleavage/bedding intersections plunge at about 35° to the north-east at the north-eastern closure of the antiform and at less than 20° to the south-west at its south-western end.

A thin feldspathic quartzite can be traced from the shore at Loch Leven, north-eastwards along the south-east side of the outcrop of the Binnein Quartzite and Binnein Schists on Tom Mheadhoin (Figure 12). This outcrop of the Glen Coe Quartzite is also well exposed to the south-east of Doire Ban, from about NN 097 636 to NN 092 641, where it defines a synform and an antiform. These folds plunge to the north-east, as is seen from the changing dip of bedding and the plunge of the intersection of a crenulation cleavage with the bedding. The crenulation cleavage is axial-planar to the major fold-pair.

The Leven Schists and younger formations to the east and north of the succession described above are not well exposed in the area of this GCR site. However, the Ballachulish Slide, which brings the younger formations (the Ballachulish Limestone, the Ballachulish Slates and the Appin Quartzite) against the Leven Schists can be located within the area. In a gully of a burn draining east from Doire Ban, about NN 096 645, the Leven Schists are in contact with the Ballachulish Slates, with an intervening thin remnant of Ballachulish Limestone in places. The location of the slide can be followed south-west around the antiform/synform pair discussed above. To the north-east of Tom Meadhoin the slide can also be located at the head of a burn at NN 091 625, where the Ballachulish Limestone is missing and the Ballachulish Slates are brought against the Leven Schists. The flagginess of the rocks at these exposures of the Ballachulish Slide appears to be parallel to the penetrative cleavage in the adjacent rocks.

5.3 Interpretation

Perhaps the most important aspects of this GCR site are the re-interpretation of the quartzite of Tom Meadhoin as the Binnein Quartzite, surrounded by the Binnein Schists, and the identification of the dominant structure as an F1 fold core by Roberts (1976). Bailey (1960) had interpreted both this outcrop of quartzite and the quartzite outcrop to its south-east as the Glen Coe Quartzite, occupying two antiformal cores, with a synform in the intervening schists (his Leven Schists). He interpreted the three folds as comprising the upward-facing hinge of the Kinlochleven Anticline, one of the major early recumbent nappes folded into an upright position by the secondary Stob Ban Synform (see the *Stob Ban* GCR site report). The relations of the S1 penetrative cleavage to bedding seen at this GCR site confirm that the Tom Meadhoin Antiform is indeed a D1 structure and a true anticline (Roberts, 1976). However, the quartzite in the fold core on Tom Meadhoin is undoubtedly the Binnein Quartzite, from its clean, white, well-bedded character and its characteristic transition to the Binnein Schists. This revision of the stratigraphy removes the need for the two folds to the south-east of Tom Meadhoin. It also confirms the progressive thinning of the Glen Coe Quartzite from 2 km at its type locality on the south side of Loch Leven, to a few hundred metres north of Mam Gualainn (118 638) (Figure 12), as described by Treagus (1974), to a few tens of metres at Doire Ban. Furthermore, to the north-west of this GCR site, the expanse of pelite identified as Leven Schists by Bailey (1960) must represent a direct passage from the Binnein Schists into the Leven Schists, in which the Glen Coe Quartzite is not represented at all.

A second important structural observation is that the two NE-plunging folds of the outcrop of the Glen Coe Quartzite on Doire Ban are associated with a crenulation cleavage and are therefore of D2 age in the regional deformation sequence. These folds are subsidary folds to the regional SW-plunging F2 Stob Ban Synform, which crops out to the south-east (see Figure 12 and the *Stob Ban* GCR site report). This F2 fold is responsible for the folding of the once-recumbent Kinlochleven Anticline to its upward-facing position at Tom Meadhoin and its downward-facing attitude farther east (see the *Rubha Cladaich* and *Nathrach* GCR site reports).

As Bailey (1960) pointed out, the Ballachulish Slide appears to be contemporary with the early (D1) deformation in this area, which is confirmed by the observations at this GCR site. However, as Bailey also pointed out, the slide must be an original low-angle normal fault rather than a thrust, as it thins the upper limb of a major anticline, the Kinlochleven Anticline. Soper and Anderton (1984) have suggested that such movements may have taken place during sedimentation. Further research at the site might help to shed more light on this problem.

5.4 Conclusions

The Tom Meadhoin and Doire Ban GCR site is of critical importance for the light that it sheds on both stratigraphical and structural arguments in the Dalradian on the west side of the Grampian fold-belt. As well as clarifying the local stratigraphical succession, it enables the dramatic thinning of one formation, the Glen Coe Quartzite, to be reconstructed. It also provides an unusually complete view of the hinge area of one of the major folds of the region, the F1 Kinlochleven Anticline. This fold, which was originally flat-lying, extends over a distance of at least 15 km from Tom Meadhoin eastwards to the *River Leven* GCR site. A further period of deformation was responsible for the bending of this fold from its original flat-lying attitude into its present upright position and the superimposed structures associated with this D2 event can be well demonstrated. One of the major structural dislocations of the region, the Ballachulish Slide, is contemporary with the earlier folding and is also well seen. This GCR site promises to be important for future investigations of the structure of the region.

6 STOB BAN
(NN 138 658–NN 149 668)

J.E. Treagus

6.1 Introduction

This GCR site, on the northern side of Stob Ban, one of the highest mountains in the Mamore range, contains the magnificently exposed core of one of the major F2 folds of the Loch Leven area, the Stob Ban Synform. This upright, SW-plunging fold is responsible for the change from the downward-facing D1 structures of the *Nathrach* and *Rubha Cladaich* GCR sites, to the south-east of this site, to the upward-facing D1 structures of the *Tom Meadhoin and Doire Ban* and *Onich* GCR sites to the south-west. At the Stob Ban GCR site, the Stob Ban Synform refolds the Ballachulish Syncline, which, along with the underlying Kinlochleven Anticline (seen in the *Tom Meadhoin and Doire Ban* GCR site) is one of the major, originally flat-lying, F1 nappe structures of the western part of the Grampian fold-belt. The interpretation of the structure is dependant upon Bailey's (1960) interpretation of the stratigraphical succession, which in this area is very abbreviated and is also hornfelsed by a granitic pluton. This interpretation was supported by Roberts (1976) but doubted by Hickman (1978). It is clear from Bailey's description (in Bailey, 1960) that the realization of the existence of this refolding was central to his interpretation of the whole regional structure.

6.2 Description

This remote and poorly known GCR site extends from Coire an Lochain, the north-western coire of Stob Ban, across the mountain's north ridge and down the eastern flank into Coire a' Mhusgain. According to Bailey (1960, pp. 47–49), and as recorded by him on the Geological Survey's 1" Sheet 53 (1948), the GCR site contains the isoclinal core of the recumbent Ballachulish Syncline, folded by the upright secondary Callert Synform (now known as the Stob Ban Synform). As Figure 13 shows, the right-way-up sequence of thick Leven Schists and 30 m of Ballachulish Limestone on the lower limb of the syncline (equivalent to the upper limb of the Tom Meadhoin Anticline, as seen in the *Tom Meadhoin and Doire Ban* GCR site) is followed upwards by 30 m of the Ballachulish Slates in the core and then the reverse sequence of Ballachulish Limestone–Leven Schists on the upper limb. The two limbs of this once-recumbent F1 fold have subsequently been folded into the tight upright SW-plunging F2 Stob Ban Synform. All of the lithologies have been hornfelsed by the granitic Mullach nan Coirean Pluton.

Further details have been given by J.L. Roberts (1976 and in Roberts and Treagus, 1977b). The first penetrative cleavage (S1) is everywhere parallel to bedding; it has steep south-east dips of 75° to the south-east on the north-west limb of the Stob Ban Synform and near vertical dips on the south-east limb. The closure of the F2 synform is well exposed on the steep eastern slopes of the north ridge of Stob Ban (at about NN 146 666). The outcrop of the Leven Schists in the core terminates some 20 m below the crest of the ridge and the underlying thin Ballachulish Limestone can be traced around the hinge. Below this, the Ballachulish Slates in the core of the early F1 syncline and the lower, repeated Ballachulish Limestone and Leven Schist sequence, now right-way-up, can be traced from the hinge both to the north-west and south-east along the ridge (between about NN 147 663 and NN 144 668). Minor F2 folds are symmetrical in the hinge-zone and become increasingly north-west vergent to the north-west and increasingly south-east vergent to the south-east, thus demonstrating the D2 age of the major fold.

Another well-exposed section is along the Allt Coire an Lochain which drains north-west from the lochan at NN 141 662 just south-east of the synformal fold core. The two outcrops of Ballachulish Limestone (now calcsilicate hornfels) and the intervening Ballachulish Slates are well seen in the gorge (at about NN 140 663), with the upper part of the Leven Schists (now pelitic hornfels) seen at the lip of the corrie (NN 1407 6624). Throughout this section F2 folds, with steeply dipping axial planes, are seen plunging to the south-west and verging to the north-west on the north-west limb of the major F2 synform. The Ballachulish Limestone can be seen on the south-east limb of the synform midway along the north-east shore of the lochan, followed uphill to the east (to about NN 143 661) by the Ballachulish Slate–Ballachulish Limestone–Leven Schist sequence, in which the minor folds verge south-east on the south-east limb of the major F2 synform.

6.3 Interpretation

The existence and identity of the Ballachulish Syncline was deduced by Bailey (1960) from the apparent repetition of the Leven Schists and Ballachulish Limestone about the core of Ballachulish Slates. The identities of these formations is made difficult both by their great abbreviation from their thicknesses at their type localities and from their severe hornfelsing by the adjacent granite. Roberts (1976) confirmed the folding of the regional S1 cleavage, parallel to bedding, around the major F2 synform, but he regarded Bailey's interpretation of the stratigraphy and D1 structure to be a working hypothesis, being unable to provide any way-up evidence or D1 minor structure evidence to add to Bailey's observations. Hickman (1978) suggested that the supposed Leven Schist and Ballachulish Limestone sequences are local facies variations within the Ballachulish Slates, although such variations have not been reported elsewhere. In fact, the reality of the stratigraphy of the inverted limb of the major F1 syncline is better demonstrated to the south of the Stob Ban GCR site, between Tom Meadhoin and Callert House (Figure 12), where the Ballachulish Slates are succeeded upwards by a large expanse of Ballachulish Limestone and Appin Quartzite occurs in the fold core.

The sympathetic relations of the S2 crenulation cleavage and F2 minor folds to the major Stob Ban Synform in the area of the GCR site, as reported by Roberts (1976), support Bailey's (1960) identification of that structure as a major component of the secondary deformation in the Loch Leven area.

6.4 Conclusions

The Stob Ban GCR site not only provides sections across one of the major early folds seen in the western Grampian fold-belt (the F1 Ballachulish Syncline), but also contains the hinge of one of the major later folds (the F2 Stob Ban Synform). Later folds such as this are responsible for major variations in attitude of the early folds throughout the Loch Leven area. Despite considerable reductions in thickness of some of the lithological units, relative to their type areas and despite contact metamorphism in the aureole of an adjacent granite, the stratigraphy within the GCR site is clear enough for the repetition of formations on the two limbs of the early fold to be unusually well seen. Moreover, the striking manner of the changing geometry of minor folds across the site can be used to demonstrate perfectly the existence and age of the later, F2 fold. The detailed structural relationships at this GCR site are only poorly known and there is considerable scope for further study.

7 ST JOHN'S CHURCH, LOCH LEVEN (NN 065 587)

J.E. Treagus

7.1 Introduction

The St John's Church GCR site, on the south shore of Loch Leven 1.5 km south-east of the Ballachulish Bridge, provides a rare section across one of the 'slides' (synmetamorphic low-angled faults) that are a major feature of the Dalradian in the western part of the Central Grampian Highlands. An Appin Group succession from the lower part of the Leven Schists up to the base of the Appin Quartzite, is exposed across the core of one of the major recumbent nappes of the area, the Ballachulish Syncline; the Ballachulish Slide occurs on the lower limb of this fold. Here the fold core and the slide are turned into a steeply dipping attitude as a result of later folding.

The exposures were described and the structure was illustrated by Bailey (1960, pp. 58–59, figure 7G); Roberts (1976) and Roberts and Treagus (1977b) have described the general context.

7.2 Description

The exposures on the eastern side of the GCR site provide a section from the Ballachulish Slates through transitional beds (the Appin Transition Formation) at the base of the Appin Quartzite, which lies on what was originally the upper limb of the Ballachulish Syncline. To the west, two tectonic junctions bring in respectively, a thin slice of Ballachulish Limestone and the basal facies of the Leven Schists (Figure 15). The former lies in the core of the syncline; the latter lies on the original lower limb. The bedding and a penetrative schistosity dominantly dip steeply to the north-west, an attitude acquired during later folding. The section is described from south-east to north-west from the shore opposite St John's church.

A group of exposures on the first peninsula on the south-east side of the GCR site (Figure 15, locality A; NN 0669 5869) expose phyllitic graphitic pelites with thin semipelite beds, which are attributed to the upper part of the Ballachulish Slate Formation. Thin beds of gritty quartzite, typical of the transition into the Appin Quartzite Formation, occur at the north-western end of this peninsula. Strongly deformed ripple-drift lamination can be discerned, but way-up is not easily determined. The bedding, together with the penetrative schistosity, strike north-east and dip steeply north-westwards at 80–85°; rarely, the two planar surfaces can be seen at a narrow angle to one another and to be axial planar to tight folds plunging steeply to the south-west. A strongly developed stretching lineation (pyrite blebs and mica) and possibly the intersection lineation pitch down the dip of the schistosity. The schistosity is folded by minor tight folds, which plunge subvertically and dominantly have a 'Z' geometry and an axial-planar crenulation cleavage.

After a gap of some 50 m, the rocks at the south-eastern end of the second peninsula (Figure 15, locality B; NN 0665 5875) are black phyllitic pelites, with a more variable strike than in the previously described exposures. They become more-dominated by beds of gritty quartzite, up to 70 cm thick, towards the north-west. Here too, the penetrative schistosity is very close to the bedding and their cross-cutting relationships and the direction of their intersection are difficult to determine. The outcrop of these transitional beds ends at a NE-trending, 4 m-thick microdiorite dyke. Between this dyke and a second 5 m-thick dyke, occurs a 10 m-thick unit of yellow-weathered, grey metacarbonate rock, which is interbanded with millimetre- to centimetre-thick beds of dark semipelite, a lithological association typical of the Ballachulish Limestone Formation. These NE-striking beds are locally strongly folded by steeply plunging minor folds exhibiting both 'S' and 'Z' geometries. A critical locality (NN 0663 5882) occurs at the junction of the metalimestone with the western dyke where, over a distance of about one metre, a few centimetres of platy quartzose schist are seen (Figure 16). This schist is interpreted as a slither of the basal facies of the Leven Schists, which crop out over the remainder of the peninsula to the west of the dyke. The Leven Schists here consist of quartz-rich psammite interbedded on a centimetre scale with ribs of semipelite; no way-up criteria have been established. One well-exposed minor fold has a plunge of 40° to the north-east and an 'S' geometry, but otherwise there are no well-developed minor structures.

7.3 Interpretation

According to Bailey (1960, pp.55–59) the succession of Ballachulish Slates and the Appin Transition Formation, described above, is corrugated by intermediate-scale folds subsidiary to the Ballachulish Syncline (an F1 fold in modern nomenclature). The core of this syncline lies close to the junction of the transitional beds with the Ballachulish Limestone; the Ballachulish Limestone and Leven Schist exposures to the west belong to the lower limb. The minor folds and cleavage/bedding relationships, seen in the section of Ballachulish Slates and transitional beds, certainly show varying vergence directions, suggesting such intermediate-scale folds of perhaps several tens of metres wavelength. S0/S1 intersections appear to be parallel to the steeply pitching stretching lineation. However, the D1 age of these structures has not been confirmed in thin section in any of the more-recent studies. In fact the existence of the syncline has not been confirmed in current studies, either from minor folds and cleavage/bedding relationships, or from sedimentary way-up structures, (although the synformal structure is clear from the regional stratigraphical context (Figure 15).

According to Bailey (1960) the Ballachulish Syncline, which was originally recumbent, has been rotated into its present steep, NW-dipping, upward- and SE-facing, attitude by the secondary folding of the region. Some of the folds seen in the section described above are associated with a crenulation cleavage, and their south-westerly plunge and 'Z' geometry agree with them being F2 folds on the western limb of the major F2 Stob Ban Synform, similar to those described in the *Tom Meadhoin and Doire Ban* GCR site to the north-east.

Although the junction between the Appin Transition Formation and the Ballachulish Limestone to its west is obscured by a microdiorite dyke, the increase in quartzite content towards the junction certainly supports the concept that this junction is a 'slide' (the regional Sgorr a'Choise Slide, a minor branch of the Ballachulish Slide according to Bailey (1960). The axial trace of the Ballachulish Syncline, according to Bailey, lies within the outcrop of the Ballachulish Limestone. Minor folds in this outcrop show reversals of vergence that would be expected in D1 structures.

The junction to the west between the limestone and the few centimetres of quartzitic Leven Schists, does not exhibit the usual transition from metalimestone into the pelitic top of the Leven Schists and according to Bailey represents the Ballachulish Slide on the western limb of the syncline. The exposure of the 'slide', although only one metre in length, shows a slight discordance of bedding orientation across it, between the limestone and the flaggy schist (Figure 16). There is no evidence that it is a much later dislocation that post-dates all the folding, but thin sections would be needed to establish the exact age of movements. On the west side of the western dyke, which obscures the remainder of the outcrop of the 'slide', schistose psammites are typical of the basal part of the Leven Schists; no 'way-up' evidence has been found. Thin-section investigation of the folds and cleavage here would be particularly useful in the delineation of the structural relationships.

Since the Ballachulish Slide occurs on the lower limb of a once recumbent syncline and involves no repetition of strata, Bailey (1960) noted that it would have to have originated as a low-angle normal fault (i.e. a lag) and not as a thrust as would have been associated traditionally with nappe structures. This is a common occurrence in the nappes of the Central Grampian Highlands and led Soper and Anderton (1984) to suggest that such 'slides' might have originated as synsedimentary extensional faults. Further research at this locality might help to resolve this debate.

7.4 Conclusions

The St John's Church, Loch Leven GCR site contains one of the few exposures across a major dislocation (the Ballachulish Slide) of the type that has disrupted many of the major early folds of the Grampian Fold-belt. These 'slides' are of great interest since the faults might have been initiated at the time of sedimentation and developed further during the onset of folding, when they translated the rocks above for many kilometres. The section is well exposed in coastal outcrops that are much visited by student and professional geologists and would benefit from further research.

8 ONICH DRY RIVER GORGE AND ONICH SHORE SECTION (NN 025 617–NN 031 626 AND NN 030 614–NN 052 612)

J.E. Treagus

8.1 Introduction

The two adjacent GCR sites at Onich (Figure 17), especially the almost continuously exposed section on the north shore of Loch Leven, are important for two reasons. Firstly, the sites expose four formations of the Ballachulish Subgroup (Appin Group) in unrivalled sedimentary detail; exposures along the hill to the west of Dubh ghlac, a glacial meltwater channel north-west of Onich village, exhibit particularly striking sedimentary structures in the Appin Quartzite. Secondly, clear minor structure observations can be made across a major syncline that has not been complicated by later deformation. The syncline is the regionally important Appin Syncline, which can be traced for 50 km down the west coast of Argyll and within which the *Ardsheal Peninsula* and *Lismore Island* GCR sites also lie.

The shore section has been described in detail by Bailey (1960), Roberts (1976), Roberts and Treagus (1977b) and Treagus (1991). It is possibly the most visited section in the whole of the Grampian Terrane, attracting professional geologists, student parties and interested amateurs. It provides an example of a key part of the Dalradian succession, and is used as a mapping exercise and for demonstrating the use of minor structures to deduce the geometry of major structures.

8.2 Description

The Onich shore section provides excellent sections across all formations of the Ballachulish Subgroup, except for the Ballachulish Limestone. It is described here from east to west. The oldest formation, the Ballachulish Slates, is well seen in the steep, SE-dipping beds of a small quarry at NN 0494 6109 to the north of the main road, as well as in shore exposures between NN 0495 6102 and NN 0465 6103. This formation is typically a pyritiferous black slaty pelite with thin semipelite beds that exhibit small-scale graded bedding and cross-lamination indicating younging both to the south-east and to the north-west (for explanation, see structural detail below). Cubes of pyrite, up to 1 cm across, make the slate very distinctive and roofing slates from here, but mainly from the quarries at South Ballachulish, can be seen throughout Britain. In the Onich area, most of the pyrite has been altered to red-brown pyrrhotite, due to contact metamorphism by the Ballachulish granitic pluton, which crops out 1.5 km to the south.

The Appin Quartzite is particularly well exposed on the foreshore at NN 0437 6105, where steep, overturned, SE-dipping beds show many examples of trough cross-bedding younging to the north-west (Figure 19). Unfortunately, the junction with the Ballachulish Slates to the east is not exposed and the Appin Transition Formation is not represented. Here the Appin Quartzite is white and gritty, containing pebbles of pink feldspar and creamy quartz in various concentrations. Individual clasts, only slightly deformed, are up to 2 cm in longest dimension. The shore exposures, on the east limb of the Appin Syncline, are complemented by those on the west limb in the Onich Dry River Gorge GCR site. The latter occur along the track in the valley bottom (Dubh ghlac) and on the hill to its north-west (Druim nan Sleibhean), from NN 0242 6178 to NN 0314 6254. Numerous small exposures occur, particularly in a drainage ditch to the north-west of the track, exhibiting ripple marks of various dimensions and orientations on NE-striking bedding surfaces that dip at 50–75° to the south-east. The ripple marks commonly have a wavelength of some 30 cm but smaller (2–3 cm scale) structures are also seen. Most ripples have a sub-horizontal orientation, but others with a down-dip orientation or a steep pitch to the south-west or north-east can be observed locally and produce interference patterns with the former set. Most importantly, 20–30 cm-high cross-sets can be seen (e.g. by the track at NN 0250 6180 and on the hill at NN 0265 6200), which clearly demonstrate that the beds are right-way-up and young to the south-east. The overall width of the quartzite outcrop suggests that an intermediate-scale fold must occur in the unexposed ground to the east of the track, as shown in Figure 18.

The Appin Limestone, which occupies most of the shore section from its faulted junction with the Appin Quartzite to NN 0390 6126 (below the school), is a very varied member, which in this area comprises the lower part of the Appin Phyllite and Limestone Formation. For the first 150 m west of the Appin Quartite it contains much platy pink quartzite, probably repeated in folds, but typically it consists of thin beds of cream-coloured metadolostone (tens of centimetres thick) and lesser white metalimestone with local interbeds of phyllitic semipelite, pink quartzite and psammite. Small-scale graded bedding and cross-lamination in the steep SE-dipping beds are well seen near the faulted junction with the Appin Quartzite and in psammite interbeds 150 m to the west. These sedimentary structures mostly indicate younging to the south-east, so that the beds are right-way-up (for explanation, see structural detail below). A pink microdiorite dyke at NN 0395 6125 marks the core of an anticline in metalimestone, exhibiting south-east younging on its south-east limb.

For a further 200 m, on the north-west limb of the anticline, thin metalimestones are seen in gradational contact with the upper part of the Appin Phyllite and Limestone Formation, here called the Appin Phyllite. The latter consists of grey, phyllitic semipelites containing numerous intercalations of schistose calcsilicate rock and purer metalimestone as well as flaggy quartzite. The Appin Phyllite to the west is exposed continuously between NN 0371 6127 and NN 0318 6129 (below the Onich Hotel). Centimetre-scale graded bedding and cross-laminations are common and these structures show consistent younging to the north-west in the overturned, steeply SE-dipping beds. SE-verging minor folds of thin metalimestones are seen from NN 0371 6127 to the centre of the main synclinal fold, which is marked by some 50 m of younger dolomitic metalimestone at NN 0342 6131 (Figures 17, 18). The excellent exposures at the far west end of the section, below the hotel, show the same sedimentary structures, including slump-folds, younging to the east in shallower SE-dipping beds on the *west* limb of the syncline. Isolated exposures of Appin Phyllite, Appin Limestone and Appin Quartzite are seen on the west limb, at NN 0302 6140 (south of the road), NN 0259 6146 and NN 02416153 (north of the road), respectively.

As demonstrated above, the gross stratigraphical repetition across the site, together with change in the dip of bedding and the abundant sedimentary way-up indicators, clearly reveals the presence of a major tight syncline, with an overturned south-east limb. This is interrupted by one conspicuous intermediate-scale anticline at NN 0393 6125 and a faulted-out syncline as described above. In addition, the shore section presents an unusual wealth of first phase (D1) minor structures (folds and cleavage/bedding relationships) that can be used to demonstrate the presence and geometry of the major syncline, the anticline and several other smaller-scale folds, which are described below from east to west (Figures 17, 18).

The outcrops of the Ballachulish Slates at the east end of the shore section are too isolated to be useful in the interpretation of the major first fold geometry. However, these outcrops, do contain reversals of younging and of cleavage/bedding relationships that demonstrate the presence of intermediate-scale F1 folds. The exposures also contain a later crenulation cleavage and minor folds, which indicate that a major synform is to be expected to the east of the GCR site.

Proceeding westwards, the Appin Quartzite outcrop at the eastern end of the shore section is isolated by a fault or slide along its western margin with the Appin Limestone, marked by a few centimetres of platy schists with lens-shaped quartz-veins. The dolomitic metalimestone a few metres west of the fault contains both E- and W-verging, vertically-plunging, isoclinal folds; W-verging minor structures in the E-younging rocks for 150 m to the west show that a major- or intermediate-scale syncline must be replaced by the fault, as illustrated in the cross-section of Figure 18.

On the hill to the north-east of the shore section, at NN 4096 6175, a 10 m-thick psammitic bed within the Appin Limestone closes in the probable core of this syncline (J.L. Roberts, personal communication, 1977). The intermediate-scale anticline at NN 0393 6125 can be identified both from exposure of its hinge and from changes in minor fold and cleavage vergence in the Appin Limestone for 100 m around the hinge area. To the west, at NN 0375 6128, another fold-pair with a 20 m wavelength can be identified from vergence reversals in beds transitional into the Appin Phyllite.

On the foreshore, from NN 037 613 westwards, well-developed minor structures in the Appin Phyllite consistently verge to the east, indicating that a major syncline lies to the west (Figure 18); the hinge of this fold can be identified in metalimestones at NN 0338 6130. Excellent minor structures can then be seen, verging west, away from the hinge, in the remaining 150 m of exposure. Minor folds throughout the shore section plunge on average at 10–30° to the south-west, although locally they plunge at up to 50° to the south-west and at low angles to the north-east. A penetrative phyllitic cleavage, axial planar to the minor folds, dips at 60–80° to the south-east. A down-dip stretching lineation is well seen on the cleavage planes in the phyllitic rocks, emphasized by the orientation of millimetre-long biotite crystals.

8.3 Interpretation

The Onich GCR sites provide good type examples of the lithologies and of sedimentary structures within the Ballachulish Slate and Appin Quartzite formations. The exposures of the Appin Limestone and the Appin Phyllite and their transitional junction are also unrivalled for their clarity and detail. In contrast to exposures of these two stratigraphical units farther to the south-west (e.g. at the *Arsheal Peninsula* GCR site), at Onich they exhibit considerable interleaving of phyllitic rocks, metadolostone and grey metacarbonate rock as well as of local psammites. Some of this interleaving can be attributed to tight interfolding (see below) but it did lead Bailey (1960, pp. 37–38) to abandon the distinction of the two units and in most areas they are now combined formally as the Appin Phyllite and Limestone Formation. A separate Appin Limestone Member is recognized only where it can be clearly distinguished.

Structurally, there can be no doubt that the minor folds and cleavage are of the first regional generation (D1) and they clearly demonstrate that the major syncline, the Appin Syncline of Bailey (1960) is of this age. Although strictly this D1 age can only be demonstrated from thin section examination (Roberts, 1974; Treagus, 1991) the cleavage as viewed in the field is penetrative and the folds do not refold any earlier cleavages, lineations or folds.

It should be noted that Hickman (1978) regarded the Appin Syncline as a D2 structure, partly on regional considerations and partly from comparisons with observations on the structure farther to the south-west (see the *Ardsheal Peninsula* and *Lismore Island* GCR site reports). His explanation for the penetrative nature of his 'S2' slaty cleavage was that the regional first cleavage, seen in the schists to the east (see the *Rubha Cladaich* and *Nathrach* GCR site reports) has been overprinted to become unrecognizable at Onich.

8.4 Conclusions

The two GCR sites at Onich are important for two reasons. Firstly, they contain unrivalled sections of four stratigraphical units of the Ballachulish Subgroup—the Ballachulish Slates, the Appin Quartzite, the Appin Limestone and the Appin Phyllite. These are rich in detail revealing the nature of the original sediments, particularly structures showing the original order of deposition. Secondly, they contain a wealth of minor structures (folds and cleavages) resulting from the deformation of the sedimentary rocks. The latter structures can be used to demonstrate the D1 relative age, position and shape of a major fold having an outcrop width of several kilometres. This Appin Syncline is a key component of the overall structure of the Grampian mountain belt.

9 ARDSHEAL PENINSULA (NM 961 555–NN 007 579)

J.E. Treagus

9.1 Introduction

The Ardsheal Peninsula GCR site, on the south-east side of Loch Linnhe, gives a superbly-exposed section across five stratigraphical units in the Appin Group, from the Appin Transition Formation of the Ballachulish Subgroup, up into the Cuil Bay Slates of the Blair Atholl Subgroup. Although the whole outcrop width of the F1 Appin Syncline is represented on the peninsula, the almost continuous clean coast section described here is the on the north-west limb. Minor structures related to the major F1 fold are exceptionally well exposed, and minor structures belonging to the regional D2 phase are superimposed on the early structures in the eastern part of the GCR site.

The area of the GCR site was described in general by Bailey (1960), who was the first to recognize the major structure as an upward-, NW-facing primary syncline. It was subsequently described in detail by Treagus and Treagus (1971), after Bowes and Wright (1967) had given a very different account of the structure in their examination of the setting of the igneous rocks of the area. The latter are discussed in site reports in the *Caledonian igneous rocks of Great Britain* GCR volume (Stephenson *et al*., 1999).

9.2 Description

The five most instructive areas of exposed Dalradian rocks in this GCR site are situated along the south-west and north-west coasts of the peninsula (Figure 20, localities 1–5). The youngest formation, the Cuil Bay Slates, is exposed at locality 1, the type locality for this formation on the north-west side of Cuil Bay, between NM 9763 5539 and NM 9724 5544. At the east end of these exposures, on a small peninsula below a fishing croft, centimetre-thick graded beds of grey silt to black mud (now slaty semipelite and pelite) are particularly well seen. These beds are folded into 3 m-wavelength, tight to open, upright folds, which plunge to the south-west, face upwards and verge to the north-west (Figure 21b). They have an axial-planar slaty cleavage dipping at 50–60° to the south-east and a stretching lineation of elongate chlorite-muscovite stacks, which pitches steeply to the north-east on the cleavage. Elsewhere, the slaty cleavage is strongly affected by a second generation of open folds, particularly well seen on the south-east side of this small peninsula, Rubha Beag. These folds also plunge to the south-west and have a north-west vergence, but they are related to a crenulation cleavage, which dips at 60–70° to the north-west and cross-cuts the earlier folds. The effect of this folding is to rotate the earlier slaty cleavage into flat-lying attitudes and, locally, to refold the earlier fold-set. The first cleavage surfaces are strongly crenulated and kinked; some kinks are due to original refraction through the semipelite and pelite beds, others result from the second deformation and yet others are related to later deformation associated with the intrusion of dykes.

The junction with the next oldest stratigraphical unit, the Appin Phyllite, is not exposed; but this unit occupies the whole of the next small peninsula to the west, Rubha Meadhonach (locality 2). Bedding, which is less easy to see in these rather uniform grey phyllitic semipelites, dips steeply to the south-east and locally exhibits upward-younging graded units and ripple-drift cross-bedding, particularly on the north-west side of the outcrop. The first cleavage dips steeper to the south-east than the bedding, and intersections plunge gently to the south-west. The second cleavage and folds are not strongly developed, but the intersection of the second cleavage with the first plunges at varying angles to the north-east. Kink bands, commonly conjugate, are well developed.

The westernmost subsidiary peninsula of the GCR site, Rubha Mor, exposes a further three stratigraphical units, the Appin Limestone and the Appin Quartzite, as well as the distinctive transitional beds to the Ballachulish Slates (the Appin Transition Formation). The Appin Limestone and its steep SE-dipping junction with the Appin Quartzite are exceptionally well displayed on the south-east coast of Rubha Mor between NM 966 557 and NM 963 556 (locality 3). The youngest beds, on the seaward side, are mixed metacarbonate rocks, quartzites, phyllitic semipelites and psammites (Figure 21b), followed downwards by a clear sequence of white quartzite, grey metacarbonate rock, cream dolomitic metalimestone and phyllitic semipelite, each a metre or two thick, before the well-exposed junction with the Appin Quartzite is reached high on the cliff. These latter beds are seen in a spectacular fold-pair in a 15 m-long section at the south-west end of their outcrop. Here, disharmonic minor folds and refracting penetrative axial-planar cleavage are beautifully displayed; the vergence of minor folds and cleavage/bedding is to the north-west and the plunge is 20-40° to the south-west (Figure 21b).

The Appin Quartzite consists of thick-bedded (up to 2 m) white quartzite with quartz and feldspar pebbles up to 20 mm across in a gritty matrix; the clasts are only weakly elongated in a poorly developed cleavage in the finer grained beds. The quartzite commonly displays cross-beds younging to the south-east, which are especially well-seen near the top of the formation at NM 9640 5565 (locality 3) and near the base on the north-west side of the promontory at about NM 968 557 (locality 4). The Appin Transition Formation is seen on the shore of Loch Linnhe from about NM 963 558 to NM 971 565 (locality 5). These steeply SE-dipping beds of striped psammites, semipelites and graphitic pelites display a variety of SE-younging sedimentary structures including small-scale grading, ripple-drift cross-bedding, load structures, slump-folds and sedimentary dykes. Cleavage in the pelitic beds is penetrative. The vergence of minor folds and cleavage/bedding intersection is to the north-west and the plunge is 10–30° to the south-west.

9.3 Interpretation

All of the stratigraphical units that crop out at localities 1–5 exhibit the same north-west vergence of both the earliest folds of bedding and of the cleavage/bedding intersection related to those folds. According to Bailey (1960), Voll (1964) and Treagus and Treagus (1971), they lie on the north-west limb of the regional fold, the Appin Syncline, which all these authors agree is one of the early (D1) fold-set. The hinge-zone and south-east limb of this fold, affecting the Appin Phyllite and Limestone Formation, is best seen, up plunge to the north-east, in the *Onich* GCR sites. A generalized structural profile of the fold as it affects the rocks of the Ardsheal and Onich GCR sites is illustrated in Figure 18, which shows the five locations discussed above. The later folds and associated crenulation cleavage, which are seen at Ardsheal on the north-west limb of the Appin Syncline, but also on its south-east limb at Onich, show a consistent north-west vergence on both limbs. These folds belong to the regional D2 phase of Treagus and Treagus (1971) and are subsidiary to the major Stob Ban Synform, seen to the east (see the *Tom Meadhoin and Doire Ban* and *Stob Ban* GCR site reports).

The paper by Treagus and Treagus (1971) contradicted the earlier view of Bowes and Wright (1967) that the syncline is a third-phase structure associated with the retrograde metamorphism in the area. Bowes and Wright proposed that 'elongate compositional blebs' and small isoclinal fold noses in semipelites within the Appin Phyllite are evidence of an earlier D1 phase. Mica flakes that cut across these earlier features were said to be attributable to a D2 phase. The lineation resulting from the mica flakes was said to be folded around the Appin Synform, which was therefore interpreted as a D3 phase. No locations nor detailed measurements of these structures were given and no evidence was found by Treagus and Treagus (1971), or has been found since, to support these views. Importantly, thin-section examination of the pelites from the Ardsheal Peninsula GCR site has shown that the penetrative cleavage that is axial planar to the dominant minor folds and to the major syncline was developed as part of the regional, progressive, chlorite-muscovite metamorphism.

9.4 Conclusions

At the Ardsheal Peninsula GCR site it can be demonstrated that the Appin Syncline, one of the major folds in the western part of the Grampian Fold-belt, was produced as part of the earliest deformation of these rocks. The site provides superlative examples of the minor folds produced by this deformation as well as evidence of the effects of a later period of deformation, superimposed on the earlier one. The site also provides excellent clean exposures of five stratigraphical units in the upper part of the Appin Group with clear evidence of the nature of the original sediments; it contains the type locality of one of them—the Cuil Bay Slates. The site is a necessary complement to the GCR sites at Onich to give a complete cross-section of the Appin Syncline. The site is of exceptional importance educationally and is used extensively by undergraduate parties and students undertaking mapping projects.

10 SOUTH COAST, LISMORE ISLAND (NM 798 386–NM 784 366–NM 813 383)

J.E. Treagus

10.1 Introduction

The South Coast, Lismore Island GCR site comprises the coastal exposures and much of the inland outcrop at the south-western end of the elongate island of Lismore to the north of Oban (Figure 22). It is important primarily for its unique exposures of the Lismore Limestone, one of the formations of the Blair Atholl Subgroup of the Appin Group. The substantial middle and upper divisions of the formation are represented; these comprise dominant metalimestone with lesser slaty pelite and transitional facies. Structurally, the site lies in the core of the F1 Appin Syncline, a major structural feature of the western side of the Grampian Fold-belt, which is also the focus of interest of the *Ardsheal Peninsula* and *Onich* GCR sites, at progressively lower structural levels. On Lismore, the D1 structure is strongly modified by D2 structures.

The geology of the island was described briefly in the Geological Survey memoir by Lee and Bailey (1925) and both the stratigraphical and structural features have been described subsequently in great detail by Hickman (1975, 1978). The following descriptions are largely based upon the work of Hickman, with additional observations by the author.

10.2 Description

The Lismore Limestone Formation is estimated to be about 1 km thick and the sequence of blue-grey metalimestone and minor black slaty pelite has been divided into fifteen members by Hickman (1975). These members can be grouped into three distinct lithological 'units'. Of these only the middle and upper units are exposed within the area of the GCR site (Figure 22). The middle unit (about 450 m thick) comprises three metalimestone-pelite cycles, each containing a lower metalimestone member (50–200 m thick), a transitional banded argillaceous metalimestone member (20 m thick) and an upper pelite member (10–20 m thick). The metalimestone is blue-grey, recrystallized and to varying degrees graphitic and pyritiferous, with partings at 5–20 cm intervals. The transitional beds have individual beds, typically 3–10 cm thick, which are graded. The pelite members are grey, highly carbonaceous and pyritiferous with a low carbonate content. The upper unit has a lower metalimestone member (300 m) and an upper banded argillaceous metalimestone member (50 m), which rarely preserves festoon structures and load casts. Cross-stratification is rarely preserved in the metalimestones and isoclinal folds in the pelites and argillaceous metalimestones might be slump structures.

The whole sequence across the upper unit and the upper two cycles of the middle unit may be seen within the GCR site in a traverse of the craggy inland outcrops from Bagh Clach an Dobhrain (NM 799 377) to Miller’s Port (NM 812 372). Excellent clean exposures of metalimestone are seen all around the coast on the wave-cut platforms, those of the upper unit on the north-west side of the island (e.g. at NM 789 364) and those of the middle unit on the south-east side (e.g. south-west of Miller’s Port at NM 812 372). The banded argillaceous metalimestone of the upper unit is well seen at Bagh Clach an Dobhrain (at NM 799 375) and argillaceous metalimestones and pelites of the middle unit are seen inland on the ridge of Druim na Curra, near Fiart Farm (at NM 802369 and NM 803 370 respectively). The continuous ‘slate belt’ that passes through the Loch Fiart area, identified on both the original (1923) and the more-recent (1992) Geological Survey maps, was originally regarded as the eroded crest of an anticline, with the pelite underlying metalimestone everywhere on the island (Lee and Bailey, 1925). However, Hickman (1978) demonstrated that the pelite is an interbedded part of the stratigraphical succession.

The structure of the metalimestones within the GCR site is dominated by upright asymmetric tight to open folds with a wavelength of 0.5–20 m (Figure 23). The folds typically plunge at 20–50° to the south-west and have a strongly developed, steeply dipping, axial-planar crenulation cleavage in the slightly argillaceous metalimestone beds. Stretched pyrite blebs pitch steeply north-east on the cleavage. This cleavage is axial planar to folds of a bedding-parallel phyllitic cleavage. Hickman (1978) mapped a major antiform-synform fold-pair (A and B on Figure 22) related to a change in vergence of minor folds associated with the dominant later deformation. Hickman (1978) also drew the trace of a tight syncline through the site area (fold C on Figure 22), related to the earlier deformation. The evidence for the early syncline lies in a closure of the stratigraphical units in the area to the north-east of the GCR site, where it is cross-cut by the later folds and cleavage (see below).

10.3 Interpretation

The detailed stratigraphical succession within the Lismore Limestone Formation contains variations between pure metalimestone and pelite very similar to those of the Blair Atholl Dark Limestone and Dark Schist Formation of the *Strath Fionan* GCR site, with which it can be correlated confidently (Lee and Bailey, 1925). The obvious differences between the two GCR sites are the stronger representation of transitional facies between pure metalimestone and pelite in the former and of thicker pelite members in the latter. Unsurprisingly, the Lismore GCR site, with its lower grade of metamorphism, reveals more sedimentary structures, such as festoon bedding, cross-bedding and load casts. The common graded bedding however, which might be expected to survive the higher grade metamorphism, has not been recorded in the Schiehallion area.

The main feature of structural interest on Lismore is the NE-trending syncline that crops out through the centre of the GCR site and the Loch Fiart area (Figure 22, fold C). This fold was assigned to D1 by Hickman (1978) on the basis that the dominant D2 minor structures are superimposed across the stratigraphical repetition that marks the position of the D1 fold. Hickman did not provide vergence data to support the position or age of the syncline within the GCR site area. However, in the area that lies on the south-east limb of this fold, the phyllitic cleavage is seen (though rarely) at a small angle to bedding and axial-planar to small, 10 cm-amplitude isoclines (e.g. at Miller's Port, 812372). The paucity of vergence information on these folds and cleavage across the trace of the syncline does not allow confirmation of the position or age of the syncline. However, the vergence of the later folds is consistently towards the north-west across the trace of the fold (see the cross-section on Figure 22) and the steeply SE-dipping rocks on its south-east limb are consistently inverted and face down on the steeper dipping later cleavage.

The trace of syncline C in the north of the island, as drawn by Hickman (1978), can be extrapolated to the north-east, through the Island of Shuna directly into that of the F1 Appin Syncline at Cuil Bay and Onich (see the *Ardsheal Peninsula* and *Onich* GCR site reports). The vergence and plunge of the D2 structures is consistent with observations of their relations to the Appin Syncline at the above sites, and to the major F2 Stob Ban Synform to the east (see also the *Tom Meadhoin and Doire Ban* and *Rubha Cladaich* GCR site reports). Hickman (1978), however, considered that the Appin Syncline, which he regarded as a D2 structure, should be correlated with the major F2 synform A on Figure 22. However, the trace of this fold, as shown by Hickman (1975) in the north of Lismore, does not extrapolate well with the projected trace of the Appin Syncline from Ardsheal through the island of Shuna.

10.4 Conclusions

The South coast, Lismore Island GCR site is the type locality for the Lismore Limestone Formation of the Blair Atholl Subgroup, which can be examined in detail in superb coastal and inland exposures. The information gained from the cycles of limy and muddy sedimentation that made up the formation is essential to the understanding of the development of the shallow shelf on which the early Dalradian sequence was deposited, particularly in comparison with other sites in the area and elsewhere in the Central Grampian

Highlands. The site also provides, from its two sets of minor structures, valuable evidence for the location, identity and geometry of major F1 and F2 folds in the region, which play a fundamental role in the development of the Grampian Mountain-belt.

The Appin Syncline, the most important major F1 fold on the north-west side of the mountain-belt, can be traced through this GCR site and its geometry can be established. The later D2 folds and cleavage are particularly well displayed and demonstrate a consistent geometry down this side of the mountain-belt from the GCR sites at Onich and the Ardsheal peninsula into the Lismore Island GCR site. The site has great potential for future stratigraphical as well as structural research.

11 CAMAS NATHAIS (NM 874 370–NM 875 382)

P.W.G. Tanner

11.1 Introduction

This GCR site lies 7 km north of Oban in the Benderloch area and is located on the raised beach platform around the head and south-east side of a narrow inlet of the sea, Camas Nathais. Well-scoured rock exposures display an excellent example of a ductile fault, the Benderloch Slide (Litherland, 1980). The slide contact, which is the main feature of interest at this locality, is well exposed for a strike distance of over 100 m and both the plane of movement, and the structures in the rocks on either side of it, can be examined in three dimensions. Such contacts are rarely seen in the Highlands, and this example is exceptional for its clarity, and for the quality of the rock exposure.

For many years the geology of this area was the focus for a fundamental geological debate between the followers of E.B. Bailey (1922, 1953), who interpreted the abrupt east–west changes in rock type seen on a regional scale in terms of nappe tectonics, and those who supported G. Voll (1964), who invoked extreme local facies changes. Bailey considered that radically different stratigraphical successions had been brought together by syntectonic faults called slides, the slide at Camas Nathais being correleated with a major tectonostratigraphical dislocation in the south-west and Central Grampian Highlands, later named the 'Iltay Boundary Slide' (Stephenson et al., 2013a). On the other hand, Voll concluded that the lithological differences seen across the area are of sedimentary origin, and that the rocks constitute a single, unbroken succession. The situation was resolved by Litherland (1980, 1982) who, by means of detailed field mapping, demonstrated that the so-called 'Banded Leven Schists' of Bailey (1922) could be subdivided into the 'true' Leven Schists of the lower Appin Group to the west, and rocks belonging to the lower part of the Argyll Group to the east. However, he confirmed that these two parts of the Dalradian succession had been brought together by a major tectonic break, which he named the Benderloch Slide.

At the head of Camas Nathais, the Benderloch Slide appears to place part of the Ballachulish Limestone (Appin Group) against the base of the Argyll Group, so excising a significant part of the Appin sequence. The plane of movement is marked both by a strong lithological contrast between black graphitic slaty pelites on one side and orange-yellow metadolostone and pale grey quartzite on the other, and by a zone many metres thick of sheared rocks that display a pronounced stretching lineation. The tectonic break is inferred to have developed early in the tectonic history of the area, with both the fault plane and the adjacent rocks having been subjected to several phases of later movement. The Benderloch Slide is no longer regarded as part of an intraregional 'Boundary Slide', but it can be correlated with the Ballachulish Slide found farther north (Rast and Litherland, 1970). The GCR site reports for *St John's Church* and for *Tom Meadhoin and Doire Ban* also discuss the possibility that the slide might be of synsedimentary origin and was only re-activated during later 'tectonic' events.

11.2 Description

The geological setting of this site is shown on Figure 24, with the Benderloch Slide being strikingly exposed at (NM 87626 37938), near the head of the bay (Figure 25). The structural break was first recognized by Bailey, who stated that '...on the western side of Garbh Ard the margin of the quartzite, where exposed upon the foreshore, is separated from the Appin Limestone by a few feet of black slates and limestone but, unfortunately, there are signs of considerable movement having taken place near the junction line' (in Kynaston and Hill, 1908, p.36). Bailey later re-assigned the rocks described above as 'Appin Limestone', to the Ballachulish Limestone.

The slide plane dips at 42–46° to the north-west and lies within a sequence of rocks that all dip steeply (50–75°) in a north-westerly direction. The junction between a 0.5–1.0 m-thick band of boudinaged, discontinuous orange-weathering metadolostone below, and a black pelite-metalimestone unit above, marks the actual dislocation (Figure 26). When the slide plane is viewed at beach level from the north-west, flat surfaces of intensely lineated quartzite are seen in erosional windows carved out of this metadolostone sheet.

On the Fionn Ard peninsula, north-west of Camas Nathais, there is a wide outcrop of dark, finely banded semipelitic and pelitic rocks belonging to the Leven Schists. At the head of the bay, units of grey-green phyllitic semipelite and cream-coloured, finely laminated metadolostone structurally underlie these rocks, but the contact is not exposed (Figure 24). The metadolostone weathers orange-brown and forms thick units, one of which was formerly quarried at the site, but also occurs interbedded on a metre-scale with semipelite. The lowermost 10 m or so of rock above the slide consists of dark grey to black phyllitic rocks, which contain a band of black metalimestone less than a metre thick (L on Figure 25). The metadolostone-'phyllite' sequence, and the dark 'phyllite' and metalimestone, have been correlated, respectively, with the lower and upper parts of the Ballachulish Limestone Formation (Bailey, 1922; Litherland, 1980), but Litherland (1982) subsequently correlated the dark phyllitic unit with the much younger Lismore Limestone.

