The Dalradian rocks of the Highland Border region of Scotland

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Abstract

The Highland Border region is defined here by the outcrop of the Southern Highland Group that lies north-west of the Highland Boundary Fault and runs from Stonehaven south-west to the Isle of Bute, and thence to the Campbeltown peninsula. The late-Neoproterozoic to early-Ordovician rocks of the Dalradian Supergroup in this region form a stratigraphical and structural entity that encompasses the >300 km-long surface traces of both the Tay Nappe (D1–D2) and the Highland Border Downbend (D4). The least deformed and metamorphosed Southern Highland Group rocks occur along the south-east margin of the region and are in continuity with the younger, newly recognized Trossachs Group, which has therefore been assigned to the Dalradian Supergroup. The earliest (D1) structures in the Dalradian rocks are dominant close to the Highland Boundary Fault but are successively overprinted northwards by D2, D3 and D4 structures and fabrics, here represented by a series of zones near-parallel to the Highland Boundary. Regional metamorphism increases progressively away from the Highland Boundary Fault and ranges from greenschist to upper amphibolite facies (sillimanite zone). Three fundamental features of deformed and regionally metamorphosed rocks worldwide were first recognized in this area: the 'stretching lineation' by Clough in 1897; the concept of regional metamorphic 'Barrovian zones' by Barrow in 1901; and the 'facing direction' of folds by Shackleton in 1958. The Highland Border region has acquired international recognition for research undertaken into the origin and mode of emplacement of the Tay Nappe, one of the largest recumbent folds known worldwide. This structure provides a framework for linking together most of the GCR sites in this paper.

1 Introduction

P.W.G. Tanner and J.E. Treagus

The Highland Border region is defined here as the outcrop of the Southern Highland Group that is bounded to the north-west by its contact with the outcrop of the Argyll Group, and to the south-east by an ill-defined and much disputed

contact with the Cambrian to Ordovician Highland Border Complex (Johnson and Harris, 1967; Tanner, 1995, 1997, 1998b; Tanner and Pringle, 1997; Bluck and Ingham, 1997; Harris *et al.*, 1998; Bluck, 2000; Tanner and Sutherland, 2007). Both the Southern Highland Group and the Highland Border Complex outcrops are truncated to the south-east by a major structural discontinuity, the Highland Boundary Fault.

The Dalradian rocks of this area form a single narrow outcrop, up to 35 km wide and 280 km long, extending from Kintyre to Stonehaven (Figure 1). They consist of a rather monotonous pile of metagreywackes, over 5 km thick, with relatively thin units of slaty pelite that were once quarried for roofing slate at a number of localities such as Arran, Aberfoyle and Dunkeld. Volcaniclastic beds, commonly known as 'green beds', occur in the lower part of the sequence. Despite the uncertainty about its upper boundary, the Southern Highland Group in this outcrop forms a discrete unit in terms of its depositional history, structure, and regional metamorphism. It consists of a series of deep-sea fan turbidites that pass upwards into a passive-margin sequence, the sedimentary edifice being contained within a single major fold structure, the Tay Nappe.

The Tay Nappe is a large, early fold that was flat-lying, or recumbent, following the D2 deformation and was then folded by the Highland Border Downbend (F4) along a line close to, and parallel with, the south-eastern limit of the Highland Border region (Figure 1). The lower, inverted limb of this fold occupies most of the Highland Border region and the main hinge-zone crops out between Arran and Callander. Farther to the north-east, beyond Dunkeld, it is either truncated by the Highland Boundary Fault or buried beneath an unconformable cover of Siluro-Devonian sedimentary and volcanic rocks of the Old Red Sandstone Supergroup and hence is not exposed.

Most of the Dalradian rocks are affected by up to four superimposed phases of deformation (D1–D4), the first three of which are attributed to the mid-Ordovician Grampian Event of the Caledonian Orogeny and the last possibly to the mid-Silurian Scandian Event. The Grampian deformation was accompanied by regional metamorphism that reached a peak in the upper amphibolite facies (sillimanite zone). Migmatites, arising from partial melting, occur in the highest grade rocks, and the regional metamorphic minerals include chlorite, biotite, garnet, chloritoid, staurolite, kyanite, and sillimanite (see the *Glen Esk* GCR report). The regional metamorphism reached its peak some 470 Ma ago, at around D2–D3, and it is thought that the growth of the mineral assemblages in each zone occurred during a relatively brief period of 10–15 Ma (Oliver *et al.*, 2000; Baxter *et al.*, 2002).

A further compelling reason for considering this outcrop of the Southern Highland Group as a separate region is that it displays a structural unity throughout its length. This is defined in plan view by: the NE-trending axial traces of the Tay Nappe (D1 and D2) and the Highland Border Downbend (D4) (Figure 1); the line marking the onset in a north-westerly direction of intense D2 reworking of bedding and the S1 fabric; and, less exactly, the traces of the biotite and garnet isograds.

This intensively studied region is now achieving international status as a model for short-lived orogenesis (less than 10 Ma) in which the unusually rapid rise in temperature of the deforming rock mass probably resulted from advective heat introduced via circulating fluids from contemporaneous intrusions (Atherton and Ghani, 2002; Dewey, 2005). This was aided by the loading and blanketing effects of an ophiolite nappe, which was emplaced over the Dalradian sedimentary rocks early in the Grampian Event (Tanner, 2007; Chew, *et al*., 2010; Cutts, *et al*., 2011). Although some of the first radiometric ages from these rocks, especially K-Ar ages on slaty pelites and on white micas, gave ages of over 500 Ma, these are now considered to be unreliable, and there is no tangible evidence that a late-Neoproterozoic orogeny affected the Dalradian prior to the Grampian Event (cf. Hutton and Alsop, 2004, 2005; and see Tanner, 2005).

Examples of seminal studies carried out in the Highland Border region that have gained international recognition as being unique in their field include:

1. first use of minor structures in structural interpretation, and the recognition of polyphase deformation (Cowal peninsula; Clough, in Gunn *et al.*, 1897) (Figure 5). This approach is exemplified by the three GCR sites in the south-west (*Ardscalpsie Point*, *Cove Bay to Kilcreggan* and *Portincaple*), and especially by the three GCR sites around Dunkeld (*Little Glen Shee*, *Craig a'Barns* and *Rotmell*) that have been grouped together with this purpose in mind.

2. formulation of the concept of zones of metamorphic grade, and the recognition of the Barrovian and Buchan types of metamorphism (Barrow, 1912). The geology of the area in which this work was carried out is described in the *Glen Esk* GCR site report, which includes illustrations of the key Barrovian mineral assemblages.
3. introduction of the concept of structural facing in polyphase terrains to facilitate understanding of the structural evolution of an area, and to demonstrate the existence of a major fold, the Tay Nappe (Shackleton, 1958). This theme is central to many of the GCR site reports in this paper and Shackleton's work features particularly strongly in the *Duke's Pass* GCR site report and in the reports of the three GCR sites around Dunkeld.

The Trossachs area, which includes the *Bealach nam Bo* and *Duke's Pass* GCR sites, is now part of the first National Park to be established in Scotland. In the 19th Century it attracted many famous painters, including Constable, Millais and Turner, and the poet Wordsworth. But it is John Ruskin, founder member of the Pre-Raphaelite movement, who has left us the legacy of the beautiful drawing reproduced in (Figure 4.3). Ruskin was inspired by the form of natural objects and strove to reproduce their every detail; his aim was to encourage his contemporaries to replace pastoral scenes with paintings that depicted 'rocks drawn with such accuracy that the geologist's diagram was no longer necessary' (Greive, 1996).

In this paper, the GCR site reports are arranged as far as is possible in geographical sequence from south-west to north-east and, with the exception of the *Glen Esk* GCR site report on regional metamorphism, all of them deal specifically with the stratigraphy and structure of the Southern Highland Group. There are no GCR sites on the Campbeltown peninsula or on the Isle of Arran, a total area of some 30 km^2, reflecting a lack of detailed studies of the Dalradian rocks in that area.

