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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:

(i) 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.

(ii) 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.

(iii) 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 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 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 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. 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, 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, 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 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 2b) 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 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 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, 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 (Figures 1 and 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).

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 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, 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 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) (Figures 1 and 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) (Figures 4 and 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 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 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 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 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 12). They were recognized in the Cowal peninsula by Clough (in Gunn *et al.*, 1897), who called them 'strain bands' (Figure 5). This zone of intense D2 deformation can be recognized across the full width of the region (Figure 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 phyllites at 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.

2 ARDSCALPSIE POINT (NS 043 580–NS 045 576)

P.W.G. Tanner

2.1 Introduction

The Ardscalpsie Point GCR site is situated on the west coast of the Isle of Bute, just to the north of Scalpsie Bay. It consists of a narrow rock platform backed by a steep rock face that forms an almost straight, 400 m-long, section north-west of Ardscalpsie Point (Figure 6). The immediate hinterland, which consists of a raised beach backed by an ancient sea cliff, also provides some excellent exposures.

The metasedimentary rocks exposed in this section are some of the youngest in the Southern Highland Group. They were formerly assigned to the Bullrock Greywacke (*sensu* Clough, in Gunn *et al.*, 1897) and have also been referred to as the 'Lower Leny Grits' (Anderson, 1947a) and the Innellan 'Group'. They are now assigned to the Toward Quay Grit Member of the St Ninian Formation, which overlies the Bullrock Greywacke Member stratigraphically (i.e. on the BGS 1:50 000 Sheet 29E, Dunoon and Millport, 2008). Immediately east of the GCR site, the Toward Quay Grit Member is overlain by the Ardscalpsie Formation, which is assigned to the Trossachs Group. The GCR site lies well south of the outcrop of the Dunoon Phyllite Formation, which contains the closure of the Tay Nappe (see the *Cove Bay to Kilcreggan* site report), and has a splay of the Highland Boundary Fault as its southern limit.

This GCR site is of national importance as it provides a unique opportunity to examine a virtually continuous, and clean, coastal section across part of the top limb of the Tay Nappe. The closure of the Tay Nappe can be traced across Scotland but the upper limb of the structure is seldom well exposed. It is seen, for example, to the north-east of this site between Toward and Dunan on the Dunoon peninsula (where it is named the Aberfoyle Anticline: Roberts, 1974) and at the *Cove Bay–to Kilcreggan* GCR site, but is not as readily studied as at Ardscalpsie Point. Here, the inland exposures, deeply etched by weathering due to their slightly calcareous nature, complement those on the coast and reveal in detail the relationship between the spaced S1 cleavage and the bedding (Figure 7). The contact between the uppermost Dalradian and the much younger, Devonian to Lower Carboniferous strata, seldom seen in the 250 km between Arran and Stonehaven, is well exposed at the south-east end of the rock platform.

Surprisingly, considering the pioneering work carried out in the neighbouring Cowal peninsula, no details of the Dalradian rocks were given in the Geological Survey memoir covering this part of Bute (Gunn *et al.* 1903). It was left to McCallien (1938) to provide the first general account of the Dalradian of Bute. Anderson (1947a) published a more-detailed account and map of Scalpsie Bay, and concluded, from the dip of the beds combined with way-up evidence, that the Dunoon Phyllites farther north on Bute lie in the core of a 'normal' (i.e. *upward-facing*) anticline. Conversely, Shackleton (1958) suggested that the Tay Nappe structure is probably a *downward-facing* anticline, based on an admittedly small number of observations of the geometrical relationship of bedding to cleavage, combined with way-up evidence. The only detailed, modern study of this section was by Simpson and Wedden (1974) who confirmed Shackleton's interpretation, and recorded the three-dimensional relationship of the L1 stretching lineation to the local fold hinges in these rocks.

2.2 Description

The coastal section trends at about 60° to the general strike of the beds, and is excellent for cross-section construction (Figure 8). The only drawback is that, despite almost continuous rock exposure above the high-tide mark, many of the rock surfaces in the intertidal zone, which would normally yield the finer detail, are completely covered with a dense mat of barnacle and algal growth.

The rocks consist of beds of grey-green metagreywacke, generally 1–2 m thick in the northern part of the section, but reaching 3 m thick at the southern end. They are separated by thin layers of metasiltstone and/or slaty metamudstone (generally less than 10 cm thick), or form amalgamated units. The metagreywackes, formerly referred to as 'grits', are fine to coarse grained, and many of the beds show normal grading.

Over thirty examples of graded bedding have been recorded from the section shown in Figure 8 and, as previously reported by McCallien (1938), they show younging to the south-east. Beds are generally right-way-up throughout the section, only becoming overturned on the middle limbs of mesoscopic F1 folds (Figure 8, localities a and b). As a result of the bonding effect of penetrative deformation and cleavage development, the bottoms of beds are very rarely exposed. However, flame structures are seen on the bases of a few beds, and cross-lamination (showing younging to the south-east) is seen in the uppermost, finer grained parts of some beds; Simpson and Wedden (1974, plate 1a) illustrate an example from 450 m north of the GCR site.

Thin beds of metamudstone and/or metasiltstone occur commonly between the metagreywacke beds in the northern half of the section, whereas thick, amalgamated beds of metagreywacke with no intervening mudrock predominate in the younger rocks to the south. The metamudstone occurs in several guises: as grey-green slaty metamudstone with 1–5 mm-thick bands of black metamudstone; as grey slaty metamudstone with centimetre-scale green bands; and as purplish grey, slaty metamudstone. The latter variety is more common at the southern end of the section.

The matrix of the metagreywackes consists of detrital grains of quartz, feldspar, and muscovite, accompanied by flakes of chlorite and white mica, which grew during the regional metamorphism (Simpson and Wedden, 1974). The granule- to medium-pebble-sized clasts found at the bases of graded beds are mainly of quartz, with pink feldspar being common in some beds. Rip-up slabs and angular fragments of dark mudstone, a few centimetres long, occur in a number of the beds.

The beds forming the long limbs of the F1 minor folds are right-way-up, and represent the regional orientation of the upper limb of the 'Tay Nappe'. They dip consistently to the south-east at about 60°, at a steeper angle than the first cleavage (S1; dip 42°SE) throughout the section (Figures 6, 7 and 8). An L1 stretching lineation, plunging at 33° to the east-south-east, is present as a silky striation on slaty-cleavage surfaces, mainly in the northern part of the section (Simpson and Wedden, 1974).

The penetrative slaty cleavage (S1) developed in the metamudstones is fanned in mesoscopic fold closures and is continuous, via cleavage refraction, with the centimetre-scale micolithons making up the spaced cleavage that affects most of the metasiltstones and metagreywackes (Figure 7b). This spaced cleavage is even seen in some of the 2–3 m-thick metagreywacke beds. Evidence of later ductile deformation is given by a few late, open structures that fold the main cleavage (Figure 8, localities c, d and e), and by an unrelated, gently dipping, crenulation cleavage that occurs locally. Faults with varying orientations occur at regular intervals throughout the section, becoming more significant and marked by massive quartz veins or fault-breccia up to a metre thick, as the Highland Boundary Fault is approached.

The faulted relationship between the Dalradian rocks and red sandstones of the Lower Carboniferous, Kinesswood Formation is fully exposed at beach level in the intertidal zone at locality f on Figure 8. It is marked by a zone of brecciated Dalradian rock up to 14 m thick, south-east of which major rectilinear fractures separate the Dalradian from the Carboniferous rocks. A 45 cm-thick, deeply weathered, dyke runs parallel to the fault zone (Hill and Buist, 1994). Reddening of the Dalradian rocks along joints and fractures at this locality suggests that the Old Red Sandstone-facies Carboniferous rocks once lay unconformably on the Dalradian north of the branch of the Highland Boundary Fault, prior the final displacement on the fault.

The Dalradian rocks are weakly metamorphosed, and occur within the chlorite zone of regional metamorphism; detrital white mica is still present in the mineral assemblage, but is accompanied by a felt of smaller, aligned, white mica crystals making up the S1 fabric.

2.3 Interpretation

The St Ninian Formation, and in particular the Bullrock Greywacke Member, have been correlated with similar pebbly metagreywackes found south of the Dunoon Phyllite Formation on the Toward peninsula, Rosneath peninsula (Tanner, 1992; *Cove Bay to Kilcreggan* GCR site), and west of Loch Lomond, as well as north of the putative Highland Border Complex at North Glen Sannox, Isle of Arran. At all of these localities the Bullrock Greywacke is right-way-up and dips to the south-east on the upper limb of the Tay Nappe.

At the *Ardscalpsie Point* GCR site, right-way-up beds dip consistently to the south-east at a steeper angle than the first cleavage (S1) (mean difference=19°; Figures 6 and 8). This agrees with the minor fold vergence and confirms that the D1 facing direction is down-to-south, and that the 'Tay Nappe' here is a synformal or downward-facing anticline (Shackleton, 1958; Simpson and Wedden, 1974).

Stretching lineations were first described from Dalradian rocks by Clough (in Gunn *et al.*, 1897), from the Cowal peninsula to the north-east of the Isle of Bute. When plotted on an equal area stereographic projection, the F1 fold hinges and intersection lineations from this GCR site are seen to be dispersed along a great circle that contains the mean orientation of the stretching lineation. This result is consistent with the curvilinear nature of some minor folds observed in the field and indicates that a considerable rotation of fold hinges towards the stretching direction (X) has taken place (see the *Strone Point* and *Glen Orchy* GCR site reports in Tanner et al., 2013a and Treagus et al., 2013 respectively).

Late warps of the bedding and early cleavage have the step-like geometry characteristic of minor structures congruous with the F4 Highland Border Downbend (see the *Portincaple* GCR site).

2.4 Conclusions

The Tay Nappe is one of the largest fold structures in Scotland. It was excised south-east of the Highlands by movement on the Highland Boundary Fault, leaving the upper limb of the Nappe exposed only in a relatively narrow SW—NE-trending outcrop across Scotland. The importance of the Ardscalpsie Point GCR site lies in the fact that it is probably the best place for studying in detail this limb of the structure, to check whether the field relationships accord with the proposed structural model for the nappe (for details of the evolution of the Tay Nappe, see the *Cove Bay to Kilcreggan* GCR site report).

At this site, the Dalradian rocks belong to the St Ninian Formation, a thick unit of pebbly metagreywackes and thin beds of slaty metamudstone, which was deposited from turbidity flows in a submarine fan environment. It is amongst the youngest of the Dalradian formations, and occupies a position close to the top of the Southern Highland Group. Sedimentary structures, especially graded bedding, and bedding-cleavage relationships can be very clearly seen in these rocks on the 400 m-long coastal section adjacent to Ardscalpsie Point. The combination of undoubted, and plentiful, way-up evidence, with structural data, provides a very clear demonstration that the St Ninian Formation lies on the upper limb of a major F1 fold, the 'Tay Nappe', that closes *downwards* and yet has the older rocks in its core. It is a downward-facing, or synformal, anticline, as envisaged by Shackleton (1958), from preliminary observations at Ardscalpsie. This fold, originally flat-lying, was rotated into its present position by folding on the Highland Border Downbend (see the *Portincaple* GCR site report).

In addition, this GCR site is also excellent for studying the development of spaced cleavage in quartz-rich metasedimentary rocks, and is one of the few places where a branch of the Highland Boundary Fault, the major fault bounding the Dalradian outcrop on its south-east side, is fully exposed. In this part of Bute, the Highland Boundary Fault brings Dalradian rocks against Lower Carboniferous rocks: a related fault-zone is fully exposed 600 m north-west of Ardscalpsie Point and is marked by a zone of brecciated Dalradian rock up to 14 m wide, and by major rectilinear fractures, which bring the Dalradian and Carboniferous rocks into direct, knife-sharp contact. Evidence from this locality that the Carboniferous rocks once lay unconformably on the Dalradian rocks immediately north of the Highland Boundary Fault suggests that the post Early Carboniferous displacement on the fault branch at Ardscalpsie might have been relatively small.

3 COVE BAY TO KILCREGGAN (NS 215 836–NS 242 804)

P.W.G. Tanner

3.1 Introduction

The Cove Bay to Kilcreggan GCR site consists of a 5 km-long strip of coastal exposure, interrupted only by a few pebble beaches, that runs between Knockderry Castle and Kilcreggan Pier on the west side of the Rosneath peninsula (Figure 9). The site is of national importance as it provides the only well-exposed coast section across the putative closure of the Tay Nappe, one of the largest folds in the British Isles. Plentiful minor structures document the development and present-day geometry of this major fold. There is undisputed evidence for four deformational episodes (D1–D4) in the Daladian rocks farther north (see the *Portincaple* GCR site report), but only D1 and D2 are fully developed at this site. However, a major feature here is the manner in which the D2 deformation, that responsible for the southward propagation of the Tay Nappe (Harris *et al.*, 1976), increases in intensity northwards (downwards in the originally near-horizontal nappe), overprints, and finally destroys most field evidence for the prior existence of the D1 structures.

The sequence of Southern Highland Group rocks within this GCR site formed the original upper limb of the Tay Nappe and occupies a structural setting comparable to that of the *Ardscalpsie Point* GCR site. It consists mainly of right-way-up turbidite beds of the Bullrock Greywacke Member of the St Ninian Formation, which dip to the south-east and lie both stratigraphically and structurally above the Dunoon Phyllite Formation. This formation in turn overlies inverted strata of the Beinn Bheula Schist Formation. The simplest geological interpretation of these relationships is that the Bullrock Greywacke is the lateral stratigraphical equivalent of the Beinn Bheula Schists, and that these two units represent the two limbs of a downward-facing anticline, the Tay Nappe, which has the Dunoon Phyllites in its core (Shackleton, 1958; Roberts, 1974).