The rocks below and south-east of the slide plane consist largely of quartzite and were subdivided into the Baravullin Quartzite, Castle Dolomitic Flags, and Tralee Bay Quartzite by Litherland (1980). The Baravullin Quartzite is pale grey to white in colour and occurs in the footwall immediately below the slide. It has been intensely brecciated, but evidence of crudely defined bedding planes can still be detected, defining units up to 40 cm thick separated by thin phyllitic layers or films. The quartzite is underlain structurally by the Castle Dolomitic Flags, which form the spine of the Garbh Ard peninsula and consist of a banded alternation of buff-coloured quartzite ribs with dolomitic semipelite and greenish phyllitic rock.

A stretching lineation is strongly developed in rocks adjacent to the slide contact (inset to Figure 26), and dominates the fabric for a distance of some 10 m into the hanging-wall semipelites and pelites. It has a consistent orientation and plunges at an average of 34° to 352°. The orange-weathering metadolostone that lies immediately below the slide plane has been boudinaged, with boudin necks aligned normal to the stretching lineation. This lineation is deformed by a crenulation cleavage that affects rocks on both sides of the slide. Evidence for later movement on the fault plane is given by a veneer of silicified fault breccia, up to 15 cm thick, found in contact with the metadolostone (Litherland, 1982). It contains fragments of randomly orientated, crenulated slaty rocks similar to those found adjacent to the slide.

In the immediate footwall to the slide, beneath the metadolostone bed, there is a 1 m-thick zone of highly fractured quartzite, with numerous quartz veins, underlain by a considerable thickness of pervasively fractured rock. Throughout this fractured zone the quartzite consists of interlocking fragments 1 to 2 cm across, separated by deeply weathered seams and fissures, which are of possible pressure-solution origin. In some beds the fragments are equidimensional, but in general they are crudely aligned at a moderate angle to bedding. In three dimensions they have extremely flattened and elongated pancake shapes, and have a veneer of white mica on their surfaces. Where minor folds are developed in these rocks, the fragments are aligned roughly parallel to the axial planes of the folds and to the penetrative cleavage in the more-micaceous bands, so that they appear to define a rough cleavage. This relationship is seen to within 2 m of the slide plane.

Deeper into the footwall, bedding in the Baravullin Quartzite and Castle Dolomitic Flags is cut by a less-steep penetrative main cleavage dipping to the south-west, which is in turn cut and reworked by a crenulation cleavage that dips at 20–35° to the north-west, and is associated with minor folds up to a few tens of metres in wavelength.

In the hanging wall, metre-scale upright folds are associated with a penetrative axial planar cleavage in the more-micaceous bands, which dips steeply to the north-west. In places there is clear evidence that a generation of minor folds, with an axial-planar penetrative cleavage, pre-dates the main cleavage. These early folds are clearly seen in the laminated metacarbonate rocks, which develop thin axial-planar quartz veins. As in the footwall rocks, the main cleavage is cut by a spaced crenulation cleavage, which dips at a low angle (30–40°) in the same direction and is accompanied by minor folds plunging to the south-west. Calcareous bands in the phyllitic rocks preserve the main cleavage but are commonly reduced to a series of sigmoidally shaped lenses by the development of a cross-cutting, later, spaced pressure-solution cleavage having the same geometry as the crenulation cleavage in the phyllitic rocks.

11.3 Interpretation

The pelites, semipelites, psammites and dolomitic rocks in the hanging wall to the slide at Camas Nathais (units C to F, Figure 25) have been correlated with the lower part of the Ballachulish Limestone by previous workers, and the dark phyllitic pelite and black metalimestone beneath them (unit D, Figure 25) with either the upper part of the Ballachulish Limestone (Bailey, 1922; Litherland, 1980), or with the Lismore Limestone (Litherland, 1982).

South-east of the Benderloch Slide, the Barravullin Quartzite, Castle Dolomitic Flags and Tralee Bay Quartzite can be correlated with elements of the Islay Subgroup on Islay and Jura. Farther to the north-east, the Tralee Bay Quartzite is overlain by the Selma Black Slates and the Selma Breccia (Figure 24), rocks equated respectively with the Jura Slate (see the *Kilnaughton Bay* GCR site report) and Scarba Conglomerate (see the *Lussa Bay* GCR site report). Crucial to this assignment of rocks south-east of the slide to the Argyll Group is the correlation of the Baravullin Boulder Bed with the Port Askaig Tillite (see the *Garvellach Isles* GCR site report). The Baravullin Boulder Bed is not exposed at Camas Nathais but, according to Litherland (1980), it crops out inland 3 km to the north-east of the GCR site, and on the south-east side of the projected line of the slide (Figure 24). A thin sliver of the Islay Limestone (locally called the Baravullin Dolomite) was also reported from this locality. These stratigraphical correlations suggest that (1) the Benderloch Slide lies at, or close to, the base of the Argyll Group, and (2) following Litherland (1980), most of the Ballachulish Subgroup, and all of the Blair Atholl Subgroup, are cut out at the line of the slide.

Evidence from the area around Loch Creran, well to the north of Camas Nathais, shows that the main movement on the Benderloch Slide occurred before the first deformation. The latter affected both the footwall and hangingwall, and was responsible for the formation of the early penetrative cleavage. In the Loch Creran area the S1 slaty cleavage cuts across the plane of the slide (Voll, 1964) and the slide is locally folded by map-scale F1 folds (Litherland, 1982).

The Dalradian sediments preserved in this area were laid down in an unstable environment at the margin of a large basin and the slide could represent mass movement of part of the bedded sequence down the submarine slope, into the developing basin. Evidence for basin-margin instability and slumping of material at a slightly later time is clearly preserved in the form of the Selma Breccia described in the *Port Selma* GCR site report. The evidence that brecciation of the quartzite in the footwall to the slide at Camas Nathais occurred before an early phase of deformation is compatible with these conclusions, although the relationship of the earliest penetrative cleavage to the slide cannot be demonstrated directly. However, the stretching lineations associated with the slide movement are deformed by the low-angle, NW-dipping crenulation cleavage that affects both the footwall and hangingwall rocks at this site, so placing a minimum age on the main slide movement. Some rejuvenation of the faulting then occurred after the crenulation event, as is witnessed by disorientated fragments of already crenulated phyllitic pelite and semipelite in the late fault breccia.

New fieldwork carried out to date suggests that the rocks on both sides of the Benderloch Slide have been affected by the same sequence of structural events. Correlation of the early penetrative cleavage and the crenulation cleavage between footwall and hanging wall, and with the D1–D4 deformation phases documented in the wider area by Litherland (1982) is premature. It needs confirmation by a more-complete study of the geometry of the structures, and of the tectonic fabrics in thin section. The stratigraphical correlation of the hanging wall sequence with the known Dalradian succession in the area, the nature of the fault rocks, and the shear sense on the slide plane, also remain to be determined.

11.4 Conclusions

At Camas Nathais a large fault, termed the Benderloch Slide, has juxtaposed two different parts of the Dalradian sequence. As the rocks within such fault-zones are generally physically weaker than the country rocks, they are easily removed by erosion when they become exposed at the Earth's surface. In this way, crucial evidence is destroyed that could have been used to determine the nature and amount of movement that had taken place on the fault, and the relative timing of the event. Hence, it is only in exceptional cases, such as are seen at this GCR site, that the zone of crushed and distorted rocks that forms at the contact between the two fault blocks is preserved. This site is also of historical importance as there has been a dispute over the nature and significance of the junction between the two groups of rocks at this locality, since E.B. Bailey first identified it in 1908.

It is important to know whether the fault movement occurred early in the history of deformation, when the fault would be subjected to later folding and overprinted by the main cleavage, or later, when it would cut and displace the fold structures themselves. Field evidence from outwith the GCR site, as summarised above, indicates that the first movement on the fault took place before the main deformation had begun, probably at about the time that the sediments were being laid down. This plane of weakness could have provided a focus for later, repeated movement, as found at Camas Nathais, and its origin is in stark contrast to that of the Selma Breccia, described in the *Port Selma* GCR site report.

This site has considerable potential for further research. The fault rocks are well preserved, despite later folding and metamorphism, and by studying the structural fabrics under the microscope it should be possible to determine the relative direction of movement of the two blocks. Many outstanding questions still remain to be resolved before we have a clear idea of the geometry, timing, and causes, of the displacements on this major slide.

12 PORT SELMA, ARDMUCKNISH (NM 902 381)

P.W.G. Tanner

12.1 Introduction

The Port Selma GCR site consists of a small rocky headland, and the ridge inland from it, crowned by the ancient vitrified hill fort of Dun MacSniachan. It lies south of Port Selma, near Benderloch (Figure 27), and is well known for its excellent coastal exposures of the Selma Breccia. Port Selma is one of a handful of localities in the Dalradian Supergroup from which possible microfossils have been reported.

The Selma Breccia belongs to the Easdale Subgroup and has been correlated with the Scarba Conglomerate on Jura (see the *Lussa Bay* and *Kinuachdrach* GCR site reports). It consists of five metabreccia units, the uppermost of which contains numerous blocks of limestone of a type that is exotic to the local area. It was from this unit, and the interbreccia bed beneath it, that Litherland (1975) recorded the presence of the fossil remains for which the locality is best known. These microfossils, called oncolites and catagraphs, are of uncertain origin but could be fossil algae or bacteria.

This GCR site provides an important insight into the nature of the depositional environment found at the margin of the Dalradian basin during early Argyll Group times, shortly after a major late Neoproterozoic (Port Askaig) glacial episode. It also serves as an excellent case study for establishing the criteria that may be used for distinguishing between breccias of sedimentary and tectonic origin, a topic of considerable debate wherever such rocks occur worldwide. The present case is of particular significance and interest because the breccia has been deformed and metamorphosed subsequently during an orogenic event, so obscuring some of its original sedimentary features, and making diagnosis more difficult. It was first described by Flett (in Kynaston and Hill, 1908) who interpreted it as a 'crush breccia', a rock formed by the in-situ brecciation of originally intact rock layers. A detailed field and microscopic study of the formation was made subsequently by Litherland (1970, 1975) who concluded that it had formed by submarine slumping of sediment.

12.2 Description

The rocks at this GCR site consist of the Selma Black Slates overlain by the stratigraphically younger Selma Breccia (Litherland 1970, 1975); the regional geological setting is shown on Figure 24. The rocks are affected by several upright folds of bedding, but overall the succession dips and youngs to the south-east.

The Selma Black Slates, make up the northern part of the site (Figure 27), and consist largely of slaty pelites that contain thin layers and lenses of metamorphosed siltstone, sandstone, calcareous gritty sandstone and limestone, with some of the carbonate lenses being of possible diagenetic origin. The bedded metasediments commonly show the effects of slump folding, with folds reaching over a metre in amplitude; in places such movements culminated in the formation of 'balled-up' masses. The synsedimentary origin of these structures is, in some cases, confirmed by the observation that the base of an overlying bed cuts across the eroded tops of the slump structures. In addition, their pretectonic nature is revealed by the fact that both limbs of such folds are seen in thin section to be transected by the early (S1) cleavage.

A package of gently dipping gritty metasandstone beds, each up to 30 cm thick and showing clear, right-way-up graded bedding is found at NM 902 381. The dark slaty metamudstones making up the lower part of this member pass up into a thick unit of pebbly metamudstone (Figure 27). The metamudstone contains fine, barely visible, silty laminations and some lenses of gritty metasandstone, as well as isolated boulders up to 24 cm across.

The succeeding Selma Breccia was subdivided by Litherland (1970, 1975) into 5 metabreccia units separated by 4 interbreccia units, which have a total thickness of up to 100 m. They are right way up, and dip to the south-east at 33–64° (Figure 27, units 1–5). The lowest metabreccia has a conformable contact with the underlying pebbly metamudstone. The clasts in the three metabreccia beds are angular to rounded in shape, and vary from microscopic in size to over 3 m across (Figure 28). They range in original composition from homogeneous or laminated slaty mudstone, some with sandy layers, to finely banded siltstone, sandstone, quartzite, and homogeneous pale- to dark-grey limestone. The relative proportions of the different clast types varies upwards in the sequence from 60% of fine-grained quartzite clasts and 3% limestone in the lowest metabreccia, to 15% of fine-grained quartzite clasts and 60% limestone in the highest metabreccia; the other constituents making up the remaining 25–37% of the population are relatively constant in amount (Litherland, 1970). Thus the proportion of limestone clasts increases markedly up-sequence as the quartzite clasts diminish in number. Many of the clast types may be matched lithologically with underlying units such as the Selma Black Slates and Selma Quartzite, and the clasts of pale-grey limestone resemble metalimestones from the Appin Group, which crop out on Islay and on the Appin Peninsula. No exotic clasts of igneous or high-grade metamorphic origin have been identified.

The problematical microfossils occur in angular dark-grey limestone clasts (to 60 cm across) in the topmost metabreccia (B5 of Figure 27), and in the underlying interbreccia unit, IB4, exposed inland. Oncolites are seen in hand specimen as rusty-weathering spots 1–4 mm across, and are found in thin section to have a concentric internal structure; their morphology has been described in detail by Litherland (1975). The acccompanying catagraphs are up to 7 mm across and have a more disordered internal structure. Bryozoan-like fossils were also reported by Litherland. Of particular interest are 0.05–0.2 mm-diameter tubes that penetrate the clasts and, although they are now filled with sparry calcite, could represent burrows formed by parasitic algae (Litherland, 1975).

Bedding in these rocks has a north-easterly strike and the Selma Black Slates have been affected by a series of upright folds with axes plunging gently to either the north-east or the south-west. These folds are associated with the development of a steeply dipping to vertical slaty cleavage that trends north-east, dips to the south-east, and is accompanied by a gently curvilinear bedding-cleavage intersection lineation. This cleavage also affects the matrix, together with the more-argillaceous clasts in the Selma Breccia. The slaty cleavage in the Selma Black Slates and locally in the metabreccia is cut, and in places strongly overprinted by, a spaced crenulation cleavage, which dips to the north-west at a low angle.

The slaty cleavage is evident in the argillaceous matrix of the metabreccia beds, and the clasts have been tectonically deformed to varying degrees depending upon their lithology. Slaty fragments and mud wisps have been moderately flattened in the cleavage, with quartzite clasts being least deformed, as would be expected. The slaty cleavage is refracted around some of the more-competent boulders and pebbles, and in some cases faint ‘strain shadows’ are developed. Minor folds and corrugations of the internal bedding laminations are noted in a number of clasts. Where seen on the flat, clean exposures of the metabreccia in the intertidal zone, these folds have axial traces that are parallel to the 055–065° trend of the penetrative cleavage that affects the enclosing matrix (Figure 28), and also to the crude alignment shown by the longest dimensions of the clasts. Contractional deformation has resulted in the formation of internal folds in thosee clasts in which the lithological layering was initially at a high angle to the trace of the slaty cleavage. However, where such bedding laminations were originally at a small angle to, or parallel with, the orientation of the slaty cleavage, the laminations are stretched, disrupted and boudinaged but never folded. These relationships are a demonstration of the fact that the folds preserved in the clasts developed after the breccia was deposited. An analogous situation holds for the folds in the country rock xenoliths enclosed in the Ben Vuirich Granite (see the *Ben Vuirich* GCR site report in Stephenson et al., 2013b).

A major NE-trending fault cuts the Selma Black Slates and causes a displacement of the metabreccia outcrops (Figure 27).

12.3 Interpretation

Minor sedimentary structures show clearly that the Selma Black Slates and Selma Breccia form a single, conformable sequence.

These units are part of the Easdale Subgroup and are correlated with the Jura Slate Member (see the *Kilnaughton Bay* GCR site report) and the Scarba Conglomerate Formation (see the *Lussa Bay* and *Kinuachdrach* GCR site reports), respectively. There is evidence throughout this succession for increasing instability of the basin margin, as witnessed by the occurrence of slump folds, large isolated clasts and rafts of disorientated sedimentary rock enclosed in mudrock. Coarse-grained, graded beds are found in the Selma Black Slates and breccia units up to 6 m thick occur in the overlying Selma Breccia.

Early workers identified the Selma Breccia and interpreted it as a 'crush conglomerate' (Flett in Kynaston and Hill, 1908), but subsequent workers are agreed that it is of sedimentary origin (Kilburn *et al.*, 1965). Litherland (1970, 1975) referred to it as a 'sedimentary slide tilloid' but did not discuss the reasons for this interpretation.

The critical evidence for the origin of the Selma Breccia may be summarized as follows:

(i) The underlying sequence shows evidence of soft-sediment deformation and mass-flow deposits, forerunners of the more-extensive and distinctive breccias above.

(ii) The metabreccias form a bedded sequence consisting of 9 separate units, which are laterally continuous. The interbreccia units contain large isolated boulders of original sedimentary rock.

(iii) The first metabreccia unit shows a normal sedimentary contact with the underlying bed, with large boulders at the base preserved in the act of sinking into the underlying mudrock.

(iv) The metabreccia beds consist of a varied assemblage of angular original sedimentary clasts set in an originally muddy to sandy matrix. The clasts appear to have been lithified, and in the case of some of the limestone blocks, bored by organisms, before being transported to their final resting place.

(v) Although there is a random admixture of clast types in all of the metabreccia units, blocks of limestone only appear in the upper beds and are dominant in the top metabreccia unit. Some blocks consist of breccia, suggesting that earlier brecciated material has been reworked in the flows.

(vi) There is evidence of local fracturing and brecciation of clasts *in situ*.

(vii) All of the clasts are deformed in the S1 slaty cleavage but there is no evidence that the bedding in the source rocks was folded prior to their disruption, and incorporation into, the Selma Breccia.

(viii) There is a lack of cataclastic or mylonitic rocks, or evidence for intense shearing, within or between the metabreccia units.

From the above features it is clear that the deposit originated as a synsedimentary slump deposit, and did not form by the in-situ brecciation, shearing or cataclasis of lithified, bedded strata. Bedding in the clasts was not folded at the time of deposition. Another important conclusion that can be drawn from this study is that there is no evidence for either a major stratigraphical or structural break at this level in the Dalradian succession.

Although possible microfossils such as oncolites and catagraphs found in the metabreccias resemble forms that have been reported by Russian workers from the Ediacaran-age strata of Spitzbergen (Litherland, 1975), none of these forms provide reliable evidence for the stratigraphical age of the rocks. However, the tube-like structures that penetrate the oncolites and their binding matrix, were interpreted by Litherland as the burrows of parasitic algae. If this is correct then it indicates that the limestone clasts were lithified and colonized by algae whilst they were accumulating on the basin margin, prior to their transportation into the sedimentary basin by slumping. Litherland (1975) speculated that the source for these exotic limestone clasts might be the Cambro-Ordovician Durness Group on the North-west foreland of Scotland, but more-recent work (see Rushton *et al.*, 2000) on the age of the Durness Group shows that it is much too young to have provided sediment to the Dalradian basin.

12.4 Conclusions

The Selma Breccia, which is magnificently exposed at this site, is a classic example of a rock formed by the large-scale slumping of poorly sorted and very coarse-grained sediment into a marine basin. Sedimentary units formed in this way are not easy to identify with certainty, and their interpretation is commonly controversial. This is especially so where the deposit has been deformed and folded subsequently. The low grade of metamorphism and relatively low strain at Port Selma make this an exceptional locality for studying and interpreting such a metasedimentary deposit, and for this reason alone it warrants consideration as a site of national importance.

The metabreccias consist of angular blocks of rock, ranging in size from pebbles to boulders up to 3 m across, enclosed in what was originally a muddy or sandy matrix. A variety of different rock types are seen in the metabreccia, some of which can be matched in the local, or neighbouring, Dalradian sequences of slightly older age.

Port Selma is also well known for the minute fossil remains, a few millimetres across, which are found in the limestone blocks at the top of the sequence. Unfortunately these fossils are not sufficiently diagnostic to tell us the age of the rock that provided much of the material for the original sedimentary slide breccia, and hence place a maximum age on the metabreccia itself, but they do provide some potential clues as to the likely source area.

13 RIVER ORCHY
(NN 242 318–NN 247 331)

P.W.G. Tanner

13.1 Introduction

This GCR site is located in the wooded valley of the River Orchy, 10 km north-east of Dalmally. It is notable for the wealth of minor structural features that it displays, most of which can be related to the closure of an early major fold, the F2 Beinn Udlaidh Syncline. This structure folds the important sedimentary transition between the Grampian Group and the younger Appin Group (Figure 29). The Grampian Group is represented by psammites and semipelites, which can be shown to be overlain stratigraphically by the Beinn Udlaidh Quartzite and the Leven Schists, both of which belong to the lowest part of the Appin Group.

A major feature that makes this section invaluable for teaching and demonstration purposes is that most of the minor structures that can be examined in the field formed during the same phase of deformation, and can be related to a single large F2 fold (Figures 30, 31). The structures are particularly well seen, when water levels are low, on the well-scoured rock surfaces in the banks and bed of this spate river. The best localities are in the vicinity of the dramatic waterfall and rocky gorge at Eas Urchaidh (the 'Falls of Orchy', Figure 29), and along its tributary, the Allt Broileachan. This site is excellent for examining the three-dimensional form of plunging minor folds on the metre scale, and for demonstrating their relationship to the cleavages, lineations, and quartz veins found in the different rock types. Minor folds are best seen in relief in the quartzite, and in potholes in the pelite north-north-east of the Iron Bridge at 243 321; they clearly change in vergence northwards as the river section passes from the upper limb of the major fold, through the hinge-zone, to the lower limb. The curvilinear nature of the major syncline axis is revealed by the progressive change in the trend of the minor fold hinges by over 90° in less than a kilometre (Figure 29).

The general geology of Glen Orchy was established during the primary mapping by the Geological Survey for sheets 45 and 46 (Kynaston and Hill, 1908). However, it was Bailey and Macgregor (1912) who, recognizing the importance of the area, made the first comprehensive structural and stratigraphical interpretation. They recognized that the distribution of the three main rock types is controlled by a flat-lying, isoclinal nappe, the Beinn Udlaidh fold. These workers also found that this fold, which they considered to be as well exposed as any of the small-scale nappes in the European Alps, had been bent around a later upright fold, the Glen Orchy 'Anticline' (now referred to as an 'antiform' or 'dome'). Cummins and Shackleton (1955, figure 7) first identified way-up structures in Glen Orchy, some tens of metres above the waterfall Eas à Chataidh at 248 331, and confirmed the order of succession established by Bailey and Macgregor (1912). Thomas and

Treagus (1968) studied two areas adjacent to Glen Orchy on Beinn Udlaidh in more detail and published a map of the closure of the Beinn Udlaidh Syncline. The wider area around Beinn Udlaidh, including the crucial section that constitutes the River Orchy GCR site, has recently been the subject of an extremely detailed field and petrographic study of the stratigraphy, structure, metamorphism and minor intrusions by Tanner and Thomas (2010).

The pelitic rocks at this site contain abundant millimetre-sized, partly or wholly chloritized porphyroblasts of garnet, and randomly orientated crystals of biotite, and the entire sequence has been affected by amphibolite-facies regional metamorphism.

13.2 Description

13.2.1 Stratigraphy

In the River Orchy section at NN 242 318, rocks belonging to the Grampian Group are mainly of finely banded psammite and semipelite, with some pelitic beds a few centimetres thick that contain chloritized garnets. Thin grey quartzite beds, and thin calcareous seams are also present. The latter occur in a distinctive sedimentary association in which the dark brown-weathering calcareous bands, a few centimetres thick, are separated from the pelitic background lithology by a narrow zone of siliceous psammite. These zoned calcareous units generally have an extremely elongated pod-like geometry overall, and die out laterally within a metre or two.

The Beinn Udlaidh Quartzite is commonly coarse grained and feldspathic where it is least deformed, as in the hinge-zone of the major fold at NN 248 332, and locally contains gritty and pebbly layers. It varies from pale grey to white or even pink in colour. Excellent examples of festoon cross-bedding (at NN 248 331), as well as at other localities in the quartzite on the hillside to the north-east of this GCR site, show clearly that the unit is younger than the Grampian Group. Where the boundary between the two units is least affected by later deformation, it is generally transitional over several tens of metres, with interbedding of psammite, semipelite, and quartzite ribs (Thomas and Treagus, 1968, p. 127). The northern contact is not exposed in the River Orchy section, the first exposures north of the quartzite, seen immediately above the waterfall at NN 248 332, being of psammite with thin quartzite beds. At the south end of the section, the entire quartzite unit is thinned tectonically, and the contact can be located to within a metre or so below the dam at NN 242 319, although Thomas and Treagus (1968) considered that the topmost 33 m of the Grampian Group at this locality constitute a 'passage group'. A dyke and a sill-like apophyse of appinitic rock are intruded close to the stratigraphical base of the quartzite and somewhat obscure its relationship to the psammitic rocks farther downstream.

The overlying Leven Schists have a very uniform lithology and consist of finely banded, dark-grey, schistose biotite-muscovite-garnet-graphite pelites with thin layers of psammite and semipelite. The pelites are characterized by a strong bedding-parallel schistosity. They contain porphyroblasts of garnet, reaching several millimetres across in places, commonly accompanied by millimetre-sized randomly orientated flakes of biotite. Most of the garnets in the pelitic rocks have been altered to chlorite, fresh garnets being most common in the thin siliceous bands. Significantly, in the exceptionally clean exposures in the area of the gorge above the Iron Bridge, and where the river runs close to the road farther north at NN 243 323, small-scale zoned calcareous units are found, which are identical to those seen in the Grampian Group and are also accompanied by thin beds of steel-grey quartzite.

The boundary between the Leven Schists and the underlying Beinn Udlaidh Quartzite is transitional, as is shown by the presence of thin quartzite beds within the pelite for a distance of a few metres above the main quartzite. This relationship is clearly seen at several places near to the confluence of the River Orchy and the Allt Broighleachan (Thomas and Treagus, 1968, p. 127) (Figure 29).

13.2.2 Structure

The Beinn Udlaidh Syncline is a sideways-closing and upward-facing syncline whose gently plunging axis changes trend from approximately east–west to north–south as it is traced southwards along the river section. This major change can be monitored by the progressive change in orientation of the hinges of the congruous minor folds (Figure 29, stereoplot b). It consists of an upper limb (with inverted Grampian Group rocks lying above the Appin Group in the south of the area), and a lower limb to the north in which the Leven Schists lie above the Beinn Udlaidh Quartzite (Figure 29). The axial trace of the major hinge-zone passes through afforested ground to the west of the river. The marked curvature of the axial trace, as seen in Figure 29, is due to the intersection of the gently dipping axial surface of the fold with the irregular topography, and is unrelated to the fold axis curvature described above.

When viewed down-plunge to between south and west, the minor folds on the upper limb are seen to have a Z-shaped vergence (Figure 30), which changes first to a neutral vergence in the vicinity of a poorly defined major hinge-zone at about the Iron Bridge, and then to a consistent S-shaped vergence on the lower limb. These minor folds are best seen in the quartzite and the banded Leven Schists, and have wavelengths that vary from tens of centimetres to over a metre (Figure 31). The axial planes of the minor folds, together with the related penetrative cleavage in the pelitic rocks, dip consistently at less than 20° (Figure 29, stereoplot a). Throughout the section, a stretching lineation, seen sporadically on the bedding or foliation planes, maintains a constant trend of 190–180° and plunges at a gentle angle to either north or south. Evidence that this lineation is a stretching lineation and not a bedding-cleavage intersection lineation is seen in the gritty and pebbly quartzite beds in the hinge-zone of the major fold around NN 248 332, where clastic grains are clearly elongated and define a stretching lineation, which lies at right angles to the local intersection lineation and to minor fold hinges (Tanner and Thomas, 2010).

Evidence of later ductile deformation superimposed upon the major synclinal structure is restricted to the development of a crenulation cleavage, which is associated with minor folds of S-vergence in the Grampian Group rocks on the upper limb of the fold, and cross-cuts the earlier Z-folds and penetrative fabric. A weak development of a similar crenulation cleavage and lineation is also seen in the pelitic rocks on the lower limb of the Beinn Udlaidh Syncline.

The structural pattern in these rocks is beguilingly simple, and only rarely, even on the cleanest rock surfaces, are isoclinal minor folds of F1 age seen to be refolded around minor folds congruous to the major syncline (Tanner and Thomas, 2010). Care has to be taken, as some suspected refolded folds have been proved on closer examination, followed by slabbing and sectioning in the laboratory, to be of sedimentary origin In addition, examination of the garnets with a hand-lens reveals that they contain helicitic inclusion trails, which are strongly oblique to an external cleavage, which is axial planar to the F2 minor folds. Thin sections of these rocks show that (i) there is an earlier penetrative cleavage (S1), which pre-dates the formation of the S2 fabric associated with the Beinn Udlaidh Syncline, and (ii) the garnets also grew in the interval between these two deformation events (Tanner and Thomas, 2010).

13.3 Interpretation

The field relationships seen at this GCR site, supported by younging evidence from cross-bedding, show that there is a coherent stratigraphical sequence from the upper part of the Grampian Group into the lower part of the Appin Group, with no evidence of a major stratigraphical or structural discordance between the two groups (Tanner and Thomas, 2010). Of particular importance is the recognition of minor sedimentary rhythms, of unusual character, in rocks belonging to both groups. At the contact between the two groups there is evidence of sedimentary interfingering of beds, rather than tectonic interleaving. This observation is in agreement with the relationships seen at the *River Leven* and *Strath Fionan* GCR sites. This is an important conclusion as the boundary marks a major lithological change in the sedimentary record, and indeed was formerly taken to be the Moine-Dalradian boundary.

The sedimentary sequence is folded into a major syncline, the Beinn Udlaidh Syncline, which faces up to the east, and has a strongly curved axis. Previous authors have regarded this syncline and the complementary Glen Lochy Anticline as F1 structures (Cummins and Shackleton, 1955; Thomas and Treagus, 1968; Roberts and Treagus, 1975) but Tanner and Thomas (2010) have shown that it post-dates an earlier fabric (see below) and hence can be confidently assigned to the D2 regional deformation. However, only a small amount of deformation, and a gentle warping of the axial surface followed this main deformation event. This suggests that the curvature was a primary feature of the D2 deformation, and not a later effect due to refolding. Analysis of the geometrical results from this GCR site, together with those from the adjoining Beinn Udlaidh massif in which the fold is extensively dissected, indicates that this curvilinearity has resulted from the rotation of the original east–west fold axis, as seen in the least deformed rocks, towards the orientation of the north–south stretching lineation (the X-direction of the strain ellipsoid), with increasing deformation (Figure 29, stereoplot b) (Tanner and Thomas, 2010). The upper limb of the fold has been most affected by this increase in strain, and the Beinn Udlaidh Quartzite found there has a platy foliation, lacks sedimentary structures, and is considerably thinner than it is on the lower, less deformed, limb. It also carries a strong stretching lineation.

A petrographical study of the garnet-bearing assemblages shows that the major F2 fold and its associated family of minor folds, cleavage, and lineations, formed *after* a deformation event which had given rise to a penetrative cleavage and was accompanied by amphibolite-facies metamorphism. Evidence of this early, S1 cleavage has been all but destroyed by later recrystallization and mineral growth in the overwhelming majority of rocks, and it is best preserved as a helicitic fabric in the garnet porphyroblasts (Tanner and Thomas, 2010). There is no evidence from this GCR site or from the adjoining area to suggest that either minor or major folding accompanied this early tectonothermal event, and its significance is still being assessed. Tanner and Thomas (2010) concluded that the rocks belonging to the Grampian Group have been affected by the same number and sequence of events as those of the Appin Group, and that there is no evidence for additional deformation phases in the older rocks. These findings support the conclusion that the Grampian–Appin group boundary is not marked by a significant structural break.

13.4 Conclusions

The River Orchy GCR site provides an invaluable section through the upper part of the Grampian Group and its continuation upwards into the Appin Group (Lochaber Subgroup). Transitional contacts between the major rock units, coupled with sedimentary repetition of distinctive lithologies, precludes the presence of a major, orogenic, unconformity at this stratigraphical level. This finding is supported by a microscope study of rocks from this GCR site, which has confirmed the field-based conclusion that both groups have been affected by the same number of structural events, having the same intensity of development, and geometry. Thus a boundary that was formerly taken to be the contact between the Moine and Dalradian supergroups can now be confidently recognized as a normal stratigraphical contact between the two lowest groups of the Dalradian succession. This conclusion is supported by observations at the *River Leven* and *Strath Fionan* GCR sites.

The rocks at this site are folded over into a large downward-closing F2 fold, the Beinn Udlaidh Syncline, which lies on its side and has been deeply incised by the River Orchy, to reveal its internal geometry. The gorges and rocky bed of the river expose a superlative section which is invaluable as a natural laboratory in which to study the intricate three-dimensional shape of this fold and its associated minor structures, and to enable its mode of development and complex history to be further unravelled. One aspect of the work of special interest, is that it is the first locality in the western Grampian Highlands where it can be demonstrated that the so-called 'early' nappe-like folds formed after an even earlier major deformational and metamorphic event.

14 A9 ROAD CUTTINGS AND RIVER GARRY GORGE (NN 686 717–NN 804 656)

P.R. Thomas

14.1 Introduction

The rock exposures in the 20 km-long section of Glen Garry between the Drumochter Pass and Blair Atholl are of national, if not international, importance since they form an almost continuous section through the Grampian Group rocks in the Central Grampian Highlands. Not only does the bed of the River Garry itself have 75% exposure, most of it above water level for much of the year, but the parallel A9 road also provides a series of long clean rock cuts. Hence, the exposures are frequently visited by student parties and professional geologists. The GCR site is noteworthy for its wealth of minor folds and sedimentary structures, which can be used to demonstrate the position and geometry of some of the major folds that make up the central part of the Grampian fold belt.

The site lies on the inverted limb of the recumbent, SE-facing Tay Nappe and provides a unique section through D1 and D2 minor and major folds, related to that regionally important structure. It also provides an essential link between two later major upright folds, the Drumochter Dome to the north-west (see Figure 32) and the Ben Lawers Synform to the south-east (see the *Ben Lawers* GCR site report); those are the folds that control the outcrop pattern of the Dalradian in much of the Central Grampian Highlands, as illustrated and discussed by Treagus (1987, figure 1b and p.12).

The rocks of Glen Garry were originally described by Barrow (1904) as Moine 'granulites' (an obsolete term for high-grade psammitic metasedimentary rocks). The paper mentions 'water-pipe' structures at Clunes and some overturned folds, but provides little other specific data. Apart from a brief description of a fold in a quarry on the A9 road by McIntyre (1950), the main work, which forms the basis for this account, is that of Thomas (1965, 1979, 1980, 1988). Further useful comments were made on the sedimentology by Glover and Winchester (1989) and Banks (2007), and on the structure by Lindsay *et al* (1989).

14.2 Description

The following numbered descriptions of key localities start in the north-west, near the summit of Drumochter Pass, and follow the road and river down towards Blair Atholl (Figure 32). All of the exposures are within psammitic rocks of the Grampian Group. The dominant fold-set is named F2 and its axial plane schistosity S2. Rarely observed folds which clearly pre-date F2 or S2 are designated F1, although S1 is generally parallel to bedding.

14.2.1 Stalcair Cut (NN 686 717)

At the third lay-by on the southbound section of the A9 dual carriageway descending from the Drumochter Pass, gently dipping inverted beds face down to the south-east on the S2 axial-plane schistosity and lenses of calcsilicate rock in the schistose psammites are well seen. Roadside exposures 200 m to the east, by a pylon buttress, display schistose laminated psammites with superb trough ripple-laminations and larger dune beds as well as sediment slump structures (Banks, 2007; Figure 33). Overturned, NW-vergent, F2 folds in the cut face plunge gently towards 070° and are clearly downward facing. A strong S2 axial-plane cleavage cuts S1, which is parallel to bedding, and dips at 30^0 towards 160^0 at this locality. The exposures are on the north-west, inverted, limb of the F2 Garry Synform, the hinge-zone of which is seen at locality 2.

14.2.2 Wade Stone Cut. (NN 694 716–NN 699 71) and River Garry (NN 697 714–NN 714 706)

At the fourth lay-by on the southbound dual carriageway, a high rock face, on the curve of the road, cuts obliquely across the hinge-zone of a major F2 fold, the Garry Synform. The section east of the lay-by is in the gently dipping inverted limb of the synform, with NW-verging minor folds, but east from the retaining wall F2 minor folds become more neutral in vergence as the hinge is reached. The folds, plunging at 20° to 070° with an axial-plane dip of 40° to the south-east, are downward facing. Evidence is based on the many fine examples of ripple-laminated and dune-bedded schistose psammites. Lenses of calcsilicate rock are deformed by S2, but post-D2 microcline porphyroblasts in the schistose psammites could be evidence of later metasomatism.

There are both early quartz veins, which are folded, and later cross-cutting veins. NE-trending microdiorite dykes and faults can also be traced in the rock-face. The major Allt an Stalcair fault-zone, seen in the Allt Stalcair at NN 693 717 to the west, is mineralized with calcite and haematite.

The northbound lay-by, nearer to the River Garry, enables both road and river sections to be seen. Good way-up evidence is found in the river beneath the railway bridge (NN 6995 7131), and immediately upstream is the hinge of the Garry Synform. One kilometre downstream from the railway bridge, the hinge of the major F2 Creag a' Mhadaidh Antiform can be traced (NN 7090 7075), plunging at 10–14° to 070–080° with fine examples of overturned folds containing trough cross-laminations on steep limbs and an S2 crenulation schistosity dipping at 20–30° to the south. Exposures around the footbridge at NN 7120 7065 have considerably tightened and overturned minor folds involving some refolding of F1 folds. These continue downstream to a point where very regular low dips mark the commencement of the 'Dalnacardoch Banded Zone' (see locality 3b), about 200 m upstream from the confluence with the Edendon Water.

14.2.3a Edendon Cut (NN 7108 7084–NN 7140 7075)

The next lay-by on the A9 southbound is east of the major F2 closure of the Creag a' Mhadaidh Antiform. At the west end of the rock cut (NN 7114 7083), very tight F1 folds verge north-west and appear to face downwards to the south-east as indicated by deformed current-ripple laminations. At the burn (NN 712 708) a strike-slip fault trending 024° brings in a more-psammitic lithology and overturned, NW-vergent, F2 folds plunging at 16° to 075°. At the east end of the lay-by, above a low-dipping ductile thrust, slightly more-open F2 folds plunging at 20° to 082° with an axial-plane schistosity dipping at 35° to the south, fold thin quartz veins and are cut by a microdiorite dyke.

14.2.3b Dalnacardoch Cut (NN 719 705)

Half a kilometre south-east of the last locality, in the deep southbound road cut, an apparently regular sequence of flaggy to schistose psammites dipping at between 25° and 30° is far more complex when closely inspected. This is the 'Dalnacardoch Banded Zone', which envelopes very tight F1 and F2 folds as well as a later generation of reclined folds on both major and minor scales. At the north-west end of the highest section (NN 7183 7055), very tightly refolded isoclines occur, whereas farther into the cutting isoclinal folds lie within an apparently simple banding (NN 7198 7046). The cutting also contains bands of mixed gneissose lithologies, in which post-D2 boudins are quite common. Late rotational shears in the form of large kink bands also occur at the eastern end of the cut.

In the River Garry, the Dalnacardoch Banded Zone is at least 4 km wide from NN 716 706 to NN 748 694 and contains both F1 and F2 folds, as well as folds of a later deformation. The latter are associated with the north-west limb of the major post-D2 Errochty Synform, which is thought to pass through the River Garry near Dailnafraoich (NN 7375 6983); here, exposures of F1 and F2 isoclines are refolded about reclined folds of the later generation, which plunge at 10–30° to 140–170°. The river also exposes a number of interesting crush-zones parallel to banding in which angular schistose clasts are preserved in narrow breccia bands less than a metre in thickness.

14.2.4 Allt Crom Cut (NN 769 690)

Just to the west of the Allt Crom bridge on the A9 road, a cutting at NN 7688 6896 exposes the hinge of a major antiformal fold in three dimensions (Figure 34). Plunges of both major and minor folds here are in the range 16–25° towards 150–170°, but strong axial cleavage planes appear to be restricted to the hinge-zone, where they dip at 40° to 080°. The western limb dips at 35–45° towards 080° and the less-steep eastern limb dips at 20–30° towards 135°; the interlimb angle from here northwards remains at less than 40°. This undoubted major hinge can be traced for 1 km north in surface exposures and also in the Allt a' Chireachain, 3 km to the north, at NN 7752 7194, where the plunge is 20° to 140°. In the Garry Gorge immediately to the south, it is difficult to follow the precise trace of the antiform; it is seen towards Glen Errochty, though in a much more-open reclined style at this higher structural level. This fold is equated with the Bohespic Antiform, the major post-D2 fold complementary to the Errochty Synform (see below).

14.2.5 Black Tank Cut (NN 773 680)

This wide cutting is dominated by a major, tight, overturned F2 antiform, the hinge of which can be detected opposite the northbound lay-by in schistose psammites dipping at 38° to 116°. The plunge is unusual for the area at 8° to 218° with a cleavage dip of 30° to 136°. The high rock face is controlled by regularly dipping planar structures 1–3 m apart with a dip of 52–55° towards 270–290°. Some joint faces are mineralized with quartz and pyrite whilst other fault planes display slickensides, some with dip-slip and others involving strike-slip final movements. Several of these discontinuities caused wedge failures of the face during construction. At the south-east end of the cut a large red microdioritic sill, dipping to the east at 26° in very regular layers of schistose psammite, is downfaulted to the north-west.

14.2.6 Clunes Gorge (NN 782 671–NN 789 667) and Clunes Cut (NN 785 670–NN 789 668)

This superb river locality has now been rivalled by the new road cut only 150 m to the north (Figure 35). Both localities demonstrate the presence of the Clunes Antiform, a major F2 structure, folding cross-bedded and ripple-laminated psammites, quartzites and semipelites, stratigraphically located near the transition between the Bruar Psammite Formation and the Tummel Quartzite and Psammite formations. Linear features seen in the river section, such as the famous `water-pipe' mullions (NN 784 667) (Barrow *et al*., 1905, p. 68), plunge consistently parallel to the axes of the F2 minor folds. Minor folds, abundantly displayed in the road cut (Figure 35), plunge consistently at about 10° to 045°, with a strong S2 axial-planar cleavage dipping at 20–30° to 120°. At both localities the SE-vergent, overturned, folds can be seen climbing towards the hinge of the major antiform, which lies near the south-east end of the cut and some distance down the Clunes gorge (NN 787 667). The sedimentary structures consistently show that the section is inverted overall and that the F2 folds face downwards to the south-east.

Several vertical and inclined microdiorite dykes cut both the river and the road sections. The widest of these is not only porphyritic but also contains xenoliths made up from a variety of metamorphic rocks, some of which are quite distinct from normal Grampian Group lithologies. Immediately west of one of the dykes, at the north-west end of the road cut, early, presumed F1, isoclinal folds can be seen to be refolded by the F2 minor folds.

Downstream around NN 790 664, major faults cut the river section and start to bring in lithologies that can be assigned more-readily to the Bruar Psammite Formation.

14.2.7 Struan Exposures (NN 802 657–NN 808 655)

Inverted, regularly SE-dipping, flaggy psammites and quartzites form the bed of the River Garry for 1 km below the junction with the Allt a' Chrombaidh (NN 790 664), but from 200 m above the twin bridges at Calvine (NN 802 657) and downstream almost as far as Struan church (NN 808 655), numerous overturned F2 folds have been entrenched by the river. These NW-vergent folds have consistent plunges of 20–30° to 060°, and amplitudes of 5–20 m.

At the 'Salmon Leap' (NN 8037 6565), sedimentary structures are best preserved on the steep limbs of the folds, in laminated schistose psammites with interbedded semipelitic layers. The proof that the layering is true bedding lies in the presence of a number of well-preserved sedimentary dykes, washouts and slump structures (Figure 36), all of which consistently young to the south-east on steep limbs of folds, which thus face down to the south-east as at Clunes (locality 6). The rocks here are assigned to the topmost part of the Bruar Psammite Formation.

14.3 Interpretation

In essence, the sections at localities 1 and 2 and 4 to 7 are dominated by minor and major folds of the second generation, which fold all earlier planar structures (S0 and S1). In the more-pelitic lithologies, a strong crenulation cleavage is developed, axial-planar to the folds. Both the folds and the cleavage can be correlated, in style and geometry, with the regional D2 structures. The three-dimensional structure of the area is made more complex by the presence of a third deformation phase, described by Thomas (1980) as D3 but which is thought by others to pre-date the ENE-trending upright folds described as F3 by Treagus (1999, 2000) in the Appin and Argyll group rocks south of the Rannoch–Tummel area. Treagus (2000) gave these late structures a local designation of De, being unable to state categorically whether they pre- or post-date the regional D3 phase.

This late phase is associated with the major N-S-trending Errochty Synform and the Bohespic Antiform, described by Rast (1958) from the boundary of the Grampian Group with the Appin and Argyll groups to the south (see the Meall Dail Chealaich GCR site report). Minor structures associated with this phase become remarkably intense in the mid-part of the Glen Garry section, where the Errochty Synform produces the tight reclined structures at locality 3. This gives rise to the Dalnacardoch Banded Zone, which destroys most of the stratigraphical continuity and causes the re-orientation of all earlier folds around its hinge. Since no sedimentary structures are preserved in this high-strain zone, it is possible that bedding has been transposed and the schistosity might be composite. The presence of well-preserved sedimentary structures outside the banded zone introduces the possibility of some stratigraphical subdivision but the psammitic nature of most of the lithologies reduces the confidence of correlations north and west of the Dalnacardoch area.

In spite of the refolding by this later fold-pair, the major F2 folds described above, and the majority of the minor folds on their long limbs, are consistently overturned and vergent to the north-west, whilst being downward facing to the south-east on the second cleavage (Figure 32). The Garry Synform and the complementary Craig a' Mhadaidh Antiform demonstrate this relationship particularly well on the north-west limb of the Errochty Synform. In the core of the Errochty Synform and on its common limb with the Bohespic Antiform, between localities 2 and 4, the facing of the D2 structures is not clear. However, on the south-east limb of the Bohespic Antiform the north-west vergence and south-east facing of the D2 structures is very clear from the exposures of the Clunes Antiform, seen in conjunction with the Meall Reamhar Synform (see the *Creag nan Caisean–Meall Reamhar* GCR site report). It is likely that the Clunes Antiform is the lateral equivalent of the Creag a' Mhadhaidh Antiform.

The geometry, north-west vergence and south-east facing of the D2 structures is consistent with that observed in the Appin and Argyll groups to the south (see, for example, the *Strath Fionan*, *Slatich* and *Craig an Chanaich to Frenich Burn* GCR site reports). This is consistent with their origin on the lower limb of the Tay Nappe, in its development during top-to-the-SE D2 simple shear of originally upright F1 folds (Treagus, 1987). This concept is supported by the observation, in the Clunes locality particularly, that the sedimentary structures are best preserved in the steeply dipping, short limbs of the F2 folds, where they have suffered the least rotation and deformation. The rarely observed minor first generation folds also appear to be facing down to the south-east, on the long limbs of second folds. This suggests that, on the removal of the second deformation, these folds would have been part of an upward-facing fold train (see 1.1 *Introduction*), originally on the south-east limb of a major F1 anticline.

14.4 Conclusions

Glen Garry, from Drumochter to Calvine, is traversed by two parallel, excellently exposed ribbons of rock, one natural (the River Garry) and one man made (the A9 road). Both have been instrumental in providing vital evidence to help our understanding of the complex geological structure of the Grampian Group and without them very little three-dimensional interpretation of the structure would have been possible. Both minor and major folds, as well as sedimentary structures, are clearly and spectacularly displayed in exceptional clean and continuous exposures of rocks that are poorly exposed elsewhere. Most of the folds belong to the regional D2 phase of deformation, are north-west verging and face downwards to the south-east on the inverted lower limb of the F1 Tay Nappe. However, this site also exposes the hinges of an important pair of later folds, the Bohespic Antiform and the Errochty Synform, which exert a major influence on the overall outcrop pattern in the Schiehallion area to the south.

15 CREAG NAN CAISEAN–MEALL REAMHAR (NN 771 6017–NN 783 622)

P.R. Thomas

15.1 Introduction

The two peaks of Meall Reamhar (493 m O.D.; NN 784 618) and Creag nan Caisean (477 m O.D.; NN 778 607) form part of a NNE-trending gentle rocky ridge surrounded by plantations, north of Tummel Bridge (Figure 37). Exposures within the GCR site provide evidence for the downward-facing Meall Reamhar Synform, formerly interpreted as the primary F1 closure of the Atholl Nappe, structurally beneath the Tay Nappe (Thomas, 1979, 1980), but now regarded as one of the major F2 folds that affect the inverted lower limb of the F1 Tay Nappe (Treagus, 2000).