1.1 Stratigraphy

The Southern Highland Group in the Highland Border region consists of a thick sequence of turbidite-facies rocks (now metagreywackes) with interdigitations of slaty pelite, and uncommon chlorite-epidote-rich beds known as 'green beds', whose detrital volcaniclastic origin is discussed in detail in the *Bealach nam Bo* GCR site report (see also Pickett *et al.*, 2006). Major lateral facies changes occur at all levels within a sequence that, apart from the green beds, generally lacks lithostratigraphical marker horizons. Fault-controlled compartments have given rise to local successions that are now seen at different depths of erosion due to kilometre-scale displacements on major faults such as the Loch Tay Fault (Figure 4.2).

The *base* of the Southern Highland Group is taken at the top of the Loch Tay Limestone Formation throughout most of the Highland Border region, although to the north-east of the Glen Doll Fault it is taken above locally abundant calcsilicate beds in the dominantly psammitic Tarfside Psammite Formation (Gibbons and Harris, 1994; Stephenson and Gould, 1995).

The *top* of the Southern Highland Group (Figure 4.2) has defied definition since the late 19th century and is still the subject of controversy (see the *Keltie Water* GCR site report; Bluck and Ingham, 1997; Tanner, 1997 for discussion). This is because, despite the sharp contrast between the ubiquitous slaty metamudstones and metagreywackes of the Southern Highland Group and the great variety of rock types, such as serpentinite, black graphitic mudstones and fossiliferous limestones, found in the Highland Border Complex, the boundary between the two units is difficult to define. Clough (in Gunn *et al.*, 1897) concluded that at Callander (*Keltie Water* GCR site) there is a passage or transition between the two sequences, and Cunningham Craig (1904) reported that there is a metamorphic transition in the Loch Lomond area between a 'slate-grit series' and 'schists' to the north.

The problem facing the early surveyors was two fold: which is the younger set of rocks; and where do the 'Highland Schists' end and the Highland Border rocks begin? Amongst the early workers there were two schools of thought: (1) those like Macnair (1908) who, because the bedding or foliation in both sets of rocks throughout most of the zone dips steeply to the north-west, considered that the rocks in the south (now named the 'Highland Border Complex') are older than the 'Highland Schists' (now Dalradian) to the north; and (2) those like Peach (1930) who, persuaded by lithological similarities between the Highland Border Complex rocks and the Arenig-age mudstones in the Southern Uplands of Scotland, considered that they are the younger unit.

This latter interpretation was confirmed by the discovery of poorly preserved Ordovician fossils in the Highland Border Complex, for example in the Aberfoyle Forest (Jehu and Campbell, 1917), followed by the finding of definitive fossil assemblages of Early Cambrian age at Leny Quarry (Pringle, 1940), and of mid-Arenig age at Lime Craig Quarry (Curry *et al.,* 1984) (see the *British Cambrian to Ordovician Stratigraphy* GCR volume; Rushton *et al.*, 1999). This shifted the focus of the argument to deciding whether or not the two units are in stratigraphical sequence, or whether they are separated by a tectonic break. Resolution of the main problem, that of defining the top of the Dalradian succession, was not furthered by Gregory (1931) who proposed that the ‘Dalradian’ rocks should be divided into five separate units, with the most southerly of these, the ‘Lennoxian’, being unconformable on the 'Dalradian' and containing clasts derived from it. No evidence has been published by later workers to support that interpretation.

In the decade that followed the publication by Curry *et al*. (1984), it became generally accepted that the Highland Border Complex is an ‘exotic terrane’ that docked with the Grampian Terrane in Silurian to Devonian times. This hypothesis was challenged by Tanner (1995), who confirmed the conclusions of Johnson and Harris (1967) and considered that much of the Highland Border Complex is in stratigraphical and structural continuity with the accepted Dalradian sequence. Tanner and Sutherland (2007) then proposed that all of the Highland Border Complex that crops out north-west of the Highland Border Ophiolite should be included in the Dalradian Supergroup and assigned to a new Trossachs Group, which ranges in age up to topmost Tremadocian. Although the tendency in recent years has been to include an increasing proportion of the Highland Border Complex in the Dalradian succession (e.g. BGS 1:50 000 Sheet 38E, Aberfoyle, 2004; Henderson *et al*., 2010), this topic is still being debated (Bluck, 2010; Tanner and Bluck, 2011). For the purpose of this special issue, the top of the Dalradian succession is taken to be at the south-eastern limit of the Keltie Water Grit Formation (see the *Keltie Water* GCR site report).

The Dalradian outcrop is terminated locally at its south-eastern margin by a faulted or unconformable contact with Silurian, Lower Devonian, Upper Devonian, or Lower Carboniferous rocks in the Highland Border region, as seen at the *Ardscalpsie Point, Cove Bay to Kilcreggan,* and *Duke’s Pass* GCR sites.

Having defined the top and base of the Southern Highland Group, the stratigraphical sequence is now described with reference to the NW–SE-trending serial cross-sections shown in (Figure 4.4). The Loch Tay Limestone, which marks the top of the Argyll Group, occurs in the hinge-zones of the early folds and, together with the Green Beds, provides a marker horizon for correlating between the sections. It clearly shows that, although there is stratigraphical and structural continuity along the whole belt, a marked difference in structural level occurs across the Loch Tay Fault. This fault has a significant downthrow to the east, and rocks now exposed at the surface west of the fault ((Figure 4.4), sections AA′ to CC′) represent a deeper structural level than those to the east.

1.1.1 West of the Loch Tay Fault

The oldest exposed rocks of the Southern Highland Group occur both along the north-west margin of the Highland Border region, and close to its south-east margin, within the closure of the downward-facing F1 Aberfoyle Anticline, in the hinge-zone of the Tay Nappe. These slaty pelitic rocks appear to pass laterally into impersistent volcaniclastic metasedimentary rocks that occur in various places near the base of the Southern Highland Group ((Figure 4.4), sections AA′ and CC′) and have been correlated with the Loch Avich lavas at the *Loch Avich* GCR site (Treagus et al., 2013). They are generally referred to semiformally as the Green Beds (e.g. at the *Barmore Island* and *Cove Bay to Kilcreggan* GCR sites) (Figure 4.2), but at the *Duke’s Pass* GCR site, where they are particularly well developed, they define the Loch Katrine Volcaniclastic Formation. The latter is overlain by the Craig Innich Sandstone Formation, a local, laterally discontinuous formation containing beds of microconglomerate up to two metres thick.

The ‘slate’ formations are represented in the south-east by the Aberfoyle Slate Formation, which is seen in its type area at the *Duke’s Pass* GCR site as black, dark grey, purple, and olive-green slaty metamudstones that are commonly slightly calcareous. These metamudstones appear to be laterally continuous within the Highland Border region but south-west of Aberfoyle there are several such outcrops and their exact correlation with the metamudstones at Luss on the west side of Loch Lomond is not secure. However, the ‘Luss Slates’ may be traced along strike across several sea lochs to equate with metamudstones in the Dunoon Phyllite Formation at the *Cove Bay to Kilcreggan* GCR site and on Bute. As the hinge of the Aberfoyle Anticline is contained within the metamudstone outcrop, the rocks on either side of it

should young away from the metamudstones, and be stratigraphically equivalent, if not lithologically identical.

The rocks to the north-west of the Aberfoyle Slate/Dunoon Phyllite outcrop have much the same character for over 15 km across strike, as characterized by the Beinn Bheula Schist Formation seen at the *Portincaple* GCR site. South-east of the metamudstone unit, on the upper limb of the Tay Nappe, (Figure 4.2)b the right-way-up St Ninian Formation in the south-west (i.e. at the *Ardscalpsie Point* and *Cove Bay to Kilcreggan* GCR sites) consists largely of pebbly metagreywackes in beds up to 3 m thick that commonly show graded bedding. The more-extensive lower part of the St Ninian Formation is the Bullrock Greywacke Member but locally the upper part of the succession contains units of black slaty metamudstone and thin beds of metacarbonate rock and has been referred to by some as the Innellan 'group' (e.g. Roberts, 1966a). On the current BGS 1:50 000 Sheet 29E (Dunoon and Millport, 2008) most of the former Innellan 'Group' is termed the Toward Quay Grit Member of the St Ninian Formation but on the Isle of Bute the highest beds are termed the Ardscalpsie Formation and are assigned to the Trossachs Group.