All of the rocks have been affected by greenschist-facies regional metamorphism. White mica-chlorite-bearing assemblages are ubiquitous and give many of the rocks a greenish tinge.

Although the first published map of the Rosneath peninsula was produced by the Geological Survey in 1878, it was not accompanied by a sheet explanation or memoir. The first account of the geology was by Roberts (1966a), who concentrated mainly on analysing the depositional environment of each stratigraphical unit. This work was followed by the publication of two field guides that described the salient features of several localities within this GCR site (Roberts, 1977b; Tanner, 1992). The geology of the peninsula was also described succinctly by Henderson (in Paterson *et al.*, 1990) in the memoir to accompany the BGS 1:50 000 Sheet 30W/29E (Greenock, 1990).

3.2 Description

The Bullrock Greywacke consists of gritty and pebbly feldspathic metagreywacke, interbedded with some finer-grained metagreywackes and metasiltstones, and some layers of black slaty metamudstone. The pebbles are mainly of quartz and feldspar. Normal graded bedding, confirmed in some cases by an accompanying erosional base to the bed, or the presence in the same bed of bottom structures, trough cross-bedding or channel infills, is seen at a number of places. Sets of finely spaced cross-laminae are present in the silty tops of a few turbidite beds. However, many of the beds are apparently homogeneous or show evidence of amalgamation. Calcareous concretions of diagenetic origin are common locally. They occur as bedding-parallel lenses and pods up to a few decimetres thick and reaching several metres in length, and as pod-shaped bodies oblique to bedding. In each case, bedding laminations preserved in the calcareous body are continuous with those in the host greywacke (Tanner, 1992).

Due to faulting, combined with a 200 m gap in exposure, the contact between the Bullrock Greywacke and the Dunoon Phyllites is not seen on the coast, but evidence from outwith the area in Aldownick Glen (NS 270 850) shows that it is a normal transitional contact (Paterson *et al.*, 1990).

The Dunoon Phyllite Formation consists mainly of black, purple, grey, and olive-green slaty and phyllitic metamudstones, with some beds of gritty metagreywacke, and of finer-grained metagreywacke and metasiltstone. Rare beds of pebbly metagreywacke up to 2 m thick are also present. Thin lenses and pods of metacarbonate rock occur in the black, phyllitic, graphitic metamudstones. They weather to a dull brown colour and are probably dolomitic in composition. The un-named bed of metagreywacke within the Dunoon Phyllites, exposed on the coast at Barons Point (Figure 9), appears to be in normal stratigraphical contact with the metamudstones to either side of it. There is sparse evidence of way-up from chanelling and cross-lamination in most of the coastal outcrop of the Dunoon Phyllites, but the northern part appears to young towards the Beinn Bhuela Schists.

The Beinn Bheula Schist Formation consists of generally well-bedded grey-green metagreywacke, less feldspathic than the Bullrock

Greywacke, with bands of phyllitic metamudstone and metasiltstone, and uncommon pods of brown-weathering metacarbonate rock. Based on the evidence of sporadic graded bedding and cross-lamination, that part of the sequence exposed south of Knockderry Castle is inverted. The formation includes an 18 m-thick unit of metabasaltic sheets and (?) tuffaceous rocks just to the south of Knockderry Castle (Figure 9) which resemble the green beds of the Loch Lomond area. The contact between the Beinn Bheula Schists and the Dunoon Phyllites is well exposed at NS 220 828 and is transitional over more than 20 m. Way-up structures show clearly that the structurally overlying Dunoon Phyllite is the older formation and that both formations young to the north close to their mutual contact.

The structures seen at this GCR site are almost entirely due to the first two deformations, D1 and D2. The S1 cleavage is seen as a centimetre-spaced set of anastomosing microlithons in the gritty rocks; a shape fabric (deformed grit particles) in the finer grained metagreywackes; or a slaty cleavage in the metamudstones. No structures or fabrics related to D3 have been detected. The D4 deformation is very localized and is expressed as NNW-verging, step-like folds, associated with a steep to vertical, millimetre-spaced crenulation cleavage that folds S1 and S2.

Three major folds of D1 age occur in the Bullrock Greywacke west and north of Kilcreggan Pier, but their hinge-zones are poorly exposed. However, one of the closures is well exposed along strike at Creag na Goibhre, Camsail Bay, north-east of Kilcreggan (NS 262 822) (Figure 9), and provides an analogue for the closure of the Tay Nappe itself (Tanner, 1992). Structural analysis of the orientations of bedding, S1 cleavage (axial-planar to millimetre-scale minor folds and warps), bedding/cleavage intersection lineations, and minor fold hinges show that this fold is a synform with a near-vertical axial plane and a fold axis plunging at less than 10° to the south-west. Way-up evidence from graded bedding and cross-lamination shows that it is a downward-facing anticline.

D1 structures in the south of the area are in their pristine state, unaffected by later deformation, but north of a line drawn approximately through the Cove Burgh Hall a few hundred yards south-east of Barons Point, the early cleavage can be seen in the field to have been affected by the development of a later spaced cleavage (S2). From this point northwards, the D2 deformation takes over and S2 rapidly becomes dominant. It is the main, and in some places only, planar structure in the Ben Bheula Schists in the northern half the area, where the sedimentary structures are progressively destroyed; in places only the coarser grained, granule to pebbly metagreywackes and calcareous concretions and layers preserve evidence of bedding surfaces.

D2 microlithons developed in the coarser metagreywackes have centimetre-scale spacing, and in homogeneous gritty metagreywackes, the anastomosing microlithons very closely resemble those of undoubted D1 age seen farther south. The difference is that further inspection usually reveals relics of the earlier spaced cleavage within the D2 microlithons, a striking example of which is shown in Figure 10. The S2 fabric in metamudstones is subtle; in the field, it appears to be a slaty cleavage (S1), but under the microscope it is a very closely spaced crenulation cleavage that has clearly deformed an earlier fabric (Tanner, 1992).

F2 minor folds are rare; they fold an earlier cleavage and have hinges plunging at moderate angles to the south-west. The latter are statistically parallel to local bedding/cleavage intersection lineations on a micro-crenulation cleavage (S2) that poses as 'slaty cleavage'.

Inland mapping shows that three major faults cross the coast section and cause a significant displacement of the outcrop of the Dunoon Phyllites (Figure 9). Evidence for only one of these faults is seen on the coast section. The Highland Boundary Fault is marked by an erosional hollow at the south-eastern limit of the GCR site but is not exposed.

3.3 Interpretation

The lateral correlation of stratigraphical units recognized on the Rosneath peninsula is well established. The Bullrock Greywacke, a right-way-up unit of gritty and pebbly, feldspathic metagreywackes, correlates with rocks having a similar character from the Isle of Bute to Loch Lomond side; the Dunoon Phyllites equate with slaty metamudstones on the Isle of Bute and the Luss slates at Loch Lomond; and the inverted sequence of Beinn Bheula Schists seen north of the Dunoon Phyllites occupies the same relative structural position at all of these localities. The metabasaltic and associated rocks at Knockderry Castle may be correlated with the green beds seen east of Loch Lomond.

The Bullrock Greywacke and Beinn Bheula Schists in the area of this GCR site, the 'greywacke affiliation' of Roberts (1966a), originated mainly as sequences of siliciclastic turbidites deposited in a submarine fan environment. In contrast, the Dunoon Phyllites were most likely deposited in a deeper water, oceanic setting, and consisted of pelagic muds diluted by the periodic influx of siliciclastic turbidites.

The structural situation is more enigmatic. On the Rosneath peninsula and at this GCR site in particular, the limbs of the major D1 structure, the Tay Nappe, are clearly defined by the thick unit of consistently inverted Beinn Bheula Schists (in the north-west) and the largely right-way-up Bullrock Greywacke (in the south-east), but the hinge-zone of this structure is difficult to locate.

This problem had been recognized earlier (Roberts, 1974; Paterson *et al.*, 1990) and it was suggested that there is a major slide along the south-eastern margin of the Dunoon Phyllite outcrop, which cuts out some of the southern limb of the major fold. However, this does not agree with the evidence from outwith the peninsula that this boundary is a normal sedimentary contact (Paterson *et al.*, 1990). There are two alternative possibilities; either the actual hinge-zone is poorly defined and is represented by a number of mesoscopic fold closures, or it is hidden by faulting. There is no field evidence to indicate the presence of mesoscopic folds in the Dunoon Phyllite. On the other hand, three large N-S-trending faults, each having a component of sinistral transcurrent displacement, cause a considerable displacement of the

Dunoon Phyllites (Figure 9). The combined effect of this faulting is to remove about three kilometres of cross-strike exposure of the Dunoon Phyllites from view on the coast section within this GCR site. This 'hidden section' probably contains the closure of the Tay Nappe, with the folds seen to the south in the Bullrock Greywacke being congruous with the major fold.

The coastal section at this GCR site represents a depth profile of some 4 km through the Tay Nappe, at a time when it was a flat-lying, or recumbent, anticline closing to the south-east (Tanner, 1992) (see the *Introduction* to Tanner et al., 2013b for a fuller explanation). At that time, the rocks at Kilcreggan formed part of the top limb of this structure, and were at a higher level in the Earth's crust than those at Knockderry Castle, on the lower limb.

D1 minor structures dominate the southern part of the section, but north of Barons Point, the pervasive spaced or slaty S2 fabric overprints the earlier one and evidence of D1 vergence can no longer be recognized. D2 shear results in very regular planar S2 surfaces but several stages in the development of the D2 microlithons that formed at a high angle to the spaced S1 cleavage are preserved. These features provide a reliable fingerprint for identifying the D2 fabric in rocks of the Flat Belt to the north and enable complex fold interference patterns to be unravelled (see the *Portincaple* GCR site report, Figure 12). In some cases they show the relative shear sense during D2 deformation (Harris *et al.*, 1976; Krabbendam *et al.*, 1997).

Subsequently, the nappe was affected by two further deformations (D3 and D4), the second of which was responsible for rotating the rocks at this GCR site into their present steeply dipping attitude. The effects of these phases are best seen in the *Portincaple* GCR site, where the relationship of D2 to both D3 and D4, and the geometry of the Highland Border Downbend, may be examined.

3.4 Conclusions

The rocks seen in the coast section between Cove Bay and Kilcreggan belong to the upper part of the Southern Highland Group and are divided into three stratigraphical units. Both the Bullrock Greywacke and the Beinn Bheula Schists consist of coarse-grained, sometimes pebbly, metagreywackes that show graded bedding and cross-lamination. They were deposited in a submarine fan environment, whereas the Dunoon Phyllites, which consist largely of varicoloured slaty rocks, were deposited farther away from the continental margin in an oceanic basin setting. The exposures of the Dunoon Phyllites are of such quality as to constitute a reference section for this formation. All of the rocks have been deformed and metamorphosed subsequently during the Grampian Event of the Caledonian Orogeny, and now dip to the south-east at a moderate angle.

This GCR site provides a unique coastal section across the closure of the Tay Nappe, a structure that can be traced north-east–south-west across the Dalradian outcrop from the Isle of Bute to the east coast of the Grampian Highlands. The Bullrock Greywacke and the Beinn Bheula Schists, although rather different in lithology and mineralogy, have been correlated with each other, and are thought to represent the right-way-up limb and inverted limb, respectively, of the Tay Nappe. The Dunoon Phyllites, sandwiched structurally between them, occupy the core of the fold.

The great value of this GCR site is that it preserves structural information, in particular, that may be used to analyse and model early stages in the development of the Tay Nappe, and test the various hypotheses that have been proposed to explain its mode of emplacement. The evidence for the first two stages is charted by the sets of minor structures and cleavages so splendidly preserved in places in these rocks. In addition, there are few locations in the British Isles where the mechanisms involved in transforming an early, spaced, pressure-solution cleavage to a new cleavage of the same type can be studied in such detail.

4 PORTINCAPLE
(NS 227 928–NS 232 937)

P.W.G. Tanner

4.1 Introduction

This GCR site is situated on the eastern shore of Loch Long at the small hamlet of Portincaple (Figure 11a). It consists of a rock platform fringing the coastline in the south, and low cliffs in the north that together expose an excellent section through the southern part of the hinge-zone of the Highland Border Downbend. This structure was responsible for rotating the Tay Nappe from an originally gently dipping orientation now represented by the Flat Belt, to its steeply dipping orientation in the Highland Border Steep Belt (as represented by the *Cove Bay to Kilcreggan* GCR site).

Here, the broad, open form of the F4 hinge-zone and the concordant geometry of the related minor structures are clearly shown. The geometry and vergence of D3 structures may also be readily examined, and there is clear evidence of their refolding by the major F4 downbend. The value of this site is also enhanced by the fact that it is the first significant accessible coastal section on the lower limb of the Tay Nappe north of Coulport, 5 km to the south. All of the intervening ground has been acquired by the Ministry of Defence and closed to public access.