The site also has stratigraphical significance and contains outcrops of two major formations of the Grampian Group, the Bruar Formation and the Tummel Quartzite Formation. On the particularly well-exposed south-east flank of Creag nan Caisean, consistent younging evidence has played a vital role in establishing the stratigraphy on the upper limb of the major fold. This is the type area for the Tummel Quartzite Formation, which here contains a number of distinctive quartzite units separated by laminated schistose psammites. .

15.2 Description

The southern boundary of the GCR site coincides with a forestry road, which is accessible either from Easter Bohespic (NN 756 603) in the west or Grenich (NN 804 603) in the east.

The Bruar Formation is exposed on the forestry road to the west of the surge shaft of the Dalcroy Power station (notably at NN 767 603), and on Meall Reamhar. Laminated schistose psammites with way-up evidence are dominant, but there are fewer quartzites and more schistose pelites and semipelites than in the overlying formation. On the summit of Meall Reamhar (NN 784 618) the formation contains more interbedded layers of schistose pelite and is intruded by late-Caledonian NE-trending dykes in the hinge-zone of the Meall Reamhar Synform.

Some 200 m to the east of the surge shaft, the lowest of the quartzite units at the base of the Tummel Quartzite Formation is well exposed. This is the first of numerous individual 5–30 m-thick beds of feldspathic quartzite, which are characteristic of the Tummel Quartzite in this area and extend north-eastwards for 9 km towards Glen Garry. In general they dip steeply to the south-east. Interbedded with the quartzites are schistose psammites, which display laminations with abundant examples of ripple drift, dunes, convolutions and, more rarely, sedimentary dykes, all younging consistently to the south-east, towards the upper boundary with the Tummel Psammite Formation.

Small-scale minor folds are common, especially within the quartzites. The polyphase nature of the deformation means that styles and plunges vary greatly throughout the formation. Two penetrative schistosites are related to two sets of early minor folds, which are commonly difficult to distinguish one from the other. However the dominant vergence of the later of the two sets is to the south-east, and they are associated with an axial planar cleavage dipping steeper than the bedding. Two further sets of crenulation cleavages cross-cut the early sets.

Immediately to the north-west of the summit of Meall Reamhar, the dip of the bedding and the subparallel schistosity become less steep (25–40°) and the second, dominant, penetrative schistosity is steeper (40–60°), indicating that the axial trace of the major Meall Reamhar Synform has been crossed. This is confirmed by the occurrence of inverted cross-bedding in the laminated schistose psammites on the southern slopes of Glen Errochty, to the north of the GCR site. The axial trace of the synform trends north-east below the summit ridge, where there is an antiformal plunge culmination; from here the hinge plunges at low angles to the south-west and north-east.

15.3 Interpretation

The excellent exposures in this GCR site provide critical evidence for the key, upward-younging, stratigraphical succession of the Grampian Group from the Bruar Formation through the Tummel Quartzite into the Tummel Psammite above.

The main structural debate concerns the age of the major Meall Reamhar Synform. The presence of small-scale interference structures involving both of the primary deformation phases (D1 and D2), as well as the two later cross-fold phases, indicates the structural complexity of the area, but it is considered that the primary deformation has dominated the large-scale structure. The major closure was initially interpreted by Thomas (1965, 1980) as an F1 closure. Two hundred and fifty metres to the west of the surge shaft at NN 771 601, near the forestry road, there is evidence suggesting that some folding may be earlier than that associated with the Meall Reamhar Synform. Here, very steeply dipping schistose psammites with cross-bedded laminae are cut at right angles by a single (or composite) penetrative schistosity, with no sign of any bedding-parallel schistosity. (Figure 38) This was interpreted by Thomas as being representative of the downward-facing (F1) closure of the major Meall Reamhar Synform. However, it is now thought that this might be an early minor F1 fold hinge facing south-east, which is not related to the Meall Reamhar closure and certainly does not affect the general upward younging on the steep limb of that fold.

The Meall Reamhar Synform has been recently re-interpreted to be of D2 age, complementary to the Balliemore Antiform and other NW-verging major folds within the Appin and Argyll groups to the south (Treagus, 2000). The evidence for this, as well as that in this GCR site, comes from the consistent south-east vergence of F2 minor folds in Grampian Group formations to the south-east (e.g. in the Kynachan Quartzite Formation on Creag Kynachan at NN760 576) and the north-west vergence of the F2 folds to the north-west (as is also described at Clunes–locality 6 of the *A9 and River Garry* GCR site report). These folds are associated with a penetrative S2 schistosity in semipelites, on which the folds face down to the south-east.

15.4 Conclusions

The Creag nan Caisean–Meall Reamhar GCR site provides important evidence that helps to establish a succession in the Grampian Group, through its excellent younging evidence and distinctive quartzite lithologies. The Bruar Formation and Tummel Quartzite Formation are both well represented. Creag nan Caisean is one of the best areas in the Central Grampian Highlands to see interference structures in minor fold outcrops, which reflect the regional polyphase fold pattern. The site also provides dramatic evidence, from minor tectonic structures, for the presence of the two limbs of the F2 Meall Reamhar Synform, a downward- and SE-facing anticline that is an important component of the major folds that affect the lower, inverted, limb of the Tay Nappe. This fold is complementary to the Balliemore Antiform described in the *Strath Fionan* GCR site report.

16 MEALL DAIL CHEALACH (NN 703 676–NN 716 675)

P.R. Thomas

16.1 Introduction

The NW-elongated ridge of Meall Dail-Chealach (510 m O.D.) rises above open moorland, 2 km north of the Errochty Dam. Exposed at this GCR site is one of the best examples to be seen in the Central Grampian Highlands of a late, post-metamorphic, major kink fold, the Trinafour Monoform. This fold refolds the sharp closure of the Errochty Synform and is responsible for its final orientation.

The steep middle limb of the monoform is marked by a narrow line of steep dips that was first recorded by the Geological Survey on Sheet 55 (1902) and was described as 'a line of disturbance' in the subsequent memoir (Barrow *et al.*, 1905). It was not however noted by subsequent workers in the area, Anderson (1923), Bailey and McCallien (1937) or Rast (1958). Its significance was realized by Thomas (1965, 1980), who interpreted it as the steep limb of one of a number of major post-metamorphic angular kink folds in this area and named it the Trinafour Monoform (Ft on Figure 39a, following the nomenclature of Treagus, 2000).

16.2 Description

Exposures on the ridge of Meall Dail-Chealach from NN 708 671 as far north-west as the mid-slopes of Meall Breac (NN 686 697) (Figure 39a) are composed of Grampian Group metasedimentary rocks. The rocks are thinly layered schistose psammites and quartzites containing isoclinal folds of earlier generation structures (D1/D2). These rocks are affected by their proximity to the major ductile thrust, the Boundary Slide, which separates them from rocks of the Appin and Argyll groups. All of these rocks are affected by the post-D2 Errochty Synform, which is locally associated with minor folds and a schistosity (Fe and Se on Figure 39a, following the nomenclature of Treagus, 2000). The ridge follows the outcrop of the steep limb of the Ft Trinafour Monoform.

The bedding and subparallel S1 and S2 schistosities on the steep limb of the Trinafour Monoform range in dip from 65° north-east up to vertical, with a strike of 155°, which is oblique to the main north-west trend of the steep belt. Some of the exposures display minor open folds (Ft on Figure 39a), plunging at 20–30° towards 140–150° with axial planes dipping gently to the south-west (Figure 39b). Near the base of the crag on the north-east side of the hill, the layering is seen to curve away towards Dubh Lochan (NN 711 674), beyond which the laminated gneissose psammites dip at 30–40° towards 210° on the north-eastern gentle limb that marks the north-east margin of the monoformal structure. The south-west closure of the monoform in the Grampian Group rocks is seen 2.5 km to the north-west (at NN 687 695) and also more clearly in the Appin and Argyll group rocks downstream from the Errochty Dam (at NN 718 653) (Figure 39a). The plunge of the major fold varies from 10° to 25° to the south-east and both the amplitude and the wavelength of the fold decrease downwards, so that the fold dies out up plunge on the slopes of Meall Breac (NN 685 698). Down plunge, the monoform broadens to an open structure south-west of Trinafour, where it is accompanied by the open upright Allt Culaibh Antiform and the asymmetrical Croftnagowan Synform to the north-east and south-west respectively (Figure 39).

16.3 Interpretation

It is clear that this major line of disturbance refolds all earlier structures, including the Boundary Slide and associated D1 and D2 minor folds and schistosities, and especially the axial trace of the post-D2 Errochty Synform and its associated minor folds and schistosity (the De phase of Treagus, 2000). The Trinafour Monoform is related to distinctive brittle-style minor kink folds with a low plunge to the south-east (Figure 39b). The occurrence of major and minor open and kink folds with gentle south-east plunges is rare in the Central Grampian Highlands, but they appear to be particularly well developed in the flaggy rocks on the gently dipping north-west limb of the Errochty Synform, where they are referred to as the Dt phase by Treagus (2000). The north-east vergence of the Trinafour Monoform is reflected by the minor folds, which also occur in conjugate and oblique sets, exemplified by the Sron Chon folds to the south-west. Late folds of presumably the same generation as the monoform that occur to the west and east (the Allt Sleibh Antiform, Meall na Leitreach Synform and Allt Culaibh Antiform) have progressively steeper axial surfaces with depth (Figure 39b).

The age relationship of the Trinafour Monoform, and the related Ft folds mentioned above, to the other deformation events late in the history of the Grampian orogenic belt is not clear. Their brittle style would suggest that they post-date the ENE-trending folds of the D4 phase, such as the Ben Lawers Synform, described in the *Ben Lawers* GCR site report. The Dt folds must be the consequence of a NE-directed shortening along the length of the orogenic belt. This is in contrast to the supposed transtensional deformation in that direction that is responsible for the NE-trending, late-Silurian, fault set (Treagus *et al.*, 1999) discussed in the *Ben Oss* GCR site; the age relationship of the Dt folds to these faults is not known.

16.4 Conclusions

The Meal Dail Chealach GCR site is of national importance since it is representative of a number of spectacular NW-trending folds, the most impressive of which is the Trinafour Monoform, that formed late in the Caledonian deformation process. In this part of the Central Grampian Highlands these semibrittle-style, monoformal kink folds, which are the latest set of folds that can be identified, appear to be restricted in development to the area between Craiganour Forest and Glen Garry, and have formed in the gently dipping, flaggy, Grampian Group rocks. Around the Errochty Dam area they have also deformed the younger Appin Group rocks above the Boundary Slide. The site lies only a few kilometres west of the Trinafour to A9 road and is frequently visited by student parties.

17 STRATH FIONAN
(NN 720 580–NN 745 560)

J.E. Treagus

17.1 Introduction

This GCR site is located on the slopes of Strath Fionan, immediately adjacent to the minor road which runs around the north side of the isolated mountain, Schiehallion (Figure 41). It provides the only continuous section in the Central Grampian Highlands, from the top of the Grampian Group through the Lochaber and Ballachulish subgroups of the Appin Group (Table 1). Each of the formations has observable sedimentary boundaries with its neighbours and sedimentary structures can be used to establish the continuity and the way up of the succession. Additional attractions include minor folds, a great variety of metamorphic minerals and microdiorite dykes and the area is popular for student field parties and mapping projects.

The uniformly south-dipping sequence was originally interpreted by Bailey and McCallien (1937) as the folded and faulted repetition of the Blair Atholl 'Series' (now the Blair Atholl Subgroup) and of the Schiehallion Quartzite and Killiecrankie Schist, which occur to the south of the GCR site. The junction at the base of the Blair Atholl 'Series' with the 'Moines' (now the Grampian Group) was interpreted as a major synmetamorphic dislocation, since the interpretation required considerable excision of the stratigraphical succession. This tectonic junction, named the Boundary Slide, the equivalent of the Iltay Boundary Slide in the south-west Grampian Highlands (MacGregor, 1948; Rast, 1963), plays a major role in Dalradian tectonics. This interpretation was supported subsequently by Rast (1958), who interpreted a persistent outcrop of schist immediately above the slide, the Beoil Schist, not as a stratigraphical formation but as a product of localized ductile deformation.

The present interpretation is that of Treagus and King (1978) and Treagus (1987) who maintained that the sequence may be directly correlated with the type Appin Group sequence *below* the Blair Atholl Subgroup and that it is a continuous south-younging sequence, uninterrupted by major folds or dislocations. The zone of Appin Group formations, including the Beoil Schist, immediately above the Grampian Group, although the locus of high strain, was not considered to contain a major dislocation.

The geometry of the dominant set of minor folds, seen in most of the lithologies, shows that the succession lies on the short, overturned limb of a fold (the Balliemore Antiform of Bailey and McCallien, 1937), which is one of the major F2 folds in the region according to Treagus (1987). The stratigraphy and structure of the Strath Fionan area has been described more fully in the Geological Survey memoir for Sheet 55W (Treagus, 2000).

17.2 Description

The principal lithologies of the GCR site may be conveniently examined in transects A–A', B–B' and C–C' (Figure 41).

17.2.1 Lochaber Subgroup

Good exposures of the uppermost Grampian Group and of the lowest four formations of the Appin Group can be seen on or close to the line of transect A–A' (NN 723 577–721 576). The transect provides the type section for the lowest two formations of the Lochaber Subgroup, the Dunalastair Quartzite and Dunalastair Semipelite.

The Grampian Group psammites (the Kynachan Psammite Formation of the Glen Spean Subgroup) are in sharp contact with the Dunalastair Quartzite and exhibit clear south-younging cross-beds a few metres from the boundary; there is no evidence of unusually high strain or of structural discordance at the contact. The typically rather pink-weathering quartzites and quartzose psammites of the Dunalastair Quartzite, in well-bedded 100–300 mm-thick units, exhibit slight variations in feldspar content, but are rarely as feldspathic as the adjacent Grampian Group psammites. Cross-bedding is evident from feldspar and heavy mineral concentrations, and truncated foresets may be observed within a few metres of the Grampian Group, confirming the age relationships.

Good exposures of the Dunalastair Semipelite within the area of Figure 41 can be seen along the ridge crossed by the transect A–A', on Speirean Ruadh (NN 735 570) and south-west of Lochan Beoil. Although the dominant lithology in this formation is a biotite-muscovite-garnet semipelite, its characteristic feature is a ribbed appearance on a variety of scales, owing to the presence of psammitic laminae, which are dominant close to the lower boundary. Cross-bedding is apparent in the thicker psammites, which are similar in character to those of the Grampian Group; no way up has been determined near the line of transect but evidence of the southward younging has been found near Lochan Beoil.

The Beoil Quartzite and Beoil Schist are well exposed to the south-west of the above formations in transect A–A′, but the type section of these formations occurs to the north of transect B–B′, on the steep south-facing scarp west of Lochan Beoil. Generally within the area of Figure 41, the Beoil Quartzite can be traced as discontinuous 100–300 mm-thick ribs of pure white quartzite separated by layers of semipelite 10–500 mm thick. Thin beds (100–300 mm) of pelite of Beoil Schist aspect and of quartz-feldspar psammites similar to those in the Dunalastair Semipelite also occur within the formation. The ribs of quartzite are commonly seen to be affected by tight folds with wavelengths of several metres (F1 and F2 of Figure 42, see Interpretation below) and it is clear that this results in considerable duplication. No certain sedimentary structures have been detected in these strongly deformed rocks. The Beoil Schist is well exposed within the area of Figure 41, forming a prominent topographical feature. The schist is characterized by an unusual concentration of muscovite and the presence of pods of vein quartz. The stratigraphically lower half, apart from these characteristics, is very similar to the Dunalastair Semipelite described above. It is a biotite-muscovite-garnet pelite or semipelite with thin ribs of quartzofeldspathic psammite and some quartzite ribs towards the lower, well-exposed, gradational boundary. The upper half has striking muscovite-rich schistosity surfaces studded with 1–8 mm garnets and streaked with quartz veins and pods; it is noticeably less biotitic than the lower part and bedding is not as obvious. No certain sedimentary structures have been detected in these strongly deformed rocks. Boudins of garnetiferous amphibolite are present.

A pronounced topographical hollow separates the Beoil Schist from exposures of the Meall Dubh Striped Pelite and the junction is nowhere well exposed. It is best seen north of the transect B–B′ in an area where the stratigraphy is repeated by several F2 isoclinal folds. The type section of the Meall Dubh Striped Pelite Formation is at the northern end of transect B–B′, in a 20 m-long ridge at NN 7386 5661. Here, the delicately striped alternations of fine-grained psammite and schistose muscovite-biotite pelite are well displayed in a 5 m-wide section. Garnet and feldspar porphyroblasts seen here are characteristic of this lithology, as is grading in the 10–30 mm stripes of fine-grained psammite. Although the junction with the Meall Dubh Limestone is not well displayed, the youngest beds in this section are calcareous; carbonate-rich rocks are seen a few metres to the south, suggesting a transitional boundary. This junction marks the Boundary Slide of Bailey and McCallien (1937).

17.2.2 Ballachulish Subgroup

The exposures along the line of traverse B–B' (NN 7386 5661–7432 5630) give the opportunity to examine the constituent formations of the Ballachulish Subgroup in reasonable proximity, although some of the type sections detailed below occur elsewhere in Strath Fionan.

Yellow-weathering, 'grey-hearted' carbonate rock, calcareous schist and tremolitic amphibole schist are all represented in the thin, poorly exposed, Meall Dubh Limestone Formation. Biotite or phlogopite porphyroblasts are usually conspicuous in the latter two lithologies; colourless tremolite and green actinolite occur locally as rosettes. No sedimentary structures have been observed.

The Meall Dubh Graphitic Schist Formation is particularly well displayed on the ridge to the east and west of the line of transect B–B'. The type section is a prominent crag at NN 7409 5645, where the graphitic schist displays 30–100 mm crystals of kyanite (black, as a result of graphite inclusions) as well as common biotite and garnet and rarer staurolite and feldspar porphyroblasts. Bedding is seen as non-graphitic semipelite ribs at 100–200 mm intervals. Concordant garnetiferous amphibolites are a feature of this formation. The boundary with the Meall Dubh Limestone is not well exposed, although isolated occurrences with admixtures of graphitic schist and calcareous schist show that it is gradational. The upper boundary is seen along strike to the east at NN 7422 5640, on the north side of the ridge of Meall Dubh Quartzite. Here graphitic kyanite-bearing semipelite and pelite merge into a metre of transitional muscovitic, rusty quartzite containing graphitic seams. At the eastern edge of the quartzite outcrop on Meall Dubh (NN 727 567), 2–3 m of a very characteristic transitional facies of the graphitic schist is developed. This consists of finely bedded, fine-grained quartzite with black graphitic laminae, which exhibits cross-lamination in some exposures. Some of the 20 mm-thick semipelitic beds exhibit grading of their graphite content. The younging is consistently towards the overlying quartzite, allowing for the presence of major and minor folds that affect this boundary.

On transect B–B' the upper 20 m of the Meall Dubh Quartzite Formation may be examined on the south bank of the Allt Strath Fionan at NN 7424 5634, where 200–500 mm-thick beds display a characteristic strong pebble lineation and feldspar-rich and heavy mineral laminae. Cross-bedding in 100 mm beds youngs south towards the Strath Fionan Banded Semipelite, some 20 metres distant. The junction between the two formations is not exposed here, but may be identified farther east on the south bank at NN 7432 5631; exposure is poor but there appears to be no transition. The exposures on Meall Dubh (NN 729 567), where the outcrop is greatly thickened by folding, provide many clean sections where the detailed mineralogy, deformation and sedimentary structures of the formation can be seen.

The Meall Dubh Quartzite typically comprises 70–80% coarse-textured quartz; the remainder consists of pink and milky-white feldspar occurring as 2–10 mm-long rod-shaped clastic grains, commonly concentrated in thin (50 mm) beds. Plate-like aggregates of quartz grains (up to 30 mm in maximum dimension and 5 mm thick) appear to represent highly deformed original clasts and indicate that the original rock was partly conglomeratic. Cross-bedding on the ridge above the roadside at NN 7275 5654 and to the east, youngs south towards exposures of the Strath Fionan Banded Semipelite.

Exposures of the Strath Fionan Banded Semipelite Formation in the Allt Strath Fionan (transect B–B′, NN 7424 5634–7432 5631) are typical of the usual, rather friable, slightly rusty-weathering, muscovitic, interbedded pelite and semipelite in this formation. Four metres of schistose metacarbonate rock mark the transitional junction of the pelite with the succeeding metalimestone in the steep south bank of the burn. These exposures comprise the type section. Typical lithologies can also be seen along the roadside to the west, as far as the junction with quartzite described above at NN 7275 5656. Bedding is usually a prominent feature on a 10–100 mm scale and broken or cut specimens reveal a wealth of sedimentary structures, in particular channelled cross-laminations and small-scale grading. Sedimentary structures consistently indicate younging to the south. Biotite, but not garnet, is usually evident.

The southern end of transect B–B′ provides an almost continuous section from the Strath Fionan Banded Semipelite Formation, through the Strath Fionan Pale Limestone Formation into the Tullochroisk Semipelite Formation. However, the quality of the exposure is poor and the latter two formations are better seen at the northern end of transect C–C′. This transect (NN 7137 5675–7186 5658) also permits the examination of all the remaining formations of the Appin Group.

The type section for the Strath Fionan Pale Limestone Formation is at prominent crags south of the road at NN 7275 5638. Although the base of the formation is not seen here, the crags expose 20 m of white, almost pure, dolomite-tremolite rock. Bedding can usually be detected as 2–3 mm-spaced slightly quartzose laminae; other beds are conspicuously muscovite rich and phlogopite is a minor constituent. The lower beds (to the east) are noticeably more tremolite rich, some exhibiting rosettes 100 mm across. At the west end of this locality the sharp junction with the overlying Tullochroisk Semipelite is seen. Similar rocks occur at the start of transect C–C′ on the north bank of the burn (NN 7237 5675), although here the rocks are more pelitic.

The Tullochroisk Semipelite Formation is well exposed in the burn draining Lochan an Daim, and its sharp lower boundary is well seen in exposures above the type locality of the Pale Limestone at NN 7275 5638. However, the formation is best seen on or near the line of transect C–C′, (Figure 41). A burn section to the south of the transect (NN 7235 5662–7223 5663), where the outcrop is considerably thickened by F2 folding, is the type section of the lower half of the formation. Here the dominant lithology is a rusty-weathering semipelite with psammitic beds, not unlike the Strath Fionan Banded Semipelite, although the Tullochroisk Semipelite contains a greater proportion of fine-grained psammite than the older formation. It is generally a non-graphitic, but pyritic, muscovite-biotite schist, with fine-grained psammite laminae 1–5 mm thick and quartzose psammite ribs 100–200 mm thick. Small-scale cross-laminations and graded bedding have been observed younging south near the boundary with the underlying Strath Fionan Pale Limestone.

The upper half of the formation has its type section on the line of transect C–C′, where the upper junction is well seen.

Lithologies in the upper half of the formation are distinctly more-graphitic than those typical of the lower half, and locally they are as graphitic as the pelites of the overlying Blair Atholl Dark Limestone and Dark Schist Formation. They commonly contain small garnet, staurolite and kyanite crystals, but are characterized by large (*c.* 5 mm) biotite porphyroblasts. Fine-grained psammitic laminations (2–3 mm) and ribs of coarser grained psammite (100–200 mm), with rare small-scale grading, are usually evident. This change of character defining the upper part of the formation is marked by a gully between NN 7226 5656 and NN 7220 5663, and by a grey metalimestone (maximum thickness 8 m) to the east, between NN 7235 5646 and NN 7278 5636. The junction with the first grey metalimestone of the Blair Atholl Dark Limestone and Dark Schist Formation, marking the start of the Blair Atholl Subgroup, is seen on, and to the north-west of, the line of transect at NN 7186 5660, followed by excellent exposures of the complete Blair Atholl Subgroup (Figure 41). It is also especially well seen to the west and south of Lochan an Daimh (Figure 43).

Immediately to the south of transect C–C′, there is a very clear repetition of the formations of the Blair Atholl Subgroup about a major antiformal core, enclosing the Schiehallion Boulder Bed of the Islay Subgroup. This is the Balliemore Antiform of Bailey and McCallien (1937), a major fold of F2 age according to Treagus (1987). Minor folds, sympathetic to this major closure, verging to the south, plunging to the east and associated with an intensely developed crenulation cleavage, can be observed in most of the lithologies described above.

17.3 Interpretation

The sequence exposed in Strath Fionan is a continuous stratigraphical succession from the uppermost formation of the Grampian Group through the Lochaber and Ballachulish subgroups of the Appin Group. The boundaries between formations are usually transitional and sedimentary structures show consistent upward younging; there is no evidence for major repetition by folding nor of dislocation. However, the formations of the lower part of the Appin Group, from the Dunalastair Semipelite through to the Meall Dubh Striped Pelite do show, from the intensity of folding and of schistosity and the absence of sedimentary structures, that these rocks have suffered high strain. This interpretation (Treagus and King, 1978; Treagus, 1987, 2000) contradicts previous interpretations (Bailey and McCallien, 1937; Rast, 1958) that this is a folded sequence of formations now assigned to the Blair Atholl Subgroup and the lower Argyll Group, and that the contact with the Grampian Group is a ‘slide’.

The present interpretation is supported by the clear correlation that may be made between this succession, albeit in a very condensed sequence, and the Lochaber and Ballachulish subgroups of the Appin Group in the type area (Figure 2). The latter succession, which contains thicker and more-fully developed correlatives of all of the formations seen in Strath Fionan, is illustrated by the GCR sites in the Loch Leven area (*River Leven*, *Nathrach*, *Rubha Cladaich*, *St John’s Church*, *Onich*) and Appin area

(*Ardsheal Peninsula* and *Lismore Island*) discussed elsewhere in this paper. Of particular significance in making this correlation is the clear similarity of the Meall Dubh Quartzite with the Appin Quartzite of the type area and, in its pebbly nature, its total dissimilarity with the Schiehallion Quartzite, with which it had been previously correlated.

Two other aspects of this GCR site are important in the context of the interpretation of the Grampian Fold-belt. Firstly, in general the site has an unusual wealth of porphyroblastic metamorphic minerals, including biotite, garnet, staurolite, amphibole, epidote and feldspar. In particular, the spectacular kyanite of the Meall Dubh Graphitic Schist was used in a study by Wells and Richardson (1979) to determine that the Dalradian of the Central Grampian Highlands has been buried to a depth of some 30 km.

Secondly, the wealth of minor structures (folds, cleavages and lineations) in the site has allowed it to be shown that the rocks have undergone four distinct episodes of deformation (Treagus, 1987). The dominant set of minor structures, which can be confidently correlated with the regional D2, show from their consistent southerly vergence that the succession described lies on the northern limb of a major antiform. This is the regional Balliemore Antiform, the axial trace of which lies immediately to the south of the GCR site and is the complementary fold to the Meall Reamhar Synform described in the *Creag nan Caisean–Meall Reamhar* GCR site report (Treagus, 1987, 2000).

17.4 Conclusions

The Strath Fionan GCR site is of national importance in demonstrating the continuity of sedimentation between two of the major groups, the Grampian and the Appin, of the Dalradian Supergroup. Of particular importance is the unusual preservation of sedimentary structures in such strongly deformed rocks. The continuity of both the stratigraphical succession and of the structural history across the Grampian–Appin group boundary precludes this junction being interpreted as a major tectonic unconformity. A comparison can be made in this respect with the *River Leven* and *River* Orchy GCR sites, where the same conclusion has been reached. Neither is there convincing evidence for the presence of a major low-angled ductile dislocation, the Boundary Slide, which had been suggested by earlier researchers because of the high strain exhibited by units in the lower part of the Appin Group succession.

The site is critical to the reconstruction of the Dalradian sedimentary basin, particularly in the comparison of the very thin succession here with the much thicker equivalent sequences seen in other GCR sites in the Central Grampian Highlands (in the Loch Leven and Appin areas), as well as with those on Islay and on the Garvellach Islands in the South-west Grampian Highlands and with GCR sites in the North-east Grampian Highlands. The site reveals a quite exceptional development of minor-scale structural features which, in conjunction with those of other nearby GCR sites, help to demonstrate the presence of the major structures that make up the Grampian Fold-belt. Minerals that grew during metamorphism are also unusually visible to the naked eye in many of the rocks in the GCR site. The geochemical analysis of the mineral kyanite from this site has been of key importance in establishing the great depth of burial that this part of the Grampian Terrane has undergone.

18 TEMPAR BURN (NN 691 575–NN 696 562)

J.E. Treagus

18.1 Introduction

This GCR site, off the Kinloch Rannoch road on the south side of Strath Tummel, includes part of the Tempar Burn and exposures along an adjacent track that together comprise one of the classic sections through the Schiehallion Boulder Bed Formation (the local equivalent of the Port Askaig Tillite Formation), at the base of the Argyll Group (Table 1). The particular interest of this formation is that it is interpreted as having been deposited from a grounded ice-sheet, which carried material on to a shallow continental shelf. The tillite generally consists of a gritty matrix, in which are scattered clasts of various underlying rock types a few centimetres in length. Most spectacularly, in the upper half, are boulders of pink granite up to 30 cm across. The site also includes a section through the Schiehallion Quartzite (the equivalent of the Jura Quartzite), which originated as shelf sands above the tillite, and through a metaconglomerate of reworked tillite. The Schiehallion Boulder Bed Formation is possibly the most important 'marker' horizon that has enabled stratigraphical correlation within the Dalradian outcrop from the west of Ireland to Banffshire. It has also been a key horizon in the correlation of the Dalradian with Neoproterozoic successions in Greenland and Scandanavia.

Although this section through the formation was first described by Bailey (1917) and was correlated by him with the Port Askaig 'Conglomerate' of Islay, it was Anderson (1923) who first discussed the arguments for its glacial origin. The formation has also been described by Treagus (2000). Together with the classic localities of the Port Askaig Tillite (see the *Caol Isla* and *Garvellach Isles* GCR site reports), the site has attracted wide international interest in the ongoing investigations and debate on the evidence for and implications of Neoproterozoic glaciations.

18.2 Description

The Schiehallion Boulder Bed Formation, where most fully developed and exposed as in this section, may be divided into a sequence of lower calcareous metadiamictites with dominantly calcareous clasts and an upper sequence of quartz-rich metadiamictites with a mixture of clast-types, including distinctive pink granitic rocks. The two metadiamictite sequences are generally separated by discontinuous units of quartzite (Figure 44). Exposures and loose material immediately south of East Tempar Farm (at NN 691 575) and along the track to NN 696 564, are especially good and accessible, illustrating both calcareous and granitic metadiamictites, as well as the intervening quartzites (Figure 44). Further exposures are seen in the tributary of the Tempar Burn downstream of where it crosses the track at NN 6958 5628.

The sequence of the lower calcareous metadiamictites, up to 50 m thick, is best seen 100 m east of the sheep dip (NN 6938 5737) and 100 m east of the track at NN 6954 5705. Exposures of the tremolitic and dolomitic metalimestone that underlies the tillite (the Drumchastle Pale Limestone, equivalent to the Islay Limestone of Islay) can be seen in the grassy hollow some 20 m to the north-east of these exposures, but the contact is not seen. Individual metadiamictites are separated by beds of schistose calcareous rock free of clasts; bedding is not otherwise observed, except for rare thin (0.5–12 mm) beds of cream-coloured schistose dolomitic metalimestone, and tremolitic psammite.

The matrix of these lower metadiamictites is a schistose calcareous (dolomitic) rock, locally rich in amphibole (radiating blades of white tremolite or pale green actinolite and large hornblende porphyroblasts) and generally rich in a phlogopitic biotite. The matrix, commonly weathering to a rusty-brown, characteristically shows a regular network of depressions, owing to small patches of carbonate minerals, which are possibly small clasts. According to Bailey and McCallien (1937) 'lime-rich' scapolite and diopside occur locally in the matrix. The dominant clasts in the lower metadiamictites are 1–20 cm diameter, disc-shaped fragments of schistose dolomitic limestone or limestone, elongate parallel to the schistosity. Although commonly completely weathered out, vestiges of the clasts can be seen at the rims of the holes. Biotite-muscovite semipelite clasts, which are less common, are very elongate and up to 20 cm in length, and the rarer quartzite and granitic clasts, are up to 25 cm long but less elongate (ratios of 2:1 or 3:1) and more angular; these clasts become more common upwards.

Two discontinuous units of quartzite, each up to 50 m thick and occurring at slightly different levels, are seen east of the track around NN 6945 5709 and NN 6963 5678. These quartzites are not as clean as the Schiehallion Quartzite above, being sugary and feldspathic; they are generally massively bedded and locally they are strongly schistose. Although bedding-plane laminations have been observed, cross-stratification has not been widely detected.

The younger part of the Schiehallion Boulder Bed Formation, up to 70 m thick, is best seen on both sides of the track above the small burn that crosses at NN 6956 5672); exposure is particularly good around NN 696 565 (Figure 45). Clasts of grey or pink granite and microgranite are the most common, followed by pink and white quartzite, biotite-muscovite semipelite, and dolomitic limestone (least common). The pink granite is the 'nordmarkite 'of Bailey and McCallien (1937). Clasts are rarely in contact and spacing appears to be random. Within the clast-rich metadiamictites, the proportion of the rock composed of clasts (greater than 5 mm in length) varies from 70% to zero. Some beds, up to several metres thick, are free of obvious clasts (greater than 5 mm in length) but still have the gritty, feldspathic texture of the metadiamictite matrix. The maximum length of clasts, which might be somewhat flattened in the schistosity, is 0.5–30 cm. The more-rare biotite-muscovite semipelite and dolomitic limestone clasts are the smallest, the most strongly deformed (flattened) and consequently appear to be more rounded. The more-common quartzite and microgranite clasts seldom exceed 10 cm, but might display very irregular, angular and non-flattened shapes; the clasts of the granite are typically the largest and display similar variations. Clasts might show pressure-shadow fringes of quartz, carbonate minerals and mica. As with the lower metadiamictites, there is no evidence of sorting by size or composition, although some beds that are several metres thick are clearly free of clasts.

The contact with the Schiehallion Quartzite is not exposed, but evidence elsewhere in the district shows that it is sharp (Treagus, 2000). A thin bed of metadiamictite with reworked granitic clasts is present near the base of the quartzite in the East Tempar track exposures at NN 6953 5631. Clean exposures of the lower part of the Schiehallion Quartzite are exposed in the Tempar Burn downstream of the tributary at NN 6942 5643; scattered clasts of granite and quartzite are present and of particular interest is a 30 m-thick metaconglomerate that is well exposed in the burn at NN 6935 5654. The quartzitic matrix of the metaconglomerate is very similar to the Schiehallion Quartzite itself, but with a somewhat more-gritty appearance. The rock types and sizes of the clasts are much as in the metadiamictites, described above, but they are more-obviously rounded and locally they are in contact with one another. Clasts of grey or pink granite and microgranite are the most common, together with pink and white quartzite, biotite-muscovite semipelite and carbonate rocks.

The metaconglomerates have great potential for both sedimentological and strain studies. Where measured, in the Tempar Burn section, the proportion of clasts to matrix is very variable over a few square metres, from 1% with isolated single clasts, usually granite, to approximately 70%, with crowded clasts of a mixture of rock types. The clasts are deformed into disc shapes within the dominant cleavage, which is very close to the bedding; observation of shape is difficult, but most clasts display approximately circular sections. Deformation appears to be more pronounced than in the metadiamictites; measured on surfaces perpendicular to the bedding, granite clast length:width ratios, range between 10.4:1 and 2.1:1, but are commonly about 5:1 and longest dimensions ranged from 2 to 47 cm. Semipelite clast ratios are from 5 to 13:1, and sizes range from 3 to 18 cm.

Downstream, after a further few metres of quartzite, the burn and banks provide excellent exposure of the Tempar Dolomitic Member, the probable equivalent of the Bonahaven Dolomite of Islay.

18.3 Interpretation

Subsequent to Bailey's (1917) correlation of the Schiehallion Boulder Bed with the Port Askaig 'Conglomerate', Anderson (1923) discussed the arguments for its glacial origin. He pointed out that the uniform, unbedded nature of the matrix and the haphazard arrangement of the clasts strongly suggest an origin as a till. He noted the similarity of the carbonate-rock and the quartzite clasts to the underlying 'Pale Limestone' and 'Banded Group' formations respectively (now the Drumchastle Pale Limestone and Cnoc an Fhithich Banded Semipelite formations of Treagus, 2000), which are exposed to the east of the GCR site. He used this correlation to demonstrate the order of superposition. He further pointed out that the granitic ('nordmarkite') clasts have no likely local source in Britain and must be far travelled. He noted that the base of the Schiehallion Quartite closely approaches the 'Blair Atholl grey limestone' (now the upper calcitic metalimestone of the Blair Atholl Dark Schist and Dark Limestone Formation) in the north of the district, but accepted the possibility that this might be due to either erosion of the sub-quartzite surface, or to later tectonic movements. He noted that the presence of amphibolite clasts suggests a period of igneous activity that pre-dated the diamictites. The present investigation, however, has failed to reveal clasts of true amphibolite, as against green-amphibole (actinolite)-bearing mica-schist.

More-recent discussion concerning the depositional environment of the diamictites in general has concentrated on evidence from the superior exposures of the Garvellach Islands and Islay, e.g. Kilburn *et al.* (1965), Spencer (1971, 1981, 1985), Eyles and Eyles (1983), Eyles (1988). These authors considered that the diamictites represent a major glacial event of global extent and that they may be correlated with the Varanger tillites of Scandanavia and East Greenland (but see Stephenson et al., 2013a for more-recently suggested correlations with other global glacial events). It is generally accepted that the geographically extensive, though discontinuous, distribution of the deposits in the British Isles favours a glacial origin, as opposed to sedimentary slide deposits of a more-local character. The general evidence, throughout their outcrop in the Dalradian, of the mixture of locally derived and exotic clasts, the random distribution and size of the clasts, the lack of bedding within the ill-sorted matrix, the record of dropstone structure and the particular evidence of other glacially-related structures in the South-west Grampian Highlands, makes the glacial origin indisputable.

In the Schiehallion district, the massive nature of the diamictites, their inclusion of stratified, sorted sands, and the subrounded shape of some clasts, supports the interpretation of a marginal glaciomarine environment (Edwards, in Reading, 1986). The local thinning and probable absence of the formation from some areas and the inclusion of clasts of at least two of the preceding formations in the lower diamictites, strongly suggests an unconformable base. The distinctive sedimentary structures attributed to tillites and present in some exposures of the Port Askaig Tillite (see the *Caol Isla* and *Garvellach Isles* GCR site reports) have not been observed at this GCR site. Possible dropstone structures have been recorded, but it is difficult to exclude the effect of the strong tectonic deformation. The clasts show no evidence of having been sorted or of having had their distribution controlled by water movement.

There are two beds of metaconglomerate, within the Schiehallion Quartzite, that have clasts of identical lithologies to those in the metadiamictites (Anderson, 1923; Treagus, 2000). The significant difference between the metaconglomerates and the metadiamictites is that there appears to be a more strongly bimodal size distribution in the metaconglomerates, such that the intermediate 1–5 cm sizes are missing; in addition the clasts are less dispersed, although rarely in contact, and they are significantly more rounded. This supports the interpretation of Anderson (1923) that these rocks represent reworked diamictite material derived by fluviatile or marine erosion.

18.4 Conclusions

The Tempar Burn GCR site is of international importance for its clear exposures of a Neoproterozoic glacial deposit. The 'boulder beds' (metadiamictites) that make up the Schiehallion Boulder Bed Formation are composed of blocks and pebbles up to almost a metre across, sitting isolated in a matrix that was originally sand and silt. The blocks and pebbles can only have been dropped from floating ice. They include a wide range of rock types, including some derived locally from underlying formations, but particularly significant, are the commonly occurring 'stones' of a type of granite that does not crop out in Britain and therefore might have been carried a great distance across an ocean. The GCR site is thus of great importance for the light it sheds upon climate and sedimentary processes in the late Precambrian, but it is also celebrated for its significance in the correlation of Dalradian formations across the British Isles, as well as with possibly equivalent deposits in Greenland and Scandinavia. Studies of the deformed shapes of the 'stones' are important for estimating the strains that the Dalradian rocks were subjected to during the Caledonian Orogeny.

19 ALLT DRUIDHE
(NN 6422 5723–NN 6423 5662)

J.E. Treagus

19.1 Introduction

The lower part of the Allt Druidhe, which drains into Loch Rannoch 3 km south-west of Kinloch Rannoch, has been selected as offering the best section across the Boundary Slide, the most important synmetamorphic high-strain zone and dislocation to affect the Dalradian rocks of Scotland. The Boundary Slide is known to extend for at least 90 km from the Dalmally district (see the *Ben Oss* GCR site report) to the Schiehallion district, although demonstrable dislocation and excision of strata decrease towards the north-east (see the *Strath Fionan* GCR site report). If proposed correlations with similar structures are correct (e.g. the Benderloch and Ballachulish slides; see the *Camas Nathais* and *St John's Church* GCR site reports; Roberts and Treagus, 1977c) the dislocation can probably be traced for most of the length of the Scottish Dalradian outcrop from the Appin district in the south-west to the North-east

Grampian Highlands (see the *Bridge of Brown* GCR site report in Stephenson et al., 2013b).

In its outcrop between Dalmally and Loch Errochty (9 km north-east of this GCR site), the slide marks a hiatus in the Dalradian stratigraphical succession (Table 1), juxtaposing Grampian Group psammites below, against quartzites, semipelites and pelites of the Argyll Group above. It is only in the area south and east of Loch Errochty that members of the missing Appin Group gradually appear between the other two groups, until the complete succession is restored locally in Strath Fionan (Roberts and Treagus, 1977c; Treagus, 1987, 2000).

The slide was first recognized in the Schiehallion area, to the north-east of this GCR site, by Anderson (1923) and its outcrop was mapped throughout the district by Bailey and McCallien (1937). Its origin was discussed further by Rast (1958) and Treagus (1987, 2000). The present account is based on the mapping and descriptions of P.A.R. Nell (BGS 1:10 000 Sheet NN65NW, and in Treagus, 2000).

19.2 Description

The description below is taken principally from the almost continuous exposures in the Allt Druidhe (NN 6419 5731 to 6420 5604), complemented by information from the hillside on its two sides, especially that towards Meall Druidhe to the west.

From NN 6419 5731 to NN 6421 5713, the course of the burn is controlled by a steep NNW-trending fault with SE-dipping Grampian Group psammites exposed on its two sides (Figure 46). Bedding on a 1 to 30 cm scale is evident; cross-sets are also seen, but way-up has not been determined. At NN 6421 5713, south of a prominent microdiorite dyke, the psammites become more schistose and flaggy and are seen for a further 100 m as far as NN 6421 5704, where the fault crosses the bed of the burn. The psammites are succeeded, as far as NN 6423 5690, by a sequence of pink and white quartzites, interbedded with platy psammites and semipelites containing a highly muscovitic pelite; several concordant sheets of microdiorite cut these beds. In the lower part of this sequence, the lowest pink, feldspathic quartzite can be correlated clearly with the Dunalastair Quartzite, the lowest formation of the Lochaber Subgroup, and the highly muscovitic pelite is correlated with the Beoil Schist. Striped biotite-muscovite psammites and semipelites below and above the Beoil Schist must represent the Dunalastair Semipelite and Meall Dubh Striped Pelite formations respectively, both of the Lochaber Subgroup. Above these units, a few centimetres of graphitic kyanite schist, an upper 15 m-thick unit of pebbly quartzite and a 50 m-thick unit of banded semipelite and pelite can be equated with the Meall Dubh Graphitic Schist, the Meall Dubh Quartzite and the Strath Fionan Banded Semipelite formations, respectively, of the Ballachulish Subgroup as seen in the *Strath Fionan* GCR site. The Meall Dubh Limestone Formation is not represented.

At NN 6421 5704, the Strath Fionan Banded Semipelite Formation (Ballachulish Subgroup) is in contact with strongly deformed and boudinaged strata that can be assigned to the Easdale Subgroup of the Argyll Group, thereby marking a major dislocation and excision of strata. Some 40 m of strongly deformed, schistose, rusty-coloured, feldspathic quartzite with thin interbeds of amphibolite (equivalent to the Carn Mairg Quartzite), followed by a few metres of graphitic schist (equivalent to the Ben Eagach Schist) are followed by a major sequence of calcareous schist, calcareous quartzites and interbedded amphibolites. The latter sequence can be traced laterally, to the north and south into outcrops of certain Ben Lawers Schist Formation (see, for example, the *Slatich* GCR site report). Above the Ben Lawers Schist outcrop, at NN 6421 5638, are 10 m of graphitic schist (better seen on the hillside to the north-east) followed by a major unit of schistose pebbly quartzite, a repetition of the Ben Eagach Schist and Carn Mairg Quartzite formations.

From the uppermost psammites of the Grampian Group southwards, throughout the section, a 30–40° SE-dipping, penetrative schistosity, is parallel to bedding where the latter is visible. The schistosity planes in the amphibolites and the pebbly quartzites exhibit a strong lineation of hornblende and of the pebbles, generally pitching at a high angle (over 50°) to the south-west. Amphibolite boudins, intersection lineations and rare isoclinal fold hinges pitch with the same general reclined attitude.

The Lochaber Subgroup formations in particular are cut by fault-planes, usually associated with brecciation, dipping at lower angles to the south-east than the schistosity and pre-dating the microdiorite sheets.

19.3 Interpretation

The Boundary Slide occurs here on the short common limb of the regional Meall Reamhar Synform–Balliemore Antiform F2 fold-pair, the latter being represented at the GCR site by the repetition of the Ben Eagach Schist and Carn Mairg Quartzite about the Ben Lawers Schist in the fold core. The penetrative schistosity at the site (the regional S2) is essentially parallel to bedding but can be demonstrated to be axial planar to the fold-pair elsewhere (e.g. in the *Strath Fionan* GCR site).

No measurement of the scale of displacement on the slide is possible, nor have directional movement indicators been identified. The apparent parallelism of the intersection lineations, the fold-hinges and the extension direction is attributed to the high strains in the slide-zone. The locally strong pebble and hornblende stretching lineations, pitching steeply to the south-west on the S2 schistosity planes, give an indication of the intensity of the strain, as do the common boudinage axes pitching in the same direction. These features together suggest strong flattening strains in the slide-zone with a finite extension direction pitching steeply to the south-west on the schistosity.

Some of the telescoping of the stratigraphical succession of the Appin Group at the GCR site is considered to be the result of small movements (metre-scale) on the low-angle SE-dipping faults, which cut down section. Evidence in similar sections to that seen at the GCR site, between Loch Rannoch and Loch Errochty, suggest that such thrusts are numerous in the slide-zone and are commonly occupied by the later, slightly discordant, microdiorite sheets.

There can be little doubt concerning the stratigraphical assignations given above for the formations of the Appin Group, as the formations can be traced north-eastwards into the type formations of the Loch Errochty and Strath Fionan areas (Treagus, 2000). Similarly, the formations belonging to the Argyll Group can be traced southwards into type areas in Glen Lyon. Thus it is clear that a major hiatus exists between the Strath Fionan Banded Semipelite and the Carn Mairg Quartzite formations, in this highly strained sequence. The missing formations include the metalimestones and graphitic semipelites of the upper Appin Group, together with the Schiehallion Boulder Bed, the Schiehallion Quartzite and Killiecrankie Schist of the Argyll Group, certainly representing several hundred metres thickness of the type stratigraphical succession seen in the *Strath Fionan* GCR site and to the south of Schiehallion. In addition to this major hiatus, it is considered that the whole section from the top of the Grampian Group into at least the lower part of the Ben Lawers Schist represents a zone of high strain, in which there are probably many planes of discrete movement.

From consideration of evidence along the Boundary Slide-zone elsewhere in the Schiehallion area (Treagus, 1987, 2000), it is clear that the stratigraphical hiatus can be explained, at least in part as a result of top-to-the-NW thrust-like movements during the regional D2 deformation. However, this does not exclude the possibility of movements contemporary with the D1 deformation, which have been identified elsewhere in the Schiehallion area.

It is not clear to what extent any, or indeed all, of the hiatus can be attributed to sedimentological causes. Treagus (2000) provided evidence, from elsewhere in the Schiehallion district, that some substantial thinning of parts of the succession is an original sedimentary variation and suggested that such parts were preferentially thinned tectonically. Soper and Anderton (1984) have suggested that movements on some Dalradian slides might have originated as low-angle normal faults during sedimentation, and Anderson (1923) most-perceptively considered the possibility that the hiatus could represent an original normal fault, later subjected to intense shear. Both Anderson (1923) and Bailey and McCallien (1937) considered, but rejected, the idea that the slide might have originated as an unconformity and essentially favoured the explanation of a synmetamorphic dislocation, as presented here. Further research at this GCR site could well help to resolve these matters.