The predicted correlation of the Bullrock Greywacke with the Beinn Bheula Schist Formation, around the closure of the Aberfoyle Anticline, is problematical (as discussed in the *Cove Bay to Kilcreggan* GCR site report), for the pebbly and gritty metasandstones of the former contrast with the thinly bedded, chlorite-rich Beinn Bheula metagreywackes. Apart from the facies change, the problem is compounded by the fact that the rocks on the north-west limb are schistose and strongly deformed and rarely preserve way-up structures. In order to clarify this difference, the stratigraphical columns in (Figure 4.2) show the lateral correlations separately for the north and south limbs of the Aberfoyle Anticline.

1.1.2 East of the Loch Tay Fault

Along the north-western edge of the Southern Highland Group outcrop, the Loch Tay Limestone is succeeded by the Pitlochry Schist Formation, which includes green beds at several stratigraphical levels (e.g. Treagus, 2000).

On the south-east limb of the Aberfoyle Anticline, the Bullrock Greywacke Member of the St Ninian Formnation passes north-east along strike into the Ben Ledi Grit Formation, as seen at the *Duke's Pass* GCR site (Figure 4.2). The *Keltie Water* GCR site is particularly important as the section demonstrates both structural and stratigraphical continuity between strata of the Ben Ledi Grit Formation that are indisputably in the upper part of the Southern Highland Group and strata of the Keltie Water Grit Formation that include the fossiliferous Leny Limestone. Hence, not only did Dalradian sedimentation extend into the Early Cambrian, but its principal phases of deformation must all have occurred in post-Early Cambrian time, two crucial age relationships that until recently had been widely disputed.

Farther north-east, the exact stratigraphical affinity of the Birnam Slate, the Birnam Grit and the younger Dunkeld Grit Formation, described in the *Little Glen Shee* and *Craig a' Barns* GCR site reports, is uncertain. They were at one time correlated with the Aberfoyle Slates and the Ben Ledi Grits, but more-recent mapping has shown that they occur at a higher level in the Southern Highland Group succession ((Figure 4.4), section DD′). The stratigraphical status of the psammites and semipelites at the *Rotmell* GCR site is also not clear, but they could be a lateral equivalent of the Pitlochry Schist Formation.

North-east from the Dunkeld area, the general stratigraphical relationship of a lower, more-pelitic metagreywacke sequence passing south-eastwards into an upper, more-psammitic metagreywacke sequence persists to the coast north of Stonehaven (Anderson, 1942). The more-pelitic facies forms an outcrop continuous with the Pitlochry Schist and contains similar lithologies, dominated by garnet-mica schists but passing into slates or sillimanite gneisses depending upon metamorphic grade. In the Glen Clova area this basal unit has been termed the Longshank Gneiss Formation. This unit shows a marked facies change from dominantly pelitic in the south-west to dominantly psammitic in the north-east and is characterized by strongly magnetic beds throughout (Chinner, 1960). The younger, graded metagreywackes and schistose psammites of the Rottal Schist Formation are continuous with the Ben Ledi Grit to the south-west. Green beds are abundant between Kirkmichael and Glen Clova but are notably absent north-east from Glen Clova.

An extensive right-way-up sequence that crops out around the *Glen Esk* GCR site was assigned by Harte (1979) to a separate Tarfside Nappe (see below). The sequence consists of an intimate metagreywacke association of pelites, semipelites and psammites typical of the Southern Highland Group. A lower unit, the Glen Effock Schist Formation,

passes upwards into the Glen Lethnot Grit Formation, characterized by beds of pebbly psammite, and hence a broad correlation is suggested with the Pitlochry Schists and Ben Ledi Grit of the Tay Nappe. The outcrop of the Glen Lethnot Grit can be traced to the coast around the *Garron Point to Muchalls* GCR site, where the sequence is once again upside down, as in the Tay Nappe.

1.2 Structure

Aspects of particular structural interest in the Highland Border region are the geometry and mode of formation of two of the largest folds in the British Isles, the Tay Nappe and the Highland Border Downbend, and the intriguing geometrical relationship between the D1 and D2 structures as expressed in the splendid development of superimposed, spaced cleavages in the metasandstones. The latter are matched only in the UK by those at Trearddur Bay, Holy Island, Isle of Anglesey. The huge monoclinal downbend divides the region into the Flat Belt to the north-west and the Highland Border Steep Belt to the south-east (Figure 4.1) and (Figure 4.4). It folds the originally recumbent or flat-lying Tay Nappe and brings the fold closure down to ground level just north of the Highland Boundary Fault, so exposing at the surface part of the upper limb of the nappe (Figure 4.4).

Over almost the whole outcrop of the Flat Belt, the level of erosion lies in the lower, inverted limb of the Tay Nappe. However, in a wide area around the *Glen Esk* GCR site a broad late antiform, known as the Tarfside Culmination, exposes a sequence of non-inverted strata, which Harte (1979) assigned to a separate Tarfside Nappe and interpreted as a major recumbent structure below the Tay Nappe. According to Harte the axial zone of the fold separating the two nappes has been replaced by a slide, the Glen Mark Slide. However, the structural relationships are not clear and the distribution of units could also be explained in other ways, for example by invoking later large-scale tight folding of the Tay Nappe on gently dipping axial planes. Farther to the north-east (around the *Garron Point to Muchalls* GCR site), the structural relationships revert to those seen in the Tay Nappe to the south-west. The flat-lying sequence is inverted and, south-east of a marked downbend, it passes into a steep zone with downward-facing D1 structures (Booth, 1984; Harte *et. al*., 1987) (Figure 4.33). The relationships of these major structures to the Tarfside Nappe, or indeed to the main Tay Nappe, are not clear.

1.2.1 The Highland Border Downbend

The regional significance of the Highland Border Downbend was recognized by Clough (in Gunn *et al.*, 1897) who noted that it folds an earlier foliation and stretching lineation, and is associated with a crenulation (strain-slip) cleavage. On the Cowal peninsula, it is an open structure with the south-eastern limb dipping south-east at less than 30°. As it is traced north-east, this limb becomes vertical between Loch Lomond and Aberfoyle ((Figure 4.4), sections BB’ and CC’), and NW-dipping farther towards the north-east (sections EE′ to GG′). Thus, the beds on the south-eastern side of the Tay Nappe axial plane are right-way-up in Cowal and become inverted to the north-east. This relationship has a direct bearing upon the earlier debate as to whether the ‘Highland Schists’ are older or younger than the Highland Border Complex, and it is a sobering thought that one of the earliest workers in the field made the most prescient observation of all: Nicol (1863) stated that the rocks in question on Bute dip south and are right-way-up, and in the Aberfoyle area dip north, and are inverted. North-east of Birnam, the Highland Border Downbend approaches close to the line of the Highland Boundary Fault and/or the margin of the unconformable Lower Devonian sequence, and its south-eastern limb is reduced to a width of less than 2 km (Figure 4.1).

The *Portincaple*, *Craig a’Barns*, and *Garron Point to Muchalls* GCR sites each show different features of this structure. At Portincaple, minor F3 folds on all scales up to several metres in wavelength are clearly folded around the hinge zone of the major downbend structure, and are cut by a sporadically developed, steeply dipping, S4 crenulation cleavage (Figure_12). It is significant that evidence for the presence of all four deformation phases can be seen on a single rock face at this locality, leaving no doubt as to the nature of each and of the relationship between them. At the *Craig a’Barns* and *Garron Point to Muchalls* GCR sites, the D3 deformation is absent and step-like minor F4 folds related to the downbend hinge deform the familiar spaced S2 microlithons. At the *Craig a’Barns* GCR site, the Highland Border Downbend gives rise to the Steep Belt of downward-facing F1 folds seen in the *Little Glen Shee* GCR site. Elsewhere, uncommon minor F4 warps, up to a few metres across, are seen as far south of the downbend as the *Cove Bay to Kilcreggan* and *Ardscalpsie Point* GCR sites.