The rocks consist of metagreywackes belonging to the Beinn Bheula Schist Formation. Bedding was thoroughly reworked during the formation of two pressure-solution cleavages (S1 and S2) and has been largely destroyed or rendered obscure during the process. However, a wealth of folded and overprinted cleavages, intersection and stretching lineations, and minor folds belonging to the three latest generations of structures, are very well preserved in clean rock exposures above mean tide level.

The Portincaple GCR site lies on the eastern margin of BGS 1:50 000 Sheet 37E (Loch Goilhead, 1990), but neither the map nor the original sheet memoir (Peach *et al.*, 1905) provide any geological information specific to this site. The Tay Nappe and the manner in which it is bent down by the Highland Border Downbend were first recognised by Shackleton (1958), from mapping in adjoining areas and the hinge structure at Portincaple was first mapped by Stringer (1957). The area then received no further attention until Roberts (1977b) gave a brief description of the minor structures seen at Portincaple. This was followed by a more-detailed field guide to the locality by Tanner (1992).

4.2 Description

The Beinn Bheula Schist Formation belongs to the upper part of the Southern Highland Group and consists of fine- to coarse-grained metagreywacke and metasiltstone interbedded with lesser amounts of grey-green phyllitic rock. Bedding in these rocks has been largely destroyed, except in a few gritty, non-graded metagreywackes and one prominent, non-graded, pebbly metaconglomerate, less than 1 m thick, which appears to be little deformed.

The Beinn Bheula Schists are highly contorted due to the cumulative effects of four separate deformation events. The main planar element is the spaced S2 fabric, generally seen as anastomosing microlithons a few millimetres to over 1 cm thick, within which traces of the S1 spaced fabric can be seen in places. This fabric is identical to that which dominates the northern part of the *Cove Bay to Kilcreggan* GCR site but here it has been deformed by two further deformations, D3 and D4.

A SSE-plunging stretching lineation is seen as silky striations that make a high angle with the L2 on S2 cleavage surfaces. It is also present as quartz-fibre lineations in many of the quartz-carbonate veins.

The D3 deformation is represented by fairly common sideways-closing folds which invariably have the same vergence and Z-shaped down-plunge profile throughout the area. The axial-planar dip of these folds varies in a progressive but non-systematic manner from 50° N at the southern end of the section, to around 20° N in mid-section, to about 5° N at the northern end. The minor folds are on a decimetre scale and are curvilinear, plunging at a low angle to both east-north-east and west-south-west. In these rocks they fold the S2 spaced cleavage, the L2 intersection lineation seen on the S1 cleavage, and the stretching lineation (?L2). A weak S3 crenulation cleavage is largely restricted to the hinge-zones of these folds, where it cuts across and dissects the folded S2 cleavage.

Step-like, metre-scale, F4 minor folds are found throughout the coastal section (Figure 11b). These folds are open to close, upright structures that have nearly horizontal, slightly curvilinear fold hinges. Their steep limbs are parallel to the mean orientation of the foliation in the Steep Belt, and the near-horizontal middle limb is parallel to the general orientation of the same foliation in the Flat Belt (Figure 11b). The associated crenulation cleavage is near vertical and has a fairly constant strike (070–080°) but can be seen in the field to vary in dip about the vertical as a result of cleavage refraction through rock packages of differing competence. It is characteristically widely spaced (1–2 mm) (Figure 12c). Flat-lying kink bands that rework the S4 cleavage are seen locally. An equal-area stereographic plot of poles to S2 and S4 shows that the major fold plunges at 10° to 079° (Figure 11c).

A number of faults are seen in the southern part of the GCR site. They are either vertical or dip steeply to the south and have a mean spacing of about 4 m (Figure 11b).

4.3 Interpretation

This GCR site is situated at the northern extremity of the Highland Border Steep Belt where it turns into the antiformal closure of the Highland Border Downbend, which is in effect a monoform. The northern limb of the downbend (the Flat Belt) is best seen 3 km farther north near Glenmallan (NS 249 965), where the exposures are on two natural rock platforms formerly accessed by fixed steel ladders from road level. There, the composite S1/S2 fabric is generally flat-lying but is affected by strongly developed upright F4 folds associated with a steep to vertical crenulation cleavage.

In the southern part of the Portincaple GCR site, F4 minor folds with wavelengths of over 2 m are clearly congruous to a major antiformal structure to the north and adopt a neutral vergence in northern part of the section as the major fold hinge-zone is entered. The axial trace of the major antiform/monoform trends parallel to the strike of the measured crenulation cleavage and this fold correlates with that identified on Loch Lomondside by Stringer (1957) and Shackleton (1958).

No major F3 folds have been recognized in this area and this phase of folding appears to have only local significance, for D3 structures are absent to the north-east along strike from Aberfoyle (Tanner and Leslie, 1994) (see the *Craig a' Barns* GCR site report). Ever since it was first discovered by Clough (in Gunn *et al.*, 1897), there has been disagreement over the relative age of the downbend, but from the data presented here it is clear that it is a D4 structure.

4.4 Conclusions

The *Portincaple* GCR site provides the best accessible coastal section through part of the hinge-zone or closure of the Highland Border Downbend to be found in the south-western Grampian Highlands. This major D4 structure is responsible for folding the Tay Nappe into a downward-facing structure along the entire Highland Border zone from Loch Lomond to Stonehaven.

At this GCR site, minor structures formed in all four of the main deformation episodes to affect the Dalradian succession can be identified, and it is an excellent section for demonstrating the effects of three-dimensional polyphase deformation. Geometrical integrity of individual phases can be demonstrated, despite the seemingly chaotic assemblage of ductile structures and the complexity of their interference patterns. The clean rock exposures provide a wealth of information on the minor folds, cleavages, lineations, veins and fracture geometry found in this complex zone.

This site could be considered as the type section for studying the D3 deformation and for separating it clearly from the effects of D2 and of D4. It therefore contrasts with and complements the section farther north-east in the Birnam area at the *Craig a' Barns* GCR site, where D3 is not developed.

5 BEALACH NAM BO (NN 479 065–NN 485 079)

C.W. Thomas

5.1 Introduction

Bealach nam Bo (Gaelic: 'Pass of the cattle') is a narrow pass formed by a glacial overflow channel on the northern flanks of Ben Venue, immediately west of the southern end of Loch Katrine in the Trossachs (Figure 14). It lies at the centre of this GCR site, which comprises about 4 km^2 of ground underlain by volcaniclastic metasandstones, ubiquitously referred to as 'green beds', and quartz-rich, gritty and commonly pebbly metasandstones, assigned to lithostratigraphical units within the lower part of the Southern Highland Group. The green beds are distinctive and have been treated as lithostratigraphical markers. The numerous exposures around Bealach nam Bo illustrate the wide range in styles, varying according to lithology, of the commonly spectacular structures associated with the second phase of deformation and the nature of the interaction between the first and second phases.

The area around Bealach nam Bo was mapped in the latter part of the nineteenth century by officers of the Geological Survey, but the manuscript for the accompanying memoir was never published and has only recently been made available (Cunningham Craig, 2000). Subsequently, the ground immediately south of the pass was included in R.M. Shackleton's work on the structure of the Dalradian rocks adjacent to the Highland Border (Shackleton, 1958). He showed that the metasedimentary rocks are inverted, young towards the south and dip steeply northwards. He also noted a conspicuous 'later fracture-cleavage or slip-cleavage', now known to result from the main phase deformation, described below. The area was resurveyed by the British Geological Survey between 1996 and 1998 as part of the general mapping programme and lies within the BGS 1:50 000 Sheet 38E (Aberfoyle, 2004).

5.2 Description

The metasedimentary rocks within the GCR site area include green beds and associated metasandstones in the north, structurally overlying commonly gritty or pebbly, quartz-rich metasandstones in the south. Finer grained metamudstones and metasiltstones are generally rare. Although bedding generally ranges up to 1 m in thickness, some massive and coarse-grained beds are in excess of 2 m thick. Graded bedding is commonly developed and shows that the steep northerly dipping succession is generally inverted. Determination of way-up of the succession in this and adjacent areas has been critical in understanding the structural history of the rocks within the site, and in the region in general.

Following the BGS resurvey, the green beds and associated rocks have been assigned to the Loch Katrine Volcaniclastic Formation (Figure 14). The green beds are chlorite- and epidote-rich metasandstones, locally with abundant magnetite. The background sediment with which the abundant mafic minerals were mixed is fine to coarse grained, quartz rich and commonly gritty. The chlorite and epidote impart an olive to dark bottle-green colour to fresh surfaces, but the green beds weather to a characteristic sandy brown colour, often with a sandpaper-like surface texture where finer grained. The weathered rind extends up to a centimetre or so into the surface. Careous weathering is also a feature in places, yielding a surface honeycombed by rounded pits up to about 15 cm across and 3 cm deep. Although the green beds display little visible lithological variation in individual exposures, small lenses of quartz-rich, gritty metasandstone are quite commonly developed, often serving to highlight bedding.

The metasandstones associated with the green beds are chiefly coarse-grained, gritty quartz- and feldspar-rich metasandstones with only small amounts of chlorite and epidote. Although there is, in effect, a continuum in composition between these and the green beds, individual green beds are commonly sharply enough defined to be mapped out as separate units within the Loch Katrine Volcaniclastic Formation.

Typical green-bed lithologies are very well exposed in cliffs at Bealach nam Bo and on ground to the south-west and north-east. In these outcrops, they are massive, thickly to very thickly bedded units of coarse metasandstone, as detailed in the sedimentary log in Figure 15. A notable feature of some beds is the presence of ellipsoidal, nodular structures concentrated in bedding-parallel trains. They are up to about 10 cm long in the longest dimension and usually have weathered-out cores.

The metasandstones that lie lithostratigraphically above, but structurally underneath, the Loch Katrine Volcaniclastic Formation are assigned to the Creag Innich Sandstone Formation (see also the *Duke’s Pass* GCR site report). These are predominantly clean, quartz-rich, coarse metasandstones with minor intercalations of metasiltstone and more-micaceous metasandstone. In places, spectacular pebbly lithologies form microconglomeratic units that can exceed 2 m in thickness; good examples of such rocks are to be found on the higher ground *c.* 600 m south-west of Bealach nam Bo (around NN 478 069). The pebbly rocks are notable for their well-rounded pebbles, their compositional maturity (chiefly quartz-vein material) and their high degree of sorting.

The structures developed in the metasandstones within and around the GCR site are complex, but allow the relationships between the regional first (D1) and second (D2) phases of deformation to be discerned. Although the D2 phase affected the whole region, it is the lithologies and the architecture of the structures formed during D1 that control the ways in which D2 structures are manifest at both local and outcrop scale.

The very thick and massive green-bed lithologies, such as those exposed in the cliffs at Bealach nam Bo (NN 480 070), commonly appear to be only weakly deformed and cleavages are poorly developed. In the exposures of metasandstones to the west and north of the pass, metre- to decimetre-scale, south-verging folds are common. In general, the hinge-zones of these folds host only a single, moderate, penetrative, axial planar cleavage, good examples of which are seen in exposures around NN 478 075 (Figure 16). Even though this cleavage might have been modified by subsequent D2 deformation, it is considered to result principally from D1 deformation. This style of cleavage is very different to the coarsely spaced, anastomosing S1 cleavage characteristic of metasandstones that crop out to the south of the GCR site, towards the Highland Boundary Fault.

Bedding dips consistently and steeply to the north-north-west on either side of the F1 axial traces, showing that these early folds are tight to isoclinal. The F1 folds plunge consistently to the north-east at moderate angles. Abundant younging evidence, combined with bedding/cleavage relationships, shows that the F1 folds face steeply downwards to the north-north-west throughout the area.

The second phase of deformation, D2, is characterized by a coarse crenulation of the first cleavage; S2 is approximately parallel to bedding on the long limbs of F1 folds. The D2 crenulation is particularly well developed in the ground *c*. 400 m south-west of Bealach nam Bo (around NN 477 071). In general, the first cleavage is folded by D2 folds on a small scale (Figure 17), but bedding is not affected. The small-scale F2 folds plunge to the north-east and south-west and commonly have strongly curvilinear hinges. The style of folding varies from a chevron type with planar limbs and very sharp angular hinges, to a type that has the sinusoidal form of a classical crenulation. Domains bounded by the S2 cleavage planes ('microlithons') can be planar but are more typically lenticular in shape. Discrete S2 cleavages only form locally within the hinges of chevron-style folds and are rarely intensely developed. In lenticular, crenulated domains, the cleavage that defines the lenticle margins is a composite S1-S2 fabric. This cleavage is discontinuous along its length and is variably and widely spaced.

5.3 Interpretation

The lithologies that occur within the Bealach nam Bo GCR site are typical of Southern Highland Group metasedimentary rocks in general. The green beds are interpreted as metasandstones with a mafic volcaniclastic component, the latter derived either from contemporaneous or near-contemporaneous volcanic rocks, such as those in the Tayvallich peninsula of the South-west Grampian Highlands, or from the reworking of older volcanic terrains. How the nodular structures formed is unclear at present; Cunningham Craig (2000) suggested that they might have originated as clay-galls, although it is possible that they could have had a volcanic origin.

The cleaner metasandstones associated with the green beds and within the Creag Innich Sandstone Formation are evidence that the background sedimentation was dominated by generally coarse sand deposited by turbidity currents and mass debris flows. The pebbly component is likely to have been derived from a mature, well-sorted beach deposit within the source area and admixed during redeposition with the finer grained sediment that forms the matrix.