19.4 Conclusions

The Allt Druidhe GCR site provides a rare opportunity to observe the zone of rocks that contains the Boundary Slide, a high-strain zone critically important in the development of the structure of the Dalradian and contemporary with folding and metamorphism. It can be demonstrated within this GCR site that there is a major gap here in the normal stratigraphical succession, with several hundreds of metres of rocks missing. It is likely that there are many discrete dislocations within a zone of strongly deformed rocks. The evidence for this high strain is in the unusual nature of the small-scale structures seen in the section. It is considered possible that some of the movements on the slide might be associated with early faulting and changes of thickness during the deposition of the sediments, a hypothesis that could be tested by further work in the area of this GCR site.

20 SLATICH (NN 632 477–NN 641 486)

J.E. Treagus

20.1 Introduction

The Slatich GCR site, on the low slopes of middle Glen Lyon, provides exceptional exposures across the hinge-zone of a major F2 antiform. It also exhibits minor structures of both the preceding D1 phase and the succeeding D3 phase. These exposures also give a rare, accessible section across three formations of the Argyll Group, from the calcareous schists of the Ben Lawers Schist Formation up through the Farragon Volcanic Formation into the kyanite-garnet schists of the Ben Lui Schist Formation (Table 1).

The major F2 fold, the Ruskich Antiform, is the correlative of the Ben Lui Fold of the South-west Grampian Highlands, one of the major structures of the Grampian fold-belt. This correlation was first made by Bailey and McCallien (1937) and observations of the minor structures and development of the major structural context have been made by Nell (1984) and by Treagus (1987, 1999).

20.2 Description

The Ruskich Antiform in the area of the GCR site is represented by the zig-zag outcrop pattern of three formations of the Argyll Group, which define its hinge-zone (Figure 47).

The Ben Lui Schist can be characterized generally as a semipelitic garnet-quartz-mica schist, alternating with pelites and psammites on scales from centimetres to several metres. The formation is typically garnetiferous but, unusually for the area, also contains local kyanite, best seen in crags around NN 635 480, north of Slatich. The Farragon Volcanic Formation is well exposed in the crags above and east of Slatich around NN 640 477, where it comprises a delicately striped, centimetre-scale, alternation of amphibolite and quartzite. A good section of the Ben Lawers Schist is seen above Roromore, where virtually the whole formation may be examined in a small burn from NN 6385 4686 to NN 6404 4642; it is typically a chloritic calcareous schist with a hundred metres or so of dolomitic quartzite at its base, and with concordant amphibolites above. This section allows the junctions with the Farragon Formation below and the Ben Eagach Schist above to be seen.

The principal interest of the site is in the closure of the Farragon Volcanic Formation around the Ben Lui Schist in the core of the Ruskich Antiform (NN 640 487). In the south of Figure 47, around NN 638 468, the regional dip of this boundary is 40° to the south-east; farther north, the same boundary on the opposite limb, around NN 634 484, has a regional dip of 60° to the south; the major hinge plunges almost due east at 30°. Minor structures (minor folds and bedding/schistosity relationships) with opposed vergence on the two limbs, sympathetic to the major antiform, can be seen at these two localities.

The limb south-east of the hinge is considerably corrugated by co-axial intermediate-scale folds (tens of metres limb length), which are well exposed on the hillside north-east of Slatich, around NN 640 477. Some of these folds are sympathetic to the major antiform but other intermediate-scale folds, with upright axial planes and a crenulation cleavage, are superimposed. This locality therefore offers the opportunity to examine three generations of minor folds–F1, F2 and F4 of the regional phases. Not only are minor, metre-scale, structures of the latest generation (F4) superimposed on the dominant phase of minor folds (F2) (all plunging east), but also rare refolded minor isoclinal folds of the earliest generation (F1) are developed in the finely-bedded quartzites and amphibolites of the Farragon Volcanic Formation (Figure 48).

20.3 Interpretation

The Ruskich Fold was first recognized by Bailey and McCallien (1937) in their perceptive paper on the Schiehallion–Glen Lyon district. They interpreted the fold as a major primary nappe closure below that of the 'Iltay Nappe' (now the Tay Nappe) and thus equivalent to the Ben Lui Fold of the Dalmally district in the South-west Grampian Highlands (Bailey, 1922). However, the fold has been re-interpreted from a subsequent investigation of the associated minor structures by Nell (1984) and Treagus (1987) as a major F2 fold. The dominant penetrative schistosity is axial planar to the abundant minor folds which are sympathetic in vergence to the major fold. This schistosity is associated with the growth of garnet and can be correlated with the S2 fabric, which dominates the pelitic rocks of the South-west and Central Grampian Highlands. Only rare examples of F1 minor folds are seen, such as the isoclinal folds in the finely banded amphibolites of the Farragon Formation, which are clearly refolded by F2 minor folds (Figure 48).

It has been confirmed that the Ruskich Fold has a similar geometry and position in the structural pile to the Ben Lui Fold, which has also now been established as a D2 structure by Roberts and Treagus (1975). Although separated by several major, cross-strike faults (Treagus, 1991) the axial traces of the Ruskich and Ben Lui folds have been correlated on the ground (Roberts and Treagus, 1979). The Ruskich Fold can be shown to have been superimposed on major F1 folds related to the early, F1 Tay Nappe, which can be identified in Glen Lyon to the north of this GCR site (Nell, 1984; Treagus, 1987). The fold is seen as a major component of the zone of D2 complication in the Schiehallion area, which marks the northern limit of the dominantly inverted rocks of the Flat Belt to the south.

A further feature of this GCR site, not seen in the Ben Lui area, is the superimposition on the Ruskich Fold of a later fold-set, both intermediate and small scale, with an associated crenulation cleavage. These structures belong to the regional F4 set, related to the major Ben Lawers Fold to the south (Treagus, 1964b) (see the *Ben Lawers* GCR site report).

20.4 Conclusions

The Slatich GCR site provides a rare example of almost continuous exposure across the hinge-zone of a major fold, the Ruskich Antiform. The fold hinge can be traced from the detailed mapping of three of the principal formations of the Argyll Group in easily accessible exposures on either side of Glen Lyon. Observations of small-scale folds and cleavages have revealed that the major fold belongs to the second (D2) phase of the four important episodes of deformation that affect the Dalradian rocks. Unusually, small-scale folds of the first generation (F1) can also be identified, clearly pre-dating those of the second generation. The second-generation folds themselves have small-scale structures of a still later generation (the regional F4 phase) superimposed upon them. Thus the small-scale structures can be used not only to establish the sequence of deformation events but also to identify the relative age of a major fold. The Ruskich Antiform is equated with the Ben Lui Fold of the Dalmally area (see the *Ben Oss* GCR site report), and can be followed for several tens of kilometres across the Central Grampian Highlands. It is one of the most significant structures involved in the building of the Grampian Fold Belt.

21 BEN LAWERS
(NN 621 368–NN 595 415)

J.E. Treagus

21.1 Introduction

This GCR site, on the western and southern flanks of the Ben Lawers mountain range, illustrates typical structures within the inverted limb of the Tay Nappe, the major fold that dominates the structure of the south-eastern Grampian Terrane. It also contains the type locality of one of the major post-nappe folds, the F4 Ben Lawers Synform. In addition to the structure, the exposures described within this very large GCR site, have been selected to illustrate the stratigraphy of the four highest formations of the Argyll Group in the Central Grampian Highlands.

The regional inversion of the succession on the lower limb of a major fold has long been established (the Iltay Nappe of Bailey, 1922 or the Tay Nappe of Shackleton, 1958). The details of the local structure, particularly that of the Ben Lawers Synform, have been studied by Elles (1926), Elles and Tilley (1930), Treagus (1964b) and Nell (1984). The site, which belongs to the National Trust for Scotland and is famous for its plants and wildlife, has a visitor centre that is much visited by the general public who would benefit from the availability of more geological information.

21.2 Description

The localities are described from south to north, up the southern slopes of Ben Lawers which, as the succession is inverted, means that the descriptions progress approximately from the youngest to the oldest formations (Figure 49). Three phases of deformation can be discerned in these rocks, designated D1, D2 and D4 in the descriptions below; the attribution to these regional phases is justified in the subsequent 'Interpretation'.

The youngest formation represented, the Loch Tay Limestone of the Tayvallich Subgroup, is seen in the small quarry at NN 6212 3678 (Figure 49, locality 1). The dip of the beds (some 30° to the north-west) in the semipelite laminae in the limestone is typical of the regional dip on the south limb of the F4 Ben Lawers Synform. A gently NE-plunging lineation (e.g. 10° to 025°) results from the intersection of bedding and a nearly bedding-parallel schistosity (S2), dipping less steeply to the north-west, and from the hinges of rare NW-verging isoclinal F2 folds. Pelites within the limestone show a steep NW-dipping S4 crenulation cleavage.

A well-exposed section from the next oldest formation, the Ben Lui Schist of the Crinan Subgroup, through the Farragon Volcanic Formation and into the Ben Lawers Schist of the Easdale Subgroup, is seen in the Burn of Edramucky from NN 6184 3725 to NN 6125 3910 (locality 2). In the Ben Lui Schist, below and above the road at NN 6145 3756, the quartz-rich, garnetiferous, locally graphitic, interbedded semipelites and pelites show structural features similiar to those described above for the Loch Tay Limestone. NW-verging folds are well developed, with a penetrative axial-planar S2 schistosity and with plunges at low angles varying in trend from 050–020°. Going up the burn section, the north-north-west dip of the bedding gradually increases to about 50° at the Farragon Volcanic Formation junction (NN 6125 3910), and the F2 folds are more-constantly ESE-trending, with a northerly vergence. The latter formation, comprising finely interbedded semipelites and amphibolites, is exposed in the river gorge and is transitional northwards into the quartzites and calcareous schists of the Ben Lawers Schist. The Farragon Formation here contains small, NW-verging, tight F2 folds which refold earlier F1 isoclines.

The Ben Lawers Schist is not well exposed in the burn and the rocks at this structural level are better seen in the road section at NN 601 390 (locality 3), described in detail by Treagus (1964b). Here, upright metre-scale folds, associated with a well-developed ENE-trending S4 crenulation cleavage, are seen to refold north-verging, tight F2 folds, related to a subpenetrative schistosity (Figure 50). The earlier folds, which here trend between west-north-west and north-west, themselves fold an earlier S1 schistosity and a mineral (quartz-chlorite) lineation with a more north-north-westerly trend. F1 isoclines with a north-west to west trend and northerly vergence are seen rarely and appear to be associated with the earliest schistosity and mineral lineation. The upright F4 folds have an enveloping surface that defines a gentle northerly dip of the major fold limb, near to the axial zone of the Ben Lawers Synform. Farther north, near the road on the east side of Lochan nan Lairige at about NN 600 406, and on the hillside above, the same generation of F4 folds are seen to have a neutral vergence in the hinge-zone of the Ben Lawers Synform. The hinge-zone is very well seen looking across the lochan to the cliff section on its west side in which the bedding and the upright S4 cleavage are apparent on a grand scale.

The Ben Lawers Schist is not well seen on the north limb of the Ben Lawers Synform but at the tunnel portal at the north end of the lochan (NN 5953 4115; locality 4), the Farragon Volcanic Formation is exposed, with bedding here dipping at a low angle to the south. Many loose specimens provide examples of tight F2 folds that rarely show refolded F1 isoclines, subparallel to a strong hornblende lineation.

Within the Ben Lawers Schist on the north limb of the Ben Lawers Synform, there is an isoclinal infold of schistose graphitic pelite, assigned to the Ben Eagach Schist Formation; this is exposed on the north flank of Meall Corranaich. In the core of the fold, the graphitic pelites are transitional into schistose pebbly quartzites of the Carn Mairg Quartzite Formation. The two limbs of this fold, both dipping at moderate angles to the south-east, are exposed in a burn between NN 624 433 and NN 633 428 and in two burns to the south-west (NN 624 426, north limb and NN 625 416, south limb) (locality 5). In these exposures, the plunge of the tight F2 fold-set is at moderate angles (10–40°) to the east-south-east, with vergence both of the folds and of the axial-planar schistosity/bedding intersection consistently to the north; these folds are overprinted by the upright S4 crenulation cleavage. The infold must of D1 age, pre-dating the D2 and D4 deformation phases.

21.3 Interpretation

The exposures described in this GCR site have long been acknowledged to lie on the inverted limb of the Tay Nappe, where they are affected by the later Ben Lawers Synform (e.g. Elles and Tilley, 1930; Treagus, 1964b). The dominant north- to NW-verging folds with the penetrative to subpenetrative axial-planar schistosity are of the regional F2 generation, which is considered to be the main phase associated with the generation of the Tay Nappe (Harris *et al.*, 1976). The axial trend of the F2 minor folds and of the S0/S2 intersections, which is N–S in the Flat Belt south of the site, curves progressively through the area of the site from north-north-east in the south through north-east to east and then east-south-east in the north. Further research in the Ben Lawers area might contribute to the understanding of this phenomenon and of the evolution of the Tay Nappe.

The regional D1 phase is represented by the earlier fabric that can be seen to be crenulated by the S2 cleavage planes, and by the small-scale isoclines and mineral lineation in the Ben Lawers Schist and the Farragon Formation. Data are too sparse to state a trend or vergence for these structures, though the mineral lineation appears to have a north-north-west trend, both in the Farragon Formation and in the Ben Lawers Schist, similar to that widely reported elsewhere in the Flat Belt. The major infold of the Ben Eagach Schist and Carn Mairg Quartzite in the Meall Corranaich exposures is overprinted by the D2 structures and thus must also be of D1 age; from its outcrop pattern it has a north-east trend and thus must have been (at the time of D2) an anticline facing south-east. According to Treagus (1987, 2000) these major F1 folds originally faced steeply upwards.

The major fold that affects bedding and S2 within the area of the GCR site is the regionally important F4 Ben Lawers Synform, a gentle deflection of the originally subhorizontal limb of the Tay Nappe. The fold is associated, in all lithologies but particularly within the Ben Lawers Schist, with upright intermediate- and small-scale folds trending east-south-east and their axial-planar crenulation cleavage. The vergence relations of the small-scale folds and of the cleavage across the major fold are particularly clear.

21.4 Conclusions

The Ben Lawers GCR site provides exceptional sections through four of the main formations of the Argyll Group and is of national importance in providing remarkably clear evidence of the total inversion of the sequence in this part of the Central Grampian Highlands, on the lower limb of a major early fold, the Tay Nappe. These upside-down rocks constitute the Flat Belt, which extends south-east across strike for 25 km to the Highland Border and for some 250 km laterally along strike, and dominates the structure of the south-eastern Grampian Terrane. Two generations of minor structures, folds and cleavage planes, related to the D1 and D2 movements that produced the nappe are well displayed.

Within the area of the GCR site another major fold that later folded the inverted rocks, is totally displayed, together with associated minor structures. This F4 fold, the Ben Lawers Synform, is one of the most important late folds in the overall Dalradian structure.

22 CRAIG AN CHANAICH TO FRENICH BURN (NN 811 546–NN 818 545)

J.E. Treagus

22.1 Introduction

The Craig an Chanaich to Frenich Burn GCR site incorporates the principal exposures of a body of stratiform baryte that is unique in the British Isles and in Europe. As well as the unusually pure, bedded baryte, the body also contains rare barium silicate minerals and stratiform sulphides. It has a maximum thickness of 80 m and extends for 7 km to the east of the GCR site along the Meall Tairneachan–Farragon Hill ridge between Strath Tummel and Strath Tay. The baryte occurs within the Ben Eagach Schist Formation of the Easdale Subgroup; it is involved in all three of the regional phases of deformation and the regional metamorphism.

The mineralization was first discovered by the Geological Survey in 1975 during stream-sediment sampling and was described by Coats *et al.* (1978, 1981). It was the subject of a PhD. thesis by Moles (1985a) and was summarized by Hall (1993) and by Pattrick and Treagus (1996). The consensus of this research was that the body is a sedimentary deposit, resulting from the exhalation of metal-laden fluids onto the floor of a deep-sea basin. Other barium enrichments in the Ben Eagach Schist are now known near Braemar at Loch Kander (NO 192 803) and Allt an Loch (NO 196 796) (Gallagher *et al*., 1989) and near Loch Lyon (NN 414 383) (Coats *et al*., 1984). The body has been the subject of extensive underground and surface mining (Foss Mine) from 1984 to the time of writing (1999); the GCR site is largely comprised of the artificial exposures created by this mining activity.

22.2 Description

Natural exposures of the mineral body are generally poor, the most significant occurring on Creag an Chanaich (NN 8122 5457), in the Frenich Burn East (NN 8196 5492) and on Creag an Loch (NN 8267 5504). However, in the area of the GCR site, around Foss Mine, the body has been exposed extensively in opencast workings, along the access road on Creag an Chanaich and around the adits to the underground workings, especially on the north-eastern face of Creag an Chanaich (Figure 51).

The total thickness of the mineral body reaches 80 m, and the maximum thickness of baryte is 15 m. It is hosted by the graphitic muscovite schist of the Ben Eagach Schist Formation and is close to, or at the contact with, the calcareous schist of the overlying Ben Lawers Schist. There are two main mineral horizons, the Upper and Lower horizons. The high-grade Upper Mineral Horizon is characterized by bedded pyritiferous baryte, generally bounded above and below by quartz-celsian (barium feldspar) rock, barium-enriched muscovite schist and sulphide-bearing graphitic schist. Layers of massive sulphide (pyrite, chalcopyrite, sphalerite and galena) are rare but significant components. The thicknesses and relative importance of the mineral lithologies vary considerably along strike and down dip, but the bedded baryte and the quartz-celsian rock are major components and this is one of the largest occurrences of celsian in the world. The description here is confined to the exposures on or near to the mine track at Creag an Chanaich and those in the opencast pits to the east (Figure 53).

The most westerly exposure of the body is seen on the western slope of Creag an Chanaich, where massive baryte of the Upper Mineral Horizon, dipping steeply to the south, is overlain by quartz-celsian rock at NN 8109 5461. On the ridge of Creag an Chanaich, between NN 8114 5459 and NN 8122 5457, the 3.5 m-thick baryte body, containing pyritic layers, is overlain by 1 m of siliceous schist and then by quartz-celsian rock. In this area, 8 m of graphitic schist separate the Upper Mineral Horizon from the Ben Lawers Schist. On the steep, east slope of Creag an Chanaich, the surface trace of the mineral body is controlled by two WSW-plunging regional fold sets; F2 folds, which were originally upright, are here locally recumbent, having been affected by a major F3 fold-pair (Figure 52) that is well seen in the outcrop sub-parallel to the hairpin bends of the mine track, especially between NN 8128 5457 and NN 8131 5453 (Figure 51). One metre of baryte is here enclosed in an envelope of quartz-celsian rock, 2 m thick below and over 3 m thick above, which is affected by a F2 fold-pair (Figure 51). At NN 8135 5453 the baryte and quartz-celsian rock form the core of an F2 antiform. The more-penetrative S2 cleavage, as well as a superimposed well-developed upright S3 crenulation cleavage, is well seen in the schists adjacent to these folds. Within the outcrop of the Ben Eagach Schist in this area is a 3 m-thick, broadly concordant sheet of calcareous hornblende schist (a basic meta-igneous rock), which crosses the track in several places on the hairpin bends.

The mineral body is also well exposed in the western wall of the track, in a disused adit (NN 8135 5455). Here the baryte layer is 4 m thick, massive, white or grey depending on the concentration of pyrite layers and occupies the synformal core of an F2 fold. A 10 cm-thick layer of massive pyrite is present at the stratigraphical base of the baryte, in the north wall of the adit. To the east a further (lower) adit has been driven into the baryte, which is here 3.5 m thick in an envelope of quartz-celsian rock in an F3 antiformal structure. Farther down the track, the Ben Eagach Schist–Ben Lawers Schist contact is exposed (NN 8137 5450). A structural synthesis of these exposures in the mine track is shown in Figure 52.

The Lower Mineral Horizon is also present on Creag an Chanaich, although it thins progressively eastwards (Figure 51). A small outcrop is present on the top of the ridge at NN 8122 5464 and comprises quartz-celsian rock with a sheet of heavily weathered calcareous hornblende schist (basic meta-igneous rock) at the base; the associated scree contains massive baryte. A trench by the track at NN 8124 5463 has exposed 2–3 m of pyritic quartz-celsian rock with 1 m of basic meta-igneous rock at the basal contact; the lithologies are repeated in an F3 fold core and the Ben Eagach Schist is exposed in the southerly end of the trench, in which a flat-lying crenulation cleavage (local S4) can be seen as well as D3 and D2 folds and cleavages. In the most-easterly exposure of the Lower Mineral Horizon, at NN 8133 5457, 30 cm of pyritic quartz-celsian rock and sulphide-rich schist are found; here too the lower contact of the horizon is marked by a 50 cm-thick sheet of basic meta-igneous rock.

The surface trace of the Upper Mineral Horizon is offset by a pair of NNE-trending, left-lateral faults that separate the underground workings from the opencast pits; the area between the faults is occupied by mine buildings and plant (Figure 51). The most easterly fault-plane is exposed in the western end of the opencast workings and contains an altered microdiorite dyke (NN 8144 5446). To the east of the fault, the mineral horizons have been mined in several pits, which are exploiting the thickest, near-surface occurrences of the baryte (Figures 51 and 52). In the south-western part of the opencast workings, exploitation has focussed on baryte rock in the core of a southwards plunging F2 synform. On the southern limb of this synform the Ben Lawers Schist, the muscovitic, graphitic, Ben Eagach Schist and quartz-celsian rock are well exposed in the pit wall; the Ben Eagach Schist is also exposed in the core of the synform at NN 8147 5448 (Figure 53). An F3 antiformal structure causes the baryte and quartz-celsian rock to crop out again to the north at NN 8152 5450. To the east, the outcrop of the Upper Mineral Horizon is complicated by small NE-trending faults and F2/F3 folding and thins rapidly towards the Frenich Burn Fault.

22.3 Interpretation

The mineral body in the area of the GCR site is considered to be a SedEx-type (sedimentary exhalative) deposit (Coats *et al.*, 1980; Willan and Coleman, 1983; Russell *et al.*, 1984; Moles, 1985a; Hall, 1993). It is thought to have resulted from the exhalation of metal-laden mineralizing fluids onto the floor of a marine basin at the time of Easdale Subgroup sedimentation. The baryte formed by the mixing of barium, carried in reduced hydrothermal fluids, with sulphate in the relatively oxidized seawater. Barium also reacted with the aluminosilicate-rich seafloor muds to produce barian clays and cymrite ($BaAl_2Si_2O_8.H_2O$), the precursors to the barian micas and barian feldspar (celsian), the transition taking place during metamorphism, with estimates of a pressure of 6.5 kbar and a temperature of 530°C (Moles, 1985b). The hydrothermal fluid was also the source of the metals for the sulphides and iron oxides but, in contrast to many SedEx deposits, these rarely formed thick accumulations. Exhalative silica precipitated as cherts in the aluminosilicate muds and recrystallized during metamorphism.

The mineral horizons are interpreted as successive exhalative hydrothermal pulses emanating onto the seafloor, the variation in the horizons being a function of both intensity of hydrothermal activity and the distance from exhalative centres. Although two of the horizons are laterally very extensive, occurring along the 2 km strike length in the GCR site area and extending for a further 7 km eastwards, the recognition of exhalative centres within these horizons has not proved possible. To explain the sharp contacts to the massive baryte layers, Russell *et al.* (1984) suggested that the sulphate for the baryte was derived from evaporitic shallow coastal areas which periodically produced flows of dense sulphate-rich brine into the sulphate-poor basin deeps at the time of hydrothermal activity, thus providing an episodic and finite sulphate supply.

The fundamental cause of the mineral influx is considered to be the crustal instability during Argyll Group times that resulted in the break-up of the Dalradian basin into several second-order basins (Coats *et al.*, 1984; Russell *et al.*, 1984; Pattrick and Treagus, 1996, figure 7b). The basic meta-igneous rocks of oceanic affinity in the Farragon Volcanic Formation overlying the Ben Lawers Schist are a product of the continuation of this process as the basins extended and deepened. The thick basic meta-igneous sheets in the mine area that post-date the mineralization are interpreted as sills and are also associated with this process. The crustal extension and thinning that led to the break-up of the basin resulted in a high geothermal gradient and large-scale convection of seawater into the underlying lithologies (to a depth of at least 10 km) where it was heated by interaction with the buried older Dalradian lithologies. This fluid leached metals from the rocks (especially barium from the feldspathic Grampian Group), before rising to the seafloor to form the SedEx deposit. These same conditions prevailed over all of the Dalradian basins at this time and resulted in similar mineralization being developed in the Easdale Subgroup elsewhere.

In terms of the regional structure, the deposit lies on the steep, south-dipping limb of the major upward-facing F1 Creag an h-Iolaire Anticline (Treagus, 2000, figure 14); there is no significant mineral body on the north limb of this fold. F1 minor folds have not been recorded, but the structural relationships between the well-developed minor folds and cleavages of D2 and D3 age (as well as of the local D4) in the area of the GCR site are exceptionally clear. They also clearly reveal the geometry and superimposition of major folds of both D2 and D3 ages (Figure 52).

22.4 Conclusions

The Creag an Chanaich to Frenich Burn GCR site is of international importance in providing excellent exposure of a metamorphosed synsedimentary mineral body, which is unique in British and European geology and has few equals worldwide. The barium sulphate mineral baryte ($BaSO_4$), which forms a large proportion of the body in an unusually pure concentration, has been an important source of drilling mud for oil exploration in the North Sea. In addition it contains concentrations of sulphide minerals, as well as two unusual barium silicate minerals, celsian (barium feldspar) and cymrite (a hydrous aluminosilicate). The latter two minerals have been used to calculate the temperature and pressure (and hence the depth of burial) to which the Dalradian rocks were subjected during the creation of the mountain-belt; and this is one of the largest known ocurrences of celsian in the world.

The unique feature of this body is that it is of sedimentary origin, believed to have been precipitated directly from brines in a small marine basin, fed by metal-rich hot fluids percolating through the underlying sedimentary pile. The site also provides unusually clear minor structures (folds and cleavages) of two generations, which affect the mineral body and which have been used in the understanding of the geometry of some major folds that make up the Grampian fold-belt.

23 AUCHTERTYRE
(NN 354 291–NN 368 312)

R.A. Scott

23.1 Introduction

The Auchtertyre GCR site, between Crianlarich and Tyndrum, contains the most extensive and most accessible exposures of stratabound sulphide mineralization in the Ben Challum Quartzite Formation, a unit of restricted distribution at the base of the Crinan Subgroup.

Characteristic features of the quartzites are distinctive minor folds with strongly curving axes, which are restricted in this area to this particular formation.

The Tyndrum area occupies an important position for structural and stratigraphical correlations with adjacent regions. However, until the 1980s, the area had remained essentially unmapped since the original survey of Sheet 46 (Balquhidder, 1900) by B.N. Peach and others. It was the discovery of stratabound units of sulphide mineralization as part of the Mineral Reconnaissance Programme of the Geological Survey that provided the main incentive for renewed stratigraphical and structural study (Smith *et al.*, 1984, 1988; Fortey and Smith, 1986; Hall, 1993).

The new mapping in the Auchtertyre area revealed a thick sequence dominated by feldspathic quartzites, between the Ben Lawers Schist Formation and the Ben Lui Schist Formation (Figure 54a). This was named the Ben Challum Quartzite Formation and was considered to be equivalent to the Farragon Volcanic Formation at the top of the Easdale Subgroup, a unit of amphibolites and quartzites, which in upper Glen Lyon has a maximum thickness of 25 m. Subsequently it has been re-assigned to the Crinan Subgroup on sedimentological grounds, although it might merely reflect a diachronous facies variation and hence be broadly equivalent in time to the Farragon Formation. Scott (1987) showed that the Ben Challum Quartzite Formation forms a continuous mappable unit, which can be traced from the Tyndrum Fault to the Garabal Hill Fault, a total distance along strike of approximately 20 km. The formation is restricted to the area bounded by these faults. A maximum thickness of 500 m is likely but the formation thins towards the east and possibly also in the west, close to the Tyndrum Fault. With the exception of the Ben Challum Quartzite Formation, the Argyll Group stratigraphy of the Tyndrum area is identical to that in areas to the south-west and north-east (Roberts and Treagus, 1979; Nell, 1984).

The principal exposures of the formation occur at Auchtertyre, where river sections drain south-westward into Strath Fillan from the watershed with Glen Lyon and Glen Lochay to the north-east (Figure 54a). Other than the river sections, most of the valley floors are filled with thick glacial till and moraine. Exposures also occur on the main peaks that form the watershed (e.g. Ben Challum, 1022 m, NN 388 322) but in general these are not as easily accessible or as informative as the river sections.

23.2 Description

The GCR site encompasses three main river sections through the Ben Challum Quartzite Formation (Figure 54a): the Allt Gleann a' Chlachain, the Allt a' Chaol Ghlinne and, below the confluence of these two rivers, the Allt Auchtertyre. These rivers provide near continuous exposure through the entire formation at its thickest part.

The Ben Challum Quartzite Formation contains a variety of rock types but is dominated by well-bedded quartzites rich in plagioclase feldspar in the range albite-oligoclase. In some beds feldspar is more abundant than quartz (Scott *et al.*, 1988). The rock is generally fine to medium grained, but locally contains coarser pebbly beds. Beds range in thickness up to 2 m but are usually less than 0.5 m; bedding is normally continuous with no internal cut-offs and lacks recognizable way-up criteria. Individual beds are separated by micaeous layers (mainly muscovite) generally less than 10 mm thick. Rarely the rock as a whole becomes more pelitic and garnetiferous, and as such is then indistinguishable from the overlying Ben Lui Schist Formation. Conformable amphibolite units up to 2 m thick occur sporadically throughout the Ben Challum Quartzite Formation, and this contrasts with the Farragon Volcanic Formation, which is dominated by amphibolite. The fine-scale layering in some amphibolite units was clearly disrupted before the deformation described below. Several layers of calcareous semipelite up to 1 m thick form a minor component of the sequence (e.g. at NN 3601 3057), and minor occurrences of graphitic pelite occur in the lower part of the formation.

The Ben Challum Quartzite Formation contains two units of stratabound sulphide mineralization: the Auchtertyre Horizon and the overlying Ben Challum Horizon (Fortey and Smith, 1986; Smith *et al*., 1988; Scott *et al*., 1988, 1991). The weakly mineralized Auchtertyre Horizon is about 80 m thick in total; the best exposures are around the intersection of Allt Gleann a’ Chlachain and the Allt a’ Chaol Ghlinne (NN 3543 3023), and a further 100 m upstream in the Allt Gleann a’ Chlachain (Figure 54a). Mineralization occurs as bedding-parallel sulphide laminae, up to 10 mm thick, in which pyrite predominates over minor chalcopyrite and sphalerite, and leads to a characteristic rusty weathering of the host quartzites. There are substantial thicknesses of non-mineralized quartzite in the total thickness.

The Ben Challum Horizon is approximately 20 - 30 m thick at the type locality on Ben Challum (NN 387 322) to the north-east of the GCR site, and on Creag Bhocan (NN 315 280), to the west of Strath Fillan (Scott *et al*., 1988). It consists of layers of pyrite, chalcopyrite and sphalerite, up to 0.3 m thick, in chloritic schist and albitic quartzite. In the GCR site, the horizon is seen only as about 10 m of pyritized quartzite immediately below the top of the formation in the Allt Auchtertyre at NN 3541 3013.

An enigmatic unit of ultramafic rock characterizes the boundary between the Ben Challum Quartzite Formation and the overlying Ben Lui Schist Formation. It can be traced intermittently across the Tyndrum area, but exposure of this part of the succession is poor in the Allt Auchtertyre; the unit is best exposed on the flanks of Ben Challum and on Creag Bhocan (Scott *et al*., 1988). The variable mineralogy of the unit is compatible with an igneous origin and a subsequent high degree of alteration. It generally contains a combination of chlorite, ankerite, talc, fuchsite (chromian muscovite), quartz and amphibole, with accessory chromium- and zinc-bearing spinel, thiospinel, pyrite, pyrrhotite, pentlandite and millerite (Scott, 1987). The exposures in the Allt Auchtertyre occur close to the railway bridge and include chloritic schist containing carbonate porphyroblasts over 50 mm in diameter.

Two principal phases of ductile deformation are recorded in the Ben Challum Quartzite Formation. The most striking feature of the quartzites is the presence of non-cylindrical minor folds with strongly curving axes, of which numerous examples can be observed at all stratigraphical levels (Scott, 1987). The best examples occur within well-bedded feldspathic quartzites in which individual beds have constant thickness and are separated by thin partings of mica schist (Figure 55). Non-cylindrical minor folds do not occur in any of the adjacent formations.

The non-cylindrical folds are generally tight and fold hinges become more curved with a decrease in interlimb angle; a number of morphological types are present (Scott, 1987). The overall range of orientation of the hinges approaches 180° (Figures 54b and 55) so that many hinges pitch down the dip of the schistosity. The effect of this is that subparallel hinges within a few metres of each other face in opposite directions. Exposed folds range in amplitude from tens of centimetres to 3 metres, but reversals of vergence indicate that the largest fold amplitudes must be of the order of 10 - 20 m. The vergence of such reclined fold-pairs can be difficult to determine but, when 'restored' to a horizontal position, it can be ascertained that most fold-pairs, minor and major, verge to the south. Disharmonic folding affects sequences where there are marked differences in bed thickness and competence. In suitable pelitic lithologies a well-developed axial-planar crenulation schistosity is present. These folds affect the earlier bedding-parallel schistosity as well as, locally, a strong lineation of the quartz and feldspar fabric that is developed on that schistosity. Rarely, isoclinal folds of bedding are seen to pre-date the main fold set (Figure 56). No minor ductile structures post-dating the non-cylindrical folds were identified in the field, although several minor deformation phases have been identified elsewhere in the area (Scott, 1987).

A subvertical NNE-trending fault-system, named the Auchtertyre Fault, causes apparent sinistral displacement of the boundary between the Ben Challum Quartzite Formation and Ben Lui Schist Formation by as much as 800 m (Figure 54a). The fault can be observed in the Allt Auchtertyre.

23.3 Interpretation

The presence of layers of stratabound sulphide has promoted investigation of the Ben Challum Quartzite, both for scientific reasons, and in terms of its resource potential (e.g. Smith *et al.*, 1984, 1988; Fortey and Smith, 1986; Fisk, 1986; Scott, 1987; Scott *et al.*, 1988, 1991). Although no economic mineral occurrences have been discovered, the presence of this mineralization is important scientifically for two main reasons: (1) the nature of the mineralization provides information on the tectonic setting of sediment deposition and the geometry of depocentres; (2) stratabound mineralization is formed by relatively short-lived hydrothermal exhalation events on the sea floor. Geographically widespread mineralized units of limited thickness can therefore be regarded as time-lines in a succession otherwise devoid of chronostratigraphical control. In the Tyndrum area, the mineralization indicates a broad consistency between chronostratigraphy and lithostratigraphy.

The sediments that formed the Argyll Group are generally considered to have been deposited in an actively extending basin (e.g. Anderton, 1982), and there are clear indications of synsedimentary faulting at a number of levels within the Argyll Group succession in the area surrounding Auchtertyre. The evidence comes from the nature and geometry of sediment packages, the distribution of stratabound mineralization, and the metal zonation within individual mineralized layers (Scott, 1987). The exact position and original orientation of the bounding faults is difficult to constrain because of the subsequent multiphase deformation history. However, all the evidence is consistent with a fault-bounded depression in the Tyndrum area that most probably had a half-graben geometry with the controlling fault on the north-west side. The presence of a fault-bounded basin is the principal reason why the Ben Challum Quartzite Formation accumulated only in this area, and why exhalative submarine brines were also ponded in the same depocentre.

Although the evidence for active extension during Argyll Group sedimentation is convincing, the tectonic setting in which it took place has been disputed, and has ranged from a marginal basin setting (e.g. Wright, 1976; Henderson and Robertson, 1982; Nell, 1984) to an intracontinental basin setting (e.g. Phillips *et al.* 1976; Harris *et al.*, 1978). There are two principal strands of evidence from the Ben Challum Quartzite Formation that can be used to imply an arc-related marginal basin setting.

(1) A major change of sandstone provenance in the Dalradian succession appears to occur between the deposition of the Carn Mairg Quartzite and earlier formations, in which K-feldspar is the dominant feldspar, and the Ben Challum Quartzite and later formations, in which plagioclase is the dominant feldspar. It is no coincidence that this change occurs across an interval of the succession characterized by the onset of extension, stratabound mineralization and significant magmatism.

The albite-rich composition of the Ben Challum Quartzite Formation has led to speculation that the sequence may include keratophyre tuffs (Fortey and Smith, 1986; Fisk, 1986). No textural evidence now remains for a direct igneous origin but, considering the high plagioclase content, it does not seem unreasonable to conclude that the Ben Challum Quartzite Formation was derived by erosion of igneous rocks of silicic to intermediate composition, possibly with a direct volcanic input. A preliminary whole-rock geochemical study of psammites from the Ben Challum Quartzite Formation is consistent with a back-arc or continental margin arc setting (Scott, 1987).

The mineralogy of the apparently conformable ultramafic unit at the top of the Ben Challum Quartzite Formation is compatible with an igneous origin, and represents a more-intense state of alteration than serpentinization (Scott, 1987). The chemistry is also consistent with an origin as an igneous body, or as a sedimentary derivative, which was hydrothermally altered on, or close to, the seabed. More-definite conclusions about the unit's origin are precluded by the degree of alteration, but the presence of ultramafic rocks is compatible with an extensional setting in a marginal, possibly back-arc basin.

(2) The base-metal content of the mineralized layers in the Ben Challum Quartzite Formation is indicative of volcanic-associated massive sulphide (VMS) deposits, an unsurprising interpretation considering the abundant evidence for magmatic activity in the host succession. The extreme length/thickness ratio of the mineralized units in the Ben Challum Quartzite Formation, and the absence of an Fe-Mn-oxide or baryte facies, suggests similarities with Besshi deposits, a type of arc-related VMS deposit described from Japan (Scott *et al*., 1988, 1991).

The closely packed, non-cylindrical minor folds, with strongly curving hinges (Figure 55), occur in this area only in the Ben Challum Quartzite Formation. These folds refold an earlier set of fold hinges as well as the earliest (S1) schistosity and are associated with a tight crenulation cleavage and garnet growth. They can be clearly correlated with the main regional D2 deformation phase. The entire outcrop of the Ben Challum Quartzite Formation lies on the right-way-up limb shared by the F2 Dalmally Antiform to the south (Figure 54a) and the F2 Ra Creag Synform to the north (Roberts and Treagus, 1975). This is supported by the dominant southerly vergence sense of minor fold-pairs observable at the site. The axial-plane traces of the major folds trend ENE, and rocks on the shared limb generally dip at moderate angles to the south. The geometrical relationships between the isoclinal folds and mineral lineations that pre-date the dominant D2 set (Figure 56) are not clear, but both are interpreted to be of the regional D1 phase, and related to the regional major F1 fold, the Ardrishaig Anticline (Roberts and Treagus, 1975).

The origin of the non-cylindrical folds with curving axes is not entirely clear. Many other examples of such folds have been ascribed to their occurrence in zones of extreme strain; however, this does not appear to be the case at Auchtertyre. Here, two factors are considered to be important: (1) the mechanical properties of the quartzite; and (2) the position of the outcrop relative to major D2 structures (Scott, 1987).

The presence of competent quartzite beds separated by thin pelitic partings has led to pronounced strain partitioning as beds moved relative to each other during folding (Scott, 1987). Internally, the quartzite beds were not subjected to intense stretching; pebbly beds, for example, do not show any significant elongation of clasts, which commonly show only a weak flattening in the approximate plane of bedding. It is not uncommon to find S1 fabric elements preserved within quartzite beds. In contrast, pronounced mineral lineations formed by microboudinaged garnet crystals within the pelitic seams indicate high D2 strain. This interbed slip was promoted both by the continuous nature of the bedding and by the overall structural position on a major F2 fold limb. In this location, it can be assumed that the principal D2 elongation direction would lie close to the average plane of layering, thus enhancing the tendency for layer-parallel shear.

As folding progressed, the initiation of minor folds in individual quartzite beds was impeded by adjacent beds, from which they were separated by a minimal thickness of pelitic material. In a succession where interbed slip was likely, the presence of F2 buckles or existing F1 hinges would cause variations in cohesion and heterogeneous strain, thus providing a mechanism by which non-cylindrical hinges could develop. There is no evidence to suggest significant transection of axial planes by the schistosity associated with the folds, which elsewhere has been reported to be a feature of this style of folding (Treagus and Treagus, 1981).

23.4 Conclusions

The Auchtertyre GCR site illustrates a style of stratabound sulphide mineralization that is unknown elsewhere in the Dalradian of Scotland. The mineralization occurs within the Ben Challum Quartzite Formation, a unit restricted to the Tyndrum area, which is important scientifically because of the insight it provides into the depositional settings of Argyll Group sediments. There is clear evidence that faults were active during deposition, that they acted as conduits for mineralizing fluids, and that they created the topography necessary to pond the fluids once they had been exhaled onto the sea bed. Contemporaneous magmatic activity provided the source of heat required to circulate the fluids through crustal rocks beneath the sea floor, where they were able to gather base metals such as copper and zinc. The chemistry and geometry of the mineralized units, combined with the mineralogy of their host sediments, suggest an island-arc-related tectonic setting.

An additional feature of the Ben Challum Quartzite Formation is the presence of well-exposed minor folds with exceptionally curved hinges, a feature found in this area only in this formation. The distinctive folds are thought to reflect the mechanical properties of the unusually well-bedded quartzites, which were able to slip relative to each other along intervening micaceous seams. The minor folds in the section also provide important information concerning the geometry of the major regional folds of the area.

This GCR site provides the only section through the entire Ben Challum Quartzite Formation and offers an excellent opportunity for further research into both stratabound mineralization and fold mechanisms.

24 BEN OSS (NN 291 265–NN 296 271)

J.E. Treagus

24.1 Introduction

The Ben Oss GCR site has been selected to exemplify the fracture history of the Tyndrum Fault, one of the major system of NE-trending, dominantly left-lateral faults that dissect the Grampian Terrane between the Great Glen and the Highland Boundary faults (Figure 1 and Stephenson et al., 2013a, fig. 1). The principal period of fault movement was in the late Silurian and is closely associated with Caledonian intrusions, such as the adjacent Garabal Hill–Glen Fyne granitic pluton and microgranite and appinitic microdiorite dykes in the Tyndrum area. Late-Carboniferous quartz-dolerite dykes, with a regional east to east-north-east trend, cut across the fault-zone.

Previous studies have established the strike-slip component of movement on this system of faults, although the importance of dip-slip components has also been recognized (Anderson, 1951; Johnstone and Wright, 1957; Pitcher, 1967). Treagus (1991) constructed geological profiles on either side of some of the principal fault planes within the Grampian Terrane to demonstrate that the components of movement on the individual faults were both left-lateral strike-slip (up to 8 km) as well as dip-slip (up to 2 km). The Tyndrum Fault, in particular, was shown to have a significant dip-slip component of 2 km, down to the east, as well as a left-lateral strike-slip component, which is greatest (4 km) in the central portion of the fault, the area of this GCR site. Treagus *et al.* (1999) have made a detailed study of the fault and its associated mineralization.

24.2 Description

This GCR site, which lies some 4 km south-west of the village of Tyndrum, occupies a gully of the Allt Coire Chruinn, which drains the northern slopes of Ben Oss (Figure 57). On these slopes, one major fault and many minor fractures associated with the Tyndrum Fault are particularly well exposed. The fault, termed here the Ben Oss Fault, can be traced from NN 295 269 into good exposures in the 300 m-long gully in the Allt Coire Chruinn at NN 291 265 to the south-west. It is a major splay of and is very close to the line of the Tyndrum Fault, which in the area of the site is occupied by a microdiorite dyke.

At the north-east end of the gully, a quartz reef is exposed for 100 m in the hanging wall of the fault, which here trends 040° and dips at 72° to the south-east. To the south-west the reef becomes a breccia, composed of clasts of vein-quartz, 1–15 cm in length, in a cataclastic matrix of indurated fine-grained quartz and micas, evidence of extensional opening of the fault. In the wall formed by the margin of the breccia, many fault-parallel fractures are seen. These are marked by horizontal grooves, confirming strike-slip movement, and by a series of steeply N-pitching pinnate fractures, whose geometry indicates left-lateral movement. Many steep SE-dipping fractures are seen in the footwall of the fault (the north-west side of the gully), comprising both a fault-parallel set and another set orientated some 10–25° anticlockwise to the fault. The former are interpreted as Y shears, the latter as R shears, both with movement senses sympathetic to that of the main fault (see Sibson, 1977). In the schists in the footwall, 2–3 m to the west of the fault plane, small-scale, steeply plunging, drag-folding of bedding also indicates left-lateral movement.

There is also evidence of left-lateral movement in the area immediately to the north-west of the fault gully. Here, major fractures can be seen on the aerial photographs, branching at some 20° anticlockwise from the fault at regular 50 m intervals for several hundred metres to the north of the gully (Figure 58). The fractures contain both illite-quartz and pyritic gouges with textures indicating left-lateral movement. One major fracture at

NN 2925 2677, occupied by the stream, contains a 3 m-thick quartz-vein breccia, kink folds and bedding offsets in the schists that show clear left-lateral displacements (Figure 57, locality marked X and to its south-west). Slickensides and grooves (localities marked S on Figure 57) plunge at an average of 2° towards 221° on the fault-parallel fractures, and at 7° towards 197° on the anticlockwise set, confirming the dominant strike-slip movement sense. The anticlockwise set of fractures is not seen to the south-east of the fault.

However, there is also evidence of right-lateral movement on the fault. Measurements of bedding to the west of and adjacent to the fault, at about NN 292 267, show a 100 m-wide fold plunging at 43° towards 188°, the sense of deflection indicating right-lateral shear. Moreover, the swing in strike of the regional bedding, where followed for 1 km to the west of the fault, shows a similar pattern that also indicates a right-lateral deflection. Small right-lateral displacements and kinks have also been observed on some anticlockwise fractures (e.g. the two localities indicated on Figure 57), suggesting re-activation, and a 30 cm-wide Caledonian dyke at NN 291 265 shows both left-lateral and right-lateral metre-scale displacements. The north-western margin of the dyke that occupies the Tyndrum Fault shows effects of further brecciation, shearing and hydrothermal alteration (e.g. at NN 295 270), which could represent this right-lateral movement. A thick late-Carboniferous dyke shows a slight dextral deflection where it crosses the fault at NN 296 271.

24.3 Interpretation

Regional considerations suggest that the earliest movement on the Tyndrum Fault may have been a tensional opening as a normal fault (see Treagus *et al.*, 1999); this is supported by the 70° dip of the Ben Oss Fault and associated fractures, as well as by the hydrothermal breccias. Two fracture sets are evident in the GCR site, a fault-parallel set and another some 10–25° anticlockwise to the fault (Figure 58); these are interpreted as Y shears and R shears, respectively, with sympathetic left-lateral shear in response to movement on the major fracture, in the traditional manner of fault analysis (Sibson, 1977). Many fault-related features on minor fractures (pinnate structures, kink-folds, bedding displacements and gouge textures) support the left-lateral displacements. Thus the Ben Oss Fault can be confidently interpreted as a major fault with left-lateral displacement.

The principal evidence for the magnitude of the left-lateral displacement comes from the offset of the Ben Lawers Schist/Ben Lui Schist junction. On the west side of the Ben Oss Fault, this junction trends 040° and dips steeply to the south-east; it is apparently displaced by some 3 km on the east side of the fault to near Cononish (Figure 57, inset). However, Treagus (1991, figure 3) showed that the latter occurrence of the junction represents the limb of a major F2 fold (a component of the regional Ben Lui Fold) that is structurally lower than the junction on the western side of the fault; the two fold limbs have been brought together by movements which had components of displacement of 1.8 km dip-slip (down to the east) and about 4 km left-lateral strike-slip.

Evidence for significant right-lateral movement in the fault-zone can also be established from the displacement of the Ben Lawers Schist/Ben Lui Schist junction in the Ben Oss area. There is a narrow sliver of Ben Lawers Schist directly east of the Ben Oss Fault, in which the junction is shifted some 300 m to the south-west (Figure 57). This sliver is separated from the Ben Lui Schist farther east by a 14 m-wide, steeply SE-dipping, Caledonian dyke of porphyritic microdiorite. This dyke must be intruded along the major displacement plane of the Tyndrum Fault-zone, immediately east of the Ben Oss Fault. The interpretation of the movement history of the zone is shown in the inset to Figure 57. The early major movement displaced the Ben Lawers Schist/Ben Lui Schist junction as described above (with components of displacement up to 8 km in a left-lateral sense and 1.8 km of dip-slip) from its position at Cononish to that in the fault-bounded sliver. The main fault plane was then intruded and sealed by the microdiorite dyke, which is evidence of further extensional opening. A later right-lateral movement occurred on the Ben Oss Fault, which brought the Ben Lawers Schist/Ben Lui Schist junction back to its present position west of the faults. The Ben Oss Fault is therefore interpreted as a major splay of the Tyndrum Fault, having an unknown amount of left-lateral shear, but with a subsequent right-lateral movement of at least 300 m

There is no evidence of the early precious-metal-type mineralization, seen elsewhere in the Tyndrum area, apart from minor pyrite mineralization on the faults and minor fractures. However, the later right-lateral movements are equated with those at other localities in the Tyndrum area, where they are associated with the base-metal mineralization (Treagus *et al*., 1999).