1.2.2 The Tay Nappe hinge-zone

The hinge-zone of the Tay Nappe consists of the Aberfoyle Anticline and a variable number of satellite folds. The hinge was first described as a normal, upward-facing anticline closing to the south-east (Henderson, 1938; Anderson, 1947a). However, although these authors had used sedimentary way-up structures to identify the structure as an anticline, they had incorrectly interpreted it as closing upwards, a mistake easily made where the major fold is tight to isoclinal. Another approach was needed, and it was Shackleton (1958) who, using the concept of facing direction (as applied to fold structures and cleavages, see Stephenson et al., 2013a) that he had developed in the course of his work in the Highland Border region, demonstrated that the Aberfoyle Anticline is a downward-facing, or synformal, anticline. He correctly deduced that a large part of the South-west Grampian Highlands consists of rocks that are upside down because they belong to the lower limb of an originally recumbent, south-facing nappe-like structure, named the Tay Nappe.

The closure of the Tay Nappe has been traced, as a single fold from the Isle of Bute to Luss on the west side of Loch Lomond (Roberts, 1967) ((Figure 4.1) and (Figure 4.4), sections AA′ and BB′). It passes through the *Cove Bay to Kilcreggan* GCR site where it is located within the outcrop of the Dunoon Phyllites but unfortunately it is not exposed on the coast due to faulting. East of Loch Lomond, the fold closure becomes more complex and can be resolved into three, well-defined major folds, the Ben Vane Anticline, the Ben Ledi Syncline and the Aberfoyle Anticline (Mendum and Fettes, 1985) (Figure 4.4) and (Figure 4.13). The *Keltie Water* GCR site lies on the now-inverted upper limb of this tripartite structure. Farther to the north-east, the *Duke's Pass, Craig a'Barns,* and *Little Glen Shee* sites all lie to the north-west of the predicted position of the Tay Nappe closure, which in these localities is either faulted-out or buried beneath an unconformable cover of Lower Old Red Sandstone sedimentary rocks (Figure 4.1). Although downward-facing structures inferred to be on the north-western side of the Tay Nappe hinge zone can be traced to the east coast at the *Garron Point to Muchalls* GCR site, the main hinge is not seen north-east of Little Glen Shee.

1.2.3 Sequential development of the structural fabrics, and their interpretation

The structural development of this region is most clearly understood by considering the sequential development of minor structures such as cleavages along a traverse from the higher structural levels of the Tay Nappe (now seen adjacent to the Highland Boundary Fault) to the deeper levels (as seen at the Highland Border Downbend).

In a zone up to 10 km wide adjoining, and parallel with, the Highland Boundary Fault, the Dalradian rocks are least deformed, preserve abundant sedimentary structures, and carry only a single (S1) cleavage. Farther to the north-west they are affected progressively by three further, superimposed, phases of deformation (D2, D3 and D4), accompanied by regional metamorphism that reached a peak in the upper amphibolite facies (sillimanite zone) around D2–D3.

The upper, right-way-up limb of the Tay Nappe is excellently exposed at the *Ardscalpsie Point* GCR site where a single, centimetre-spaced, anastomosing S1 pressure-solution cleavage cuts across the bedding at a low angle and is unaffected by later deformation (Figure 4.7). The S1 cleavage is seen to form extreme cleavage fans in gritty metasandstones at the *Little Glen Shee* GCR site, where the full geometry of the D1 phase may be examined (Figure 4.19). Sedimentary and tectonic structures that proxy for those anticipated in the very hinge of the nappe may be readily seen at Camsail Bay, a few kilometres from the *Cove Bay to Kilcreggan* GCR site (see Tanner, 1992).

The S2 fabric and associated minor structures is first seen a few kilometres north-west of the Highland Boundary Fault and within a short distance becomes the dominant structure. It forms a set of penetrative pressure-solution-controlled microlithons. The S1 spaced cleavage was reworked during D2 and is commonly preserved within the new microlithons as sigmoidally curved traces with a distinctive appearance, unique in the structural history of the Dalradian rocks. An example is shown in the *Cove Bay to Kilcreggan* GCR site report (Figure 4.10). Minor structures of this type can be recognized far to the north within the Flat Belt and are used as event markers (see the *Portincaple* GCR site report, (Figure 4.12)). They were recognized in the Cowal peninsula by Clough (in Gunn *et al.*, 1897), who called them 'strain bands' (Figure 4.5). This zone of intense D2 deformation can be recognized across the full width of the region (Figure 4.1) and the morphology of the structures has been described in detail from Birnam by Harris *et al.* (1976) and from Stonehaven in the *Garron Point to Muchalls* GCR site report, in this paper.

A contentious issue is the interpretation of the shear sense given by the deformed early (S1) cleavage stripes within the S2 microlithons. A majority of authors favour top-to-the-SE shear displacement, with others equally convinced that top-to-the-NW displacement has taken place. In this paper, the *Rotmell* GCR site report describes the typical F2 fold style in this part of the Flat Belt, and its evolution by SE-directed simple shear, whereas the author of the *Bealach nam Bo* and *Duke's Pass* GCR site reports favours the alternative interpretation.

These views have led to fundamentally different interpretations of the tectonic regime responsible for the emplacement of the Tay Nappe and related structures. The emplacement is generally considered to have been coeval with the formation of the first folds, although some workers have questioned this. Mendum and Fettes (1985) and Mendum and Thomas (1997) considered that F1 folds must have been recumbent and hence that the Tay Nappe was emplaced during D1, with subsequent NW-directed simple-shear during D2. However, Harris *et al.* (1976) and Harris and Bradbury (1977) considered that the F1 folds were initially upright and were subsequently modified by SE-directed, mainly simple-shear within a continuous phase of deformation involving both D1 and D2. Their model was modified by Krabbendam *et al.* (1997) who proposed that only the lower levels of upright F1 folds were affected by a crustal-scale shear-zone during D2, to produce SE-facing folds with dominant inverted limbs that constitute the Flat Belt; the upper levels of the F1 folds, unaffected by D2 shearing, were subsequently brought down by the Highland Border Downbend to produce the downward-facing Steep Belt.

During D3, the rocks were affected locally, for example around Loch Lomond and at the *Portincaple* GCR site (but not at the *Craig a'Barns* GCR site farther to the north-east), by minor folding and very restricted cleavage development, but no new major folds were formed.

The final event, during D4, was the bending down of the closure of the Tay Nappe close to, and parallel with, the Highland Boundary Fault by the Highland Border Downbend. This brought the hinge-zone and a small part of the upper limb of the Tay Nappe structure down to the present erosion level. The formation of D4 structures is considered by some to be related to and also to post-date a phase of crustal extension during uplift. The initial monoformal form of the Highland Border Downbend is considered to be due to the draping of Dalradian strata over a basement step (Harte *et al.*, 1984). Subsequent compression resulted in tightening of the downbend, which became a focus for smaller-scale F4 folds.