Although the D2 phase of deformation affected the whole area, the various styles and characteristics of the D2 folding indicate that D2 strain was variable, generally not very high and locally partitioned. The finely spaced cleavage observed in the F1 fold hinges in green beds is considered to be primarily the result of D1 deformation, even though the cleavage might have been enhanced by coplanar D2 deformation. In addition, the variations in style and distribution of D2 structures indicate that S1 cleavages in the cleaner metasandstones were already closely spaced to penetrative on the grain scale *before* the D2 small-scale folding. This closer spacing contrasts with the wide, anastomosing S1 cleavage observed in coarse metasandstones to the south-east at the *Duke's Pass* GCR site. This suggests that D1 deformation was generally more intense at this structural level within the Tay Nappe than at higher structural levels to the south-east. Alternatively, the closer spacing of the S1 cleavage could be due to *early* D2 deformation modifying the spacing by flattening, prior to simple-shear folding of the S1 cleavages (see the *Craig a'Barns* and *Rotmell* GCR site reports). As discussed elsewhere in this special issue, there are strongly contrasting views on the significance of D2 deformation in the Highland Border region (Harris *et al.*, 1976; Harris and Bradbury, 1977; Roberts, 1977a; Mendum and Fettes, 1985; Krabbendam and Leslie, 1996; Krabbendam *et al.*, 1997; Mendum and Thomas, 1997). The arguments are not rehearsed again here, but it is considered that the evidence within the Bealach nam Bo site is consistent with north-westerly directed simple shear during at least the latter part of the D2 phase.

The steep north-north-west dips of bedding and the downward-facing character of the F1 folds result from overturning of the folded succession by a much later phase of deformation. This deformation is generally considered to have occurred prior to the main D4 compressive phase (see Stephenson et al., 2013a) and is responsible for the steep dips developed in this and other areas along the south-eastern margin of the Grampian Highlands (e.g. Harte *et al.*, 1985).

5.4 Conclusions

The Bealach nam Bo GCR site provides numerous outstanding and readily accessible exposures that reveal clearly the contrasting nature of two formations in the Southern Highland Group, both in terms of rock type and the response of these units to regional deformation events.

Metasandstones in the Loch Katrine Volcaniclastic Formation commonly contain volcaniclastic detritus, now manifest as chlorite, epidote and locally abundant magnetite. This detritus is sufficiently abundant in many beds within the formation to impart a strong, dark-green colour from which the 'green beds' derive their name. This detritus might have been derived from contemporary volcanic activity, although this is, as yet, unproven. The rocks within the overlying Creag Innich Sandstone Formation are dominated by clean, coarse metasandstones and locally spectacular, pebbly metaconglomerates, rich in well-rounded vein-quartz clasts.

The green beds appear to have undergone relatively simple deformation dominated by cleavage and folding resulting from the first regional phase (D1), although there might have been some modification during the second deformation phase (D2). Folds resulting from the first phase of deformation are very well exposed locally and there is ample sedimentological evidence of the way-up of beds; this allows the steeply downward- and NW-facing character of the folds to be readily demonstrated. The metasandstones of the Creag Innich Sandstone Formation are notable for the range and complexity of minor structures developed within them as a result of interaction between the D1 and D2 deformations. These observations provide important insights into the overall structural evolution of the Highland Border region.

6 DUKE'S PASS (NN 499 030–NN 523 043)

C.W. Thomas

6.1 Introduction

The Duke's Pass is followed by the A821 road between Aberfoyle and the west end of Loch Achray. Ground extending either side of this corridor provides numerous, readily accessible exposures of metasedimentary rocks belonging to the Southern Highland Group, which comprise the GCR site (Figure 18). The GCR site is particularly important in revealing the nature of the earliest phase of deformation, free of the effects of the main second deformation event, and the way in which the second deformation modified the earlier structures.

The Aberfoyle district was important in early work on the Dalradian, yielding the now well-known names of some of the key lithostratigraphical units in the Southern Highland Group, especially the Aberfoyle Slates and Ben Ledi Grits. A resurvey by the British Geological Survey of 1:50 000 Sheet 38E (Aberfoyle, 2004) has delineated other lithostratigraphical units and has determined that faults related to the Loch Tay Fault system are responsible for the mismatch of structures and outcrop pattern across the Duke's Pass.

The area is of major importance in determining the 3-D structure of this segment of the Highland Border region. The high degree of deformation was recognized during the original mapping by the Geological Survey in the late 19th Century (original unpublished manuscript released as Cunningham-Craig, 2000), although its precise nature and significance for the tectonic evolution of the Grampian Terrane was not recognized until the latter half of the twentieth century. Henderson (1938) was the first to demonstrate the way-up of the beds from sedimentary structures and showed that the Aberfoyle Slates occupy the core of the 'Aberfoyle Anticline'. Anderson (1947a) maintained that this structure extends along the Highland Border from West Water in the Edzell district, Angus, to the Isle of Arran in the south-east. Subsequently, Shackleton (1958), in his seminal paper on the structure of the Dalradian rocks of the Highland Border, demonstrated that the structures observed on either side of the Aberfoyle Slates are downward-facing. The slaty metamudstones thus occupy the core of a downward-facing anticline, constituting the inverted nose of the Tay Nappe. Mendum and Fettes (1985) showed that at least two other major early folds, complementary to the Aberfoyle Anticline, occupy ground to the north of the latter structure and lie structurally beneath it. This renders the hinge-zone of the Tay Nappe much more complex than envisaged by Shackleton. The Aberfoyle Anticline is thus just one of a number of early structures in the hinge-zone of the nappe. The northern half of the GCR site is affected by a second deformation and local, minor development of later cleavages, which become more intense northwards.

6.2 Description

The GCR site lies entirely within the Highland Border Steep Belt, the domain of steeply, generally north-west- to north-dipping strata that occupy the ground south of the Highland Border Downbend (Stephenson et al., 2013a, fig. 7). It also lies to the north-west of the Loch Tay Fault Zone, which in this area trends south-west from the north-west side of Meall Ear (NN 530 027), passing immediately south-east of Creag Gownan (NN 533 025) and the lower slopes of Craigmore (NN 510 021) (Figure 18).

Within the GCR site, the Southern Highland Group is dominated by metasandstones. Although most of these were originally wackes, carrying abundant matrix, many were quartz-rich arenites. The very local nature of lithological variation within the metasandstones limits the potential for lithological subdivision. However, mapping by the British Geological Survey has delineated three discrete metasandstone units on the western side of the Duke’s Pass Fault (Figure 18). Graded bedding is very commonly developed and other sedimentary structures, which help to constrain the way up, include scours, load structures and, very rarely, ripple marks. Rip-up clasts, now metamudstone, are abundant locally and can reach several tens of centimetres in size. The way-up criteria are critical to the understanding of the structure of the Duke’s Pass area (see below).

The bulk of the metasandstones are assigned to the Ben Ledi Grit Formation. In this unit they vary from massive, very thick, gritty to locally pebbly coarse metasandstones to thin-bedded, fine-grained units with metasiltstone and locally metamudstone interbeds. The coarser grained lithologies dominate. Excellent examples of the coarse-grained lithologies are exposed on the low hillside around NN 518 031, where they occupy a fold hinge (see below). Here, basal scours contain gravel lag deposits and loading structures are common where very coarse material has been deposited on finer grained units.

To the west of the Duke’s Pass and north of the Aberfoyle slate quarries, metasandstones are assigned to the Creag Innich Sandstone Formation. They are grey, coarse-grained, quartz-rich, medium- to thick-bedded rocks that crop out extensively in the high ground, particularly around Creag a Mhadaidh (NN 513 036). This formation lies below the Ben Ledi Grit Formation, but appears to be laterally discontinuous on a regional scale (Thomas *et al.*, in press). The metasandstones in this formation are generally cleaner, with less fine-grained matrix, than those of the Ben Ledi Grit Formation.

To the north of the Creag Innich Sandstone, metasandstones are assigned to the Ledard Burn Member, a generally finer grained unit within the Ben Ledi Grit Formation. This unit comprises medium-bedded, fine-grained metasandstones with metasiltstone interbeds; thin gritty units are present at the bases of some upward-fining packets of sandstone.

Metasiltstone and metamudstone are common as interbeds and laminae in many of the metasandstones. They also occur in much thicker units, the most notable of which forms the Aberfoyle Slate Formation west of the Duke's Pass Fault, which is well exposed in the abandoned Aberfoyle Slate Quarries (NN 505 032). This unit is dominated by grey and greenish or purplish grey metasiltstones with darker laminae of metamudstone. Bedding is commonly picked out by discontinuous thin wisps of quartzose material. Way-up is rarely determinable in these rocks, but very locally the thin quartzose laminae contain discernible cross-lamination and have small-scale scours at their bases, indicating the direction of younging. The Aberfoyle Slate Formation contains the oldest Southern Highland Group rocks within the GCR site, these rocks being correlated traditionally with the Pitlochry Schist of Perthshire. They were worked extensively for slate in the Aberfoyle quarries in the 19th century before extraction become uneconomic in the face of competition from lighter and higher quality Welsh slate.

The metasiltstones of the Aberfoyle Slate Formation pass southwards into pale, quartzose metasandstones that are correlated, on the basis of recent BGS mapping, with the Creag Innich Sandstone Formation to the north. The metasandstones pass southwards, in turn, into the more-impure metasandstones, metasiltstones and subordinate metamudstones of the Ben Ledi Grit Formation, the outcrop of which continues to the Highland Boundary Fault at the southern margin of the GCR site.

East of the Duke's Pass, within the Achray Forest, a unit of metamudstone within the Ben Ledi Grit Formation is bounded to the east by the Loch Tay Fault and to the west by smaller faults (Figure 18). The metamudstones are black, grey, green or maroon in colour and are strongly cleaved. In the ground immediately west of and within the Loch Tay Fault Zone (200–300 m west of Meall Ear, NN 530 027), metamudstones are black, rich in pyrite and contain cherty laminae. These lithologies are similar to those seen in the Leny Quarry (NN 619 101), north-west of Callander (see the *Keltie Water* GCR site report), but differ significantly from those exposed in the Aberfoyle slate quarries. Thinner units of metasiltstone and metamudstone, such as that trending eastwards about 500 m north of Aberfoyle, occur throughout the general mass of Ben Ledi Grit to the east of the Duke's Pass Fault and are generally similar lithologically to those described above. Hence, contrary to previous interpretations (Shackleton, 1958; Mendum and Fettes, 1985), the fine-grained rocks to the east of the Duke's Pass Fault are not lithostratigraphical correlatives of those seen in the

Aberfoyle Slate Quarries. The corollary is that there has been considerable displacement across the Duke's Pass Fault, resulting in the juxtaposition of different lithostratigraphical units and different structural levels (see below).

Bedding in the metamudstones, very rarely observed, is picked out by very thin silty laminae or by subtle variations in hardness that indicate a more siliceous layer. Metre- to decimetre-scale folding in these rocks is well observed in exposures on a forest track west of Creag Gownan, at NN 520 024. Very fine-scale graded bedding in silty laminae shows that the rocks are inverted and that the folds and first cleavage face downwards.

The southern part of the GCR site, south of Hill Cottage (NN 515 031), contains exposures that reveal the nature and geometry of the D1 deformation, free from the effects of subsequent deformation events, most particularly D2. Outcrops of thick-bedded, very coarse wacke metasandstone on the eastern flanks of Craigmore (NN 510 021) lie in large-scale F1 fold closures, as indicated by locally variable and moderate easterly dips and by high-angle intersections between bedding and cleavage. The dominant S1 cleavage is widely spaced (*c.* 0.5–1.0 cm) and anastomosing in the coarse-grained lithologies, becoming more finely spaced where the grain size is less. This cleavage is the S1p cleavage of the *Little Glen Shee*, *Craig a'Barns* and *Rotmell* GCR sites.

The exposures on the low hills immediately east of Hill Cottage lie within an antiform, the core of which contains very coarse metasandstones with locally developed gravel lags filling scours in bed tops. Graded bedding is well developed in these rocks, showing unequivocally that the fold is a syncline facing downwards on the first cleavage. The dominantly strongly oblique relationship between bedding and first cleavage displayed in the coarse metasandstones shows that most exposures lie within or close to fold hinges throughout the area. The F1 folds are tight to isoclinal and are generally on the decimetre scale or larger (Figure 19).

Moving north-westwards from the Highland Boundary Fault in this area, D2 structures are first seen in the coarse metasandstones of the Creag Innich Sandstone Formation to the north of Hill Cottage on the western side of the Duke's Pass and are clearly observed in exposures above the A821 road in the area around NN 518 040. D2 structures occur only as cleavages within the Duke's Pass GCR site, but these are widely enough spaced to appear as stacks of F2 minor folds of the S1 spaced cleavage (cf. Booth, 1984; Harte *et al.*, 1987). Large F2 folds of bedding are not observed. Where it is more intense, the S2 cleavage is in general nearly parallel to the steep north-dipping bedding. Towards its southern limit, it is commonly more oblique to bedding, dipping generally at shallower angles to the north. In the northern part of the GCR site, the S2 cleavage is more intensely developed and becomes the dominant fabric, manifest as a strongly planar spaced cleavage, particularly in the finer grained lithologies. D2 structures and their effects on S1 are particularly well observed at the northern limit of the GCR site at Craig Noran (NN 504 066), just north of the Achray Hotel. Here, graded bedding in a thin, coarse-grained unit beneath a massive, thick gritty metasandstone unit shows that the beds are inverted. The S1 cleavage is nearly normal to the coarse-grained, thick bed and is clearly deformed by D2, the latter resulting in a locally developed, widely spaced crenulation cleavage. The near-parallelism between S2 and bedding is readily apparent.