24.4 Conclusions

The Ben Oss GCR site provides exceptional exposures of a major fault, the Ben Oss Fault, together with associated minor and major fractures. Many of the features associated with major faults are well displayed, such as fault breccias, fault-gouge clays, slickensides and quartz veins. The fault is a component of the Tyndrum Fault, also exposed at this site, which is one of the major dislocations that traverse the Grampian Terrane from north-east to south-west.

Evidence from the exposed fault planes, together with that seen on aerial photographs, allows the movement sense on the major structure to be predicted. Both faults have a complex history, which principally involved a left-lateral sense of movement, such that the north-west side of the faults moved sideways to the south-west; the Ben Oss Fault probably only moved a few hundred metres but the Tyndrum Fault moved a minimum of 4 km and possibly as much as 8 km. The evidence also suggests that the history of the faults, involved sideways movement in the opposite (right-lateral) sense, as well as vertical movements. Regionally these movements can be linked to the history of mineralization in the area.

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Figure 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 this regional paper 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 Tempar 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 Sgluich 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 2 Comparison of Dalradian successions in the Loch Leven and Schiehallion (Strath Fionan) areas.

Figure 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, FWSl 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).

Figure 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 5 Map of the River Leven section east of Kinlochleven.

Figure 6 Near-vertical bedding in the Binnein Quartzite, on a horizontal surface in the River Leven at NN 1910 6186; the cross-sets young to the west (top of photograph). Coin is 20 mm diameter. (Photo: J.E. Treagus.)

Figure 7 Map of the area around the Nathrach GCR site, showing the boundary between the Binnein Quartzite and the Binnein Schist on the two limbs of the F1 downward-facing Mamore Syncline. At localities A, B and C, relations between bedding and the three cleavages are shown, as appropriate. The relation of bedding to the direction of younging is shown at localities along the boundary as well as at localities A and C, within the Binnein Schists.

Figure 8 Thinly-bedded quartzites and semipelites in the Binnein Schists, tightly folded by F2 folds that plunge steeply to the north-east at locality A, Figure 7 in the Nathrach GCR site. Coin is 25 mm diameter. (Photo: J.E. Treagus.)

Figure 9 Semipelites interbedded in the Binnein Quartzite, as seen on a surface sloping gently to the south-east (bottom right) at locality B, Figure 7 in the Nathrach GCR site. Cross-bedding near the top left corner youngs to the south-east and faces down on the axial-planar fabric of the minor folds; these folds, which are of D1 age, plunge at 40° to the north-east and verge to the north-east. Not clear in the photograph is the S2 crenulation cleavage, which cross-cuts the F1 folds parallel to the length of the pencil. Pencil is 15 cm long. (Photo: J.E. Treagus.)

Figure 10 Map of the coastal section at the Rubha Cladaich GCR site, showing the outcrops of the Glen Coe Quartzite, Binnein Schists and Binnein Quartzite. Principal exposures are outlined.

Figure 11 D2 folds and cleavage in the Binnein Schists at the Rubha Cladaich GCR site. F1 folds can be seen, for instance, at the tip of the pencil. Pencil is 10 cm long. (Photo: J.E. Treagus.)

Figure 12 Regional geological context of the Tom Meadhoin and Doire Ban GCR site. After Roberts and Treagus (1977b, figure 5).

Figure 13 Map of the Stob Ban GCR site. After Roberts and Treagus (1977b, figure 5).

Figure 14 Stob Ban (left) viewed from the east, showing the Binnein Quartzite dipping to the north-west (away from the camera) on the south-east limb of the Stob Ban Synform. In the centre, the area of the Stob Ban GCR site, beds of Leven Schists and Ballachulish Limestone dip to the south-east on the north-west limb of the synform. (Photo: D. Stephenson, BGS No. P 726592.)

Figure 15 Map of the Loch Leven shore section at St John's church after Bailey (1960).

Figure 16 View looking north-east along the outcrop of the Ballachulish Slide on the shore of Loch Leven, near St John's church. The slide occurs beneath the hammer shaft and can be traced along the black dotted line. To its right is the Ballachulish Limestone; immediately left of the hammer, and for about one metre beyond, are a few centimetres of quartzitic Leven Schists; the remainder of the exposure left of the slide is a NE-trending dyke. Hammer shaft is 30 cm long. (Photo: J.E. Treagus.)

Figure 17 Map of the Onich Shore Section and the south-west end of the Onich Dry River Gorge GCR sites. Areas outlined by dotted lines are exposures discussed in the text, showing typical measurements of bedding (with direction of younging where appropriate) and plunge (and vergence where appropriate) of F1 minor folds.

Figure 18 Generalized structural profile of the F1 Appin Syncline for the area containing the Onich Dry River Gorge, Onich Shore Section and Ardsheal Peninsula GCR sites, looking up-plunge to the north-east at about 25°. Use has been made of data from the Onich shore section as well as the profile drawn of the Ardsheal area by Treagus and Treagus (1971, figure 2). Data from localities 1–5 of the Ardsheal Peninsula GCR site are shown in the top left corner of the profile.

Figure 19
(a) Cross-sets, younging to the north-west (top left) on a horizontal surface of near vertical-dipping Appin Quartzite at Caigean Mor (NN 0437 6105) on the Onich shore section. Lens cap (top left) is 4 cm diameter.
(b) View to the north-east of SE-verging F1 folds of a 10 cm-thick limestone bed, and of thinner adjacent beds, in the Appin

Phyllite on the Onich shore section at NN 036 612, 300m SW of the school. Coin (centre) is 30 mm in diameter.
(Photos: J.E. Treagus.)

Figure 20 Map of the Appin Syncline on the Ardsheal Peninsula. Numbers relate to localities discussed in the text. After Treagus and Treagus (1971).

Figure 21
(a) Bedding in the Cuil Bay Slates shows upward grading, crossed by upright S1 cleavage. View to the south-west, down the plunge of a F1 fold hinge from NM 972 554, Rubha Beag, Ardsheal Peninsula. Lens cap is 5 cm in diameter.
(b) F1 folds, verging north-west and plunging gently to the south-west in phyllitic semipelites and psammites near the top of the Appin Quartzite on Rubha Mor, Ardsheal Peninsula (NM 9640 5565). The fanning S1 cleavage can be seen in the semipelite bed in the centre. Figures for scale.
(Photos: J.E. Treagus.)

Figure 22 Map of southern Lismore Island, showing the 'units' of the Lismore Limestone Formation and sedimentary cycles within the Middle unit as mapped by Hickman (1975, 1978). The traces of the major folds are also shown: A and B form a major F2 fold-pair, C is a major F1 syncline. The cross-section (after Hickman, 1978) illustrates the major folds and the relation of the (schematic) vergence of the F2 minor folds.

Figure 23 Open F2 minor folds, verging north-west in the Lismore Limestone Formation south-west of Miller's Port (NM 812 372); view to the south-west. Figure is 1.5 m tall. (Photo: J.E. Treagus.)

Figure 24 Map of the Lochnell Peninsula and adjoining area, north of Oban, modified from BGS 1:50 000 Sheet 45E (Connel). It shows the regional setting of both the Camas Nathais and Port Selma, Ardmucknish GCR sites (labelled inset boxes), and the line of the Benderloch Slide.

Figure 25 Detailed map of an area at the head of Camas Nathais (see inset on Figure 24), based upon a survey by P.W.G. Tanner using GPS for location. The irregularly shaped Palaeogene dykes and sheets provide a guide to location on this featureless rock platform. The map shows the relationship of the rock sequence and structure in the hanging wall of the Benderloch Slide (S), to those in the footwall.

Figure 26 The Benderloch Slide at Camas Nathais, as seen looking north from locality 1, Figure 25. The slide-plane dips steeply to the north-west and separates graphitic pelite (g) above, from a strongly boudinaged and disrupted unit of orange-weathering dolostone (d) below. To the right of and beneath the dolostone is the intensely fractured Baravullin Quartzite (q).
Inset: Lineations in the graphitic pelite just above the slide, as seen looking in the direction of the arrow in the main photo. Two sets of steeply plunging lineations lie in the plane of the phyllitic cleavage The lineation plunging steeply to the left

(north) is the stretching lineation associated with the slide movement, and it is crossed by later crenulation lineations and kink bands plunging to the right (south).
(Photos: P.W.G. Tanner.)

Figure 27 Map of the Port Selma, Ardmucknish area showing the distribution of breccia (B1-5) and interbreccia (IB3, IB4) beds belonging to the Selma Breccia, and their relationship to the Selma Black Slates (modified from Litherland, 1982). Structural interpretation by P.W.G. Tanner.

Figure 28 The Selma Breccia as seen on the coast at locality 1, Figure 27, showing the variations in clast type and shape within part of breccia units B1-B3 (m, mudstone raft). The direction of view is to the south-east, with the longest dimensions of the clasts being generally aligned parallel to the NE-trending slaty cleavage. (Photo: P.W.G. Tanner.)

Figure 29 Map of the closure of the F2 Beinn Udlaidh Syncline in Glen Orchy. The curved axial trace of this fold is due to the intersection of the gently dipping axial surface with the irregular topography, and does not reflect the curvilinear hinge as described in the text or later deformation. Equal-area stereographic projections for some of the structural data are shown. Stereoplot (a) shows the poles to the axial planes of minor folds related to the syncline, together with their computed mean orientation as a great circle (solid line). Stereoplot (b) shows the orientations of stretching lineations (solid triangles; N=41) and minor fold hinges (open circles; N=107), related to the major syncline. The solid line represents the computed best-fit plane containing the fold hinges.

Figure 30 Z-shaped vergence shown by main-phase minor folds, which plunge to the south on the upper limb of the F2 Beinn Udlaidh Syncline in the River Orchy. The structures are seen looking due south from the dam at locality 1, Figure 29, during low-water conditions. The hammer shaft is 78 cm long. (Photo: P.W.G. Tanner.)

Figure 31 Stacked fold hinges of minor folds (‘fold mullions’) with neutral vergence in the hinge-zone of the F2 Beinn Udlaidh Syncline in the River Orchy at locality 2, Figure 29. The structures are viewed from the south-east, and the hammer shaft is 78 cm long. (Photo: P.W.G. Tanner.)

Figure 32 The major structures of Glen Garry depicted in three dimensions and showing the localities 1–7 that are described in the text. Below is a map of the Glen Garry section showing the A9 road, the River Garry and the positions of the numbered localities. Adapted from Thomas (1988, figure 1.2).

Figure 33 Cross-bedded laminated schistose psammites at the Stalcair Cut on the A9 road (locality 1). The beds young to the right (south-east), and thus the F2 fold is downward facing. The masonry buttress is *c*. 4 m high. See Thomas (1988, figure 1.5) for an annotated sketch of this view. (Photo: P.R. Thomas.)

Figure 34 The exposed hinge of the Bohespic Antiform in the A9 road cut near the Allt Chrom, looking north (locality 4). Car gives scale. See Thomas (1988, figure 1.4) for an annotated sketch of this view. (Photo: P.R. Thomas.)

Figure 35 Downwards- and SE-facing F2 folds on the rock faces of the Clunes Cut on the A9 road, looking north-east (locality 6). Height of section about 8 metres. (Photo: J.E. Treagus.)

Figure 36 Sedimentary dykes of schistose semipelite in schistose psammite (top, centre), cross-lamination and slump folds in the River Garry, Struan (locality 7). Beds young to the right (south-east) on the steep overturned limb of an F2 fold. The compass is *c*. 5 cm in diameter. (Photo: P.R. Thomas.)

Figure 37 Map of the Creag nan Caisean–Meall Reamhar GCR site after Thomas (1965). Minor intrusions are not shown.

Figure 38 Exposure near the forestry road on the south flank of Creag nan Caisean at NN 771 601, where a strong penetrative schistosity (S1) cuts steeply dipping, cross-laminated (SS) schistose psammite. The hand lens is *c*. 3 cm in diameter. (Photo: P.R. Thomas.)

Figure 39
(a) Structural map of the Trinafour Monoform and the adjacent area around Meal Dail Chealach and Loch Errochty. AC Allt Culaibh Antiform, AS Allt Sleibh Antiform, CS Croftnagowan Synform, ML Meal na Leitreach Synform, SC Sron Con fold-pair, TM Trinafour Monoform.
(b) Schematic profile view of the map in (**a**), looking east-south-east. Adapted from Thomas (1980).

Figure 40 Minor Ft monoformal fold related to the Trinafour Monoform on the west flank of Sron Chon (NN 680 668), north of Loch Errochty. The fold is plunging at 20° to 165° (away from the camera) and is cut by a small thrust plane. The hammer shaft is 30 cm long. (Photo: P.R. Thomas.)

Figure 41 Geology of the Strath Fionan area based on mapping by J.E. Treagus and P.A.R. Nell. After BGS 1:10 000 sheet NN75NW (1997) and Treagus (2000, figure 4).

Figure 42 Thinly bedded Beoil Quartzite in Strath Fionan exhibits an F2 fold-pair, verging south in the centre of the picture. To the right of the F2 synform is a tight F1 closure folded by another F2 antiform. View to the east from NN 721 576, *c*. 300 m north-east of Lochan an Daimh. Hammer head is 15 cm long. (Photo: J.E. Treagus.)

Figure 43 The lower limestone of the Blair Atholl Dark Limestone and Dark Schist Formation in the hinge-zone of an F2 fold in Strath Fionan. View to the south-east from NN 717 570, *c*. 200 m south-west of Lochan an Daimh. Outcrop is about 10 m wide. (Photo: J.E. Treagus.)

Figure 44 Map of the Tempar Burn area based on mapping of P.A.R. Nell (BGS 1:10 000 sheet NN65NE).

Figure 45 Exposure of a boulder bed close to the Tempar Burn track at NN 696 565, showing elongation of stones parallel to a vertical cleavage; the holes are weathered-out dolomitic clasts, whilst the stones that are proud are of granite, quartzite and biotite-muscovite semipelite (e.g. large clast to the right of the hammer shaft). Hammer shaft is 30 cm long. (Photo: J.E. Treagus.)

Figure 46 Map of the lower part of the Allt Druidh, after P.A.R. Nell (BGS 1:10 000 sheet NN65NW).

Figure 47 Map of the hinge-zone of the Ruskich Antiform in the Slatich area based on mapping of P.A.R. Nell (BGS 1:10 000 sheet NN64NW). Adapted from Treagus, 2000, figure 7.

Figure 48 Cut surface of finely bedded quartzite and amphibolite of the Farragon Formation, *c*. 800 m east-north-east of Slatich, Glen Lyon (NN 6407 4778). Isoclinal F1 folds (arrowed) are refolded by more-open F2 folds. Scale bar in centimeters. (Photo: J.E. Treagus.)

Figure 49 Map and cross-section (A–B) of the area south-west of the Ben Lawers mountain range, showing localities 1–5, described in the text. Boundaries are based on the original Geological Survey 1:63 360 Sheet 46 (1900), except those of the Farragon Volcanic Formation. The latter boundaries are extrapolated from observations at localities 2 and 4, assuming a constant thickness. Structural data is from Nell (1984) and Treagus (1964b and unpublished). The geometry of folds shown at the key localities on the cross-section are representative of the vergence of the F2 folds.

Figure 50 Cut surface of a typical calcareous schist of the Ben Lawers Schist Formation from the south-east shore of Lochan na Lairige (NN 601 393). The S4 crenulation cleavage is well developed in the lower part of the specimen, while the calcareous quartzite bed near its top exhibits open F4 folding, which at the left-hand edge refolds a tight F2 fold-pair. Scale in centimetres. (Photo: J.E. Treagus.)

Figure 51 Map of Creag an Chanaich and the area of opencast pits. Mapping west of easting 8145 is based on Moles (1985a) and Treagus (2000); to the east it is based on unpublished mapping by J.M. Maclachlan and N.J. Butcher. Compilation and structural observations by J.E Treagus.

Figure 52 Schematic down-plunge profile view of major and minor F2 and F3 folds in the area of the Craig an Chanaich mine and opencast pits. A plunge of 25° to 255° is assumed; fault movement restored. After Pattrick and Treagus (1996, figure 6).

Figure 53 The opencast workings at Creag an Chanaich, in which Ben Eagach Schist (dark area, centre) is exposed in the core of an F2 synform within the stratiform baryte. Cliff exposure is 10 m high. (Photo: J.E. Treagus.)

Figure 54

(a) Map of the Auchtertyre area.
(b) Equal-area stereographic projection of poles to S2 planes and hinges of F2 folds (the range of plunge of folds with strongly curvilinear hinges is shown by the dashed lines). See text for explanation.

Figure 55 Curvilinear F2 fold hinge in the Allt Gleann a' Chlachain, Auchtertyre GCR site. Hammer head is 15 cm long. (Photo: J.E. Treagus.)

Figure 56 Refolded ?F1 folds in the Allt Gleann a' Chlachain, Auchtertyre GCR site. Pen is 13 cm long. (Photo: J.E. Treagus.)

Figure 57 Map of the Ben Oss Fault-zone with the Tyndrum Fault immediately to its south-east, occupied by a microdiorite dyke. The outcrop of the Ben Lawers Schist (ornamented) is shown between the two faults and its margin with the Ben Lui Schist is shown to the north-west of the Ben Oss Fault. The inset shows, (a) the left-lateral movement on the Tyndrum Fault and (b) the subsequent locking by the dyke and right-lateral movement transferred to the Ben Oss Fault.

Figure 58 Vertical aerial photograph of the northern flank of Ben Oss, showing the Ben Oss Fault (stream gully in centre with large arrows at each end) and fractures orientated at 20° anticlockwise to the fault on its north-west side (indicated by small arrows). See text for explanation. (Aerial Photograph © Getmapping.)

Table 1 Summary of the Dalradian sequence in the Schiehallion district (adapted from Treagus, 2000).
***** the Atholl and Strathtummel subgroups of Treagus (2000) are no longer recognized; the strata are now regarded as part of the Glen Spean Subgroup.

Table 3.1

Group	Subgroup	Formation	Metasedimentary rocks	Igneous rocks
Southern Highland		Pitlochry Schist Fm with *Green Beds*	Gritty semipelite/psammite; gritty hornblende schist	Basic volcanism — sills + volcaniclastic rocks
Argyll	Tayvallich	Loch Tay Limestone Fm	limestone and calc-schist	
	Crinan	Ben Lui Schist Fm	garnet semipelite/psammite	
	Easdale	Farragon Volcanic Fm	amphibolite and semipelite	Basic volcanism — sills + volcaniclastic rocks
		Ben Lawers Schist Fm	calc-semipelite/amphibolite	
		Ben Eagach Schist Fm	graphitic pelite/semipelite, Ba–Zn deposit near top	
		Carn Mairg Quartzite Fm	pebbly quartzite	
		Killiecrankie Schist Fm	semipelite/psammite	volcaniclastic rocks
	Islay	Schiehallion Quartzite Fm	fine-grained quartzite	
		Tempar Dolomitic Member	calc-pelite/semipelite and dolomitic limestone	
		Schiehallion Boulder Bed	diamictite with stones of granite, quartzite and limestone in calc-semipelite matrix	
Appin	Blair Atholl	Drumchastle Pale Limestone Fm	tremolitic/dolomitic limestone	
		Cnoc an Fhithich Banded Semipelite Fm	semipelite/psammite	
		Blair Atholl Dark Limestone & Schist Fm	limestone/graphitic pelite	
	Ballachulish	Tullochroisk Semipelite Fm	banded semipelite/psammite	
		Strath Fionan Pale Limestone Fm	tremolitic/dolomitic limestone	
		Strath Fionan Banded Semipelite Fm	pelite/semipelite/psammite	
		Meall Dubh Quartzite Fm	pebbly feldspathic quartzite	
		Meall Dubh Graphitic Schist Fm	graphitic pelite	
		Meall Dubh Limestone Fm	tremolite schist/dol. limestone	
		Meall Dubh Striped Pelite Fm	calc-schist and semipelite	
	Lochaber	Beoil Schist Fm	muscovite-garnet pelite	
		Beoil Quartzite Fm	thin quartzite	
		Dunalastair Semipelite Fm	ribbed semipelite/psammite	
		Dunalastair Quartzite Fm	quartzite/quartz psammite	
Grampian	* 'Strath-tummel'	Kynachan Psammite Fm	thick-bedded psammite	
		Kynachan Quartzite Fm	feldspathic quartzite	
		Tummel Psammite Fm	thick-bedded psammite	
		Tummel Quartzite Fm	quartzite/schistose psammite	
	* 'Atholl'	Bruar Psammite Fm	flaggy psammite/semipelite	

Figure 3.1

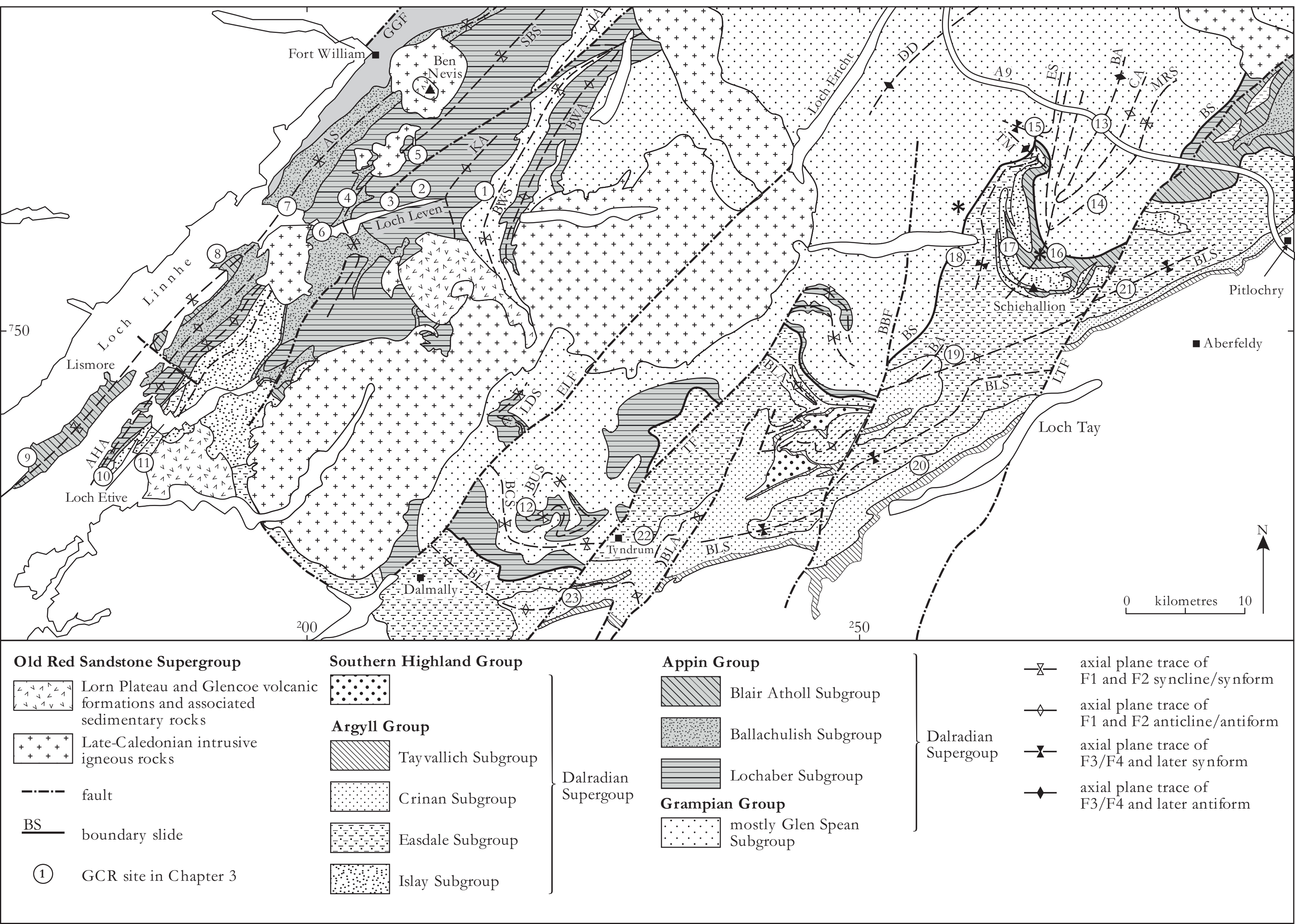
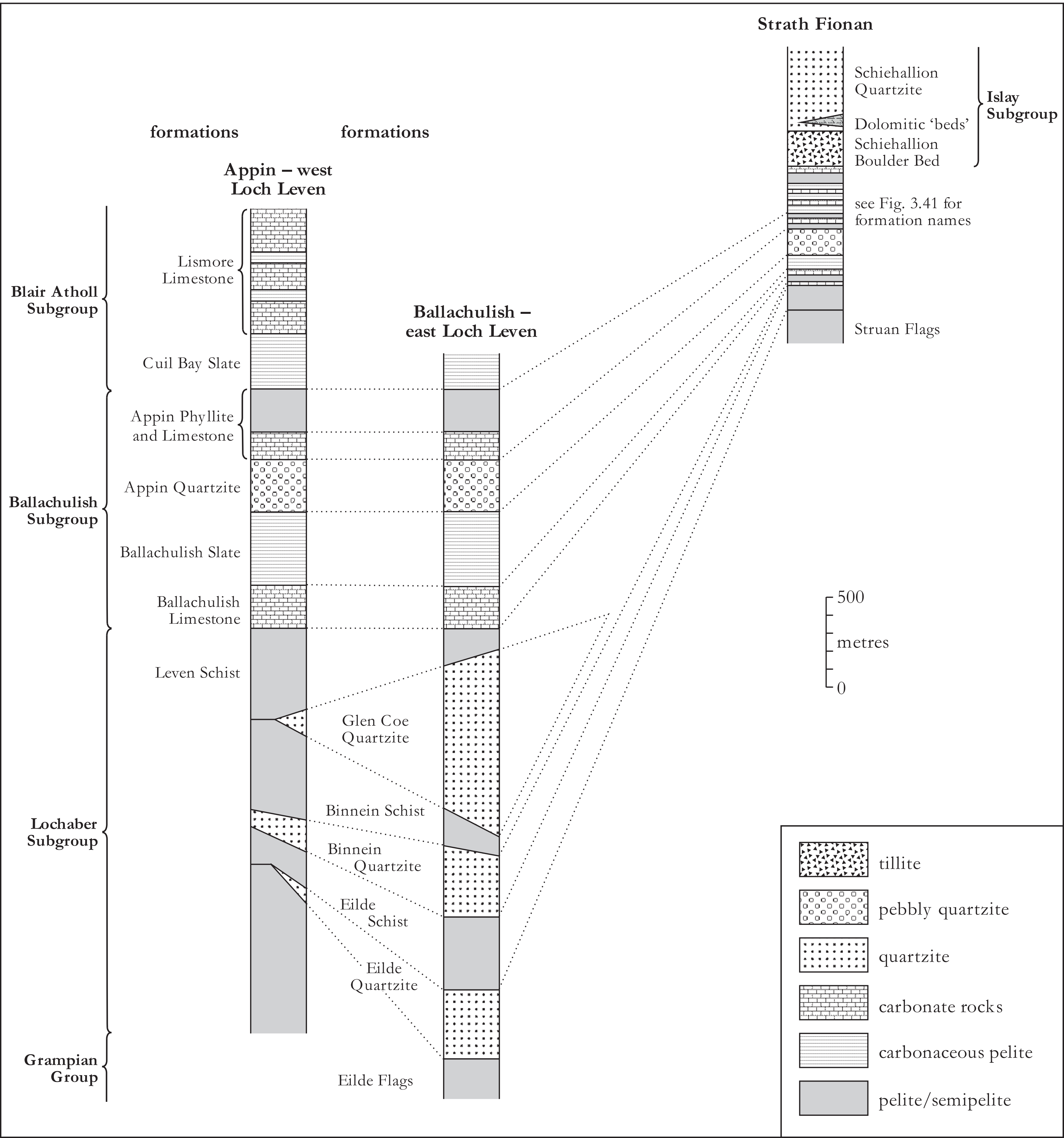

Fort William
Ben Nevis
GGF
SBS
AS
KA
BWA
BWS
Loch Leven
Loch Linnhe
Lismore
Loch Etive
AHA
LDS
ELF
BCS
BUS
Tyndrum
Dalmally
BLA
TT
BLS
Loch Ericht
DD
A9
ES
BA
CA
MRS
BS
TM
BBF
LTF
Schiehallion
Pitlochry
Aberfeldy
Loch Tay
750
200
250
N
0 kilometres 10
Old Red Sandstone Supergroup
Lorn Plateau and Glencoe volcanic formations and associated sedimentary rocks
Late-Caledonian intrusive igneous rocks
fault
boundary slide
GCR site in Chapter 3
Southern Highland Group
Argyll Group
Tayvallich Subgroup
Crinan Subgroup
Easdale Subgroup
Islay Subgroup
Dalradian Supergroup
Appin Group
Blair Atholl Subgroup
Ballachulish Subgroup
Lochaber Subgroup
Grampian Group
mostly Glen Spean Subgroup
Dalradian Supergroup
axial plane trace of F1 and F2 syncline/synform
axial plane trace of F1 and F2 anticline/antiform
axial plane trace of F3/F4 and later synform
axial plane trace of F3/F4 and later antiform

Figure 3.2



Strath Fionan
Schiehallion Quartzite
Dolomitic 'beds'
Schiehallion Boulder Bed
Islay Subgroup
see Fig. 3.41 for formation names
Struan Flags
formations
formations
Appin – west Loch Leven
Ballachulish – east Loch Leven
Blair Atholl Subgroup
Ballachulish Subgroup
Lochaber Subgroup
Grampian Group
Lismore Limestone
Cuil Bay Slate
Appin Phyllite and Limestone
Appin Quartzite
Ballachulish Slate
Ballachulish Limestone
Leven Schist
Glen Coe Quartzite
Binnein Schist
Binnein Quartzite
Eilde Schist
Eilde Quartzite
Eilde Flags
500
metres
0
tillite
pebbly quartzite
quartzite
carbonate rocks
carbonaceous pelite
pelite/semipelite

Figure 3.3a

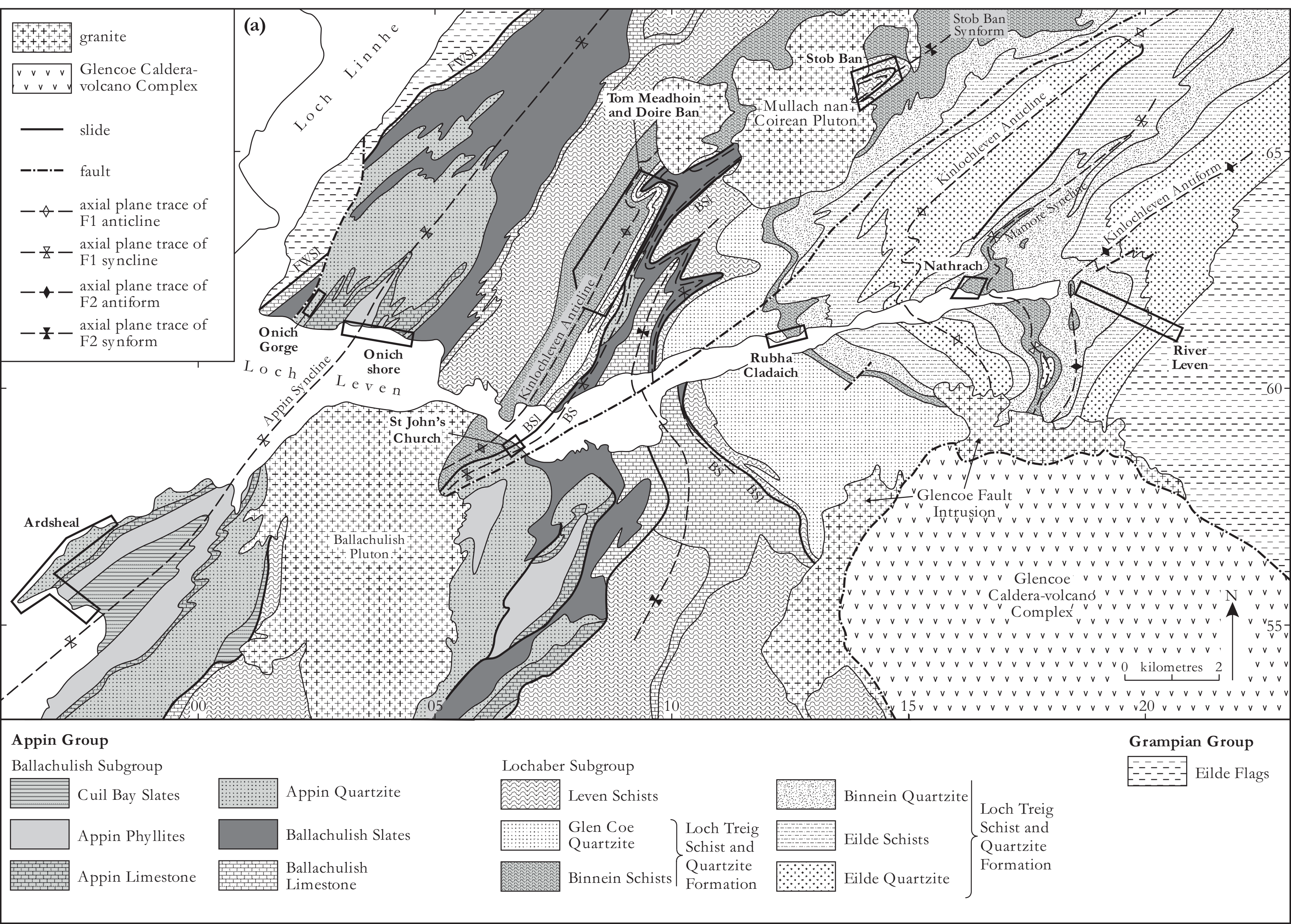
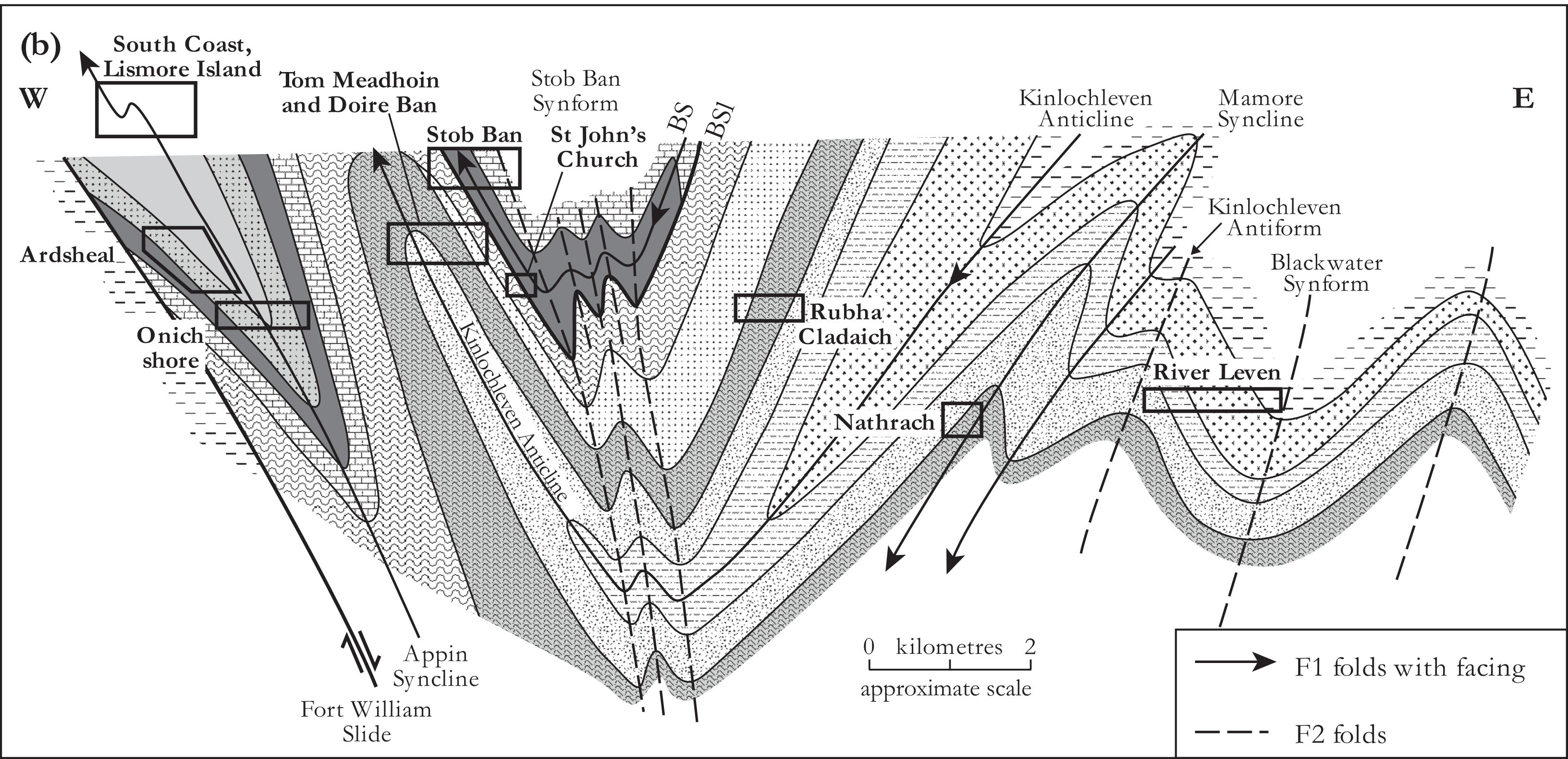

(a)
granite
Glencoe Caldera-volcano Complex
slide
fault
axial plane trace of F1 anticline
axial plane trace of F1 syncline
axial plane trace of F2 antiform
axial plane trace of F2 synform
Loch Linnhe
Loch Leven
FWSl
Onich Gorge
Onich shore
Appin Syncline
Kinlochleven Anticline
Tom Meadhoin and Doire Ban
BSl
BS
St John's Church
Ardsheal
Ballachulish Pluton
Mullach nan Coirean Pluton
Stob Ban
Stob Ban Synform
Rubha Cladaich
Nathrach
Mamore Syncline
Kinlochleven Antiform
River Leven
Glencoe Fault Intrusion
Glencoe Caldera-volcano Complex
N
0 kilometres 2
00
05
10
15
20
65
60
55
Appin Group
Ballachulish Subgroup
Cuil Bay Slates
Appin Phyllites
Appin Limestone
Appin Quartzite
Ballachulish Slates
Ballachulish Limestone
Lochaber Subgroup
Leven Schists
Glen Coe Quartzite
Binnein Schists
Loch Treig Schist and Quartzite Formation
Binnein Quartzite
Eilde Schists
Eilde Quartzite
Loch Treig Schist and Quartzite Formation
Grampian Group
Eilde Flags

Figure 3.3b



(b)
W
E
South Coast, Lismore Island
Tom Meadhoin and Doire Ban
Stob Ban Synform
Stob Ban
St John's Church
BS
BS1
Ardsheal
Onich shore
Kinlochleven Anticline
Rubha Cladaich
Kinlochleven Anticline
Mamore Syncline
Kinlochleven Antiform
Blackwater Synform
River Leven
Nathrach
Appin Syncline
Fort William Slide
0 kilometres 2
approximate scale
F1 folds with facing
F2 folds

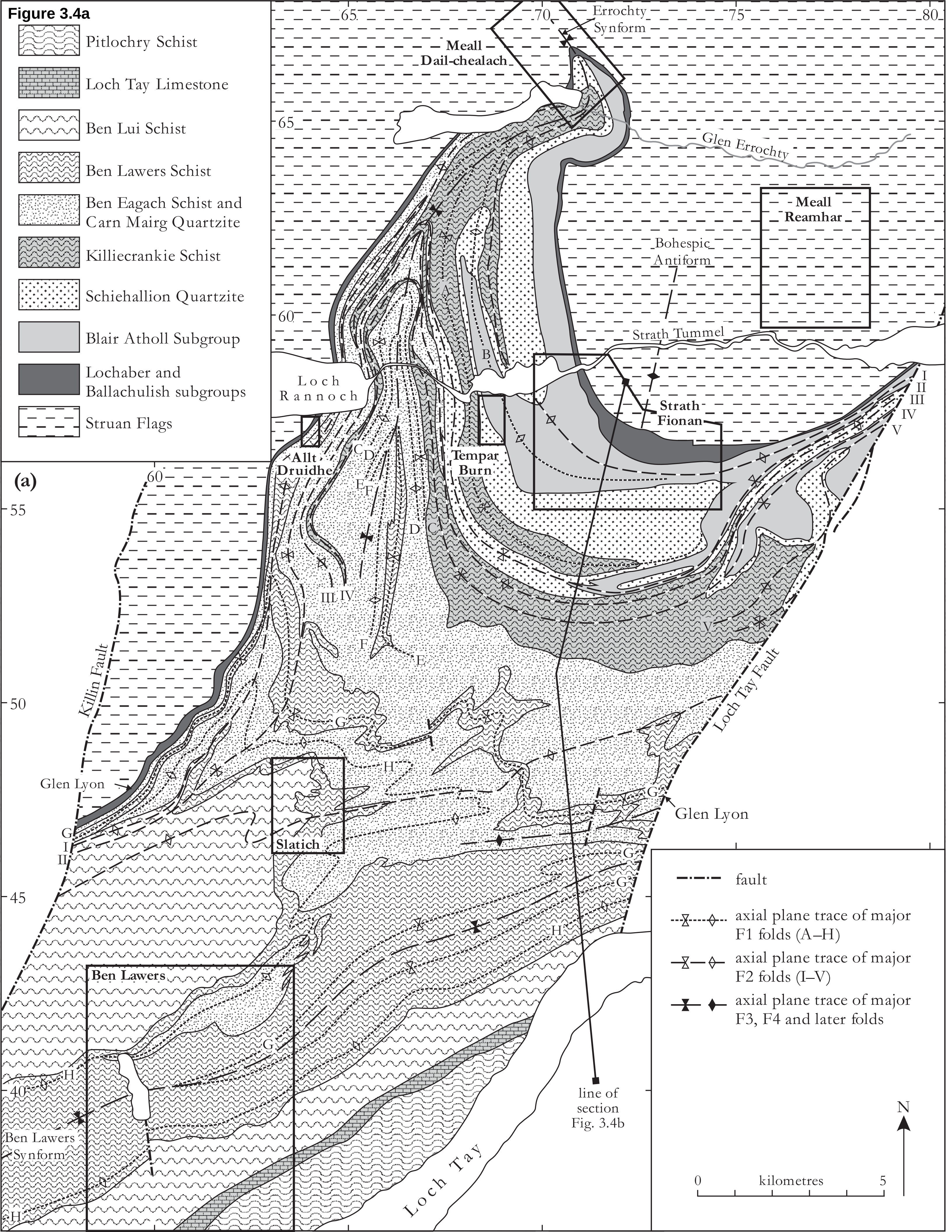


Figure 3.4a
Pitlochry Schist
Loch Tay Limestone
Ben Lui Schist
Ben Lawers Schist
Ben Eagach Schist and Carn Mairg Quartzite
Killiecrankie Schist
Schiehallion Quartzite
Blair Atholl Subgroup
Lochaber and Ballachulish subgroups
Struan Flags
(a)
Errochty Synform
Meall Dail-chealach
Glen Errochty
Meall Reamhar
Bohespic Antiform
Strath Tummel
Loch Rannoch
Strath Fionan
Allt Druidhe
Tempar Burn
Killin Fault
Loch Tay Fault
Glen Lyon
Glen Lyon
Slatich
Ben Lawers
Ben Lawers Synform
Loch Tay
line of section Fig. 3.4b
fault
axial plane trace of major F1 folds (A–H)
axial plane trace of major F2 folds (I–V)
axial plane trace of major F3, F4 and later folds
N
0 kilometres 5

Figure 3.4b

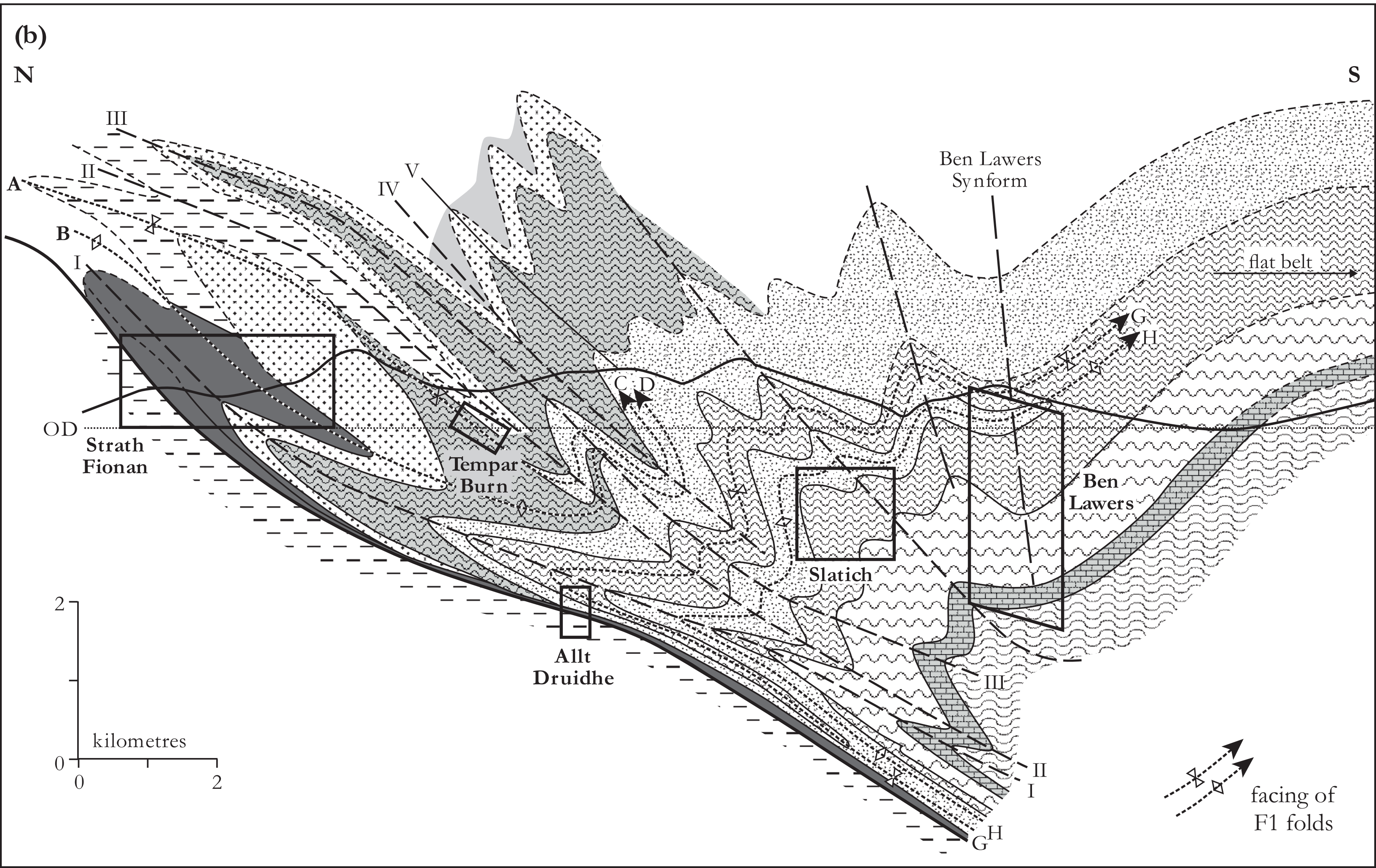
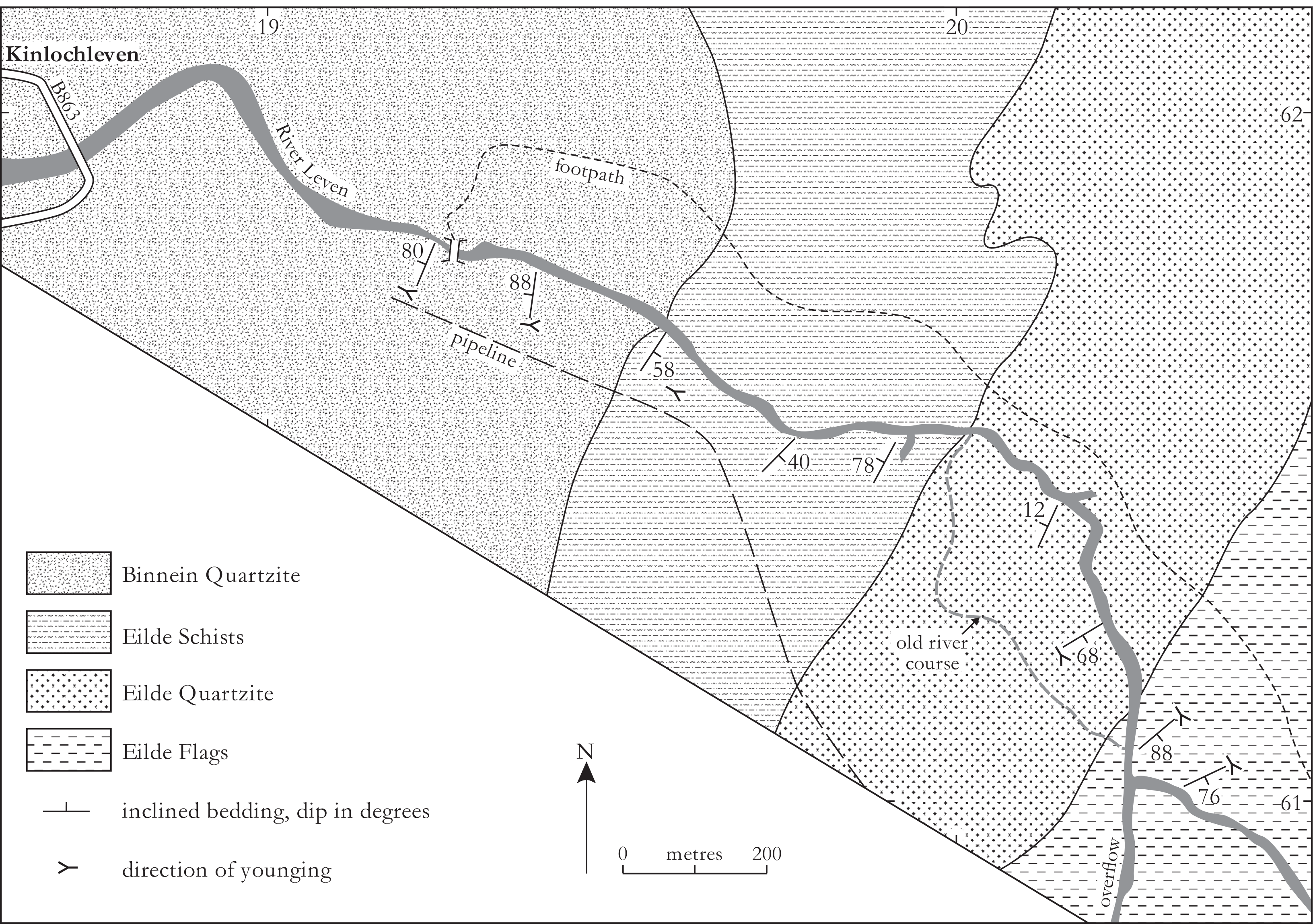