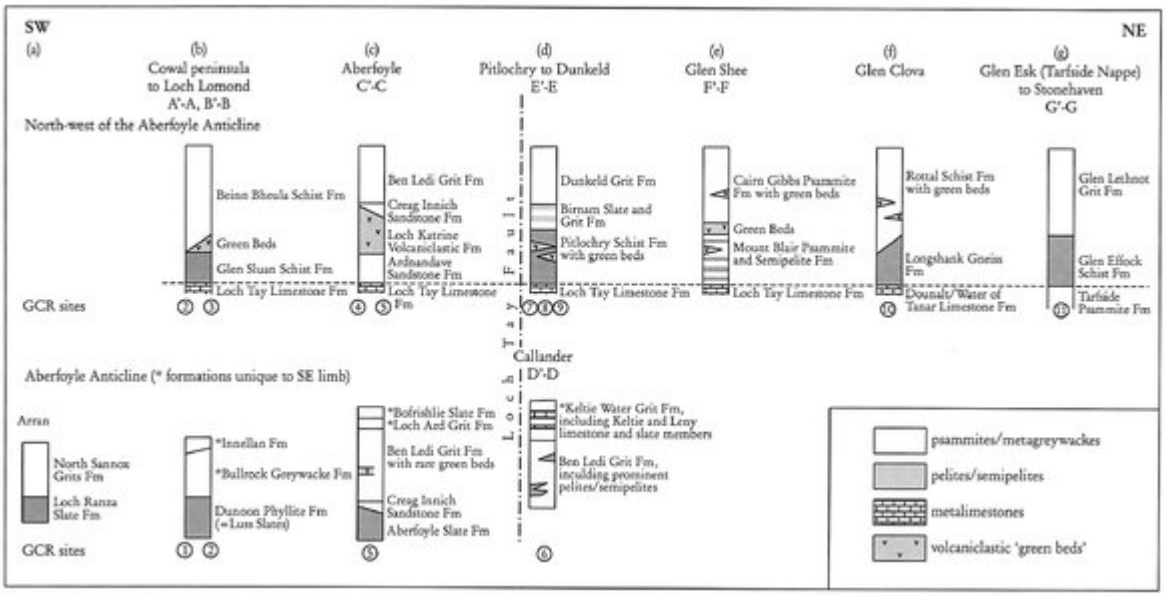
1.3 Regional metamorphism

Work in Glen Esk led Barrow (1912) to develop the concept of zones of metamorphic grade, and to recognize two main types of metamorphism in the Grampian Highlands, Barrovian and Buchan (see Stephenson et al., 2013a). Modern studies in the Highland Border region have shown that there, the regional metamorphism reached a peak during the interval D2–D3, resulting in a series of Barrovian zones characterized by the index minerals chlorite, biotite, garnet, staurolite, kyanite and sillimanite (see the *Glen Esk* GCR site report). The isograds are widely spaced in the west and become very closely spaced towards the north-east (Stephenson et al., 2013a, fig. 12). The lowest grade rocks are at greenschist facies and retain detrital white mica and biotite, whereas the highest grade rocks develop sillimanite and are associated with the formation of migmatite by partial melting. All of the GCR sites in the south-west of the region are in greenschist-facies rocks. Garnet, wrapped by the S2 fabric, is prominent in the schists of the Flat Belt at the *Rotmell* GCR site and is visible as pinhead-size crystals, with biotite, in the phyllitesat the *Craig a' Barns* GCR site. The green beds of the *Bealach nam Bo* GCR site, within the Steep Belt of the Highland Border Downbend, are rich in chlorite and epidote that are associated with the S2 cleavage. Elsewhere along the Steep Belt the pelites are characteristically chlorite-white mica-bearing slates with an S1 cleavage, as seen in the *Keltie Water*, *Duke's Pass* and *Little Glen Shee* GCR sites.

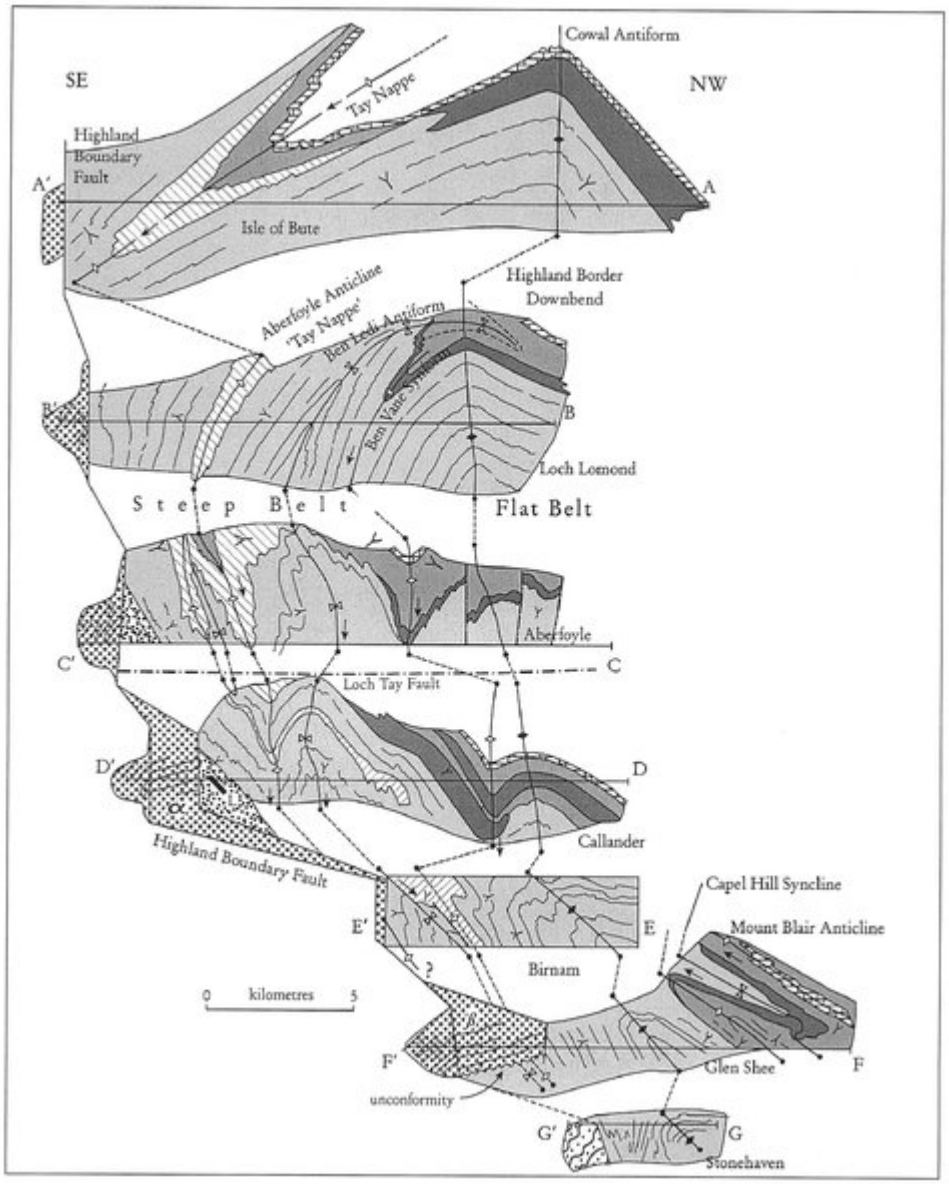
The close spacing of the regional metamorphic isograds in the north-east has been a cause for some speculation in the past but recent work suggests that advective heating by fluids from contemporaneous intrusions is the probable culprit, assisted by ductile shearing during D2 (Phillips and Auton, 1997). It has been demonstrated that peak metamorphic temperatures reached throughout these zones were synchronous to within 2 million years (Baxter *et al.*, 2002), the implication being that the deformation process was also rapid.

References

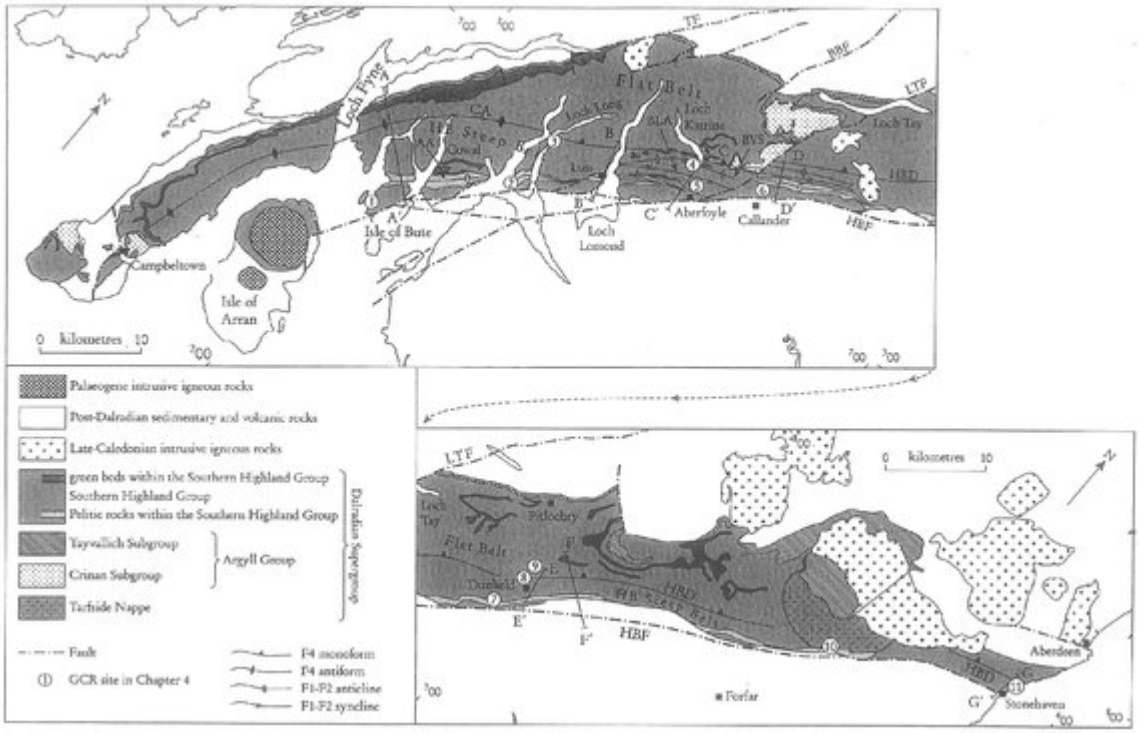
(Figure 4.3) 'Gneiss Rock at Glenfinlas', 1853-54 (pen, wash and gouache on paper), John Ruskin (1819-1900) © Ashmolean Museum, University of Oxford. This picture took several months to complete and lovingly and precisely depicts the tortuous shapes wrought by weathering of the strongly developed S1/S2 cleavage typical of Southern Highland Group rocks south-east of the Highland Border Downbend. The site is in the River Turk, by Brig O'Turk (Greive, 1996), a few hundred metres north of the northern boundary of (Figure 4.18).