Effects of the D4 deformation related to the formation of the Highland Border Downbend, as seen elsewhere along the Highland Border (e.g. at the *Craig a'Barns* GCR site), are developed only very locally within the northern part of this GCR site. For example, a shallow and northerly dipping crenulation cleavage is developed in metamudstones in a small exposure by the A821 road at about NN 516 051.

6.3 Interpretation

The overall lithological character and the bedforms of the coarse- to very coarse-grained metasedimentary rocks in the Duke's Pass area indicate that they were deposited by turbidity currents and debris flows within major channels of a fan system on a continental margin. They are, therefore, just part of the much more-extensive, extremely dynamic, depositional system manifested by the Southern Highland Group throughout the Dalradian outcrop of Scotland and Ireland (Burt, 2002). In such an environment it is likely that the finer grained rocks represent off-channel or overbank deposits. However, the locally developed, black, cherty, sulphidic metamudstones near Meall Ear (NN 530 027) suggest that more-euxinic, pelagic or isolated basinal sedimentation occurred at times. This might have reflected a major geographical shift in the depositional system as much as a major deepening of the depositional basin.

Faulting is an important feature of the Duke's Pass area, which contains the southern end of the Loch Tay Fault system. The Loch Tay Fault is known to have experienced several kilometres of oblique, sinistral strike-slip movement (Treagus, 1991). This precludes any close correlation of lithostratigraphical units across it in the Aberfoyle area, despite apparent lithological similarities. This problem applies equally to the related Duke's Pass Fault and other parallel faults within the area. Notable effects of the Duke's Pass Fault include the apparent displacement of the incoming of D2 deformation, which is farther to the north-east and in a different lithostratigraphical unit on the eastern side, implying a significant change in structural level across the fault (Figure 18).

The structures reveal that the Duke's Pass area is occupied by a major F1 fold system. The original interpretation of a single synformal closure centred on the Aberfoyle Slate Formation is likely to be an over-simplification. Evidence for extensive long fold limbs is lacking and fold hinges are commonly observed, either directly or via the changes in bedding/cleavage relationships. Mendum and Fettes (1985) have already shown that the Highland Border Steep Belt in this area is occupied by regional-scale F1 nappe structures that lie structurally beneath the Aberfoyle Anticline. The structural evidence in the Duke's Pass area, outwith the effects of D2, indicates the presence of a complex F1 fold hinge-zone, which is most easily interpreted as the front of a major nappe structure of which the Aberfoyle Anticline is part. The style and degree of deformation in the metasedimentary rocks suggest that the southern part of the Duke’s Pass GCR site, south-east of the Duke’s Pass Fault, is occupied by the upper and outer structural parts of this nappe front.

Based on the younging and structural evidence in the Duke’s Pass area, D2 structures only begin to appear at deeper structural levels within the F1 nappe system. Hence, the absence of D2 effects in the southernmost part of the GCR site suggests that these rocks were originally at higher structural levels and allows the original geometry of the major F1 fold structures to be discerned. The field evidence indicates that the F1 nappe and fold structures were recumbent when formed; their current attitude in the south of the GCR site resulted essentially from rotation around the late Highland Border Downbend and subsequent compression during D4.

Observations on the effects of D2 deformation on S1 cleavages in particular, made in the *Duke’s Pass* and *Bealach nam Bo* GCR sites, strongly suggest that D2 deformation was dominated by *NW-directed* simple-shearing accompanied by flattening (Mendum and Fettes, 1985; Mendum and Thomas, 1997). This interpretation differs fundamentally from those of other workers who interpreted the Tay Nappe and related structures as resulting from the combined effects of D1 and *SE-directed* D2 deformation, the latter dominated by simple-shearing (Harris and Bradbury, 1977; Krabbendam *et al.*, 1997). Thus, the evidence from the Duke’s Pass area, combined with that from other GCR sites in this paper (*Little Glen Shee*, *Craig a’Barns*, *Rotmell*, *Garron Point to Muchalls*), is critical to the debate on the nature of the early orogenic events that affected the south-eastern part of the Grampian Terrane as a whole (see discussion by Stephenson et al., 2013a).

6.4 Conclusions

The Duke’s Pass between Aberfoyle and Loch Achray provides outstanding and readily accessible exposures of Southern Highland Group metasedimentary rocks. These exposures not only reveal the nature of the processes that deposited the original sediments, but also the effects of the subsequent, mainly Ordovician deformation. The coarse metasandstones were deposited by sediment-laden currents (turbidity currents) and debris flows within major channel systems in a marine fan delta complex on a continental margin.

The rocks were deformed several times. The dominant early structures were flat-lying, kilometre-scale folds, of which the Aberfoyle Anticline is the best known. The true nature and orientation of the early structures are revealed in the southern part of this GCR site, because there they are unaffected by the second deformation, which is observed in the northern part of the site. There, the relationship between the first and second phases of deformation can be readily discerned; the second structures are largely parallel to the original bedding and their main effect was to deform the first cleavage.

The structural evidence indicates that the rocks in the southern part of the site occupied the upper and outer part of the uppermost of the major nappes in the region, probably close to the nappe front. The present steep orientation of the bedding and downward facing of the folds arose from refolding of the rocks around the Highland Border Downbend, a major late fold that re-orientated the nose of the nappe structures.

7 KELTIE WATER, CALLANDER (NN 644 120–NN 633 131)

P.W.G. Tanner

7.1 Introduction

The Keltie Water is a spate stream whose rocky bed and low cliffs provide the most-complete and best-exposed section through the uppermost Dalradian sequence to be found in the Highland Border region. The rocks consist of an inverted succession of low metamorphic grade slaty pelites and gritty metasandstones, with subordinate metalimestones, which dip northwards at a low to moderate angle (Figure 20). They lie stratigraphically well above the Aberfoyle Slate Formation (see the *Duke's Pass* GCR site report), and the older part of the sequence is equated with the Ben Ledi Grit Formation of the Southern Highland Group. Structurally, the rocks lie on the south-east limb of the downward-facing F1 Aberfoyle Anticline, which is the local equivalent of the main closure of the Tay Nappe.

The geology of the Keltie Water section has aroused much interest and controversy since it was first examined in detail by Clough (in Geikie, 1897, p. 28); the early history of research has been reviewed by Tanner (1995). The most significant contributions were made by Clough, who concluded that it is not possible to make a clear distinction between undoubted Dalradian rocks in the north and other rocks farther south; by Stone (1957), who recognized a single southward-younging sequence, and disproved Anderson's (1947a) interpretation that the rocks now referred to as the Keltie Limestone and Shale Member (Figure 20) occupy a synclinal infold in the metasandstones; and by Harris (1962, 1969), who concluded that there is no evidence for a major stratigraphical or structural break within the Keltie Water section. The subsequent debate has focussed on whether or not there is stratigraphical and structural continuity between undoubted Dalradian rocks belonging to the Ben Ledi Grit Formation (which crop out in the northern part of the river section) and a younger group of rocks found farther south, named the Keltie Water Grit Formation (Tanner, 1995). A full understanding of the relationship between these two groups of rocks is vitally important, for the Keltie Water Grit Formation includes the fossiliferous Leny Limestone, which is of late Early Cambrian age (Pringle, 1940; Brasier *et al.*, 1992).

If stratigraphical and structural continuity between undoubted Dalradian rocks and the Keltie Water Grits can be demonstrated in the Keltie Water section, it follows that the deformation that has affected the southern part of the Dalradian block must be younger than Early Cambrian in age, specifically post 519 Ma (Tanner and

Pringle, 1999); a conclusion that has profound implications for the age of the Grampian Event in the Scottish Caledonides. The alternative, strongly argued, viewpoint (Bluck and Ingham, 1997; but see Tanner, 1997) is that there is a major structural break between these two rock units, which is interpreted as a terrane boundary separating the Dalradian succession *sensu stricto* from the Keltie Water Grits (Brasier *et al.*, 1992). In this scenario, the Leny Limestone and Keltie Water Grits would be part of the Highland Border Complex, which is interpreted by those authors as an exotic terrane that docked with the Dalradian of the Grampian Terrane in late-Silurian to Devonian times. In this case, separation of the fossiliferous rocks from the Dalradian by a terrane boundary would remove any restriction on the maximum age of the deformation of the Dalradian rocks, and hence on the timing of the Grampian Event. The rocks exposed in the Keltie Water provide some of the key evidence for deciding between these two opposing hypotheses.

The other important feature of this site is the faulted contact of the Keltie Water Grits against Lower Old Red Sandstone conglomerate and volcanic rocks seen at the southern limit of the stream section. This fault has been referred to as the 'Highland Boundary Fault'.

7.2 Description

The emphasis in this account is upon the rocks exposed in the Keltie Water and the lower part of its tributary, the Allt Breac-nic (Figure 20). These rocks, referred to as the 'Leny Grits' by previous authors, were divided by Tanner (1995) into two main parts, from north to south:

(1) undisputed Dalradian rocks, mainly green gritty metasandstones, which are petrographically similar to those of the Ben Ledi Grit Formation in the classical Dalradian sequence farther north; and

(2) the Keltie Water Grit Formation, which comprises a thick sequence of pale-coloured gritty metasandstones associated with grey and black slaty horizons, and includes a Transition Member of metasandstones and slaty pelites at the base.

All of the metasandstones in the *c.* 1.4 km-thick sequence exposed in the Keltie Water section are of turbidite facies and have a very similar field appearance. They preserve abundant way-up evidence from graded bedding, and less common cross-lamination, in beds that consistently preserve bottom structures, probably modified load-casts. This sequence is affected by faults and is cut by many, thick, irregularly shaped bodies of felsite (?late Caledonian) and two dolerite dykes of Palaeogene age.

7.2.1 Stratigraphy

Exposures in the upper part of the Allt Breac-nic are in massive gritty metasandstones with few minor structures or cleavages. The southern boundary of the Ben Ledi Grit Formation has been drawn at the southern limit of green and grey-green gritty metasandstones with abundant chlorite, detrital pink feldspar, and quartz (commonly pale blue). Workers familiar with the Southern Highland Group would confidently label these rocks as 'Dalradian'. They almost certainly interdigitate with those of the Transition Member to the south, and include rare pale-coloured metasandstones similar to those commonly found in the main part of the Keltie Water Grit Formation.

The Transition Member comprises green, grey-green, brown and pale-coloured gritty metasandstones with green, grey and purple slaty pelites. The limit of the green-coloured rocks southwards marks the southern boundary of the transition and is accompanied by the incoming of grey and white metasandstones characteristic of the Keltie Water Grit Formation. The latter occur together with grey, black and variegated slaty pelites. The pale-coloured metasandstones are generally clast-supported, highly siliceous and have much Fe-rich carbonate in their matrix, so explaining why they are much more deeply weathered than the greenish coloured metasandstones to the north.

The Keltie Limestone and Slate Member appears to be a local facies development within a sequence of metasandstones that all young to the south-east. The black slaty pelites forming the middle unit contain numerous beds of orange-weathering, finely laminated carbonate rock, which contains abundant ferroan dolomite. A metre-sized lens of calcite metalimestone (the Keltie Limestone) is exposed in a small disused working at NN 6468 1252; major and trace element analyses show that it has the same overall composition as the Leny Limestone (Tanner and Pringle, 1999).

The black slaty pelites, which are part of the Leny Limestone and Slate Member, can be traced intermittently from Leny Quarry to the Keltie Water, and are correlated with the southernmost exposures of pelites found in the Keltie Water section. A full account of the setting, age, and correlation of the metalimestone, which is only exposed in Leny Quarry some 4 km south-west of the Keltie Water, is given in a GCR site report for that locality (in Rushton *et al.*, 1999) and in the paper by Tanner and Pringle (1999). The Leny Limestone and Slate Member consists of contorted and brecciated dull green to black slaty pelites with some chert bands, and grey and purple slaty pelites, intruded by 55 cm- and 15 m-thick dolerite dykes and by bodies of felsite; no metalimestone has been positively identified from these rocks in the Keltie Water section.

A detailed petrographical study of the entire sequence from the Ben Ledi Grit Formation to the southernmost exposure of the Keltie Water Grit Formation (Tanner and Pringle, 1999) has shown that the gritty metasandstones making up the bulk of this sequence have a distinctive detrital mineralogy throughout of quartz, plagioclase feldspar, white mica, biotite, tourmaline and zircon. K-feldspar is absent, and the amounts of detrital plagioclase and biotite decrease stratigrphically upwards. However, metasandstones of comparable grain size throughout this sequence show no discernable difference in petrographical features such as grain shape, strain fabrics and state of preservation of detrital micas (Figure 21).

7.2.2 Structure

Bedding throughout the section is generally inverted and dips to the north, except locally on the middle limbs of metre-scale minor folds where the beds are right way up and in places dip southwards.

The main cleavage is a spaced cleavage in the metasandstones, with microlithons up to 2 cm thick (Figure 22). It appears, in exposures and under the hand-lens, to be a slaty cleavage in silty and argillaceous rocks. The cleavage is axial planar to the minor folds, or forms weak cleavage fans symmetrical to them; the folds have a variable plunge, which is gentle in the north but more variable and steep (up to 50° to either south-west or north-east) at the south end of the section. The main cleavage is invariably steeper than inverted bedding throughout the section.