(b)
N
S
III
II
A
B
I
IV
V
Ben Lawers
Synform
flat belt
G
H
C
D
OD
Strath
Fionan
Tempar
Burn
Ben
Lawers
Slatich
Allt
Druidhe
III
II
I
G
H
2
1
0
kilometres
0
2
facing of
F1 folds

Figure 3.5



19
20
62
61
Kinlochleven
B863
River Leven
footpath
pipeline
80
88
58
40
78
12
68
88
76
old river course
overflow
Binnein Quartzite
Eilde Schists
Eilde Quartzite
Eilde Flags
inclined bedding, dip in degrees
direction of younging
N
0
metres
200

Figure 3.7

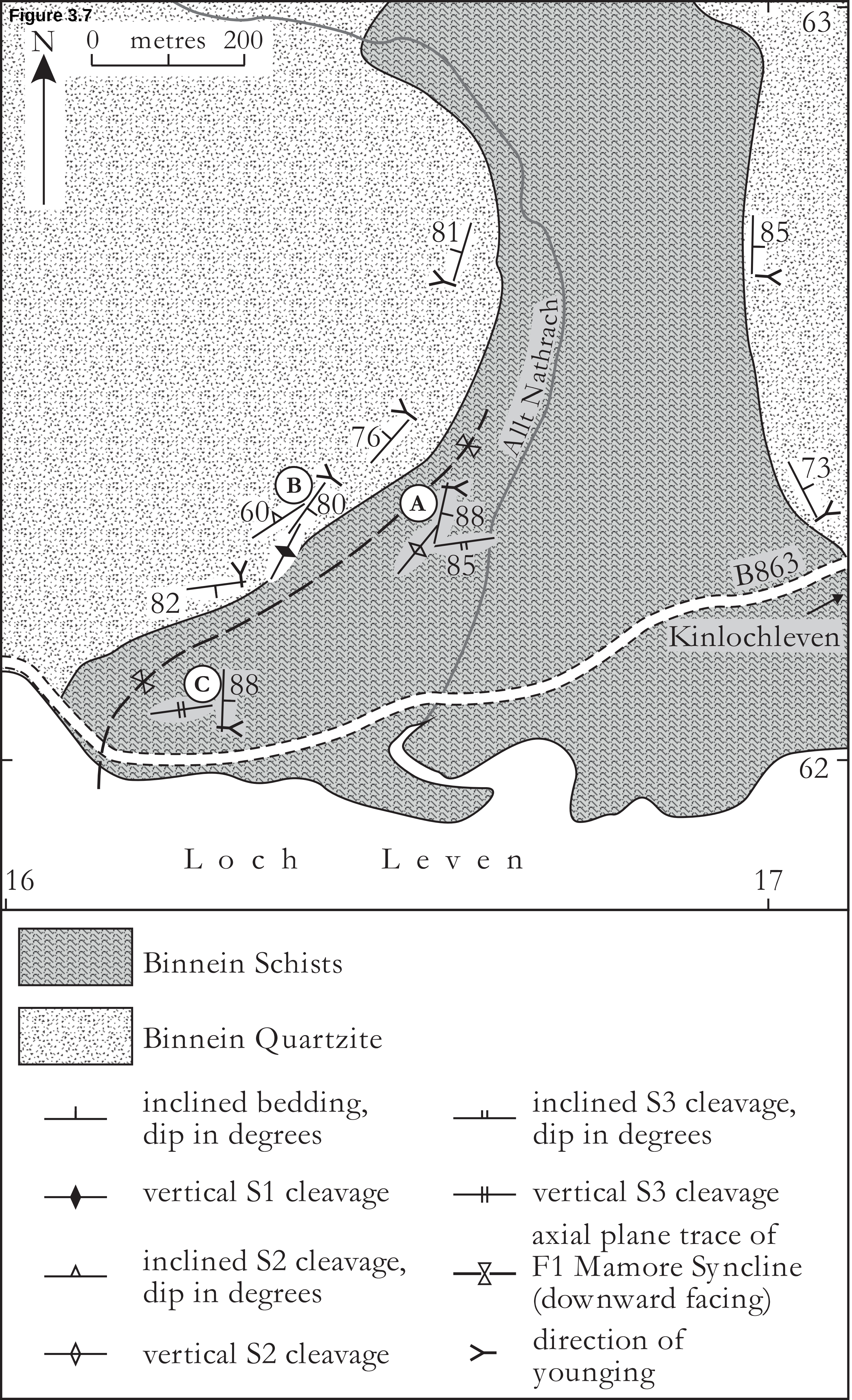
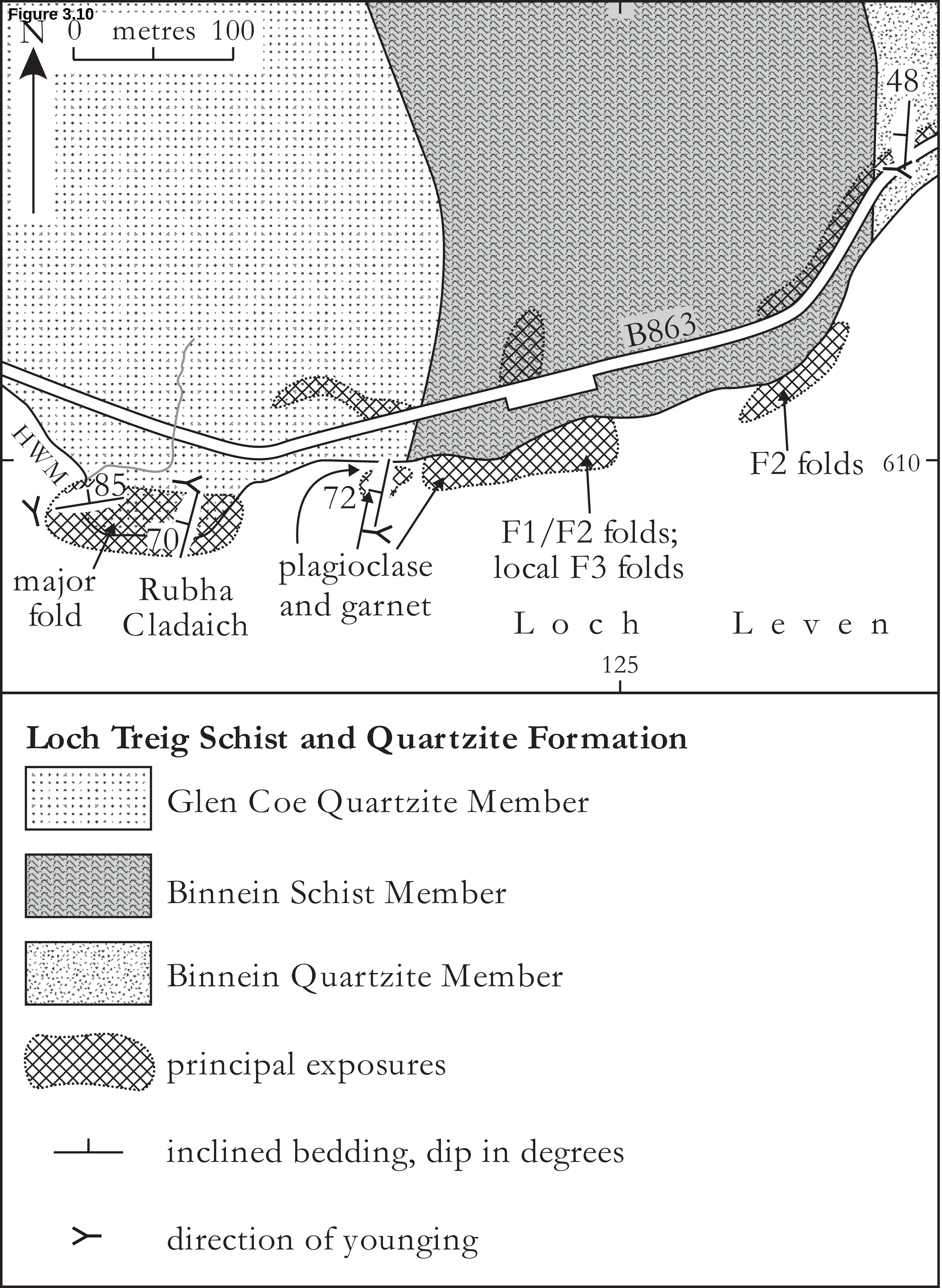

N
0 metres 200
63
81
85
76
73
B
60
80
A
88
85
82
Allt Nathrach
B863
Kinlochleven
C
88
62
Loch Leven
16
17
Binnein Schists
Binnein Quartzite
inclined bedding, dip in degrees
inclined S3 cleavage, dip in degrees
vertical S1 cleavage
vertical S3 cleavage
inclined S2 cleavage, dip in degrees
axial plane trace of F1 Mamore Syncline (downward facing)
vertical S2 cleavage
direction of younging

Figure 3.10



N
0 metres 100
48
B863
HWM
85
70
72
610
125
F2 folds
F1/F2 folds;
local F3 folds
plagioclase
and garnet
major
fold
Rubha
Cladaich
Loch Leven
Loch Treig Schist and Quartzite Formation
Glen Coe Quartzite Member
Binnein Schist Member
Binnein Quartzite Member
principal exposures
inclined bedding, dip in degrees
direction of younging

Figure 3.12

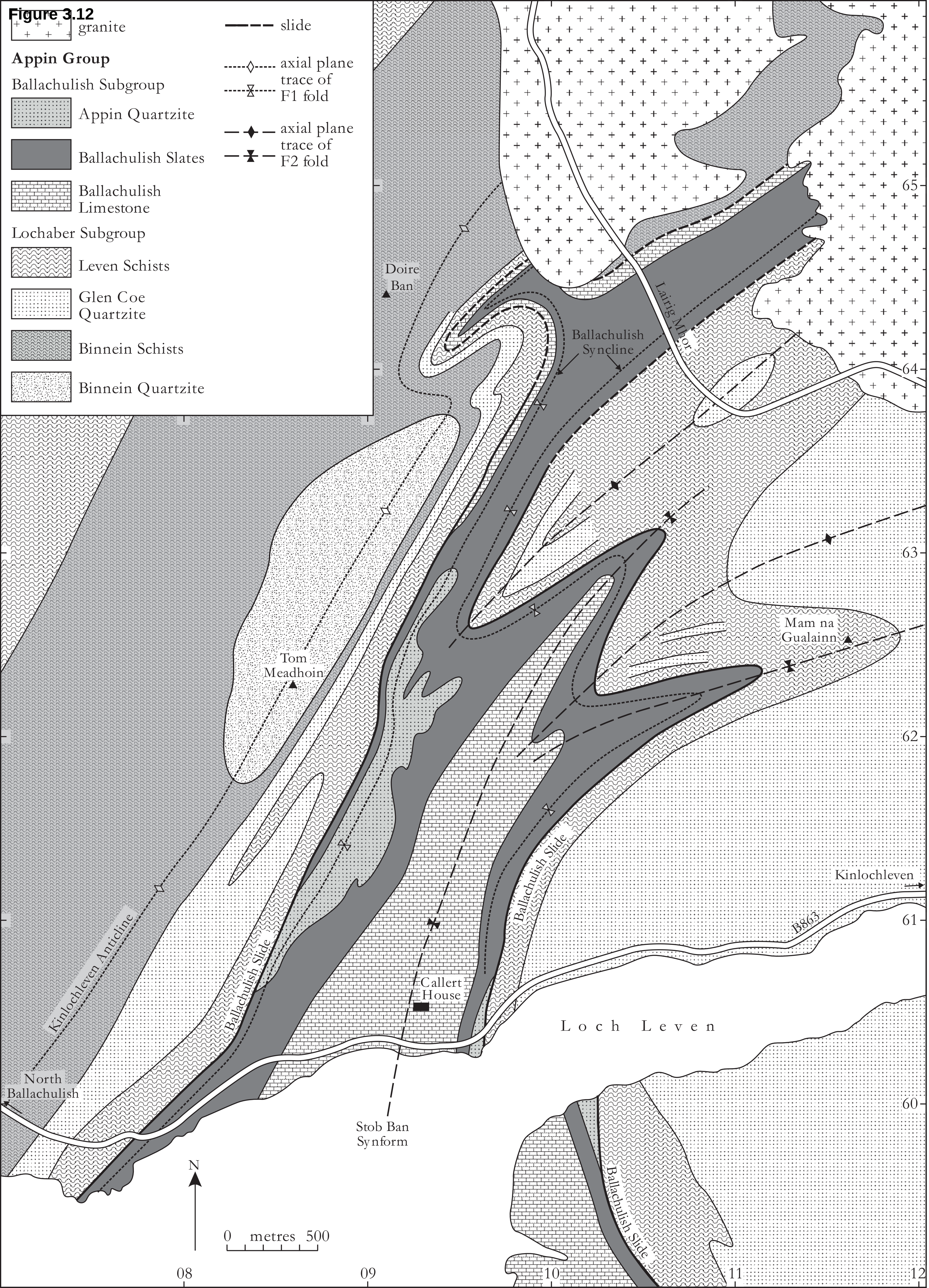

granite
Appin Group
Ballachulish Subgroup
Appin Quartzite
Ballachulish Slates
Ballachulish Limestone
Lochaber Subgroup
Leven Schists
Glen Coe Quartzite
Binnein Schists
Binnein Quartzite
slide
axial plane trace of F1 fold
axial plane trace of F2 fold
Doire Ban
Ballachulish Syncline
Lairig Mhor
Tom Meadhoin
Mam na Gualainn
Kinlochleven Anticline
Ballachulish Slide
Kinlochleven
B863
Callert House
Loch Leven
North Ballachulish
Stob Ban Synform
N
0 metres 500
08
09
10
11
12
65
64
63
62
61
60

Figure 3.13

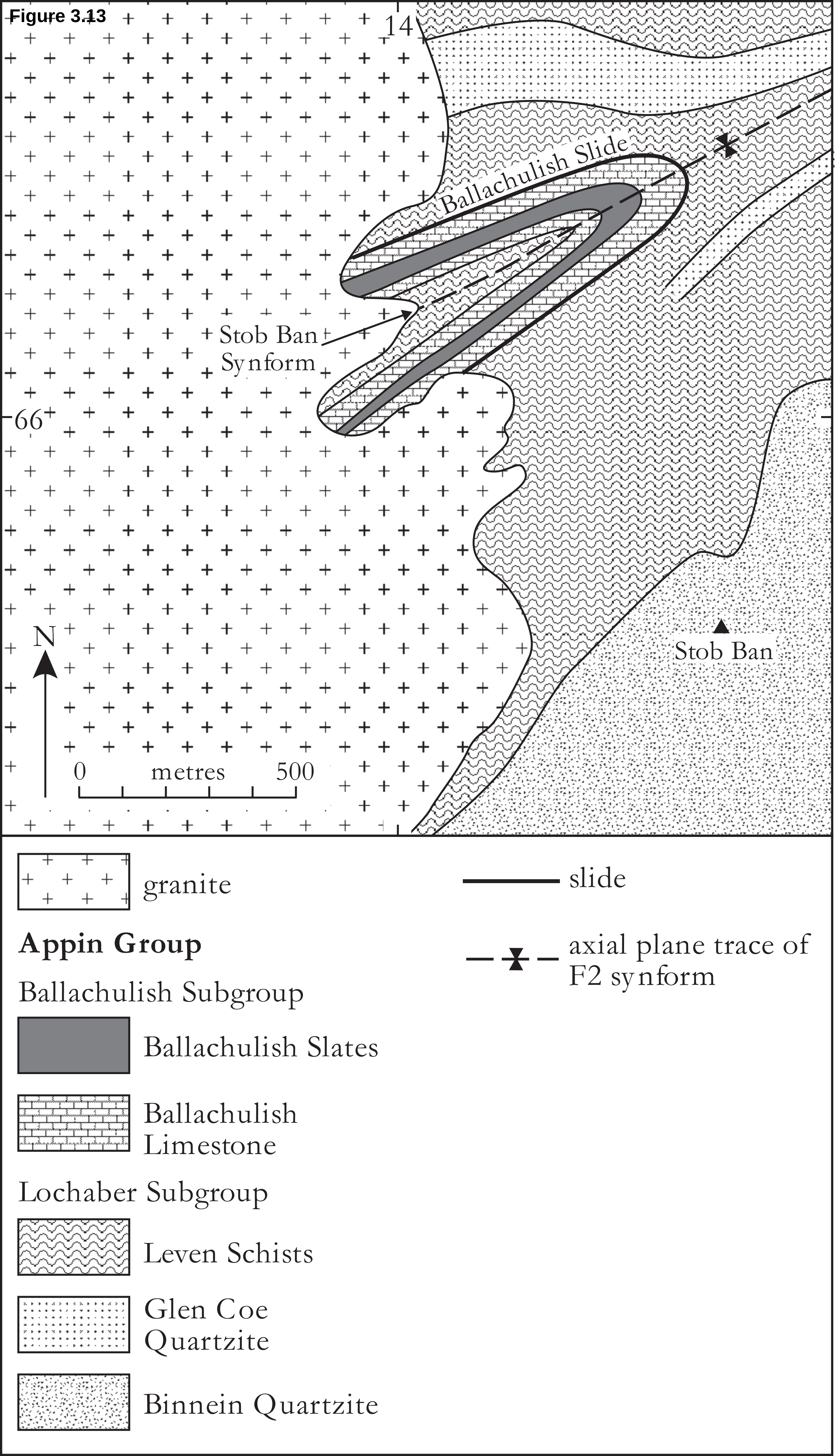

14
66
Ballachulish Slide
Stob Ban Synform
Stob Ban
N
0 metres 500
granite
Appin Group
Ballachulish Subgroup
Ballachulish Slates
Ballachulish Limestone
Lochaber Subgroup
Leven Schists
Glen Coe Quartzite
Binnein Quartzite
slide
axial plane trace of F2 synform

Figure 3.15

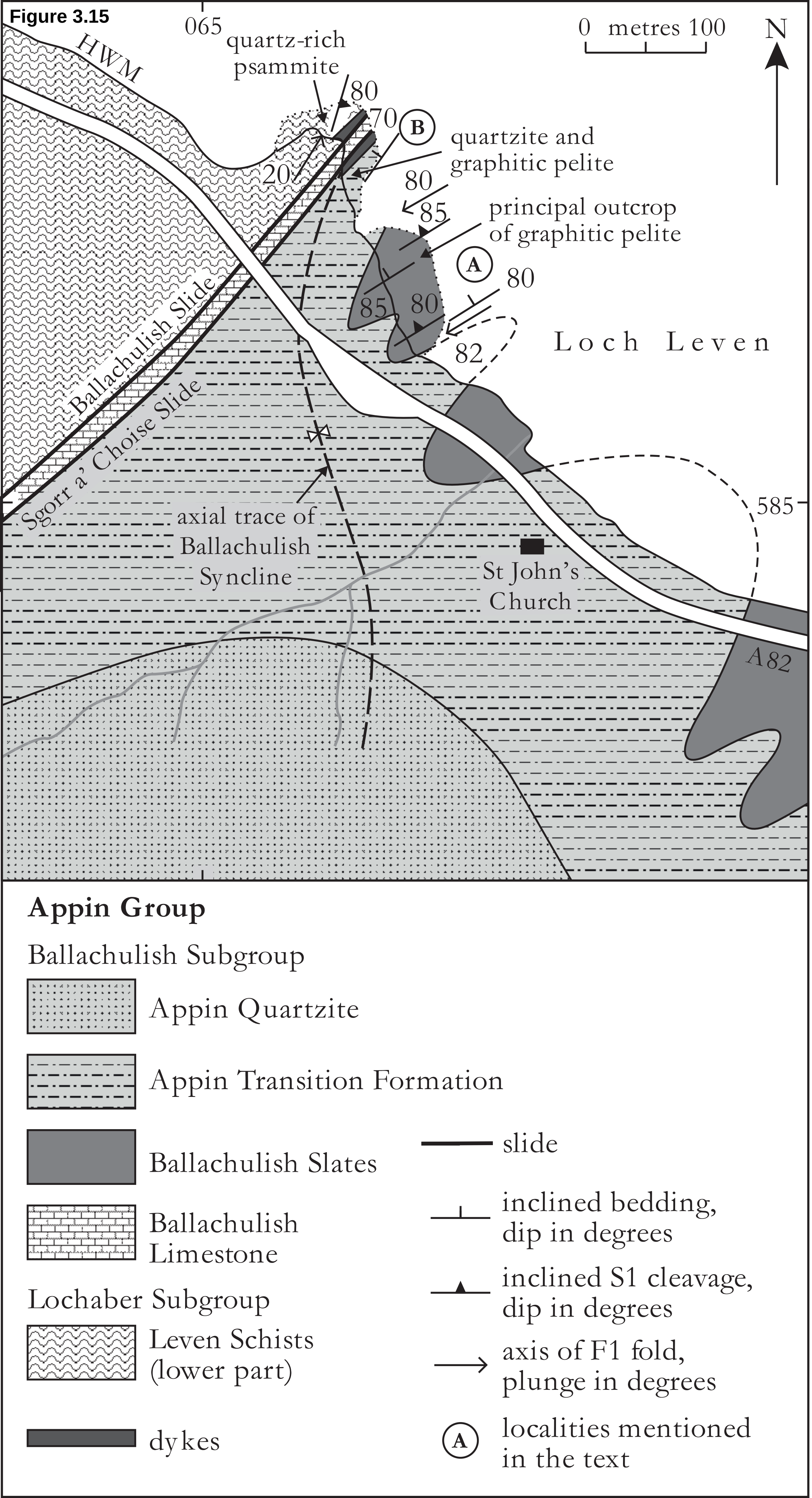
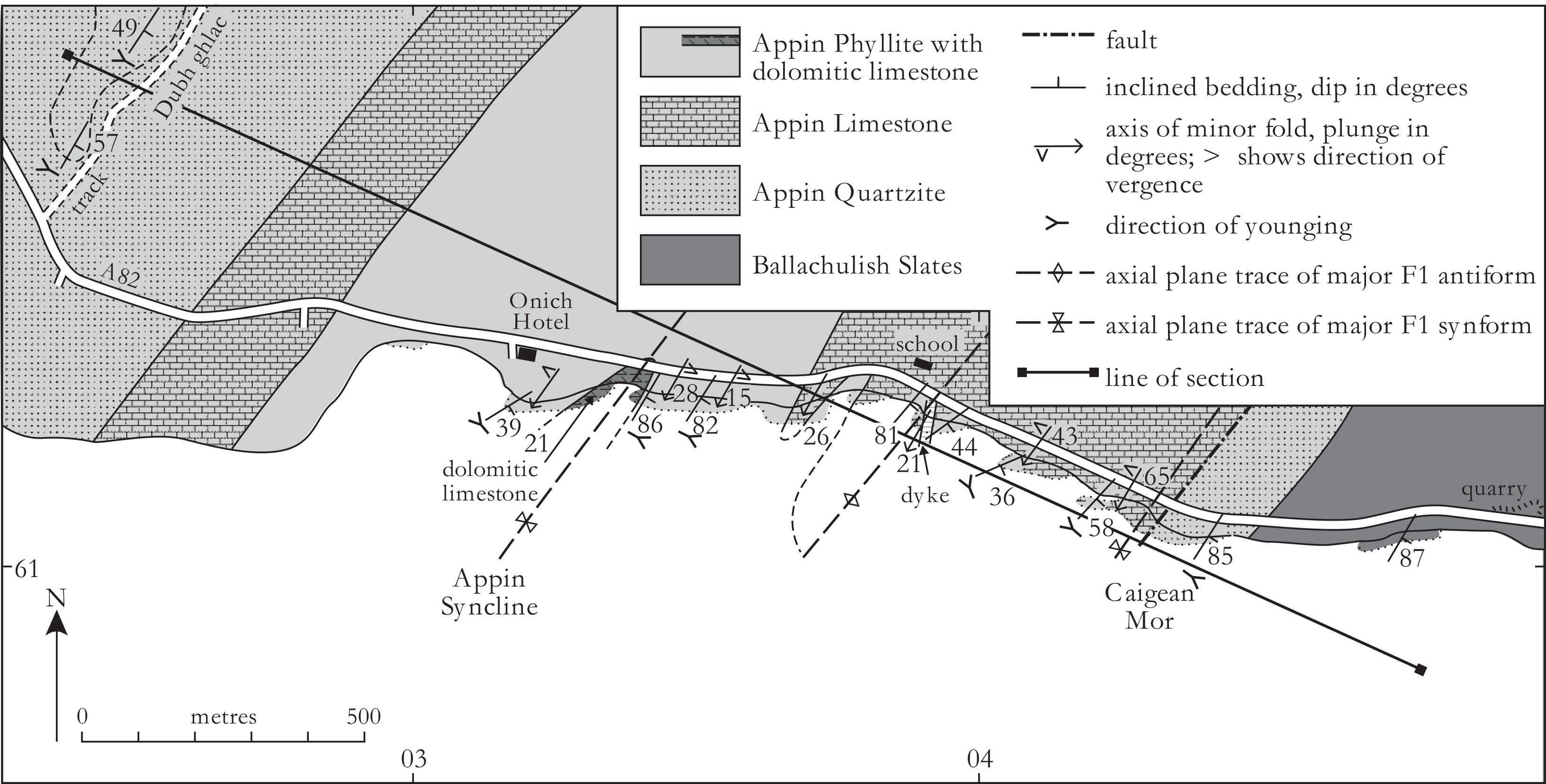

065
HWM
quartz-rich
psammite
80
70
20
B
quartzite and
graphitic pelite
80
85
principal outcrop
of graphitic pelite
A
80
85
80
82
Loch Leven
Ballachulish Slide
Sgorr a' Choise Slide
axial trace of
Ballachulish
Syncline
St John's
Church
585
A82
0 metres 100
N
Appin Group
Ballachulish Subgroup
Appin Quartzite
Appin Transition Formation
Ballachulish Slates
Ballachulish
Limestone
Lochaber Subgroup
Leven Schists
(lower part)
dykes
slide
inclined bedding,
dip in degrees
inclined S1 cleavage,
dip in degrees
axis of F1 fold,
plunge in degrees
localities mentioned
in the text

Figure 3.17



Appin Phyllite with dolomitic limestone
Appin Limestone
Appin Quartzite
Ballachulish Slates
fault
inclined bedding, dip in degrees
axis of minor fold, plunge in degrees; > shows direction of vergence
direction of younging
axial plane trace of major F1 antiform
axial plane trace of major F1 synform
line of section
Dubh ghlac
track
A82
Onich Hotel
school
dolomitic limestone
dyke
quarry
Appin Syncline
Caigean Mor
N
0
metres
500
03
04
61
49
57
39
21
86
28
82
15
26
81
21
44
43
36
65
58
85
87

Figure 3.18

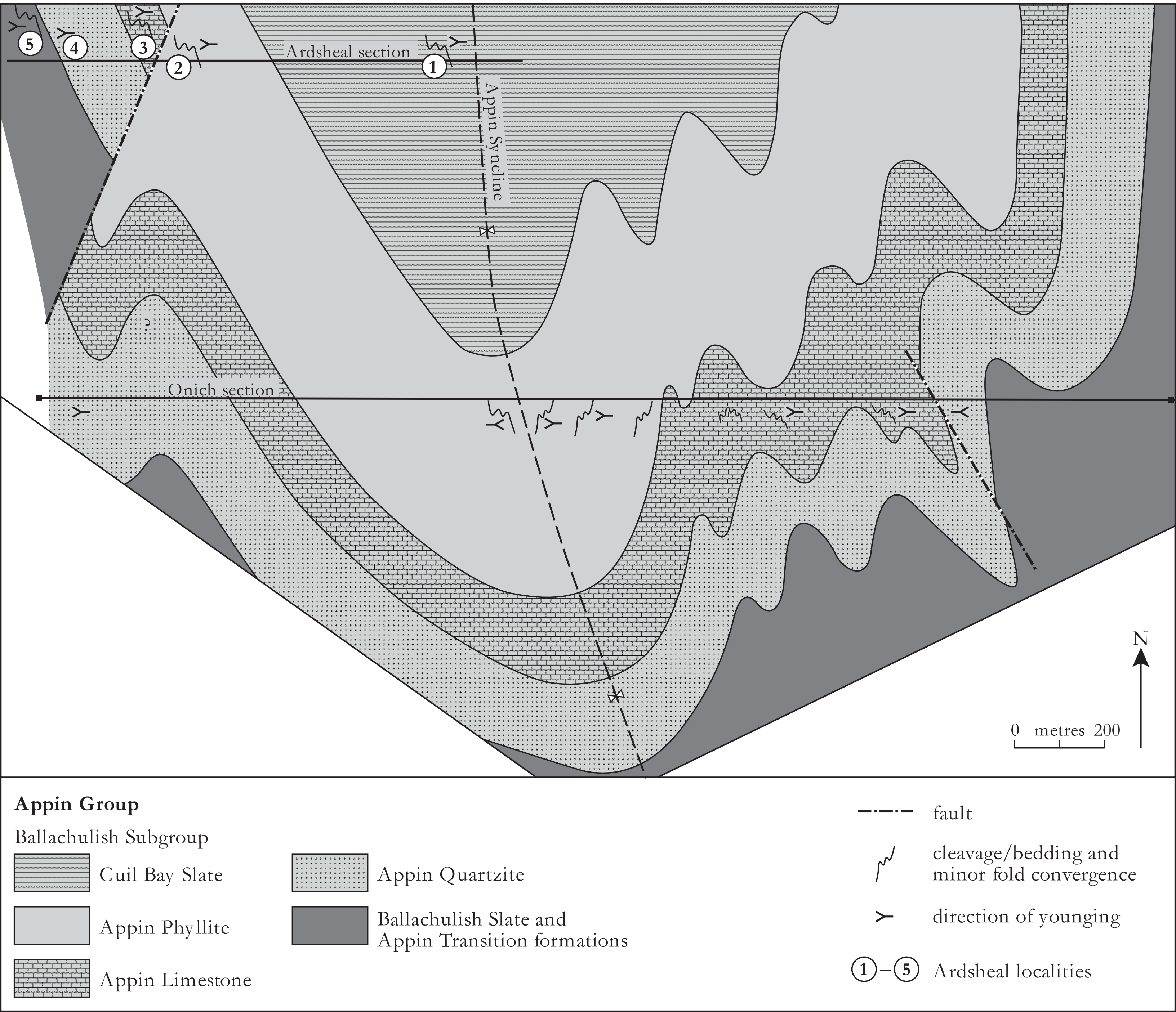

Ardsheal section
Appin Syncline
Onich section
1
2
3
4
5
N
0 metres 200
Appin Group
Ballachulish Subgroup
Cuil Bay Slate
Appin Phyllite
Appin Limestone
Appin Quartzite
Ballachulish Slate and
Appin Transition formations
fault
cleavage/bedding and
minor fold convergence
direction of younging
1 – 5 Ardsheal localities

Figure 3.20

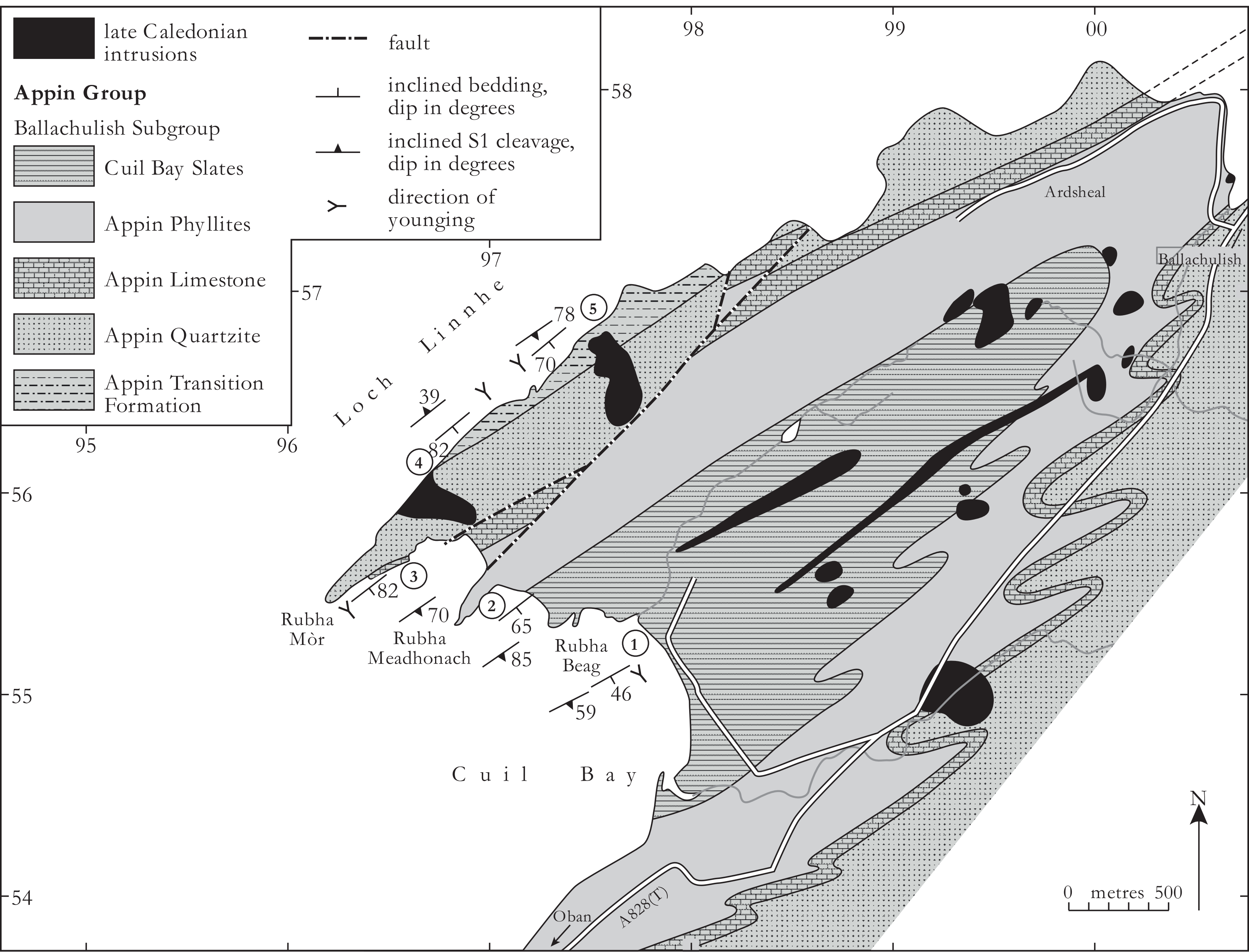
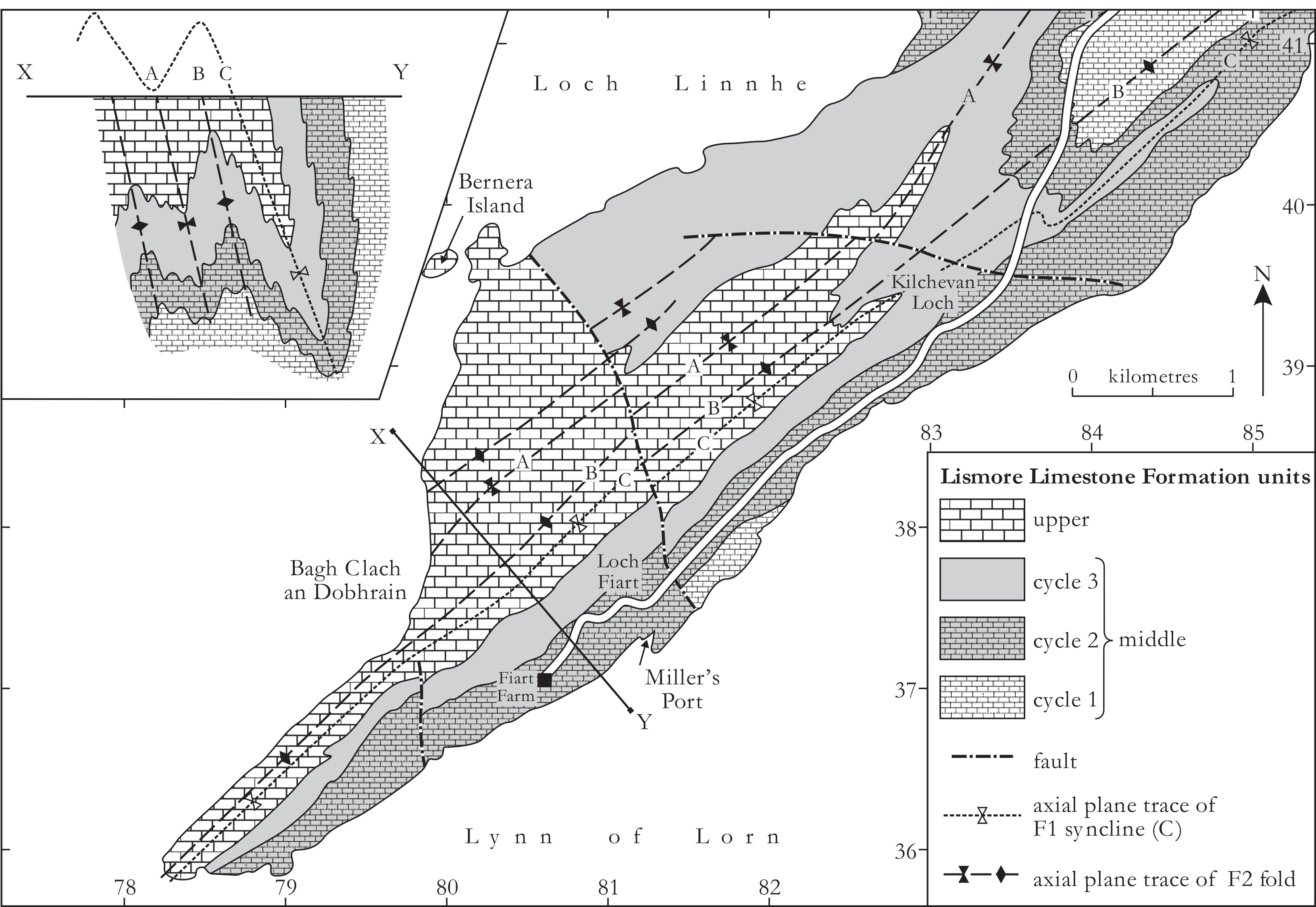
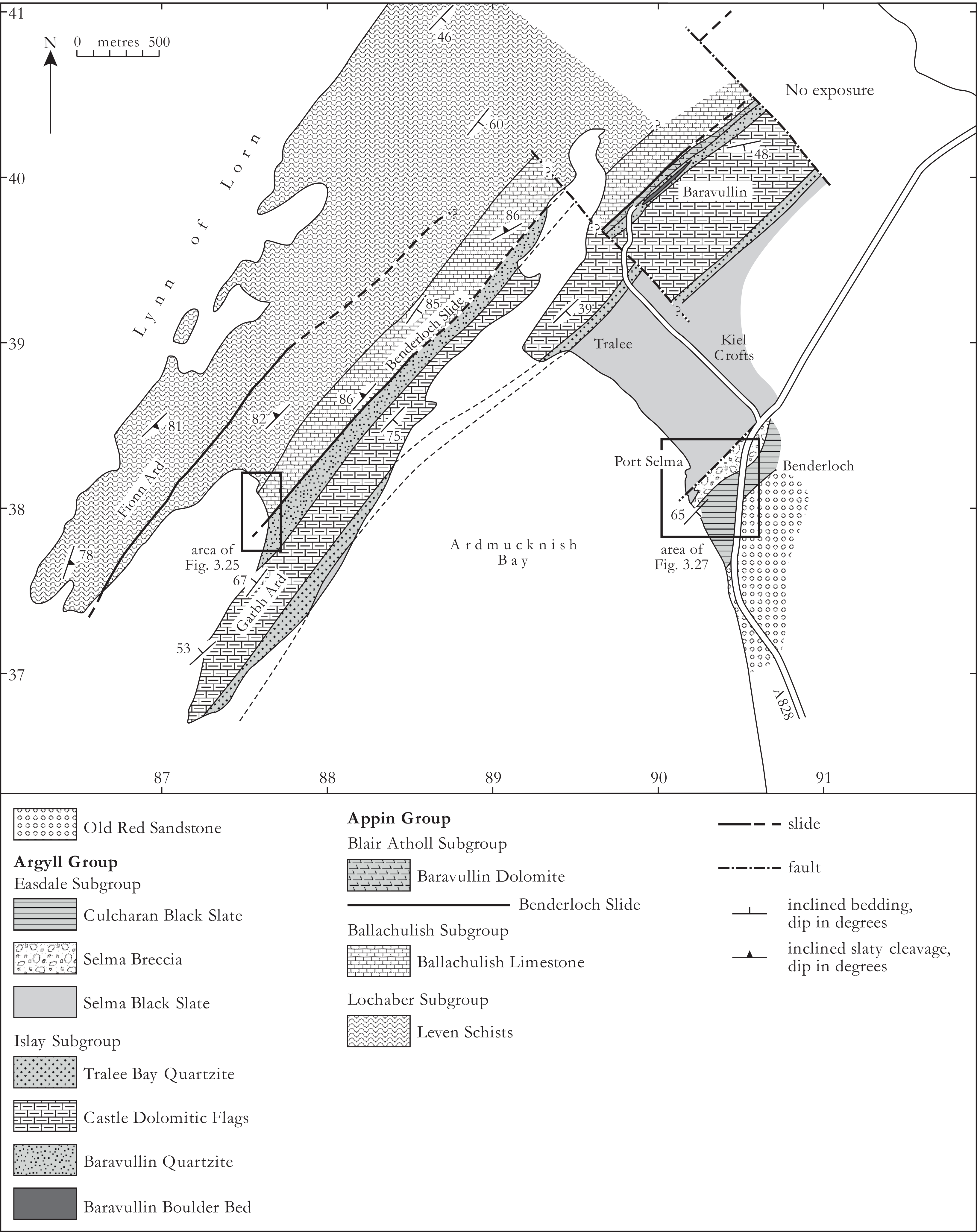

late Caledonian intrusions
Appin Group
Ballachulish Subgroup
Cuil Bay Slates
Appin Phyllites
Appin Limestone
Appin Quartzite
Appin Transition Formation
fault
inclined bedding, dip in degrees
inclined S1 cleavage, dip in degrees
direction of younging
Loch Linnhe
Cuil Bay
Rubha Mòr
Rubha Meadhonach
Rubha Beag
Ardsheal
Ballachulish
Oban
A828(T)
N
0 metres 500
95
96
97
98
99
00
54
55
56
57
58
78
70
39
82
82
70
65
85
46
59
1
2
3
4
5

Figure 3.22



X
A
B
C
Y
Loch Linnhe
Bernera
Island
Bagh Clach
an Dobhrain
Kilchevan
Loch
Loch
Fiart
Fiart
Farm
Miller's
Port
Lynn of Lorn
0 kilometres 1
N
78
79
80
81
82
83
84
85
36
37
38
39
40
41
Lismore Limestone Formation units
upper
cycle 3
cycle 2
cycle 1
middle
fault
axial plane trace of
F1 syncline (C)
axial plane trace of F2 fold

Figure 3.24



N
0 metres 500
41
40
39
38
37
87
88
89
90
91
Lynn of Lorn
No exposure
Baravullin
Benderloch Slide
Fionn Ard
Garbh Ard
Tralee
Kiel Crofts
Port Selma
Benderloch
Ardmucknish Bay
area of Fig. 3.25
area of Fig. 3.27
A828
46
60
48
86
85
39
86
82
81
75
78
67
53
65
Old Red Sandstone
Argyll Group
Easdale Subgroup
Culcharan Black Slate
Selma Breccia
Selma Black Slate
Islay Subgroup
Tralee Bay Quartzite
Castle Dolomitic Flags
Baravullin Quartzite
Baravullin Boulder Bed
Appin Group
Blair Atholl Subgroup
Baravullin Dolomite
Benderloch Slide
Ballachulish Subgroup
Ballachulish Limestone
Lochaber Subgroup
Leven Schists
slide
fault
inclined bedding, dip in degrees
inclined slaty cleavage, dip in degrees