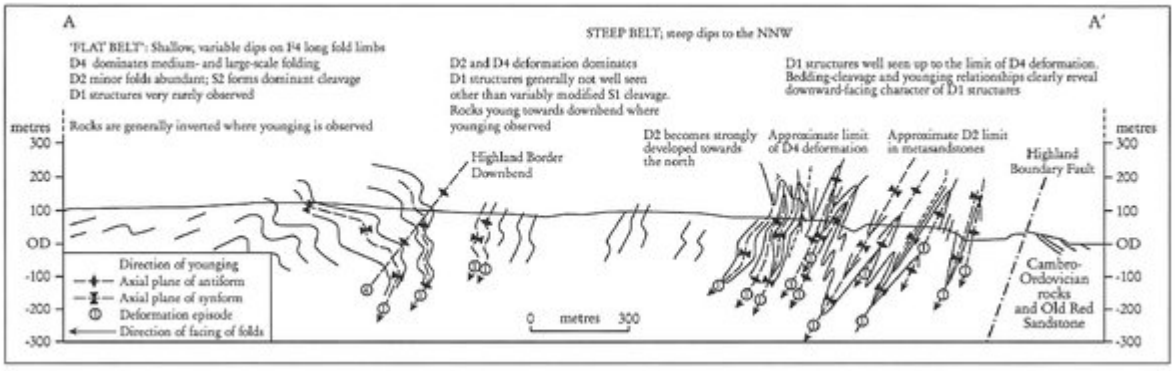
(Figure 4.2) Stratigraphical columns (not to scale) showing variations in Southern Highland Group stratigraphy along the length of the Highland Border region and variations across the strike, where present. N.B. in the Cowal to Loch Lomond area, equivalent formations on the inverted north-west limb and the right-way-up south-east limb of the Aberfoyle Anticline have different names and are shown separately. Although these do reflect some facies variations, the reason is largely historical, dating back to the period before the anticline was recognized. Capital letters in column headings refer to cross-sections in (Figure 4.4). GCR sites are numbered as on (Figure 4.1).



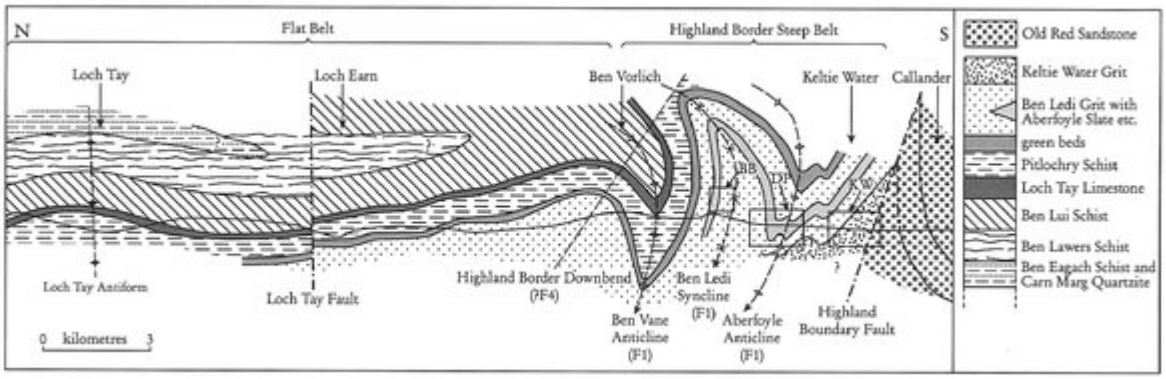
(Figure 4.4) True-scale serial sketch cross-sections across the Tay Nappe and Highland Border Downbend, as viewed to the south-west in the plunge direction of the downbend. Limits of cross-sections and lines of section as shown on (Figure 4.1) are notional and do not reflect current level of erosion. AA' Isle of Bute to Loch Fyne. BB' West side of Loch Lomond. CC' Aberfoyle to Loch Katrine. (after Section 1, BGS 1:50 000 Sheet 38E, Aberfoyle, 2005). DD' Callander. (unpublished cross-section by J.R. Mendum). EE' Dunkeld. (after (Figure 4.24)a). FF' Glen Shee. (after sections 1, 2 and 4, BGS 1:50 000 Sheet 56W, Glen Shee, 1999). GG' Stonehaven. (after (Figure 4.33)). Positions of GCR sites, projected onto the nearest equivalent cross-section, are numbered as on (Figure 4.1).



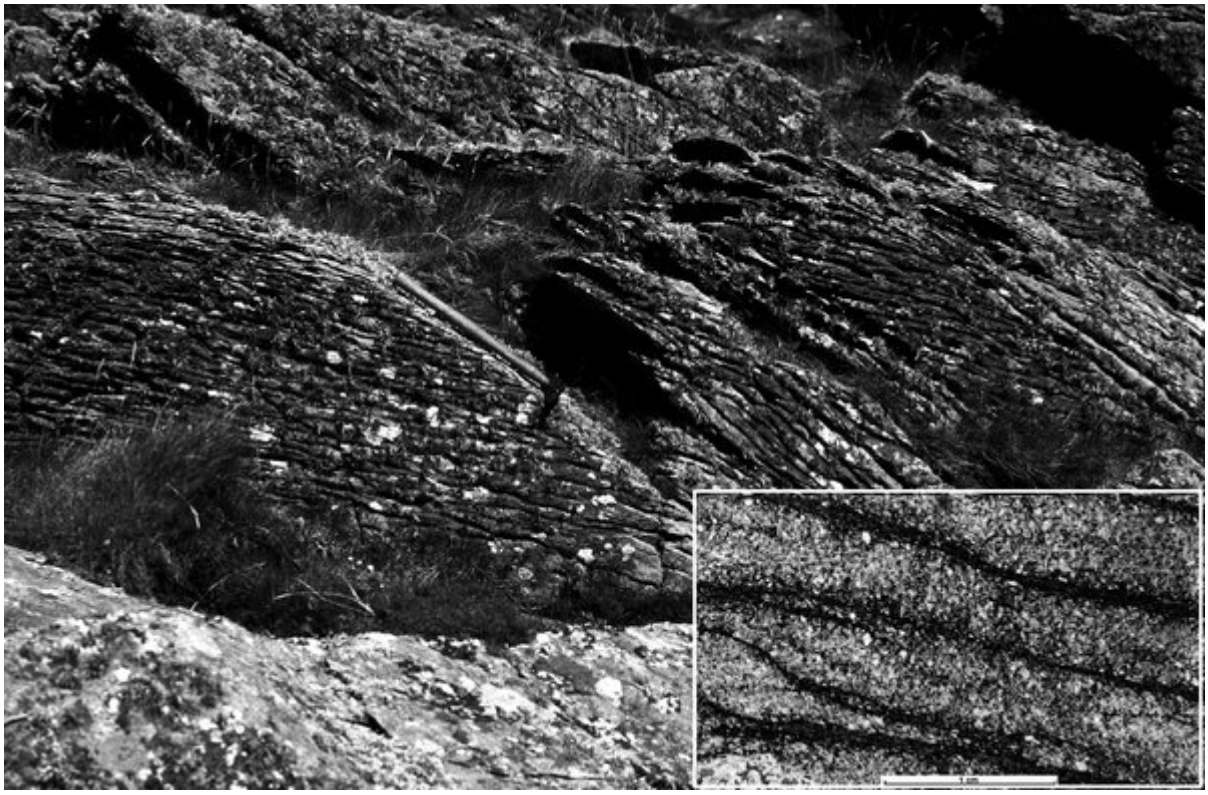
(Figure 4.1) Map of the Highland Border region showing the main stratigraphical divisions, axial plane traces of major folds, and locations of the GCR sites. Only areas described in Chapter 4 are ornamented; outcrop width of the Tayvallich Subgroup is exaggerated in places. NB south-west of the Loch Tay Fault, the pelitic rocks shown in the core of the Aberfoyle Anticline are mostly assigned to the Aberfoyle Slate Formation, which is assumed to be relatively low in the Southern Highland Group; north-east of the Loch Tay Fault, the pelitic rocks are at lower structural levels and hence are in higher parts of the succession, such as the Birnam Slate and Grit Formation (see (Figure 4.2)). Based on BGS 1:250 000-scale maps and modified by P.W.G. Tanner in the light of recent work. Lines of section AA'– GG' refer to (Figure 4.4). Axial plane traces of folds: AA Aberfoyle Anticline (F1–F2), BLA Ben Ledi Antiform (F1–F2), BVS Ben Vane Synform (F1–F2), CA Cowal Antiform (F4), HBD Highland Border Downbend (F4). Faults: BBF Bridge of Balgie Fault, HBF Highland Boundary Fault, LTF Loch Tay Fault, TF Tyndrum Fault. GCR sites: 1 Ardscalpsie Point, 2 Cove Bay to Kilcreggan, 3 Portincaple, 4 Bealach nam Bo, 5 Duke's Pass, 6 Keltie Water, Callander, 7 Little Glen Shee, 8 Craig a' Barns, 9 Rotmell, 10 Glen Esk, 11 Garron Point to Muchalls.