In order to test for continuity in structural geometry across the boundary between the Ben Ledi Grit and the Keltie Water Grit formations, stereographic projections of the main cleavage were prepared for the southern part of the Ben Ledi Grit outcrop (Figure 20, area A), the Transition Member (area B), and the northern part of the Keltie Water Grit outcrop (area C). These plots show that the mean orientation of the main cleavage in these three subareas is very similar and that it is not possible to separate the areas on the basis of structural geometry.

Harris (1969) recognized two main fabrics in these rocks, a penetrative slaty cleavage and a crenulation cleavage, which he correlated with similar structures in the adjoining Dalradian sequences. The crenulation cleavage is superimposed upon, and crenulates, the main cleavage described here and is most strongly developed in the argillaceous horizons such as the black slaty pelites above the waterfall at NN 6458 1247. The crenulation cleavage formed during a weak deformational event, which resulted in a gentle upright warping of beds in parts of the section. From a microscope study of the structural fabrics, Harris and Fettes (1972) subsequently identified an early cleavage in these rocks, which lies at a very low angle to bedding, and formed before the main cleavage. It is very difficult to see the early cleavage in the field.

The contact between the Keltie Water Grit Formation and the Lower Old Red Sandstone is seen as a fault at NN 6451 1221, first described in detail by Harris (1969). The fault plane dips at 54° to the north-west (strike 048°) and is overlain by 40 cm of fault gouge and fragmented rock, followed by several metres of contorted and polished black slaty pelites. The exposed Old Red Sandstone succession commences with 5 m of conglomerate found in the stream bed immediately south of the fault, which is overlain by volcanic rocks dipping steeply to the south-east.

7.3 Interpretation

All previous workers, from Clough in 1897 to the present day, have agreed that the Ben Ledi Grit Formation and the overlying pale metasandstones and black slaty pelites of the Keltie Water Grit Formation form an essentially unbroken stratigraphical succession (i.e. Harris, 1962; Tanner, 1995). The transition beds, which occur between them, appear to be a normal stratigraphical part of the sequence and not to have arisen from tectonic interleaving. The rocks have all been affected by the same sequence of structural events, and are all at the same metamorphic grade (Tanner and

Pringle, 1999). No evidence has been presented that contradicts any of these conclusions.

As has been demonstrated here, the main cleavage (S1) in the Keltie Water section maintains a consistent orientation and facing direction across the boundary between the Bed Ledi Grit and the Keltie Water Grit formations. Recent confirmation that there is evidence of a pre-D1 deformation phase in both the Bed Ledi Grit and the Keltie Water Grit formations, strengthens the structural correlation between these two units (Harris *et al.*, 1998; Tanner, 1998b). It is extremely unlikely that two sets of structural fabrics, which have formed at relatively low strains (Figure 20 insets) and at low metamorphic grade, could have originated independently in two terranes of entirely different age and origin and then, upon amalgamation of the two terranes, become indistinguishable in their morphology, geometry, and facing direction. No alternative interpretation has been proposed to explain the structural data.

Recent work has also shown that that the metasandstones in the sequence have many petrographical features in common, despite the fact that burial diagenesis has almost certainly altered all of the detrital plagioclase to nearly pure albite (An_{1-3}), and caused dissolution of any pre-existing K-feldspar (Figure 21). The results of a whole-rock geochemical study of these metasandstones are consistent with the conclusion reached from the petrography, that the main vertical changes in composition reflect a progressive upward decline in amounts of detrital plagioclase and biotite (Tanner and Pringle, 1999). In addition, electron-microprobe analysis of the detrital white micas from these rocks has shown that they have a comparable range in Si, Fe, Mg, and Ti contents at all levels of the sequence, with more-sodic micas occurring in the Transition Member and younger rocks. The wide range in chemistry suggests that they were derived from a complex source region.

$^{40}Ar/^{39}Ar$ laser fusion ages on detrital white micas from metasandstones at five different levels in the sequence gave age spectra which show a gradation from all old mica ages in the Ben Ledi Grit Formation (mainly 1600–1800 Ma, with a few at 2100 Ma) to a mixed population of old and younger white micas (507–886 Ma) in the Keltie Water Grit Formation. This work shows that none of the mica ages has been reset by Caledonian regional metamorphism, agreeing with the results of the petrographical work that the regional metamorphism was of low greenschist facies throughout, with no detectable metamorphic breaks, and maximum temperatures probably not exceeding 270^{o}C.

The reported differences in whole-rock geochemistry, detrital mica composition and $^{40}Ar/^{39}Ar$ age upward in the succession are, as far as can be determined, progressive. Some of these changes may be linked to the establishment of a stable shelf environment, with the incoming upwards from the Ben Ledi Grits to the top of the Keltie Water Grit Formation of black muds, dark limestones, and dolostones, and an increase in the amount of possible detrital carbonate minerals in the turbidites (Tanner and Pringle, 1999). These data do not however preclude the possibility that an intraformational break may be present somewhere in the sequence.

The most illuminating finding from these investigations is that there is no suggestion from either the field observations or the various analytical data, of a major stratigraphical/structural break at a single, discrete level within the sequence that might be taken as positive evidence for the presence of a terrane boundary. Such a terrane boundary, if it existed, would have to be located between the southernmost exposure of undoubted Dalradian rocks (Ben Ledi Grit Formation), belonging to the Grampian Terrane, and the rocks farther south which include the Leny Limestone and were once considered to belong to an exotic terrane (the Highland Border Complex), which collided with the Grampian Terrane in late-Silurian to Devonian times (Brasier *et al.*, 1992; Bluck and Ingham, 1997). In view of the conclusion supported here that the rocks from the undoubted Dalradian Supergroup to the top of the Keltie Water Grit Formation are in their original stratigraphical sequence, this latter formation should be included logically within the Dalradian Supergroup. It is the lowest formation in the proposed Trossachs Group of Tanner and Sutherland (2007), which would include all units of the Highland Border Complex that crop out structurally below (i.e. north-west of) the Highland Border Ophiolite. This new Dalradian group would include strata containing fossils as young as Arenig in age.

It follows from the above relationships that the upper part of the Dalradian succession must have been deposited between 646 Ma (the youngest reliable detrital white mica age in the Keltie Water sequence and *c.* 517–509 Ma (the probable age range of upper Lower Cambrian rocks such as the trilobite-bearing Leny Limestone; Davidek *et al.*, 1998). This conclusion is compatible with the U-Pb age on zircon of 595 ± 4 Ma for the Tayvallich Volcanic Formation, which lies near the top of the Argyll Group (Halliday *et al.* 1989), and with the 590 ± 2 Ma age for the Ben Vuirich Granite (Rogers *et al.* 1989; Dempster *et al.*, 2002), which hornfelsed previously undeformed Dalradian rocks *prior* to the Grampian Event (Tanner and Leslie, 1994; Tanner, 1996; Tanner *et al.*, 2006).

In conclusion, as all of the rocks at this site can be shown to have shared the same structural history, then the Grampian Event where it affects the Southern Highland Group, is of post-Early Cambrian age (i.e. post 509 Ma). The Tay Nappe deformations (regional D1 and D2), and a possible earlier episode of deformation (Harris *et al.,* 1998; Tanner, 1998b) are also therefore of post-Cambrian age.

7.4 Conclusions

The Keltie Water provides a unique section of national importance through the uppermost Dalradian strata exposed in the Highland Border region. Its importance lies in the fact that it is the only place in the Grampian Terrane where there is an exposed section linking undoubted Dalradian rocks with fossiliferous rocks of known biostratigraphical age. Trilobites of Early Cambrian age have been reported from the Leny Limestone, which occurs at the nearby *Leny Quarry* GCR site (Rushton *et al.*, 1999). As the Dalradian rocks were once thought to be much older than this, the stratigraphical and structural relationship between undoubted Dalradian rocks and strata in the Keltie Water that are correlated with the Cambrian rocks at Leny Quarry, has excited much scientific interest. Accordingly, the geological relationships seen at this GCR site have been the subject of much research and rigorous scientific debate in the past few decades.

Most geologists who have studied this GCR site now conclude that there is stratigraphical and structural continuity within the Keltie Water section, and a corresponding lack of evidence for a postulated terrane boundary between the undoubted Dalradian and the Cambrian rocks. The important corollary to this is that the Grampian Event, where it affects the upper part of the Dalradian sequence, commenced after the Early Cambrian, and that there is no evidence to support the hypothesis that a prior Precambrian orogenic event had affected the Dalradian rocks.

8

LITTLE GLEN SHEE (NN 979 346) CRAIG A'BARNS (NO 019 438–NO 014 442) ROTMELL (NO 014 469–NO 011 475)

A.L. Harris

8.1 Introduction

The Little Glen Shee, Craig a'Barns and Rotmell GCR sites, in the Dunkeld area of the Highland Border, collectively display the essential features of the structure, sedimentology and metamorphism of the Perthshire outcrop of the Southern Highland Group. In order to fully appreciate the overall geological situation, it is necessary to combine observations and deductions from all three sites (Figure 23). Consequently this site report consists of a general introduction, detailed descriptions of the three individual sites, an overall interpretation and combined conclusions.

The three sites, which are in fairly close geographical proximity, were selected particularly to demonstrate the increasing structural complexity and increasing metamorphic grade with tectonic depth in the Tay Nappe, the major recumbent anticlinal nappe fold of the South-eastern Grampian Highlands (Figure 24). All three occur in the inverted lower limb of the nappe, which extends across strike almost from the Highland Border to the NE-trending Tummel Steep Belt, some 17 km to the north-west (Figures 23 and 24a). Over much of its extent, the lower limb is not only inverted, but is regionally subhorizontal, comprising the Flat Belt. However, to the south-east of the Flat Belt, the flat-lying inverted rocks have been bent down through as much as 120°, across the hinge of a late, regional-scale, NE-trending asymmetrical antiform, the Highland Border Downbend. On the south-east limb of this fold, the formerly flat-lying rocks now dip steeply (*c.* 60°) to the north-west, and thus are generally the right way-up (Figures 23 and 24). These rocks constitute the Highland Border Steep Belt (Harris *et al.*, 1976). Thus, the sites have been chosen to represent rocks low in the Highland Border Steep Belt (Little Glen Shee), rocks high in the Highland Border Steep Belt and lying in the hinge-zone of the Highland Border Downbend (Craig a'Barns) and in the Flat Belt (Rotmell).

The detailed structural geology of the area containing these three GCR sites has been described and discussed by Stringer (1957), Shackleton (1958) and Harris *et al.* (1976); some of the tectonic structures and fabrics discussed here were illustrated and described by Bradbury and Harris (1982). Rose and Harris (2000), working to the south-west of these GCR sites, distinguished two zones within the Highland Border Steep Belt, which they termed A and B. The exposures comprising the Little Glen Shee GCR site relate to their Zone A, while many of the features of Zone B are displayed in the south-eastern part of the Craig a'Barns site. The transition from Zone A to Zone B is not exposed in this area.

The rocks of all three GCR sites comprise interbedded metasandstones and metasiltstones, stratigraphically assigned to the Southern Highland Group (Harris *et al.*, 1994). In the Dunkeld area, three units were proposed by Harris (1972): the Birnam Grit (oldest; base not seen), the Birnam Slate, and the Dunkeld Grit (youngest; top not defined). Elsewhere, the lower two units have been combined into a single Birnam Slate and Grit Formation, reflecting a more-complex stratigraphical distribution of the two sedimentary facies (Crane *et al.*, 2002). The depositional environment of the original clastic sediments, mainly comprising poorly sorted turbiditic sands with minor silty beds, was discussed by Harris *et al.* (1978) and Anderton (1985), who concluded that the coarse-grained clastic deposits were laid down in channels on the lower slopes and inner zones of deep-water submarine fans, with the finer grained sediments being laid down as overbank deposits or in outer-fan facies. Lateral continuity of any one facies is therefore unlikely and, even where traceable over short distances, probably has little chronostratigraphical significance. Hence conclusions about the relative ages of the rocks at the three GCR sites are tentative and are based on structural considerations (see Interpretation).

The cross-sections in Figure 24 show the relative structural positions of the three GCR sites; Little Glen Shee originally lay at a higher level in the nappe than Craig a'Barns and Rotmell, both of which lie at a similar level. The Little Glen Shee site illustrates the earliest deformation which, in addition to producing folds of bedding, induced a cleavage in the rocks that takes the form of a slaty cleavage in the metasiltstones and a pressure-solution striping (S1p) in the metasandstones. Subsequent deformation episodes modified the S1p; that associated with the second deformation (D2) modified the original planar striping into F2 folds having thick hinges but highly attenuated limbs. F2 folds, which predominate in the Flat Belt, are seen in their original attitude at the Rotmell GCR site. They have been bent down around the Highland Border Downbend at the Craig a'Barns site and there they are seen to be overprinted by the downbend-related structures and fabrics. Although the rocks of the Little Glen Shee site lay initially at a higher level in the Tay Nappe than those at either Craig a'Barns or Rotmell, they were bent down by the Highland Border Downbend so that their original stratigraphical/structural configuration has been changed and their cleavage and folds now face downwards. The Little Glen Shee GCR site therefore exemplifies the concept of 'downward facing' on first cleavage that was first developed by Shackleton (1958) in the Highland Border region (see Stephenson et al., 2013a, p. 32).