Figure 3.25

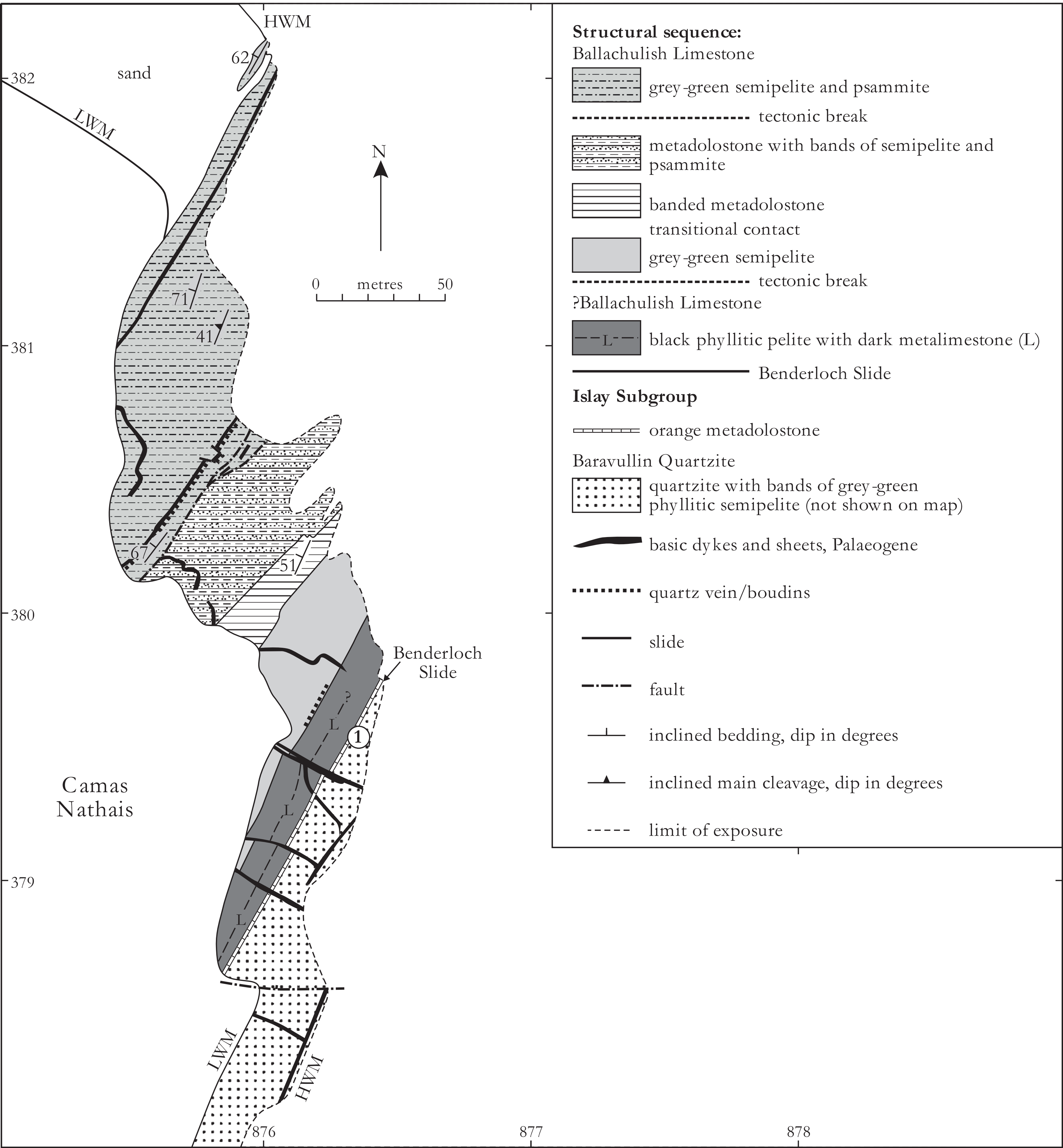
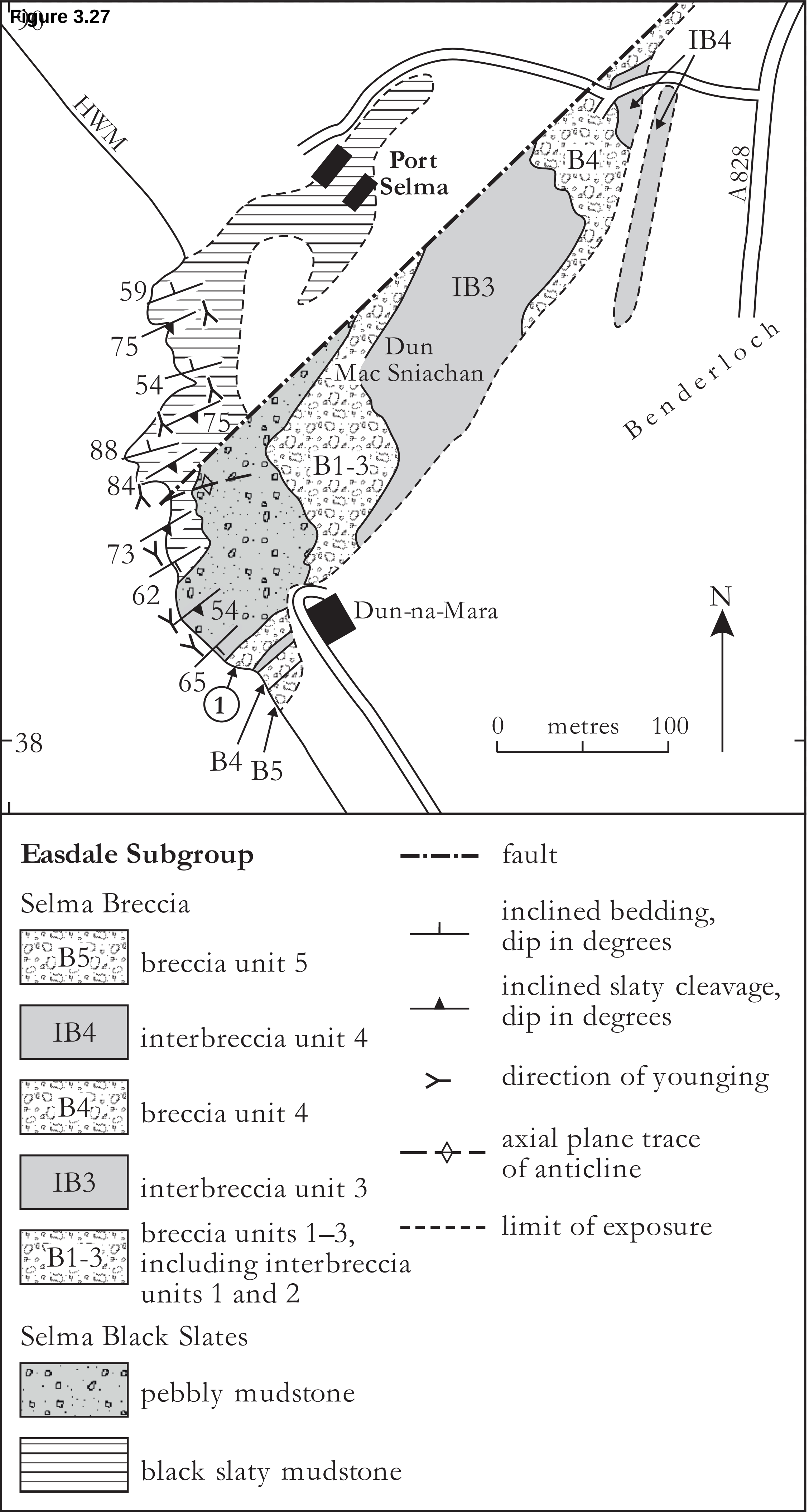

HWM
62
sand
382
LWM
N
0 metres 50
71
41
381
67
51
380
Benderloch Slide
1
L
L
L
?
379
Camas Nathais
LWM
HWM
876
877
878
Structural sequence:
Ballachulish Limestone
grey-green semipelite and psammite
tectonic break
metadolostone with bands of semipelite and psammite
banded metadolostone
transitional contact
grey-green semipelite
tectonic break
?Ballachulish Limestone
black phyllitic pelite with dark metalimestone (L)
Benderloch Slide
Islay Subgroup
orange metadolostone
Baravullin Quartzite
quartzite with bands of grey-green phyllitic semipelite (not shown on map)
basic dykes and sheets, Palaeogene
quartz vein/boudins
slide
fault
inclined bedding, dip in degrees
inclined main cleavage, dip in degrees
limit of exposure

Figure 3.27



HWM
Port Selma
IB4
B4
A828
IB3
Dun Mac Sniachan
Benderloch
B1-3
Dun-na-Mara
N
0 metres 100
38
59
75
54
75
88
84
73
62
54
65
1
B4
B5
Easdale Subgroup
Selma Breccia
B5 breccia unit 5
IB4 interbreccia unit 4
B4 breccia unit 4
IB3 interbreccia unit 3
B1-3 breccia units 1–3, including interbreccia units 1 and 2
Selma Black Slates
pebbly mudstone
black slaty mudstone
fault
inclined bedding, dip in degrees
inclined slaty cleavage, dip in degrees
direction of younging
axial plane trace of anticline
limit of exposure

Figure 3.29

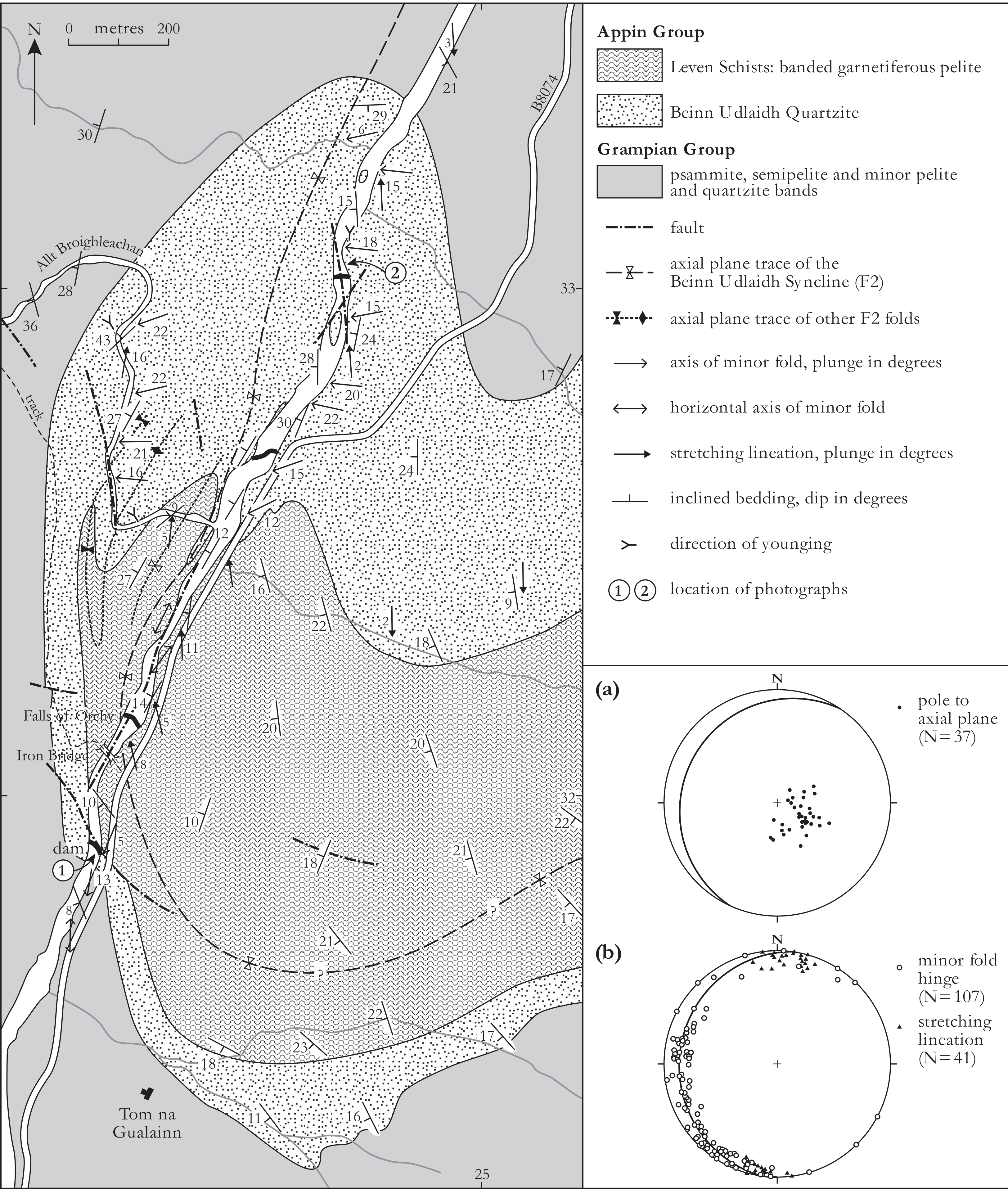

N
0 metres 200
Appin Group
Leven Schists: banded garnetiferous pelite
Beinn Udlaidh Quartzite
Grampian Group
psammite, semipelite and minor pelite and quartzite bands
fault
axial plane trace of the Beinn Udlaidh Syncline (F2)
axial plane trace of other F2 folds
axis of minor fold, plunge in degrees
horizontal axis of minor fold
stretching lineation, plunge in degrees
inclined bedding, dip in degrees
direction of younging
1 2 location of photographs
Allt Broighleachan
track
B8074
Falls of Orchy
Iron Bridge
dam
Tom na Gualainn
33
25
(a)
N
pole to axial plane (N = 37)
(b)
N
minor fold hinge (N = 107)
stretching lineation (N = 41)

Figure 3.37


77
78
79
62
61
60
N
0 metres 200
Meall Reamhar Synform axial trace
Allt na Coire Bhuidhe
Allt Charmaig
493m
Meall
Reamhar
477m
Creag nan
Caisean
surge
shaft
forestry road
26
30
25
50
25
20
40
50
60
70
5
50
10
55
46
35
70
30
70
48
40
50
30
20
26
55
45
20
60
43
30
45
76
68
60
50
60
Tummel Psammite Formation
Tummel Quartzite Formation
with beds of white quartzite
Bruar Formation
pelite in Bruar Formation
fault
inclined bedding,
dip in degrees
vertical bedding
inclined S2 schistosity,
dip in degrees
axis of minor fold,
plunge in degrees
direction of younging

Figure 3.39a

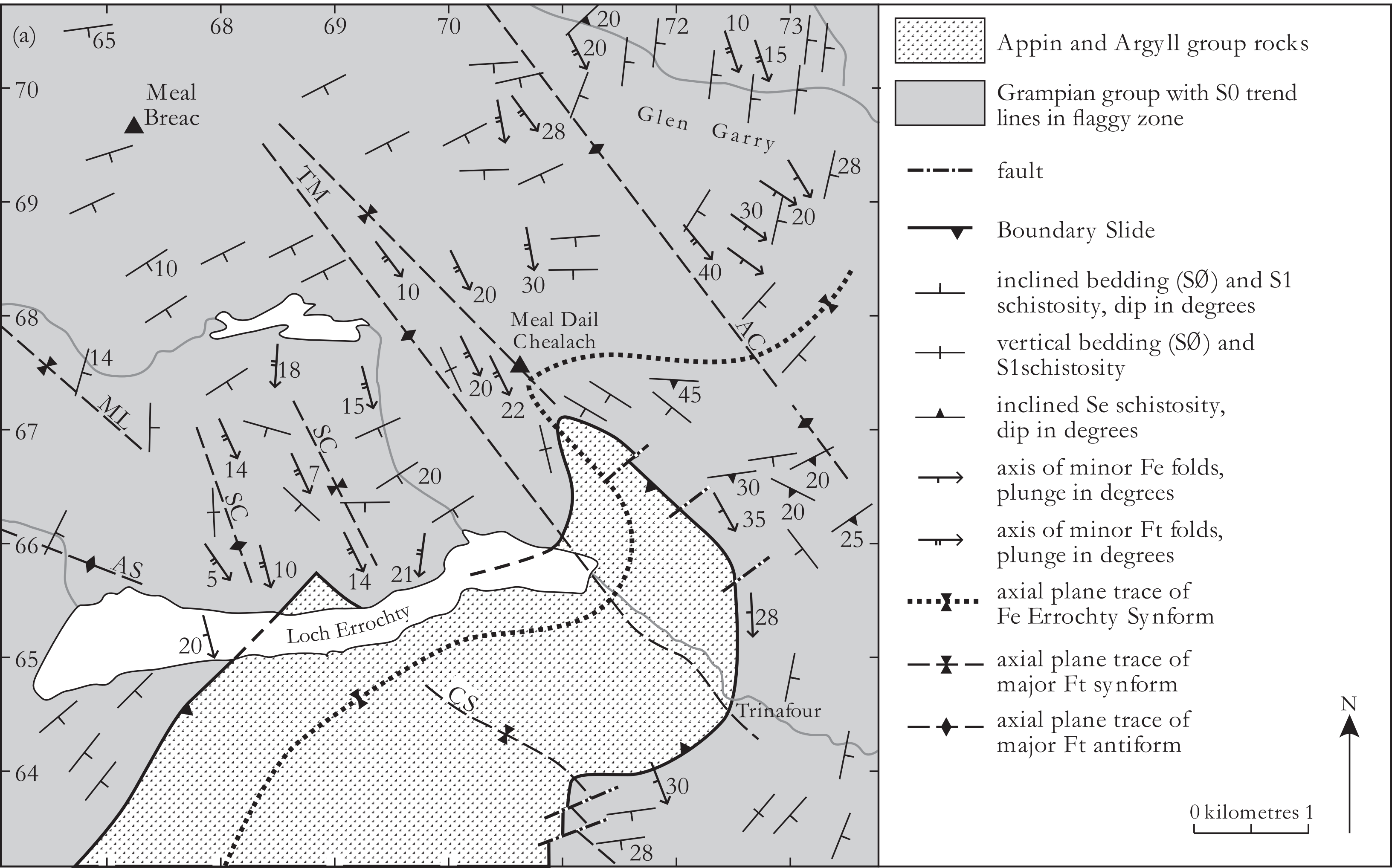
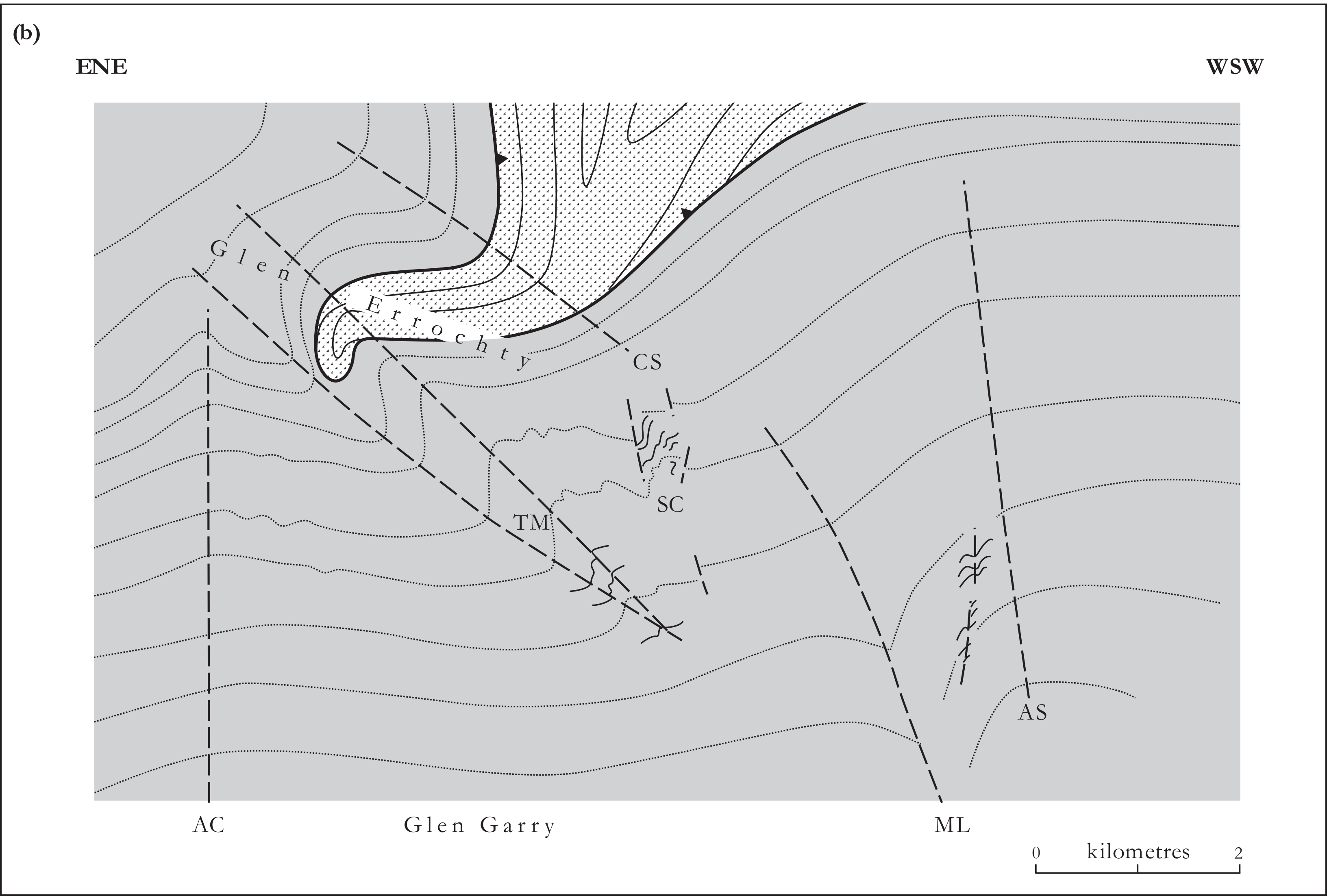

(a)
Meal Breac
Meal Dail Chealach
Glen Garry
Loch Errochty
Trinafour
TM
ML
SC
AS
AC
CS
Appin and Argyll group rocks
Grampian group with S0 trend lines in flaggy zone
fault
Boundary Slide
inclined bedding (SØ) and S1 schistosity, dip in degrees
vertical bedding (SØ) and S1schistosity
inclined Se schistosity, dip in degrees
axis of minor Fe folds, plunge in degrees
axis of minor Ft folds, plunge in degrees
axial plane trace of Fe Errochty Synform
axial plane trace of major Ft synform
axial plane trace of major Ft antiform
N
0 kilometres 1

Figure 3.39b



(b)
ENE
WSW
G l e n
E r r o c h t y
CS
SC
TM
AS
AC
Glen Garry
ML
0
kilometres
2

Figure 3.41

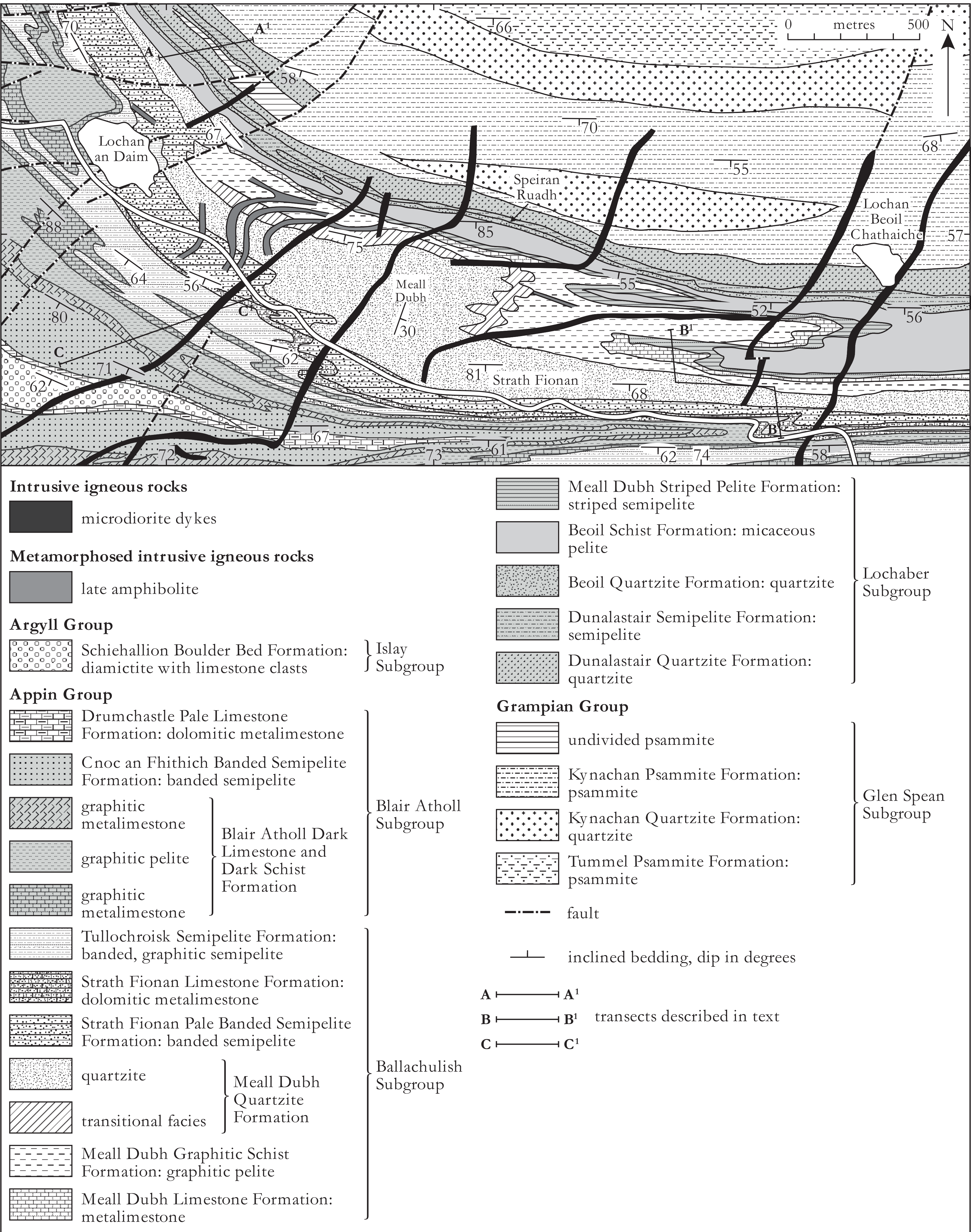

0 metres 500
N
A
A1
B
B1
C
C1
Lochan an Daim
Speiran Ruadh
Meall Dubh
Strath Fionan
Lochan Beoil Chathaiche
Intrusive igneous rocks
microdiorite dykes
Metamorphosed intrusive igneous rocks
late amphibolite
Argyll Group
Schiehallion Boulder Bed Formation: diamictite with limestone clasts
Islay Subgroup
Appin Group
Drumchastle Pale Limestone Formation: dolomitic metalimestone
Cnoc an Fhithich Banded Semipelite Formation: banded semipelite
graphitic metalimestone
graphitic pelite
graphitic metalimestone
Blair Atholl Dark Limestone and Dark Schist Formation
Blair Atholl Subgroup
Tullochroisk Semipelite Formation: banded, graphitic semipelite
Strath Fionan Limestone Formation: dolomitic metalimestone
Strath Fionan Pale Banded Semipelite Formation: banded semipelite
quartzite
transitional facies
Meall Dubh Quartzite Formation
Meall Dubh Graphitic Schist Formation: graphitic pelite
Meall Dubh Limestone Formation: metalimestone
Ballachulish Subgroup
Meall Dubh Striped Pelite Formation: striped semipelite
Beoil Schist Formation: micaceous pelite
Beoil Quartzite Formation: quartzite
Dunalastair Semipelite Formation: semipelite
Dunalastair Quartzite Formation: quartzite
Lochaber Subgroup
Grampian Group
undivided psammite
Kynachan Psammite Formation: psammite
Kynachan Quartzite Formation: quartzite
Tummel Psammite Formation: psammite
Glen Spean Subgroup
fault
inclined bedding, dip in degrees
A A1
B B1
C C1
transects described in text

Figure 3.44

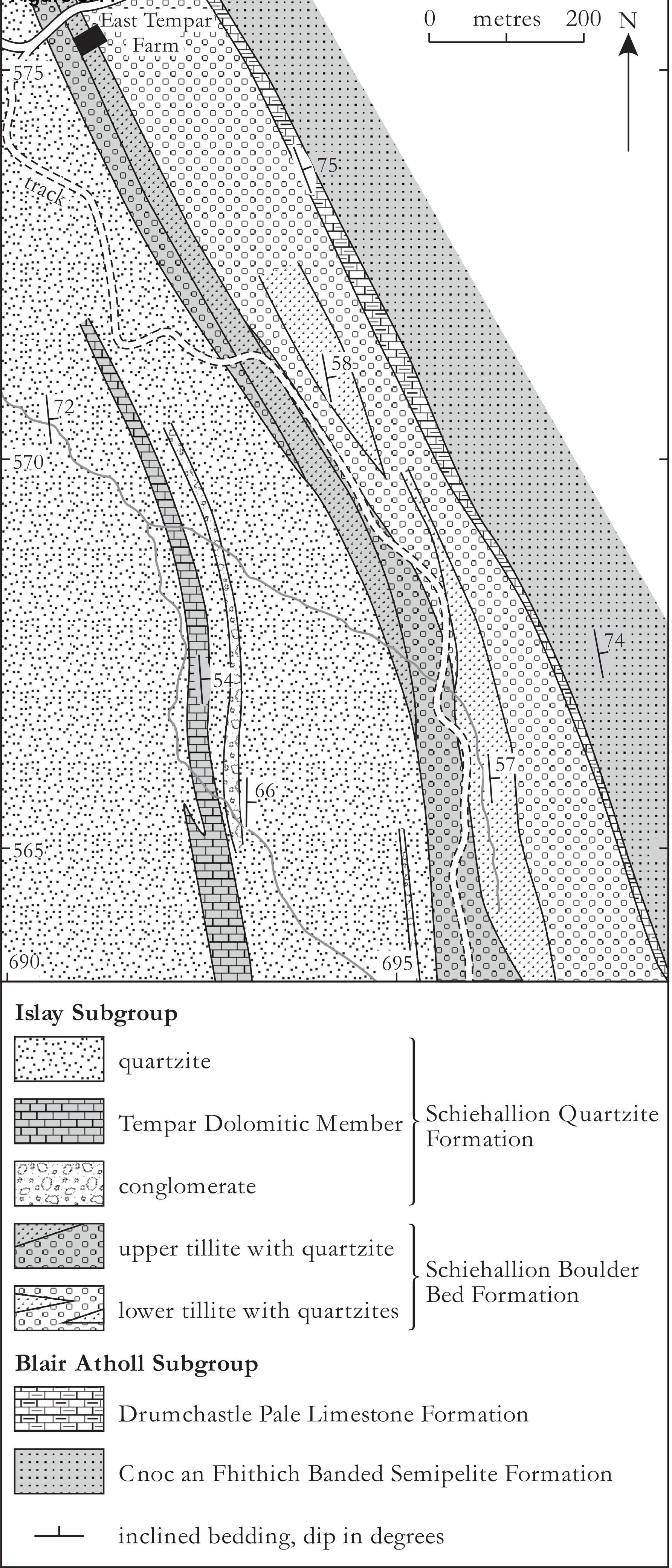

East Tempar Farm
track
0 metres 200
N
575
570
565
690
695
75
58
72
54
66
57
74
Islay Subgroup
quartzite
Tempar Dolomitic Member
conglomerate
Schiehallion Quartzite Formation
upper tillite with quartzite
lower tillite with quartzites
Schiehallion Boulder Bed Formation
Blair Atholl Subgroup
Drumchastle Pale Limestone Formation
Cnoc an Fhithich Banded Semipelite Formation
inclined bedding, dip in degrees

Figure 3.46

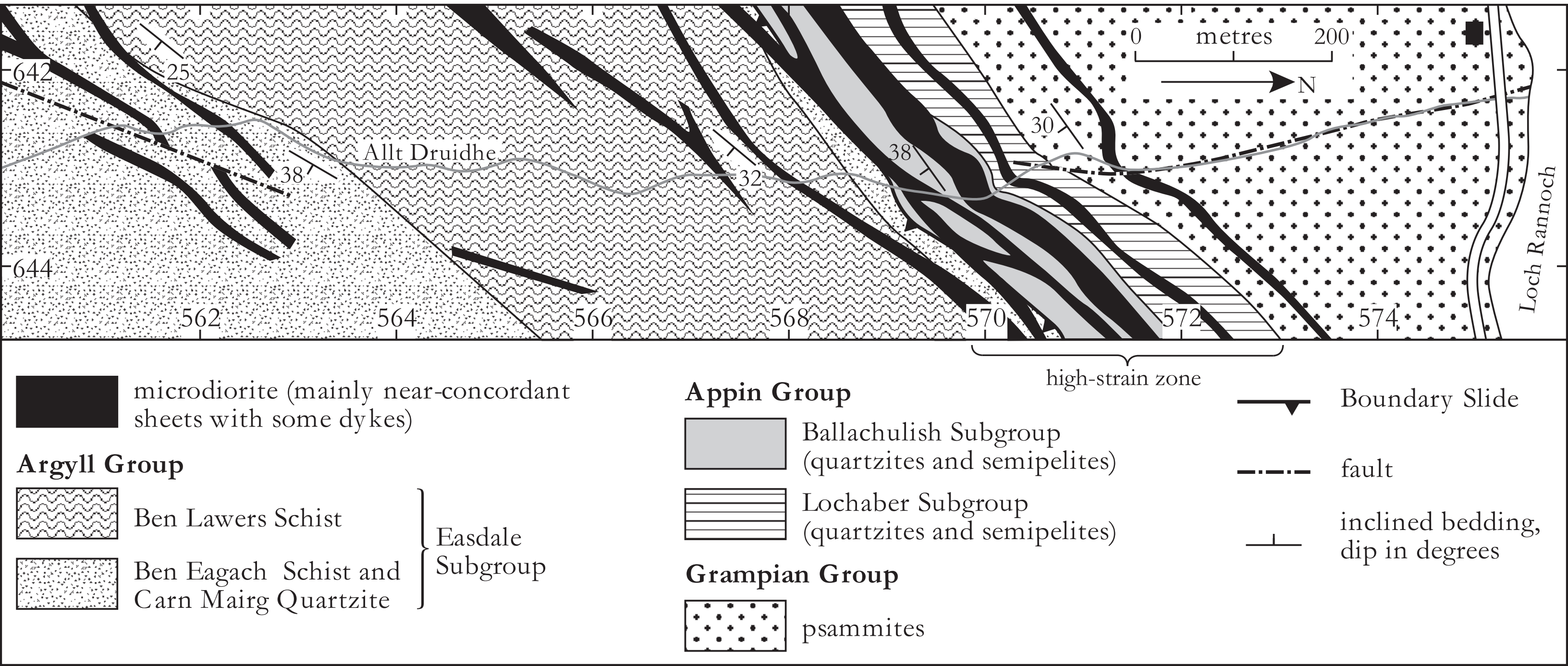

642
644
562
564
566
568
570
572
574
25
38
32
38
30
Allt Druidhe
0 metres 200
N
Loch Rannoch
high-strain zone
microdiorite (mainly near-concordant sheets with some dykes)
Argyll Group
Ben Lawers Schist
Ben Eagach Schist and Carn Mairg Quartzite
Easdale Subgroup
Appin Group
Ballachulish Subgroup (quartzites and semipelites)
Lochaber Subgroup (quartzites and semipelites)
Grampian Group
psammites
Boundary Slide
fault
inclined bedding, dip in degrees

Figure 3.47a

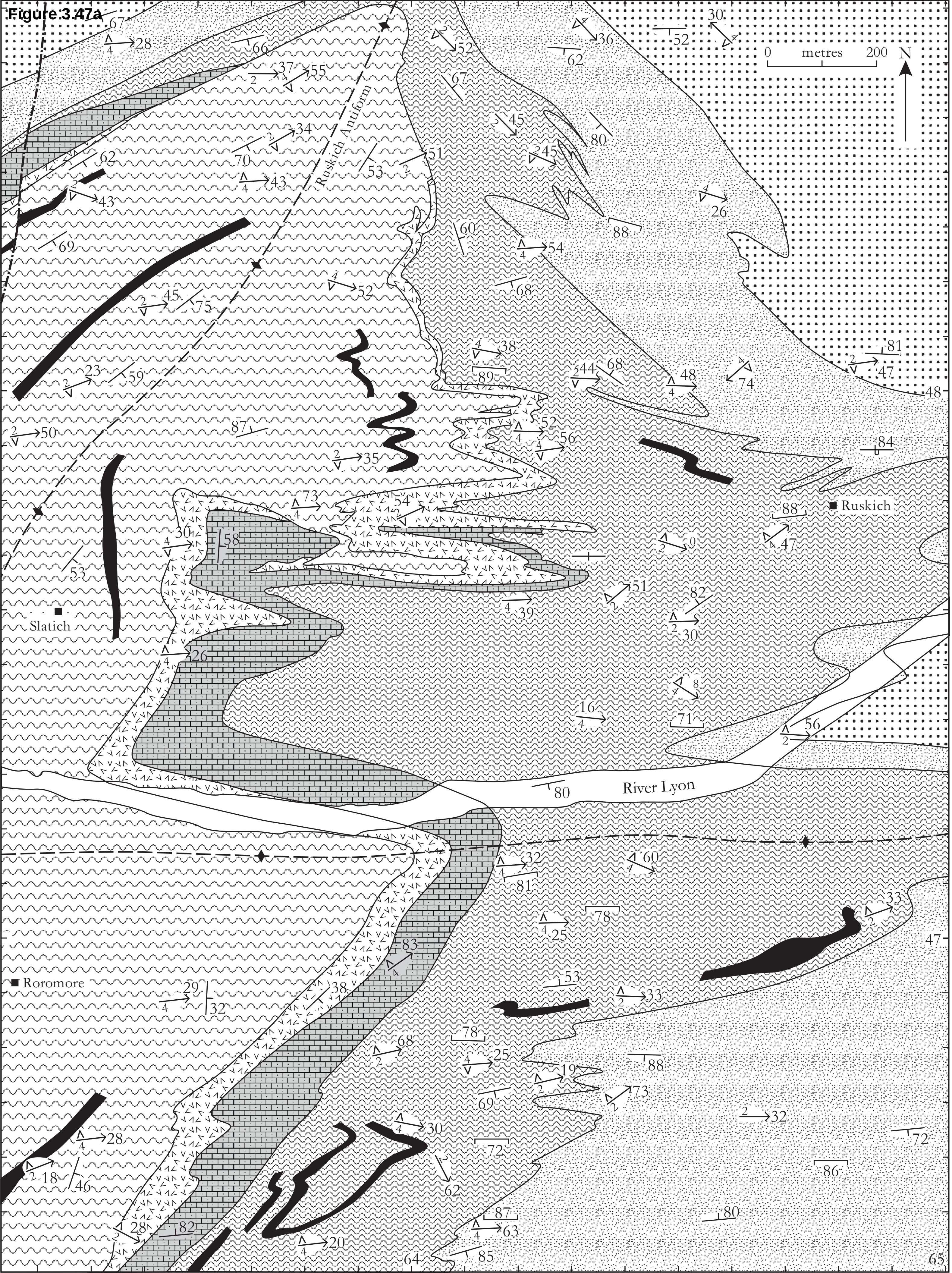

0
metres
200
N
Ruskich Antiform
Ruskich
Slatich
Roromore
River Lyon
48
47
64
65

Figure 3.47b

amphibolite

Crinan Subgroup

Ben Lui Schist

Easdale Subgroup

Farragon Volcanic Formation

Ben Lawers Schist with dolomitic quartzite at top

Ben Eagach Schist

Carn Mairg Quartzite

fault

inclined bedding, dip in degrees

inclined bedding known to be overturned, dip in degrees

vertical bedding

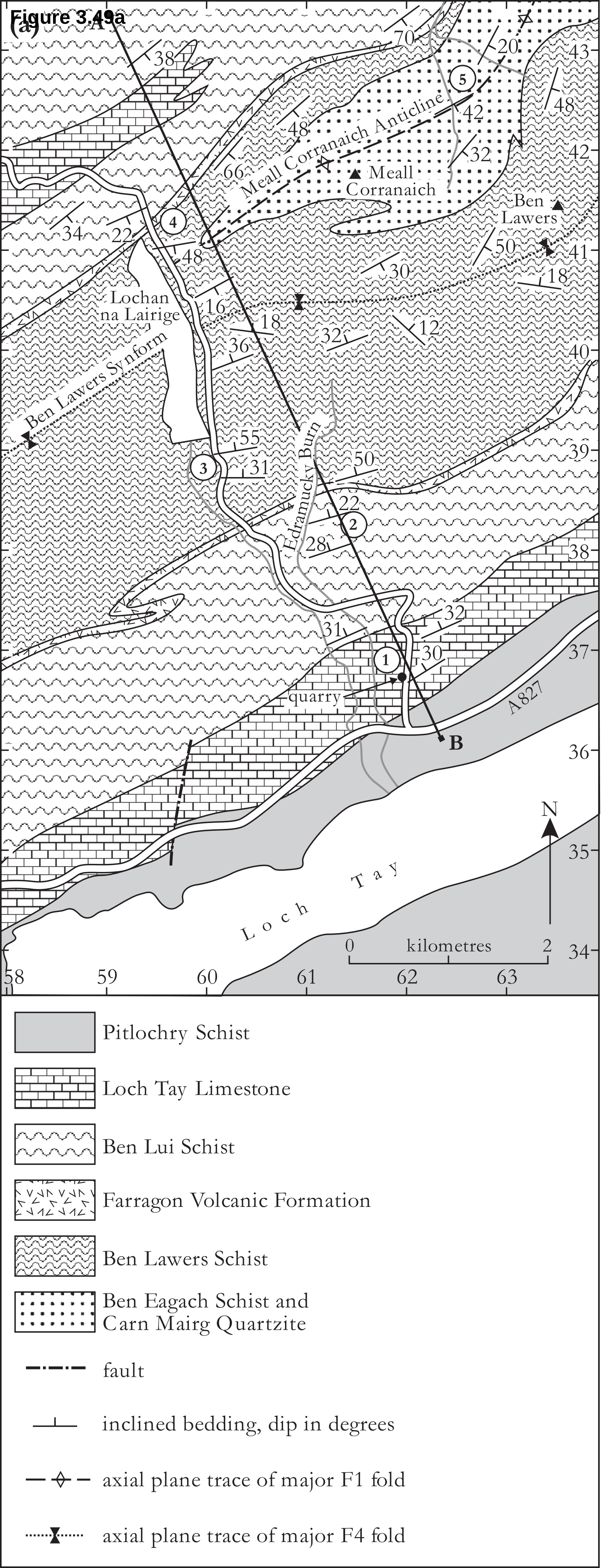
axis of F2 minor fold or bedding/S2 cleavage intersection, plunge in degrees (flag shows direction of vergence)

axis of F4 minor fold, plunge in degrees (flag shows direction of vergence)

inclined axial plane of F4 minor fold, dip in degrees

axial plane trace of major antiform

Figure 3.49a



(a)
A
B
Meall Corranaich Anticline
Meall Corranaich
Ben Lawers
Lochan na Lairige
Ben Lawers Synform
Edramucky Burn
quarry
A827
Loch Tay
N
0 kilometres 2
Pitlochry Schist
Loch Tay Limestone
Ben Lui Schist
Farragon Volcanic Formation
Ben Lawers Schist
Ben Eagach Schist and Carn Mairg Quartzite
fault
inclined bedding, dip in degrees
axial plane trace of major F1 fold
axial plane trace of major F4 fold

Figure 3.49b

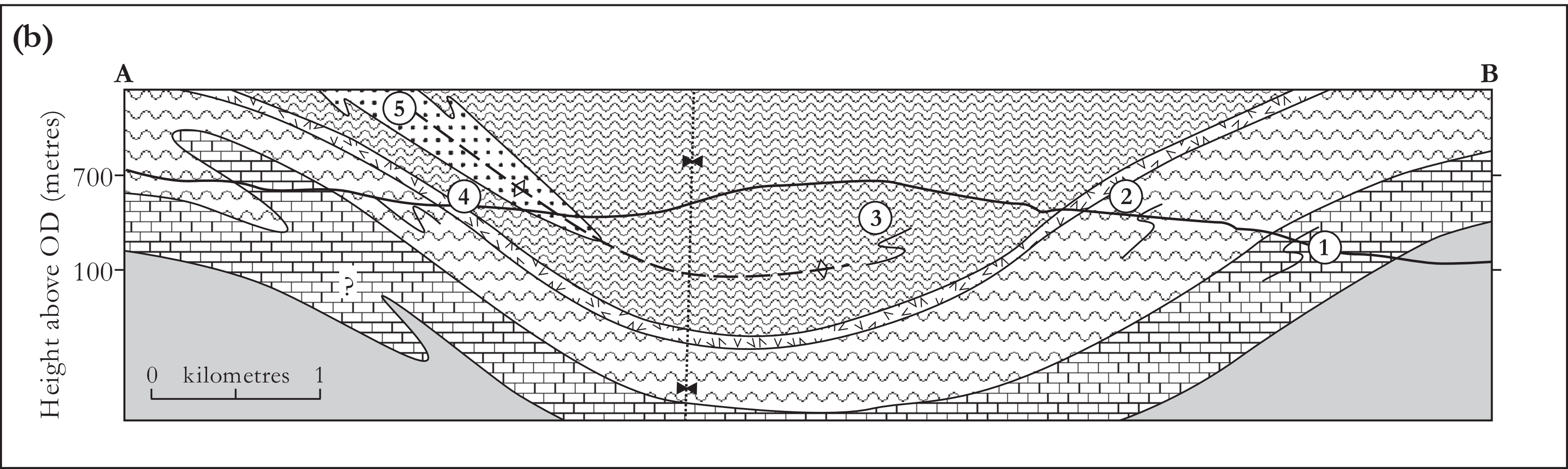


Figure 3.51

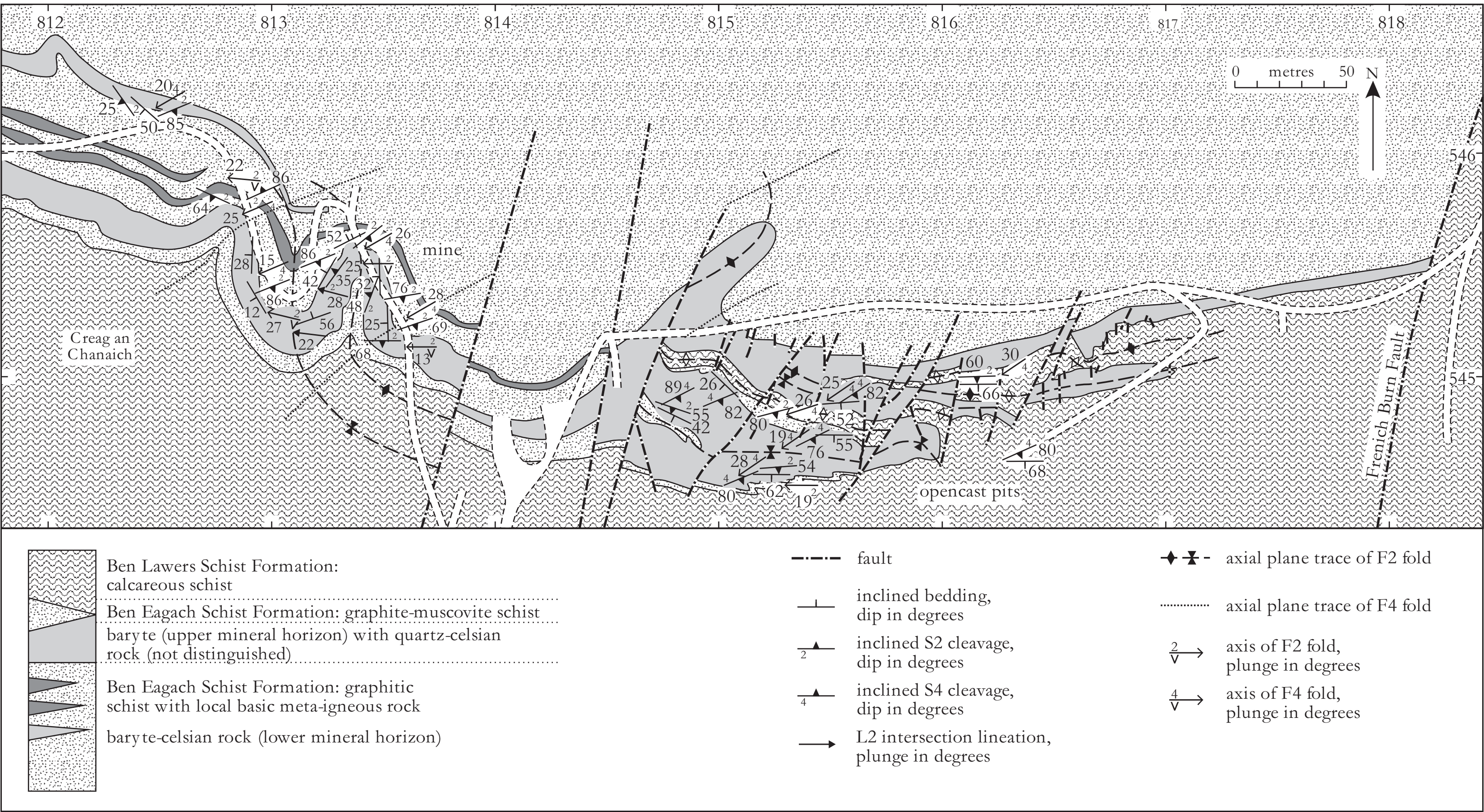

812
813
814
815
816
817
818
546
545
0 metres 50
N
mine
Creag an Chanaich
opencast pits
French Burn Fault
Ben Lawers Schist Formation: calcareous schist
Ben Eagach Schist Formation: graphite-muscovite schist
baryte (upper mineral horizon) with quartz-celsian rock (not distinguished)
Ben Eagach Schist Formation: graphitic schist with local basic meta-igneous rock
baryte-celsian rock (lower mineral horizon)
fault
inclined bedding, dip in degrees
inclined S2 cleavage, dip in degrees
inclined S4 cleavage, dip in degrees
L2 intersection lineation, plunge in degrees
axial plane trace of F2 fold
axial plane trace of F4 fold
axis of F2 fold, plunge in degrees
axis of F4 fold, plunge in degrees