(Figure 4.33) Partly schematic structural cross-section of the coast north of Garron Point, Stonehaven, showing the contrast in dip of bedding in the Flat and Steep belts, the principle F1 and F4 folds and the limits of D2 and D4 deformation in metasandstones. Structures observed on the coast have been projected onto the line A–A' shown on (Figure 4.27). Section is true scale (no vertical exaggeration). After BGS 1:50 000 Sheet 67 (Stonehaven, 1999).

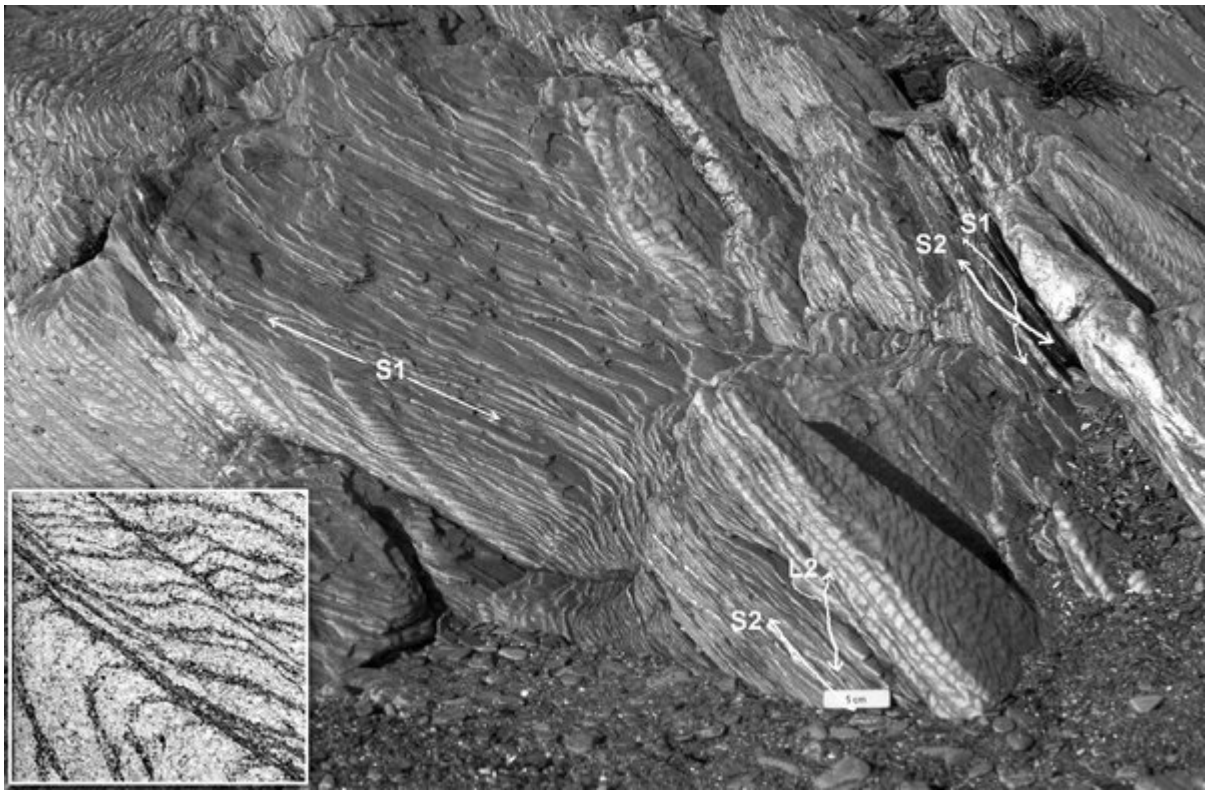


(Figure 4.13) Cross-section from Callander due north to Loch Tay. The section continues the Flat Belt from the southern end of the section in (Figure 3.3)b and shows the position of the Keltie Water (KW), Bealach nam Bo (BB)and Dukes Pass (DP) GCR sites within the Steep Belt created by the F4 Highland Border Downbend. The assumption is made that there is a single continuous unit of 'green beds'.