The three GCR sites also illustrate the variation in the metamorphic grade of the Southern Highland Group in the Highland Border region of Perthshire. Metasiltstones at Little Glen Shee are chloritic slates, whereas at Craig a'Barns they are phyllites typically containing chlorite and white mica with some biotite. Metasiltstones at Rotmell carry conspicuous euhedral, almandine garnets. While structural complexity and tectonic strain at Craig a'Barns are comparable with those at Rotmell, and are considerably greater than at Little Glen Shee, the metamorphic grade at Rotmell appears to be notably higher.

8.2 Description

8.2.1 Little Glen Shee GCR Site

Little Glen Shee intersects the Highland Border between the rivers Almond and Tay, some 15 km north-west of Perth. The GCR site is located some 450 m along the track leading north-west from Little Glen Shee farm. It was chosen as an excellent example of the sedimentary and tectonic features of the weakly deformed and metamorphosed Southern Highland Group rocks occurring originally at a high level of the Tay Nappe, but subsequently bent down to a lower structural level by the Highland Border Downbend.

The rocks described here form a large crag to the north-east of the track, about 100 m north of a large (4 m × 1.5 m) boulder (Figure 25).

The metasedimentary rocks probably belong to the Birnam Slate and Grit Formation and consist of well-defined beds of poorly sorted, matrix-supported coarse- to medium-grained metasandstone wackes that grade upwards, usually passing by rapid transition into fine-grained metasandstones and mica-rich metasiltstones. Such graded beds are up to 0.5 m thick and the grading is well picked out by cleavage refraction (Figure 25, insets 1 and 2; Figure 26a). There are abundant subangular clasts of quartz and feldspar up to 2 mm across in the coarser fraction. Some of the metasandstone beds are composite and are inferred to have been deposited by more than one turbidity current. Bedding lamination (Figure 25, insets 1 and 2; Figure 26b) and more-rarely small-scale cross-lamination are commonly well displayed in the medium- to fine-grained metasandstones. Where seen, the younging indicated by the cross-lamination is consistent with that shown by the graded bedding.

The beds have been folded into a pair of modified buckles, having rounded hinges, straight limbs, interlimb angles of *c*. 70° and wavelengths of *c*. 7 m (Figure 25). Parasitic on these, a smaller pair of modified buckles have wavelengths of *c*. 1 m (Figure 26b), and minor folds having wavelengths of 3–4 cm are developed in their core. Sedimentary structures all young unequivocally towards the cores of the antiforms and away from the cores of synforms, so that successively younger beds are encountered as axial planes are traced downwards. Hence, the folds face downwards.

In addition to the folding of the sedimentary layers, the D1 deformation imposed a cleavage which takes two distinct forms that are lithologically dependent: (1) a pressure-solution cleavage in the metasandstones (S1p of Harris *et al.*, 1976); and (2) a slaty cleavage in the metasiltstones (S1).

The S1p cleavage is confined to the metasandstone layers towards the base of each graded bed and comprises well-defined planes, normally orientated at a high angle to bedding. These planes, which are spaced at intervals of *c*. 1 cm, coalesce and ramify in detail, both laterally and normal to bedding such that the rock between the planes is rendered into lenticles, commonly referred to as 'microlithons'. Close examination of the planes of S1p shows that they comprise, not planes, but narrow zones (less than 1 mm wide) largely made up of micaceous material. The abundant mica in these zones results in their differential weathering, leaving the centimetre-scale siliceous lenticles standing conspicuously proud of the weathered surface. Hence the orientation pattern of the S1p laminae can be readily picked out and it is easy to see that it fans through as much as 100° and that it is approximately symmetrical about the fold axial planes. Fanning is a feature of the S1p in Figure 26b.

During the process of deformation and the formation of S1p, considerable re-orientation of primary bedding features within the sandstone layers evidently took place. This becomes apparent where the orientation of bedding lamination within the cleavage domains ($S0_{lam}$), is compared with the orientation of gross bedding (S0); $S0_{lam}$ is commonly 45° or more, oblique to S0, particularly on the inverted SSE-younging limbs (Figure 25). Within-bed re-orientation of cleavage is also displayed locally, although it probably occurred entirely later than the formation of S1p. In some beds, S1p has been buckled sufficiently to face upwards and downwards within the same bed without the bed itself being apparently folded.

S1 refers to the penetrative axial-planar slaty cleavage that occurs in the finer grained original tops of the graded beds. In thin section this cleavage is seen to be defined by aligned white mica and chlorite, and by quartz and feldspar having a preferred dimensional orientation. S1 is oblique to S1p except in the fold cores where it is approximately parallel. Elsewhere S1p refracts into the plane of S1, the curving surface associated with the change in orientation clearly indicating the narrow zone within each bed where the decrease in original grain size from sand to silt occurs. By contrast, the contact between the coarse-grained base of each bed and the fine-grained top of the bed immediately below it is emphasised by the sharp angular break between the S1 in the older bed and the S1p in the younger bed. (Figure 26b).

D2 and Highland Border Downbend-related structures are not developed at this site.

8.2.2 Craig a'Barns GCR Site

The Craig a'Barns GCR site lies within an area of steep crags, several of which are popular rock-climbing venues, in an area of woodland about 1 km north-west of Dunkeld. The site has been chosen to represent rocks at a relatively high structural level in the Highland Border Steep Belt and in the hinge-zone of the Highland Border Downbend. The cross-sections in Figure 24 show that the rocks at Craig a'Barns originally lay at a similar level in the Tay Nappe to those at Rotmell, but the bedding and the F2 folds, which predominate in the Flat Belt, have been bent down around the Highland Border Downbend and are seen to be overprinted by the downbend-related structures and fabrics. While structural complexity and tectonic strain at Craig a'Barns are comparable with those at Rotmell and are considerably greater than at Little Glen Shee, the metamorphic grade is not as high as at Rotmell.

The rocks at the site are probably among the youngest Dalradian rocks exposed in the Dunkeld area, and are assigned to the Dunkeld Grit Formation. They are described in a traverse through several key localities across the Highland Border Downbend, from the steep south-east limb through the hinge-zone to the gently inclined north-west limb (Figures 23 and 24). The localities are shown on Figure 27. The F1 folds exposed at the Little Glen Shee GCR site have not been observed here, the dominant structures being F2 folds of the S1 and S1p cleavages as well as D4 structures associated with the Highland Border Downbend. The rocks are metamorphosed sandstones and mudstones, but convincing way-up indicators have not been found. The rocks are in the greenschist facies of Barrovian metamorphism, so that the metasiltstones are phyllitic and typically containing chlorite and white mica with some biotite. Minute spessartine-rich almandine garnets occur in laminae between pressure-solution cleavage planes (S1p) within the metasandstones (M.P. Atherton, personal commmunication, 2000).

Locality A (NO 0194 4378) is a cliff face some 18 m high, above a short, boulder-strewn slope. On this face, a fold-pair on the scale of the crag is defined by a 2 m-thick metasandstone bed. The long limbs of the fold-pair dip at 60°–70° to the north-west and the short limb dips gently to the south-east. This fold-pair is parasitic on the south-east limb of the Highland Border Downbend and indicates that the main hinge lies to the north-west. Small-scale open folds of 2–3 cm wavelength, associated with a weakly developed crenulation cleavage dipping at moderate angles to the north-west, are inferred to be downbend-related structures.

The early cleavages, S1p and S1, lie subparallel but at a discernible angle to bedding; the millimetre-scale spacing of the S1p planes shows that the intervening microlithons are considerably attenuated in comparison with those seen at the Little Glen Shee GCR site. Both cleavages are affected locally by D2 structures. F2 fold wavelengths are on a centimetre to decimetre scale with interlimb angles from 60° to isoclinal; hinges are curvilinear about the horizontal and vergence is to the north-west. S2 cleavage is axial planar to F2 folds, whose axial surface traces are also subparallel to bedding.

Locality B (NO 0183 4389) consists of vertical to overhanging crags. Although the crags display interference between F2 and Highland Border Downbend-related folds and overprinting of S1, S1p and S2 by downbend-related crenulations and minor folds, this locality is most remarkable for its display, in microcosm, of the essential relationships of the Highland Border Downbend. Up a natural "step", about 1 m high, in the base of the crag, a 1 m^3 exposure of metasandstone displays a smooth planar surface defined by bedding and S1p that has been bent down to the south-east around a smooth open asymmetrical antiform from a subhorizontal into a subvertical attitude. This NE-trending, small-scale antiform is inferred to be parasitic on the south-east limb of the Highland Border Downbend. A well-defined shape-fabric lineation, contained within the folded planar surface, trends approximately N–S on the flat top surface of the fold and is also bent down across the antiform hinge to plunge steeply to the south-west in its steep limb. Figure 28a shows a subvertical cross-section of the antiform, illustrating the nature, attitude and sense of overturning of F2 folds on both its subvertical and subhorizontal limbs and the folding and downbending of S1p. The spacing of the S1p cleavage has been severely attenuated by D2 (see Interpretation). Adjacent metasiltstones show the NW-dipping downbend-related crenulation cleavage to be approximately axial planar to the antiform.

Locality C consists of crags that lie in the hinge-zone of the Highland Border Downbend. In particular the first crag reached to the north of the path (NO 0175 4387), probably lies very near to the downbend hinge-zone. It displays, in micaceous lithologies, a very strongly developed crenulation cleavage dipping generally to the north-north-west at 45°–50°, but variable up to 60°–70° (Figure 28b); this is inferred to mark the attitude of the downbend axial surface. The crenulation cleavage is axial planar to ENE-trending open parasitic folds in the hinge-zone of the downbend (Figure 28c). At the top of the exposure illustrated in Figure 28c, bedding is essentially parallel to both S1 and S2 but in the bottom left, S1p is at a distinct angle to bedding. Tight F2 folds of S1p (not seen in Figure 28c), having highly attenuated limbs, lie with their axial surfaces at variable, but high, angles to the inferred downbend axial surface.

The main path, running up a glacial meltwater channel, reaches a deer fence at (NO 014 442) passing on the way numerous crags above it on the right (north-east). All of these crags lie within the Flat Belt but the two nearest to the fence (locality D, NO 0149 4411) are the most rewarding. Gross bedding, defined by metasandstone - metasiltstone interlayering, and S1p are generally flat lying or gently inclined but are bent locally into a steep attitude to form the intermediate limb of a Z-shaped (looking north-east) fold-pair. These folds, which are on a scale of metres to decimetres, indicate an asymmetrical antiform to the south-east, i.e. the Highland Border Downbend, although their hinge-zones are transected by the NW-dipping crenulation cleavage also related to the downbend (see Interpretation).

8.2.3 Rotmell GCR Site

Rotmell Farm is adjacent to the A9 trunk road and 4–5 km north-north-west of Dunkeld. The Rotmell GCR site is a series of small exposures within a rectangle of open heather-clad rocky hillside above the farm, measuring some 700 m × 200 m and elongated almost precisely north-west - south-east. The site has been chosen to represent the lower, inverted limb of the Tay Nappe in the regionally subhorizontal Flat Belt, to the north of and unaffected by the Highland Border Downbend.

The rocks at the site could be assigned to either the Dunkeld Grit Formation or to the stratigraphically lower Pitlochry Schist Formation (see Interpretation). The cross-sections in Figure 24 show that they occur at a similar stratigraphical level to those of the Craig a'Barns site and that they originally lay at a similar structural level in the Tay Nappe. At this level, the original planar striping (S1p) generated during the first deformation episode (D1), has been modified during the second deformation (D2). F2 folds having thick hinges but highly attenuated limbs, which predominate in the Flat Belt, are seen in their original flat-lying attitude at Rotmell. While the structural complexity and tectonic strain at Rotmell are comparable with those at Craig a'Barns, the metamorphic grade at Rotmell appears notably higher.

The solid geology comprises metasandstones interbedded with subsidiary metasiltstones and metamudstones, now quartz-mica schists and garnet-mica schists. Locally the metasandstones are notably pebbly, containing granules of less than 5 mm diameter. These rocks, which are more highly metamorphosed than those at locality D at Craig a'Barns, some 3–4 km to the south, are typical of the Southern Highland Group at moderate metamorphic grade. The rocks are inferred to be inverted, but convincing direct evidence from sedimentary structures is lacking at this site.

Conspicuous in the metasandstones are centimetre- to metre-scale zones, in which thin seams between the early pressure-solution cleavage planes (S1p) are affected by F2 folding. The centimetre-scale, NE-trending, F2 folds occur in pairs or even-numbered multiples and the seams are notably thinner on the limbs than in the hinges (Figure 29). The zones containing folds are commonly separated from one another by zones lacking folds but in which the S1p seams are strongly attenuated. The folds are almost invariably overturned and are stacked in such a manner as to suggest that they are parasitic on a recumbent fold, the axial surface of which lies above the present erosion surface and closes to the south. F1 folds and angular relationships between bedding (S0) and S1 cleavages have not been observed. Marked lineations, similar to those described from locality B at the Craig a'Barns GCR site, comprise grain-shape and quartz rodding, and are approximately north-trending on flat-lying foliation surfaces formed by composite S1 and S2 cleavages. Together the lineations and foliation define an LS fabric, the lineation representing the finite extension direction related to D2. This is well displayed at NO 1496 4703.