Figure 3.52

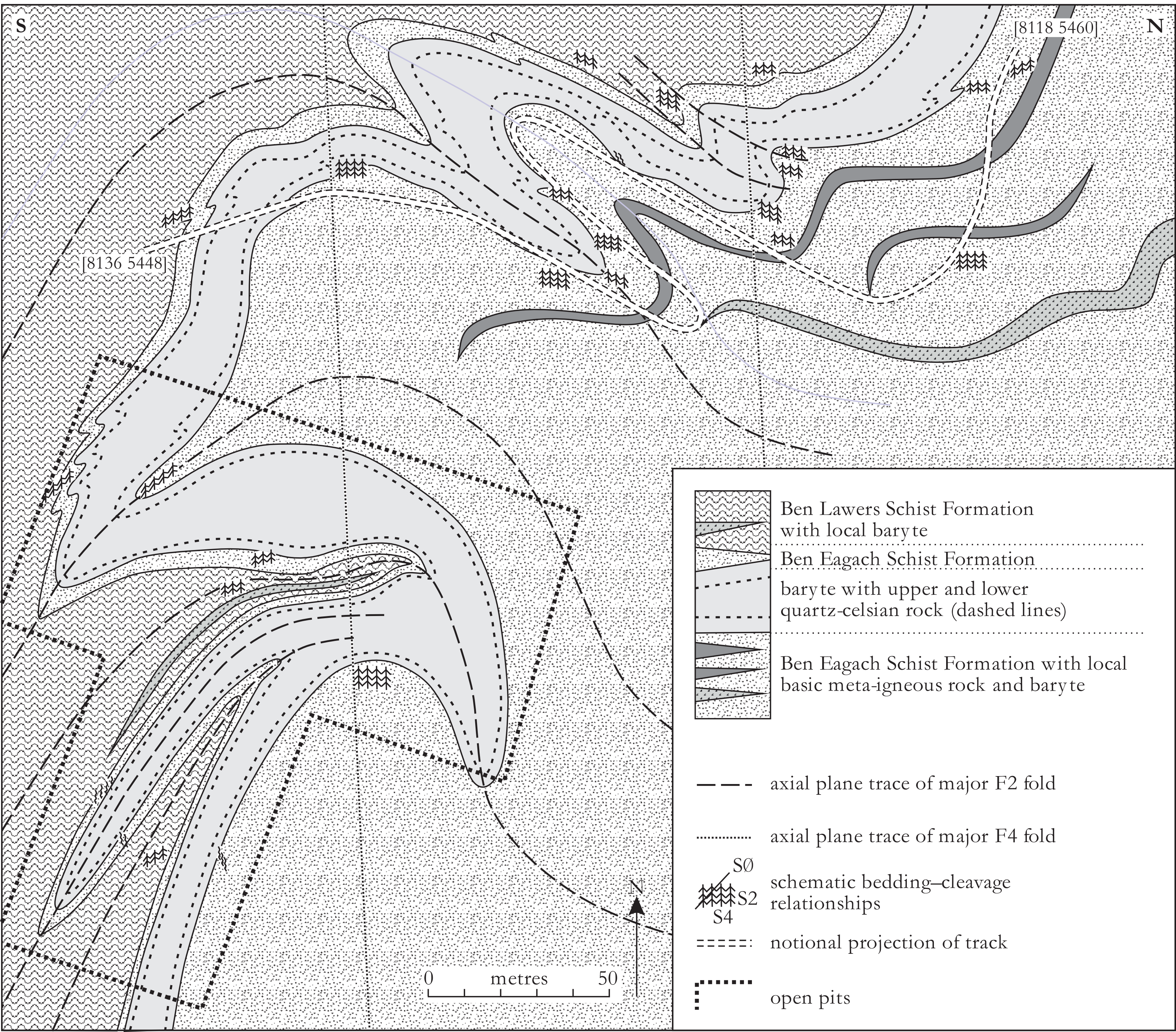

S
N
[8118 5460]
[8136 5448]
Ben Lawers Schist Formation
with local baryte
Ben Eagach Schist Formation
baryte with upper and lower
quartz-celsian rock (dashed lines)
Ben Eagach Schist Formation with local
basic meta-igneous rock and baryte
axial plane trace of major F2 fold
axial plane trace of major F4 fold
SØ
S2
S4
schematic bedding–cleavage
relationships
notional projection of track
open pits
0
metres
50

Figure 3.54

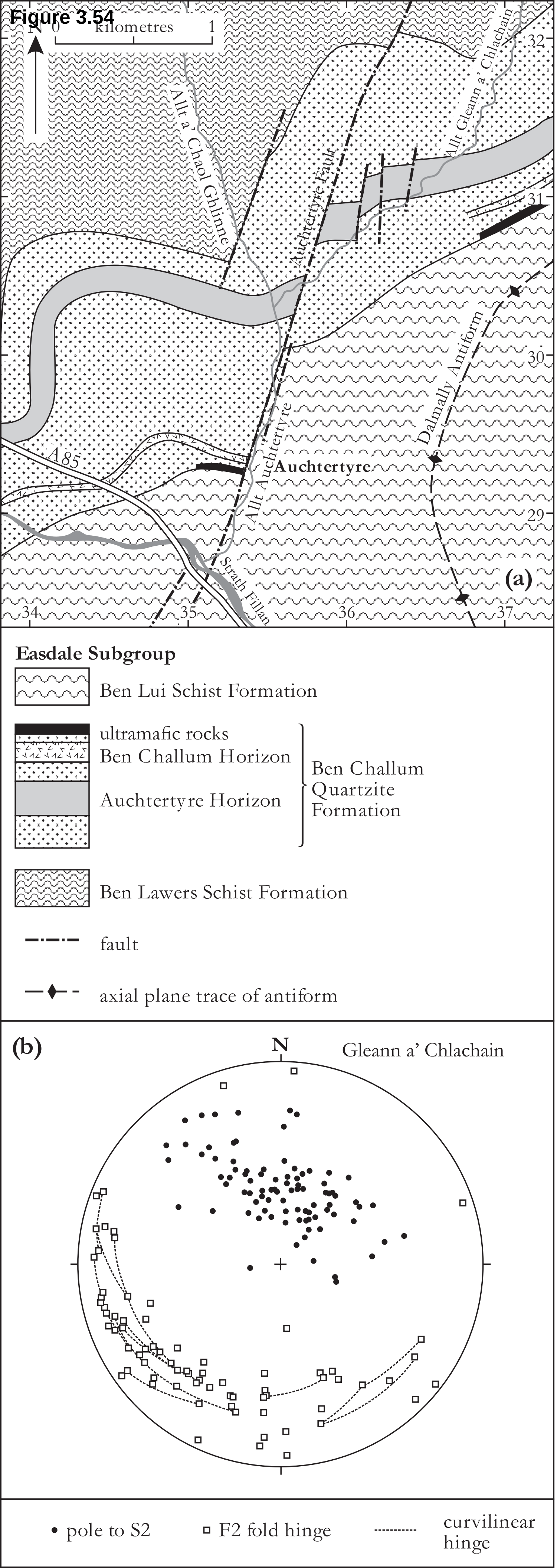
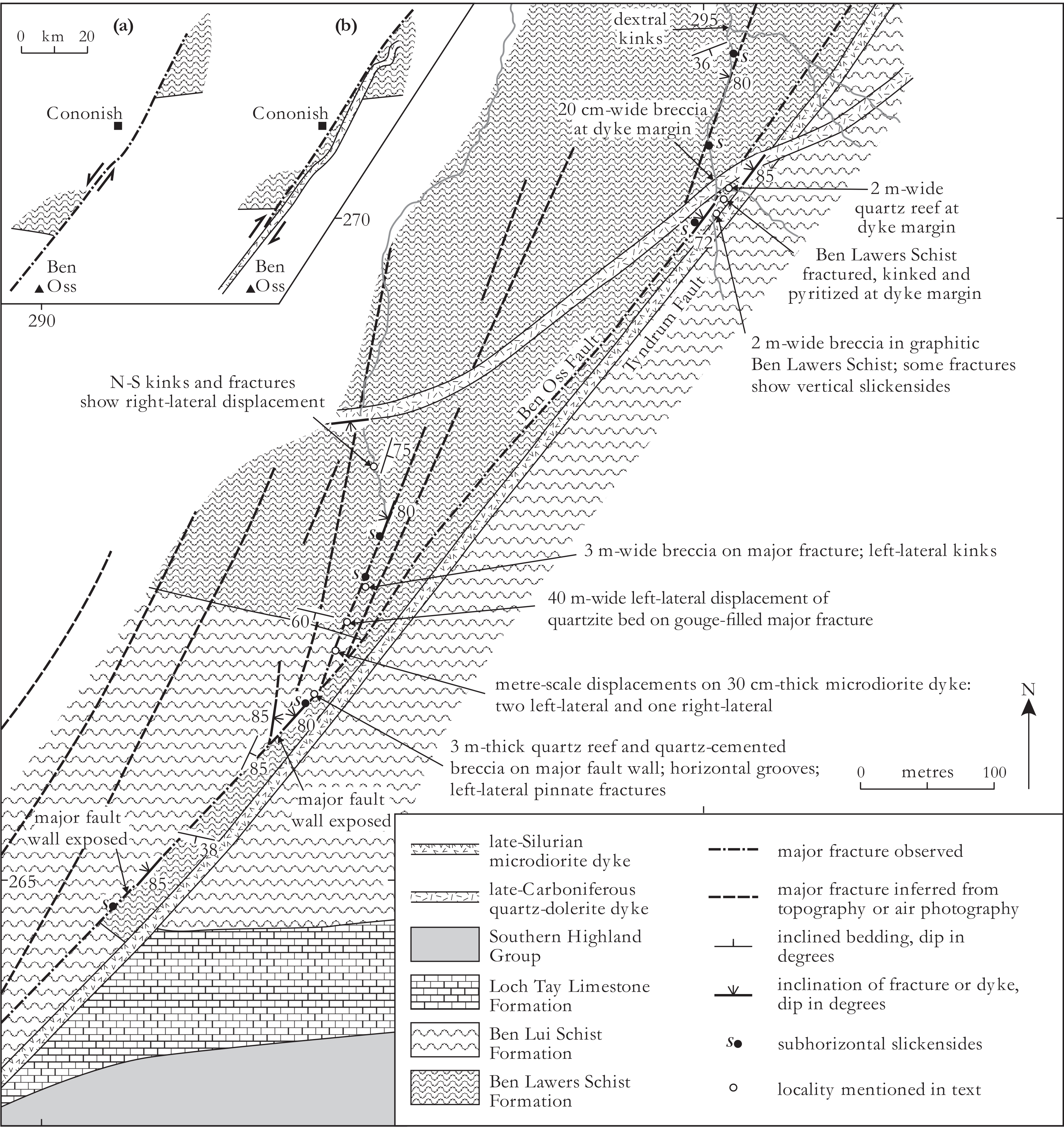
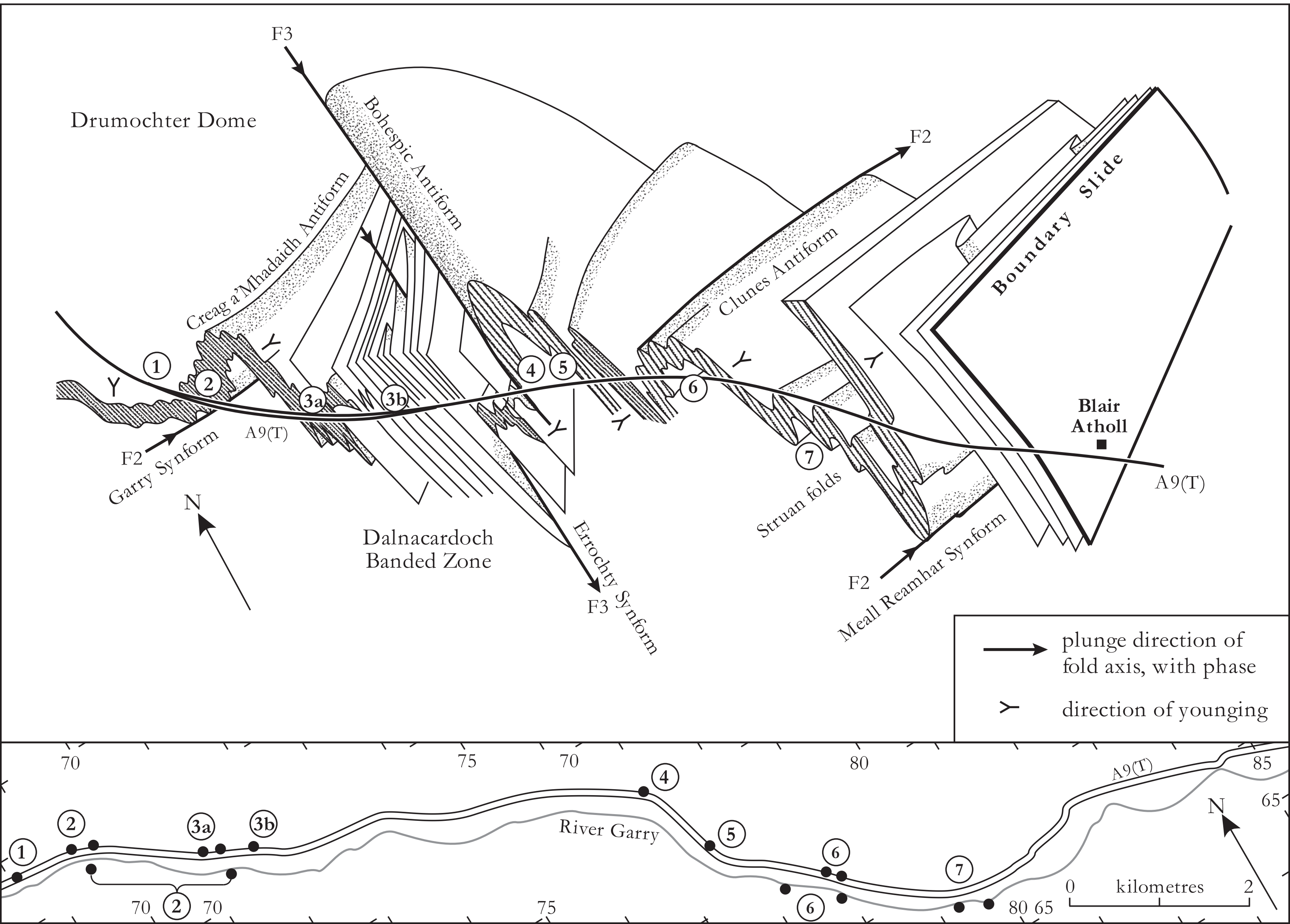

N
0 kilometres 1
Allt a' Chaol Ghlinne
Auchtertyre Fault
Allt Gleann a' Chlachain
Allt Auchtertyre
Dalmally Antiform
Auchtertyre
A85
Strath Fillan
32
31
30
29
34
35
36
37
(a)
Easdale Subgroup
Ben Lui Schist Formation
ultramafic rocks
Ben Challum Horizon
Auchtertyre Horizon
Ben Challum Quartzite Formation
Ben Lawers Schist Formation
fault
axial plane trace of antiform
(b)
N
Gleann a' Chlachain
pole to S2
F2 fold hinge
curvilinear hinge

Figure 3.57



(a)
(b)
0 km 20
Cononish
Cononish
Ben Oss
Ben Oss
270
290
295
265
dextral kinks
36
80
20 cm-wide breccia at dyke margin
85
2 m-wide quartz reef at dyke margin
72
Ben Lawers Schist fractured, kinked and pyritized at dyke margin
2 m-wide breccia in graphitic Ben Lawers Schist; some fractures show vertical slickensides
Ben Oss Fault
Tyndrum Fault
N-S kinks and fractures show right-lateral displacement
75
80
3 m-wide breccia on major fracture; left-lateral kinks
40 m-wide left-lateral displacement of quartzite bed on gouge-filled major fracture
60
metre-scale displacements on 30 cm-thick microdiorite dyke: two left-lateral and one right-lateral
85
80
85
3 m-thick quartz reef and quartz-cemented breccia on major fault wall; horizontal grooves; left-lateral pinnate fractures
major fault wall exposed
major fault wall exposed
38
85
N
0 metres 100
late-Silurian microdiorite dyke
late-Carboniferous quartz-dolerite dyke
Southern Highland Group
Loch Tay Limestone Formation
Ben Lui Schist Formation
Ben Lawers Schist Formation
major fracture observed
major fracture inferred from topography or air photography
inclined bedding, dip in degrees
inclination of fracture or dyke, dip in degrees
subhorizontal slickensides
locality mentioned in text

Figure 3.32



F3
Drumochter Dome
Bohespic Antiform
Creag a'Mhadaidh Antiform
F2
Clunes Antiform
Boundary Slide
1
2
3a
3b
4
5
6
7
A9(T)
F2
Garry Synform
N
Dalnacardoch Banded Zone
Errochty Synform
F3
Struan folds
F2
Meall Reamhar Synform
Blair Atholl
A9(T)
plunge direction of fold axis, with phase
direction of younging
70
75
70
80
85
65
River Garry
A9(T)
N
0
kilometres
2
70
70
75
80 65

Figure 3.6 colour
Click here to download high resolution image

Figure 3.8 colour
Click here to download high resolution image

Figure 3.9 colour
Click here to download high resolution image

Figure 3.11 colour
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Figure 3.14 colour
Click here to download high resolution image

Figure 3.16 colour
Click here to download high resolution image

Figure 3.19a colour
Click here to download high resolution image

Figure 3.19b colour
Click here to download high resolution image

Figure 3.21a colour
Click here to download high resolution image

Figure 3.21b colour
Click here to download high resolution image

Figure 3.23
Click here to download high resolution image

Figure 3.26
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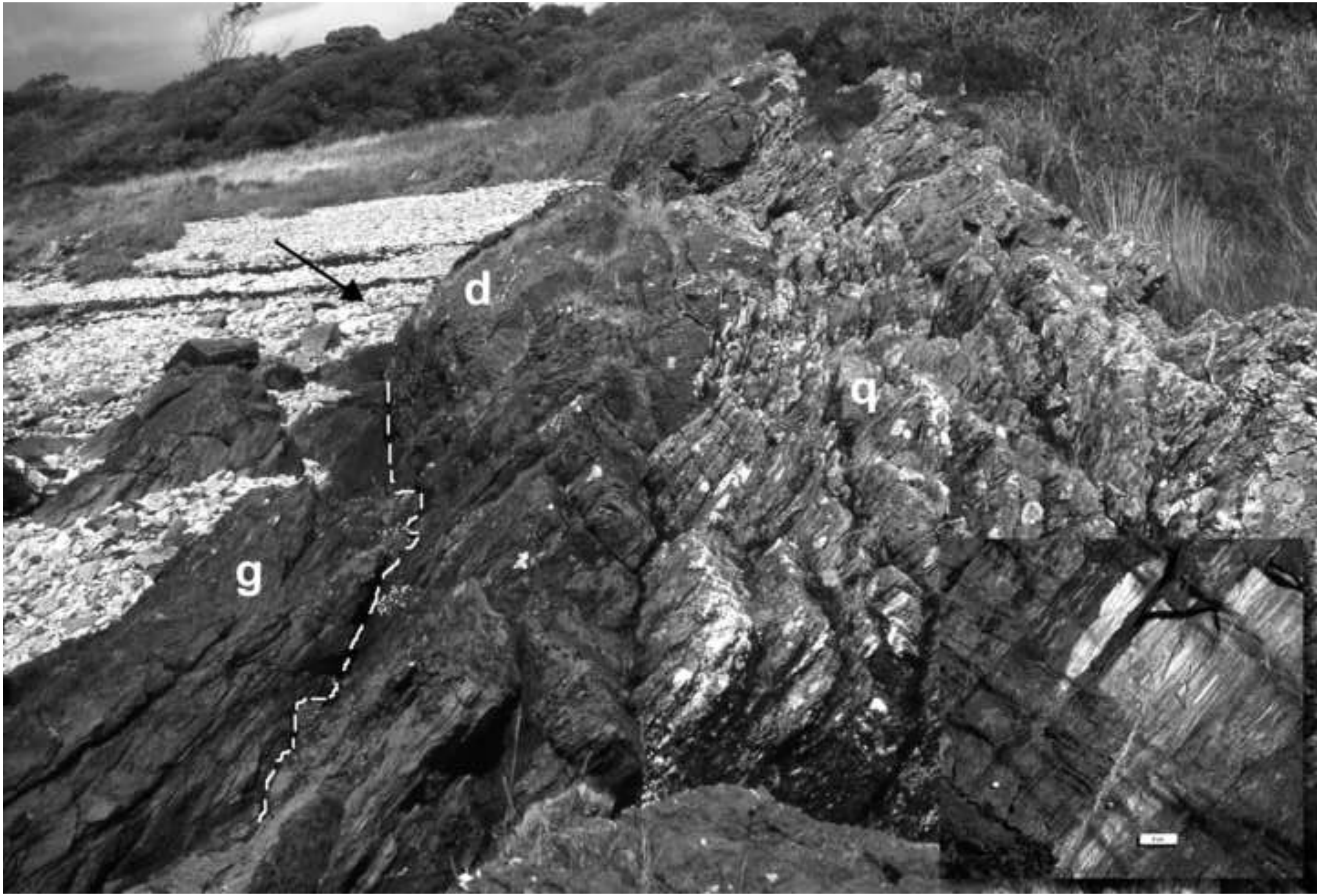

Figure 3.28 colour

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Figure 3.30 colour

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Figure 3.31 colour
Click here to download high resolution image

Figure 3.33 colour
Click here to download high resolution image

Figure 3.34
Click here to download high resolution image

Figure 3.35 colour

Click here to download high resolution image

Figure 3.36
Click here to download high resolution image

Figure 3.38
Click here to download high resolution image

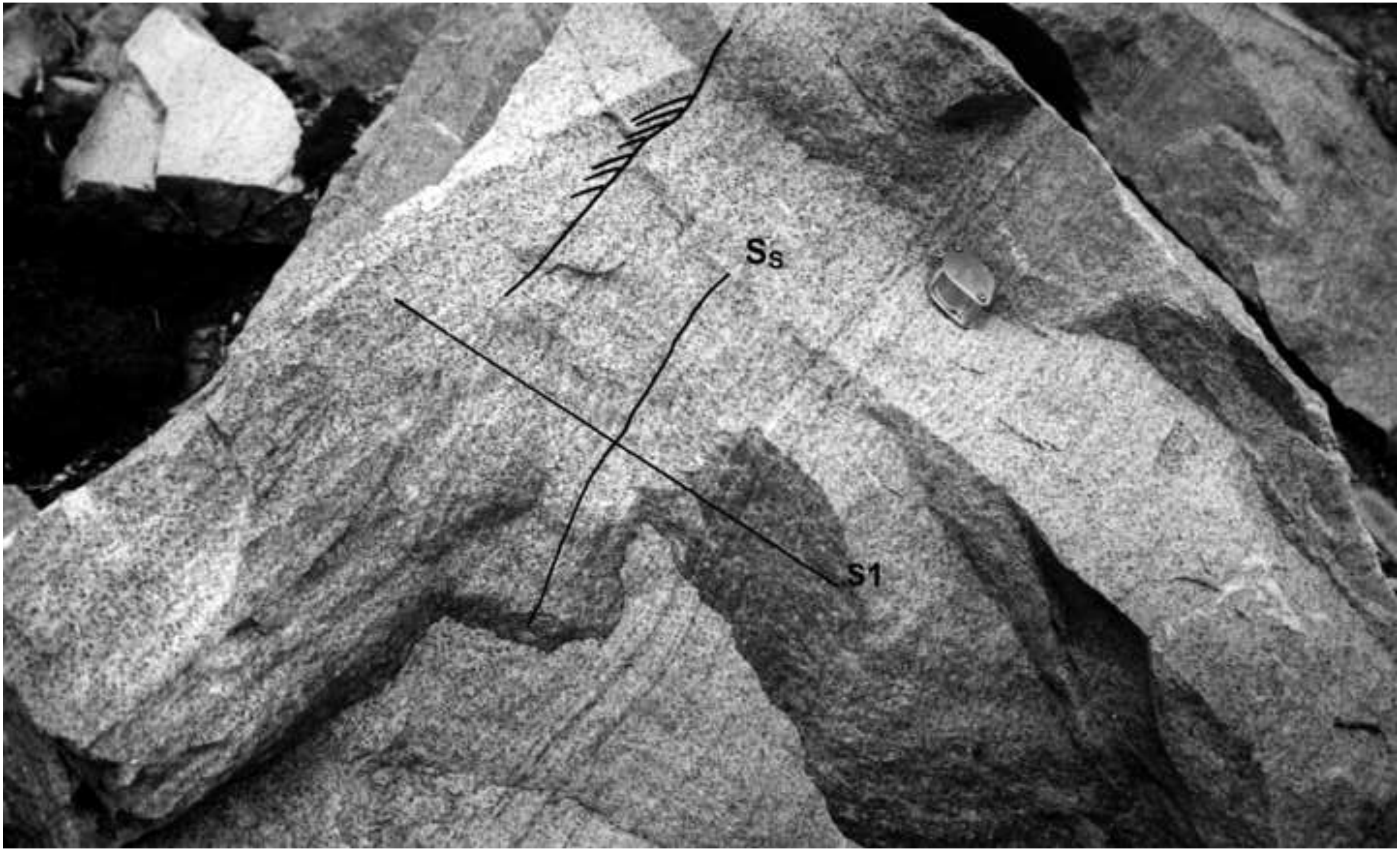

Figure 3.40
Click here to download high resolution image

Figure 3.42 colour
Click here to download high resolution image

Figure 3.43 colour
Click here to download high resolution image

Figure 3.45 colour
Click here to download high resolution image

Figure 3.48
Click here to download high resolution image

Figure 3.50 colour

Click here to download high resolution image

Figure 3.53 colour

Click here to download high resolution image

Figure 3.55 colour
Click here to download high resolution image

Figure 3.56 colour
Click here to download high resolution image

Figure 3.58 colour
Click here to download high resolution image

Figure 3.6 B&W
Click here to download high resolution image

Figure 3.8 B&W
Click here to download high resolution image

Figure 3.9 B&W

Click here to download high resolution image

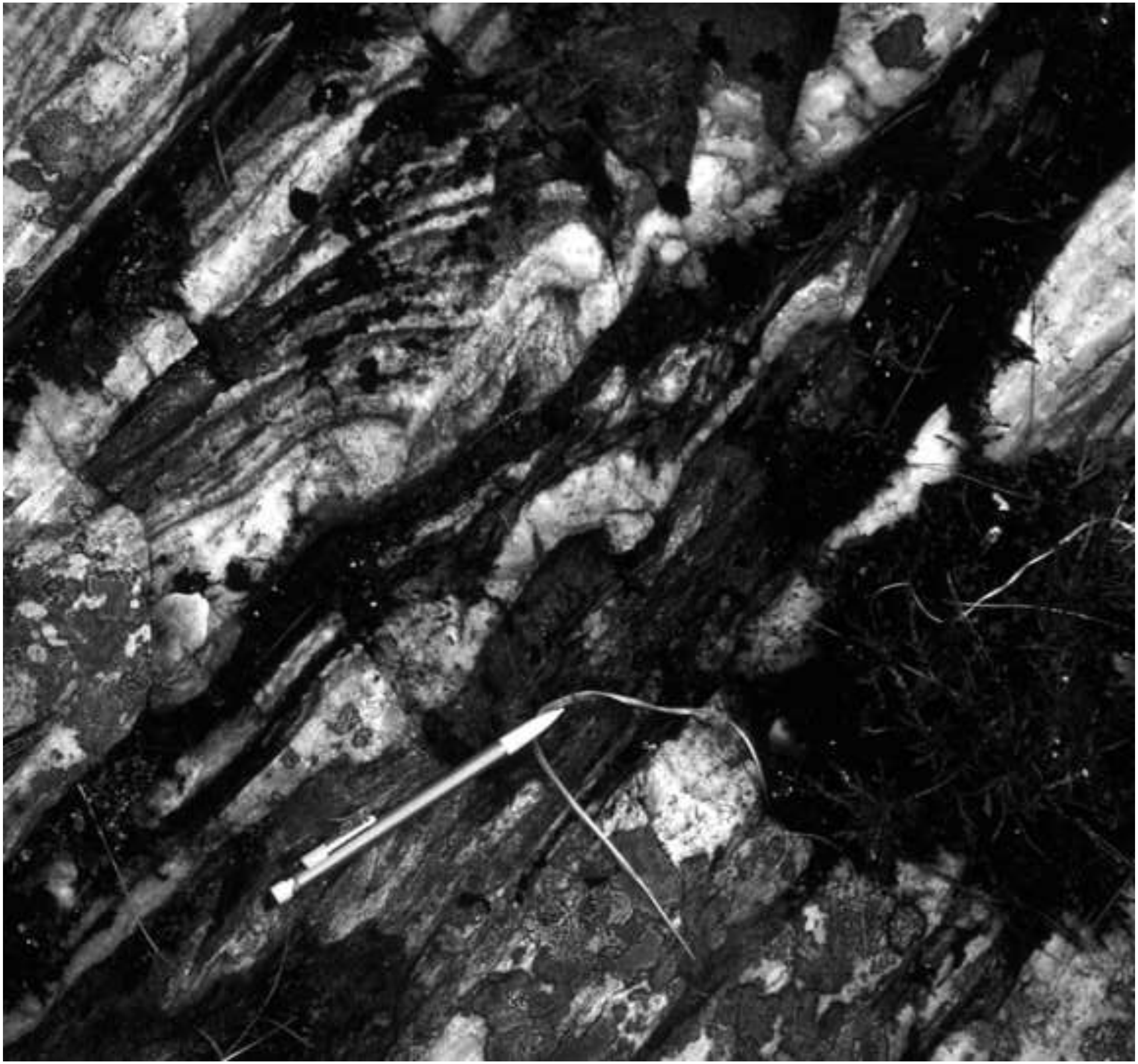

Figure 3.11 B&W
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Figure 3.14 B&W

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Figure 3.16 B&W
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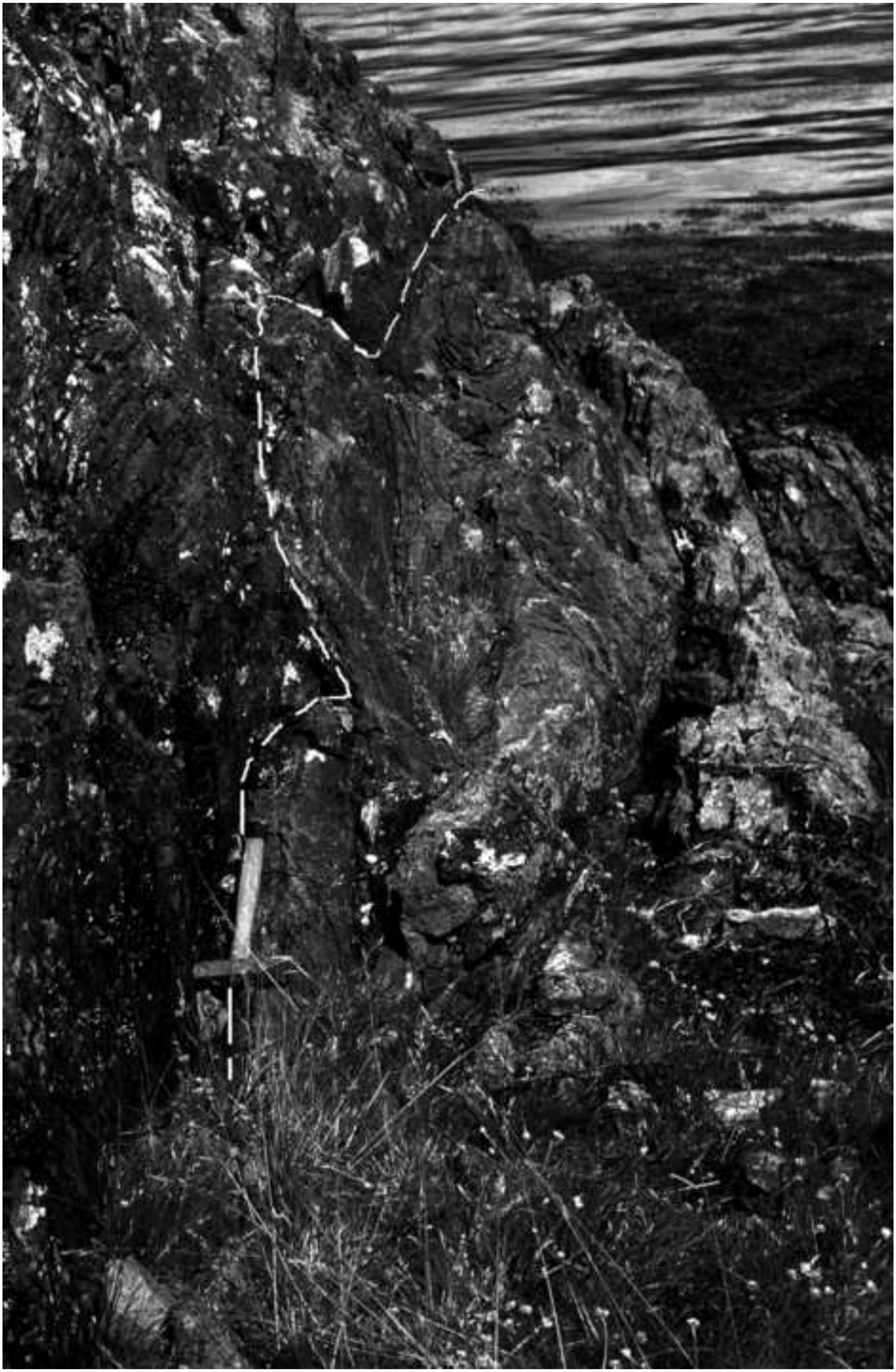

Figure 3.19a B&W

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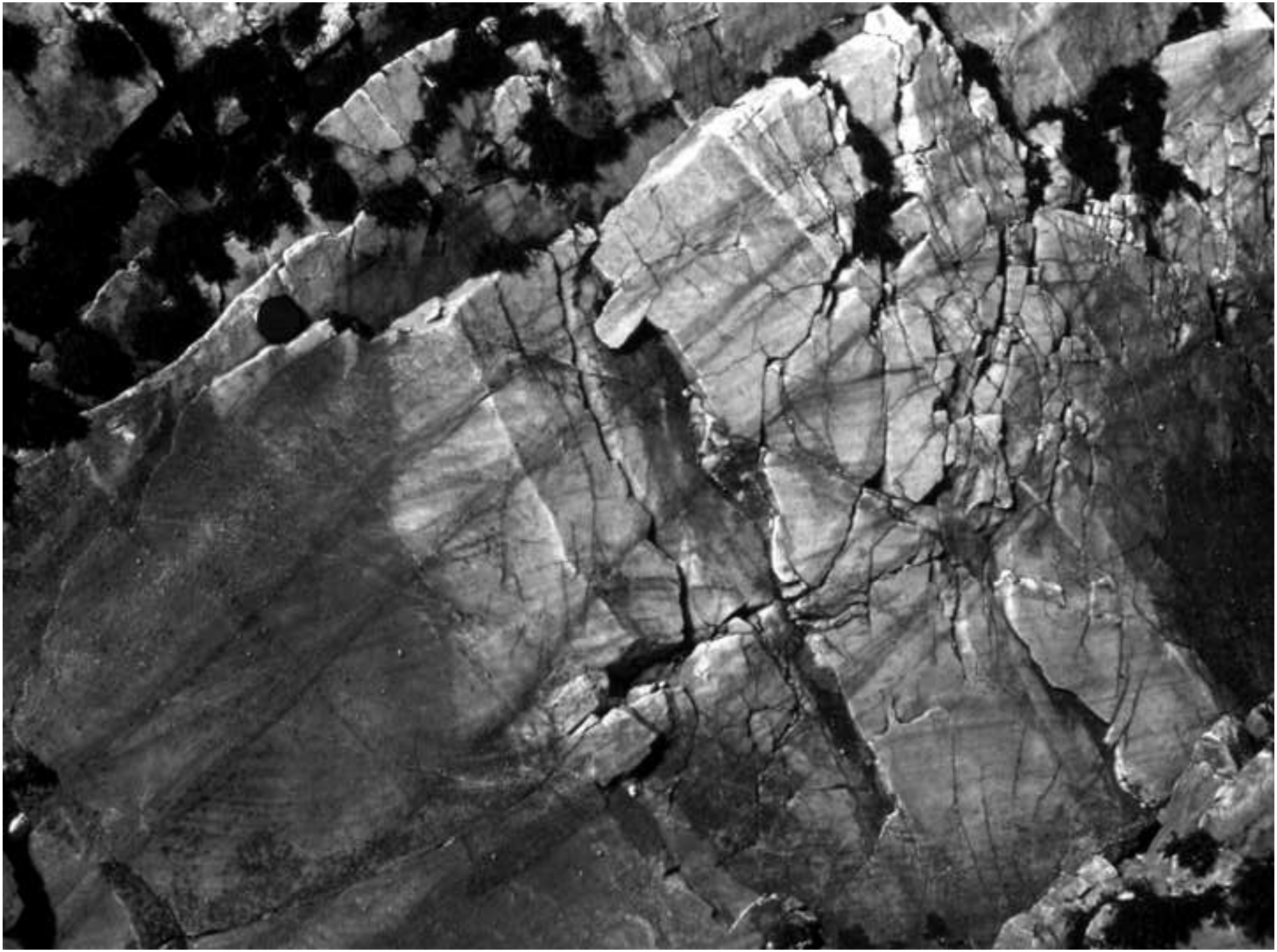

Figure 3.19b B&W

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Figure 3.21a B&W
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Figure 3.21b B&W

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Figure 3.28 B&W

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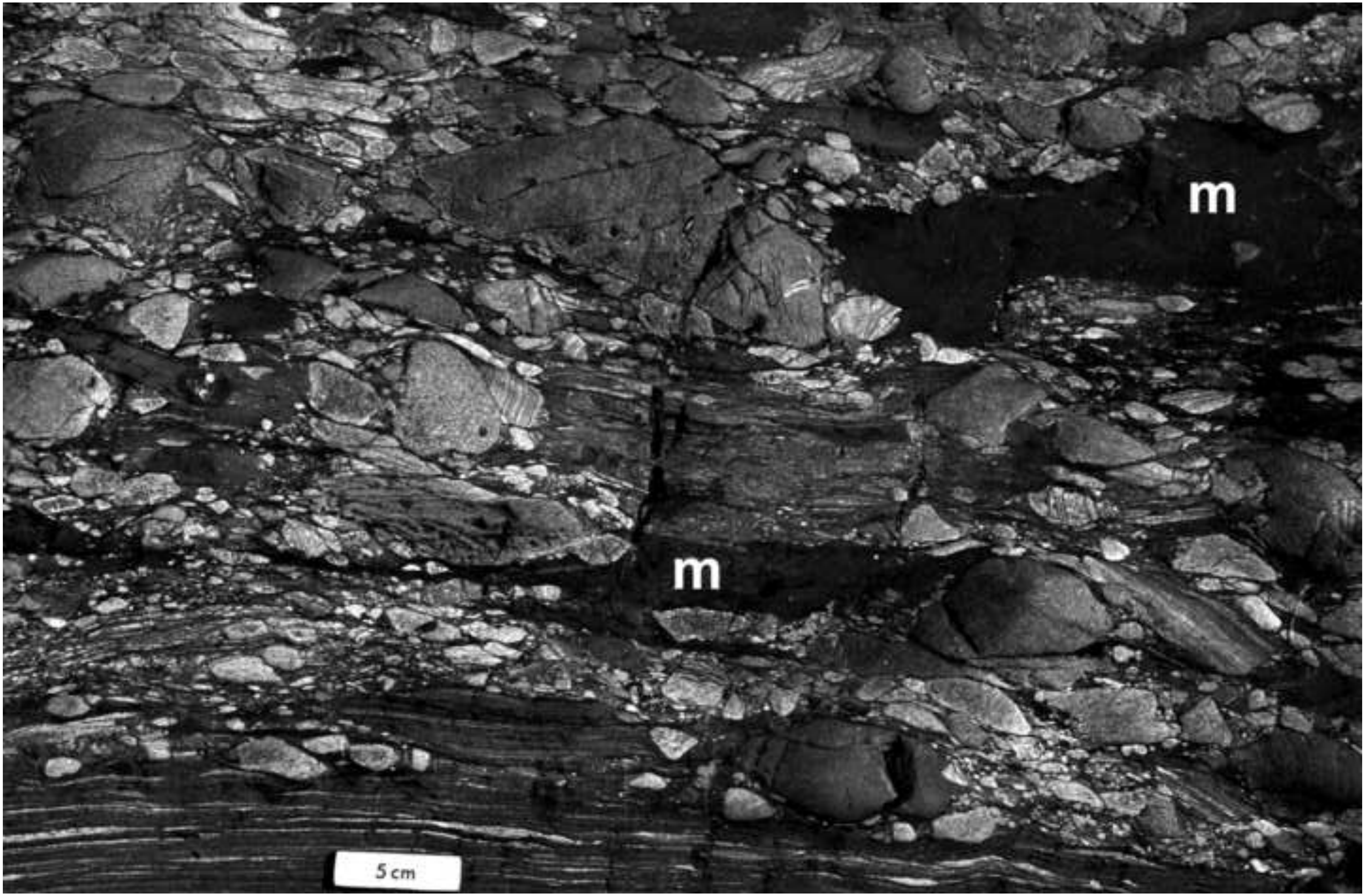

Figure 3.30 B&W

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Figure 3.31 B&W

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Figure 3.33 B&W

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Figure 3.35 B&W
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Figure 3.42 B&W

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Figure 3.43 B&W
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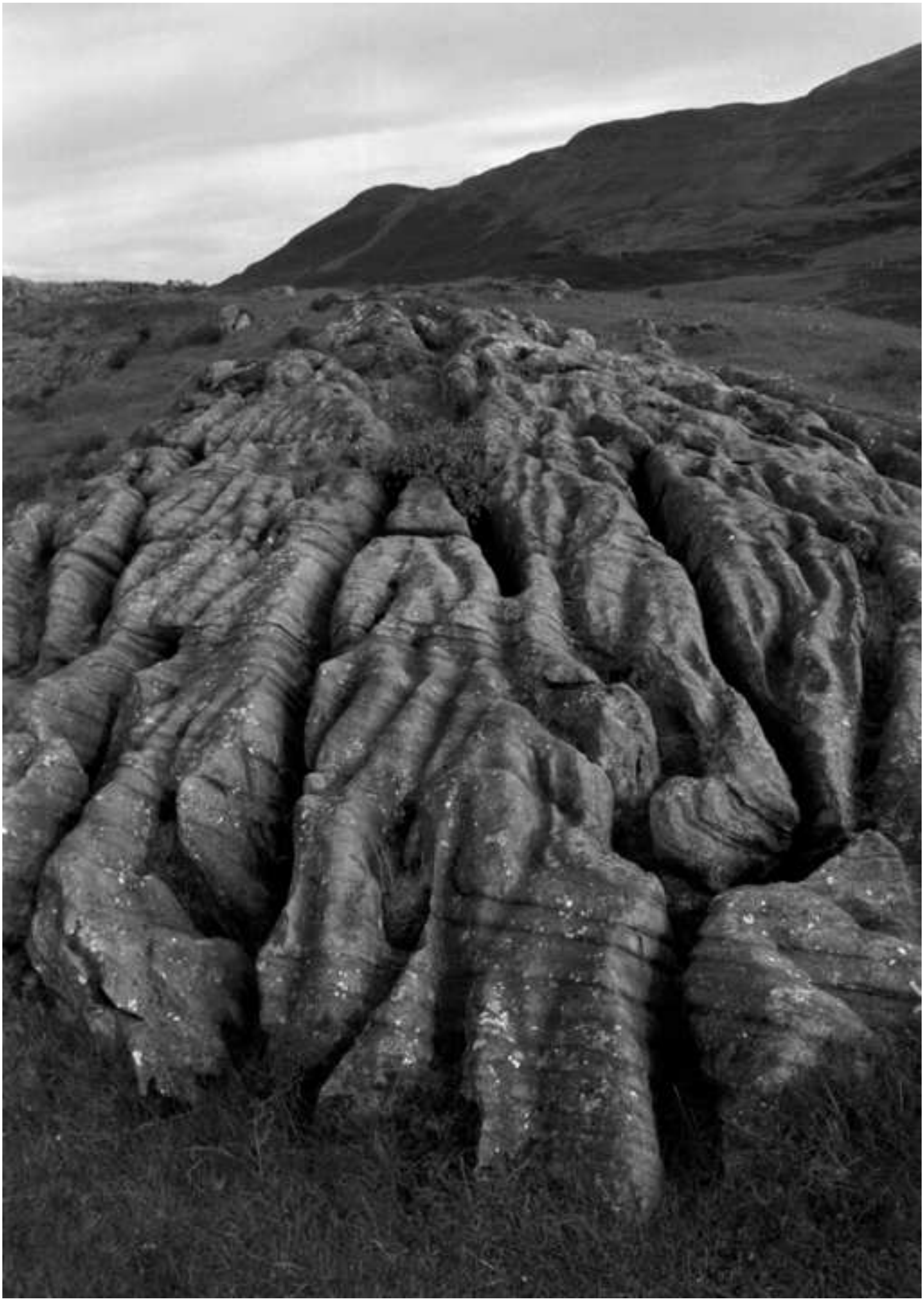

Figure 3.45 B&W
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Figure 3.50 B&W

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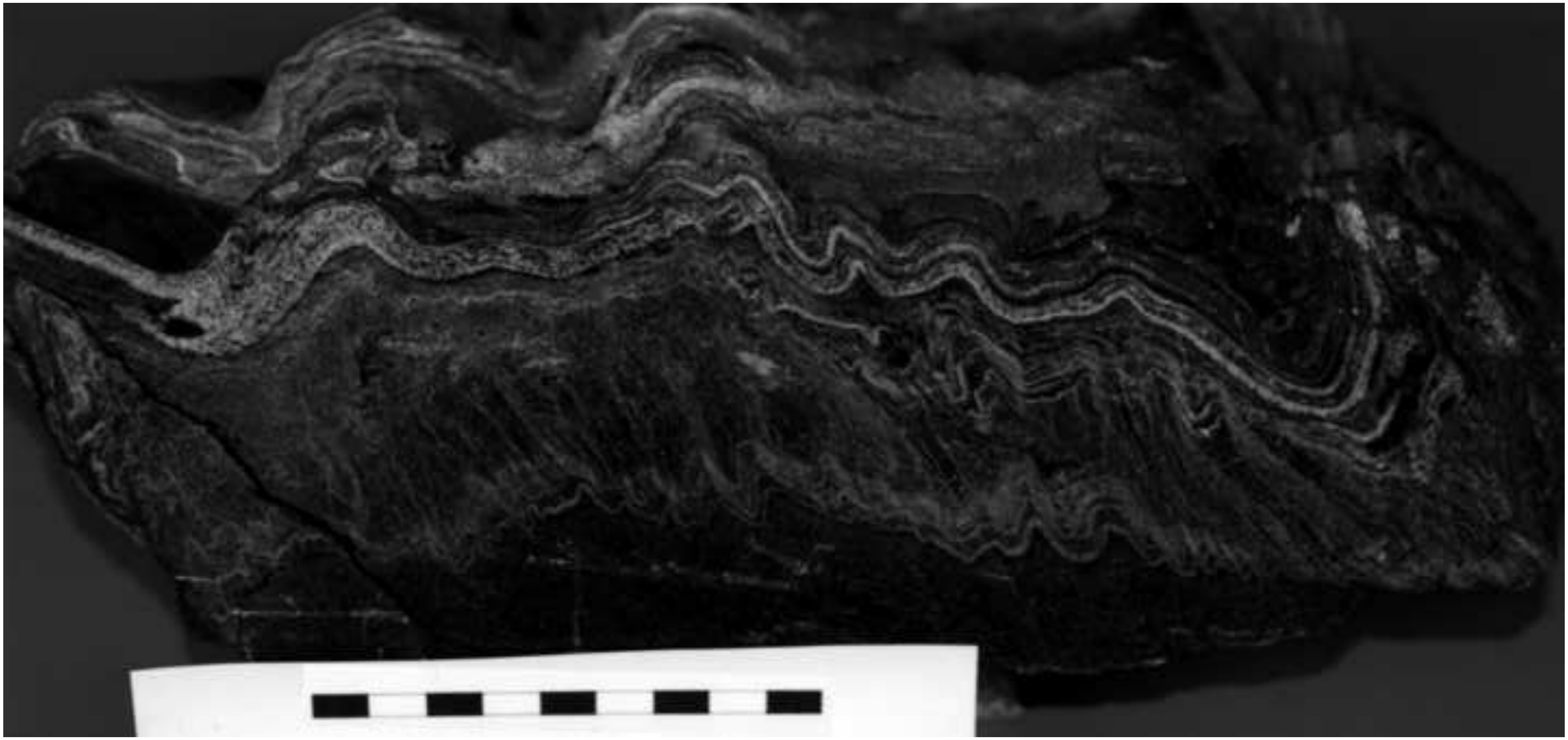

Figure 3.53 B&W

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Figure 3.55 B&W

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Figure 3.56 B&W

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Figure 3.58 B&W

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