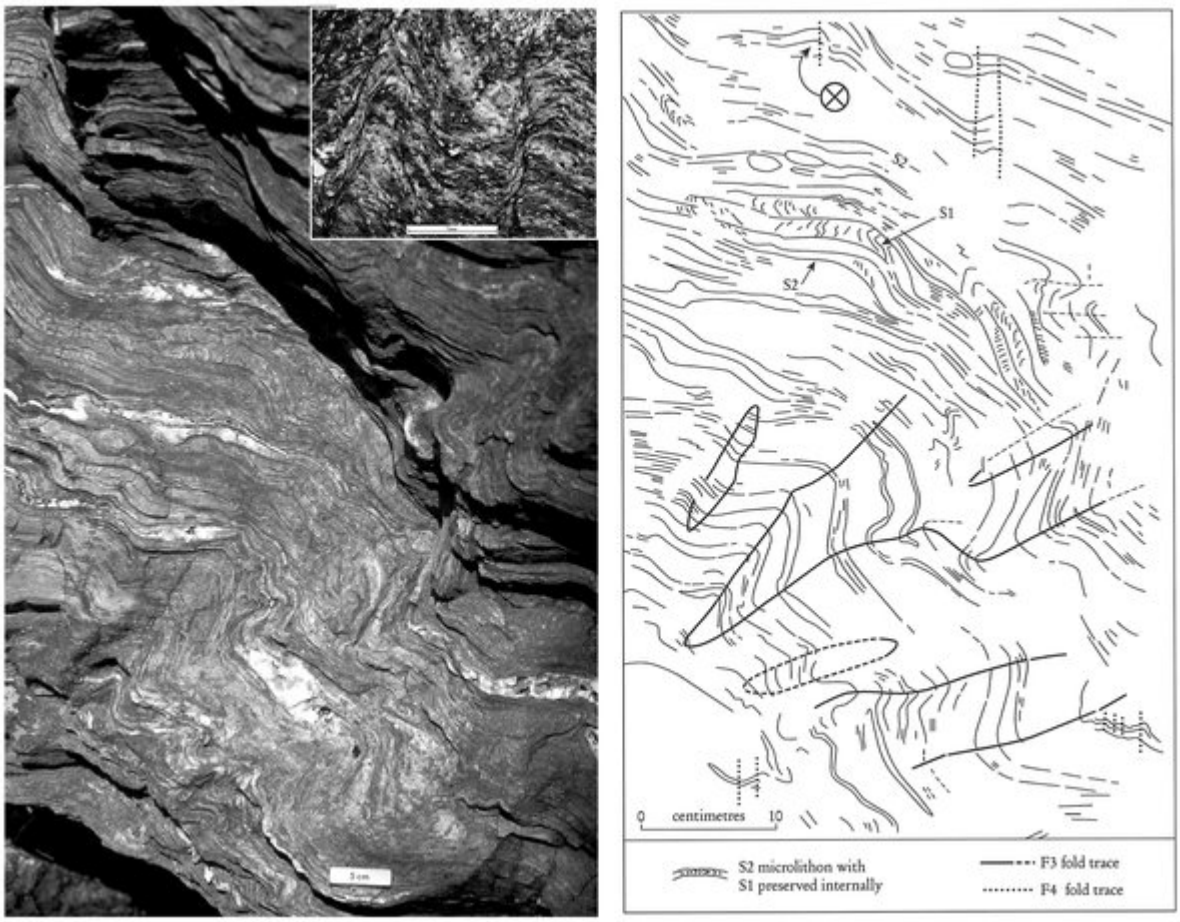


(Figure 4.7) (a) An inland exposure at Ardscalpsie Point [NS 0440 5766], showing the bedding-cleavage relationship found typically on the upper limb of the Tay Nappe at this GCR site. Bedding, which is parallel to the hammer shaft, is cut by the spaced S1 cleavage (seen as etched lines on the surface) that dips at a more-gentle angle to the south-east (right on photo). Hammer shaft is 60 cm long. (Photo: P.W.G. Tanner.) (b) Photomicrograph showing the relatively undeformed nature of the D1 metasandstone microlithons which, together with the intervening thin dark cleavage domains, constitute the S1 cleavage in (a). (Photos: P.W.G. Tanner.)

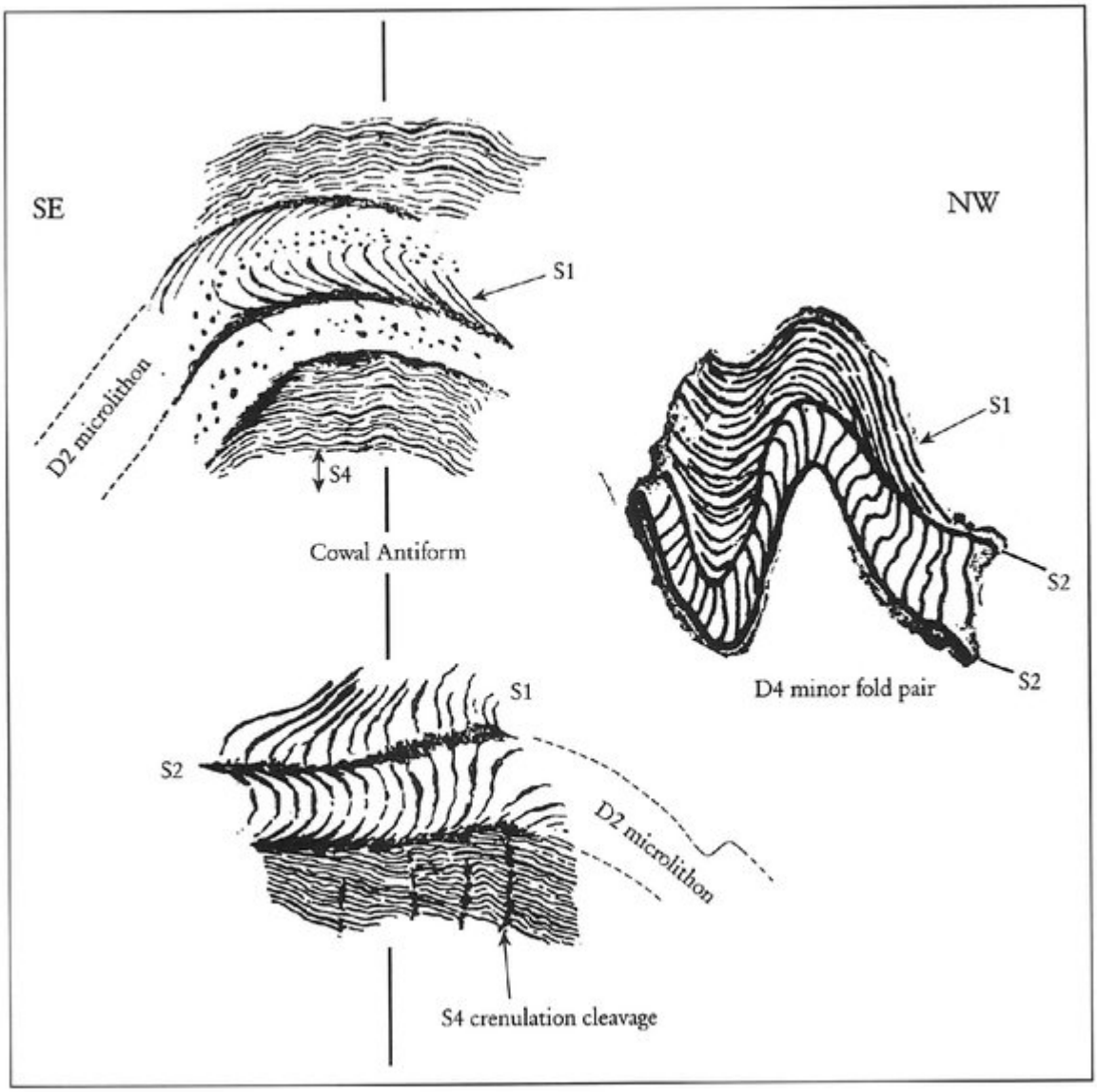
(Figure 4.19) Typical F1 fold in metasandstone of the Creag Innich Sandstone Formation at [NN 5144 0344] on the Duke's Pass, Aberfoyle. The coarse-grained base of a gritty metasandstone unit lies above the hammer head, passing down into finer grained rock towards the end of the handle. The rocks are inverted and the fold is downward facing. Hammer shaft is 36 cm long. (Photo: C.W. Thomas. BGS No. P 643897.)



(Figure 4.10) (a) Centimetre-wide microlithons, separated by narrow dark anastomosing cleavage domains which, together form the main, SE-dipping, S2 fabric in the metagreywacke unit of the Dunoon Phyllite Formation near Barons Point [NS 223 808]. The spaced S1 fabric can be clearly seen locally within the microlithons, frozen in the act of transformation to S2. The L2 intersection lineation occurs as a ribbon lineation on the main fabric surface. (b) Photomicrograph of the D2 microlithons in (a), reworking S1 pressure-solution stripes (shown in their original state in (Figure 4.7)b). (Photos: P.W.G. Tanner.)



(Figure 4.12) (a) A vertical rock face in the Bheinn Bheula Schist Formation at Portincaple [NS 2297 9327], viewed to the north-east (054°), showing asymmetrical, Z-shaped F3 folds on the southern limb of the Highland Border Downbend. The D3 structures deform the main S2 spaced fabric; the poorly developed minor upright F4 folds are accompanied by a near-vertical, crenulation cleavage that, although restricted to the pelitic seams, is clearly imprinted on and hence post-dates all of the other structures. Note the local preservation of the S1 fabric within the S2 microlithons. (Photo: P.W.G. Tanner.) (b) An explanatory outline drawing of (a). (c) Photomicrograph of the S4 crenulation cleavage at X on (b). (Photo: P.W.G. Tanner.)



(Figure 4.5) A composite figure prepared from C.T. Clough's field sketches, as reproduced in the Geological Survey's Cowal memoir (Clough, in Gunn et al., 1897, figs 12 and 13). The individual sketches are arranged diagrammatically with respect to their inferred position on the Cowal Antiform. It is clear from these sketches that Clough understood how to identify and unravel the effects of polyphase deformation some sixty years before John Ramsay demonstrated it at Glenelg (Ramsay, 1958).