The metasiltstone layers in particular carry subhedral to euhedral, spessartine-poor almandine garnets up to 0.5 cm in diameter. Close examination of these with a hand lens shows that individual garnets contain an internal planar fabric defined by relict inclusions, a pre-garnet foliation (?S1), while the garnet crystals themselves are wrapped by the conspicuous mica-defined foliation in their matrix (composite S1/S2). S1/S2 itself is crenulated by small-scale folds the axial surfaces of which dip north-west at *c*. 30° with the development of an incipient crenulation cleavage. This modification of the fabric may well be related to the Highland Border Downbend episode of deformation (D4). Excellent examples of these relationships may be seen at NO 0122 4734, about 70 m north-west of a solitary, conspicuous beech tree.

8.3 Interpretation

The Little Glen Shee, Craig a'Barns and Rotmell GCR sites complement one another and together are important to our understanding of: 1) the mechanisms of deformation and regional metamorphism, including pressure solution, that accompany the development of a major nappe, in this case the Tay Nappe, from its earliest stages to its transport and emplacement; and 2) the geological history of the Scottish Highlands and the timing of events in the Scottish sector of the Caledonide /Appalachian Orogen.

The turbiditic environment in which the sediments of these three GCR sites were deposited makes the relative ages of the rocks and the stratigraphical correlation between them difficult. Regional structural and stratigraphical relationships strongly suggest that the rocks at Little Glen Shee might lie some 2–3 km stratigraphically below the Craig a'Barns strata (Harris, 1972; Harris and Fettes 1972). The rocks at Little Glen Shee lie in the Birnam Slate and Grit Formation, which is older than the Dunkeld Grit Formation of the Craig a'Barns site, which probably includes the youngest Dalradian rocks exposed in the area. However, there is ambiguity in assigning the rocks at Rotmell to a lithostratigraphical unit. The gentle overall dip to the north-west of the rocks on the north side of the Craig a'Barns site suggests that the inverted strata there are likely to pass below those at Rotmell, which are also inferred to be inverted. If so, the rocks at Rotmell are slightly older than those at Craig a'Barns. The high metamorphic grade of the rocks at Rotmell, indicated by the coarse grain size and the conspicuous garnet also lends them obvious affinity to the Pitlochry Schist Formation of the area to the north. Defining a boundary between the Pitlochry Schist and the Dunkeld Grit formations, however, has never been attempted. The differences between them are probably due as much to secondary effects, such as metamorphic grade and intensity of pressure solution, as to any primary contrasts in the protolith.

The Highland Border Downbend, an asymmetrical, overturned open antiform, has as its steep south-east limb a zone of steeply NW-dipping, right-way-up rocks that, pre-downbend, were flat-lying and inverted on the lower limb of the nappe (Figure 24). These steeply dipping strata now crop out between the axial surface trace of the Highland Border Downbend and the Highland Boundary Fault. Consequently, a horizontal traverse from south-east to north-west across the zone is equivalent to a vertical section from high to lower levels of the nappe. Excellent examples of the contrasting phenomena typical of each level are displayed by the Little Glen Shee and the Craig a'Barns GCR sites respectively. Thus insights into the significant changes in the conditions of temperature and pressure (confining and directed) that took place with increasing depth in the nappe can be obtained by comparing these two sites. The Little Glen Shee site offers opportunities to view and interpret the effects of the earlier stages in nappe development (D1), unobscured by the overprinting of the D2 fabrics resulting from the transport and emplacement of the nappe (as seen at the Craig a'Barns and Rotmell GCR sites). North-west of the axial surface trace of the Highland Border Downbend the lower, inverted limb of the nappe is essentially at the same structural level as the Craig a'Barns site over the *c*. 17 km of gently undulating rocks that lie between the downbend and the Tummel Steep Belt (Figures 23 and 24). These are represented by the Rotmell GCR site, where the rocks are in their post-D2, pre-downbend attitude. Rotmell thus complements Craig a'Barns because, although significantly higher in metamorphic grade, the fabrics in the rocks here relate only to D1 and D2 and were not complicated by the post-D2 overprint of fabrics related to the Highland Border Downbend. The post-D2 fabrics are largely confined to the axial zone of the downbend and can be correlated broadly with the regional D4 phase.

The F2 folds that are a feature of the Craig a'Barns and Rotmell sites have been related by Harris *et al.* (1976) and Rose and Harris (2000) to SE-directed shear that contributed to the emplacement of the Tay Nappe. These sites thus offer important insights into the mechanisms of nappe emplacement in general and the Tay Nappe in particular (but see also the *Duke's Pass* GCR site report for an alternative interpretation). The thinned 'limbs' of the F2 folds are interpreted here as top-to-the-SE shear-zones (involving largely simple-shear) whereas the 'hinges' are zones in which D2 strain is low. The thin micaceous seams that comprise the conspicuously folded laminae at Craig a'Barns and Rotmell originated by pressure solution as the S1p cleavage. In its pristine state, this cleavage can be studied at Little Glen Shee, where the S1p seams normally lie at a high angle to bedding (60°–90°). At the Craig a'Barns and Rotmell GCR sites, the angle between bedding and S1p, albeit small as a result of D2 strain, is still discernable, as is their original ramifying and coalescing primary pattern of intersection. Consequently, it is concluded that, at an early stage of deformation (D1), tectonically induced pressure solution produced a lithological lamination in the rocks that was not related to primary bedding and that this lamination was subsequently deformed as the D2 emplacement of the nappe proceeded. The emplacement and transport of the nappe by the D2 structures might only have become possible as increased metamorphic grade, rising through the nappe with time, permitted the formation of the ductile shear-zones that comprise the F2 fold limbs. If so there was likely to have been a strong element of diachroneity in the imposition of both the D1 and D2 structures.

Tentative, but important and regionally significant conclusions about the pattern and timing of regional metamorphism can be drawn from the combined evidence at the three GCR sites. It seems likely from the evidence at the Rotmell site that the peak of metamorphism post-dated the fabrics included in the garnets and pre-dated the crumpling of the composite S1/S2 schistosity during the deformation that produced the Highland Border Downbend (D4). One could conclude from these relationships that the isograds reflecting the pressure and temperature patterns at the regional metamorphic peak were essentially established before the imposition of the downbend and that the isograd surfaces were bent down to the south-east into the Highland Border Steep Belt with the earlier tectonic structures. This would account for the rise in metamorphic grade from Little Glen Shee to Craig a'Barns. The contrast in grade between these two sites could be explained by isograds dipping generally south-eastwards slightly more steeply than the subhorizontal to gently inclined bedding/foliation planes in the inverted limb of the nappe. This interpretation would be consistent with the metamorphic grade at Rotmell being intermediate between that at Craig a'Barns and that of the kyanite-bearing migmatitic pelites of the Ben Lui and Pitlochry Schist formations to the north.

A general conclusion that can be drawn from these three GCR sites, taken collectively, is that the intensity of deformation and metamorphism is independent of age in rocks as complex as those described. The oldest rocks, i.e. those from Little Glen Shee, are the least deformed and metamorphosed of the three sites. However, without their comparative simplicity, explicit facing and younging characteristics and well-developed pressure-solution cleavage, interpretation of the other two sites would be more difficult and uncertain than is the case.

The sets of folds and fabrics described and interpreted above are widely recognized and correlated throughout the south-eastern Grampian Highlands. The first and second sets have been demonstrated by Rose and Harris (2000) to be the result of an essentially continuous process of early deformation producing upright folds and pressure-solution cleavage, passing into recumbent folds as the former were deformed and transported to the south-south-east on D2 shear-zones. This continuity is important in interpreting the age of orogenesis in the Grampian Terrane. The earliest cleavages overprint the Keltie Water Grit Formation of the Callander district, which includes the Lower Cambrian Leny Limestone (Tanner, 1995; Harris *et al.*, 1998; see the *Keltie Water* GCR site report) and hence must be younger than the radiometrically dated Ben Vuirich Granite (590 ± 2 Ma; Rogers *et al.*, 1989) that had formerly been used to indicate the minimum age of the orogenesis (see the *Ben Vuirich* GCR site report). The conclusion that the earliest fabrics post-date Cambrian rocks means that the orogenesis was Early Palaeozoic in age, probably mid Ordovician, rather than Neoproterozoic, as was believed formerly.

8.4 Conclusions

The Little Glen Shee, Craig a'Barns and Rotmell GCR sites together display the best set of exposures in the British Isles to exhibit the sequence of structures developed during the initiation, emplacement and modification of a major recumbent fold (nappe).

This fold, the Tay Nappe, is one of the largest and most significant major structures in the whole of the Grampian Terrane, and indeed in the whole of Great Britain. The sites also show typical examples of the primary sedimentary and subsequent metamorphic characteristics of the rocks that comprise the Southern Highland Group.

Relative to the other two GCR sites in this area, the rocks of the ***Little Glen Shee*** site originated at the highest level in the Tay Nappe and are at the lowest metamorphic grade. They display exceptionally well-preserved sedimentary structures, especially the graded bedding that results from the rapid deposition of coarse sands in a turbiditic deep-water environment. They also display unusually clear examples of the first generation of folds, together with their steeply dipping axial-planar cleavage, which in the coarser grained rocks takes the form of a widely spaced pressure-solution cleavage. The bedding/cleavage relationships, together with the sedimentary structures, show quite dramatically at this site that the folds are totally inverted; this was the classic area where Shackleton (1958) first developed the concept of structural 'facing', now an internationally accepted term. These folds are thus 'downward-facing', the explanation for which requires examination of the Craig a'Barns GCR site.

The rocks of the ***Craig a'Barns*** GCR site once occupied deeper levels of the Tay Nappe than those of the Little Glen Shee site. Consequently, the original sedimentary bedding characteristics, and the small-scale folds and cleavages that formed during the initial stage of nappe formation, have all been considerably modified by a second generation of small-scale structures, both folds and cleavage, which relate to subsequent development of the nappe. The site also contains possibly unique exposures of the hinge of a later major fold, the Highland Border Downbend, which was responsible for the rotation of the original flat-lying rocks, exemplified in the Rotmell GCR site, into the steep-dipping downward-facing attitude, seen in the Little Glen Shee GCR site.

At the ***Rotmell*** GCR site it can be clearly seen that the cleavage related to the first generation structures, as seen at the Little Glen Shee GCR site, has been strongly modified by a second deformation. It has been suggested that the second generation of small-scale structures, both folds and cleavage, are a result of the transport and emplacement of the Tay Nappe. Originally upward-facing first structures are believed to have been translated many kilometres to the south-east, and modified by the second deformation, so that much of the Southern Highland Group, such as that in the Rotmell GCR site, lies in the inverted limb of the resulting sideways-facing fold. Rocks in the Rotmell GCR site contain crystals of garnet, which are evidence of relatively deep burial, but rocks originally at a higher level in the nappe and subsequently bent down, such as those now exposed at the Little Glen Shee GCR site, exhibit a much lower grade of metamorphism.

9 GLEN ESK
(NO 586 733–NO 583 736, 579 744, 583 756, 574 766, 560 785)

D. Gould and B. Harte

9.1 Introduction

The valley of the River North Esk in the Angus Glens is in the heart of the area where George Barrow first demonstrated the development of successive mineral assemblages during the progressive regional metamorphism of pelitic rocks (Barrow, 1893, 1912). Here, the transition from low to high metamorphic grade can be studied over a distance of a few kilometres and the GCR site comprises six localities, one for each metamorphic zone, selected largely on grounds of ease of access (Figure 30). These localities, together with alternatives for some of the zones, were described by Harte (1987).

While working for the Geological Survey in this area, Barrow was the first person to define a scheme of indicator minerals for different degrees of regional metamorphism in pelitic rocks. He initially defined seven zones: the lowest grades were 'clastic mica' and then 'digested clastic mica', and up grade of these were zones defined by the progressive incoming of biotite, garnet, staurolite, kyanite and sillimanite. Tilley (1925) combined the two lowest grades into a single chlorite zone, since the distinction between clastic and non-clastic white micas was doubtful. Hence we now recognize six zones ranging from chlorite to sillimanite (Figure 31). This scheme, known as the Barrovian scheme, was found to apply to large areas of the Dalradian outcrop, and has been recognized in many other regional metamorphic terranes worldwide. In terms of overall metamorphic facies, it corresponds to a relatively high-pressure part of the greenschist and amphibolite facies.

However, in the area north of the River Dee and east of the Portsoy Shear-zone, a different sequence of metamorphic zones is developed. This, the Buchan scheme of Read (1955), corresponds to lower pressures over the same range of temperatures (see Stephenson et al., 2013b). A transitional zonal sequence between the two regimes is exposed on the coast north of Stonehaven (Harte and Hudson, 1979) (see the *Garron Point to Muchalls* GCR site report).

Barrow's original zonal scheme has stood the test of time, although Chinner (1966) regarded the development of fibrolitic sillimanite as a later thermal 'overprint' upon both the Barrovian and the Buchan zones. However, Harte and Johnson (1969) used thin sections to date the development of the metamorphic fabric of the rocks with respect to the various fold episodes in the district. They showed that prograde metamorphism continued longer in the higher grade rocks than in the lower grade rocks, and that the post-D3 crystallization of sillimanite, although overstepping the lower grade zones in places, was the culmination of a single long period of prograde metamorphism. Retrogression was associated with D4 and later movements.

Also in this area, Atherton and Brotherton (1972) showed that the first appearance of kyanite in regionally metamorphosed pelites and semipelites is controlled by the effective Mg/Fe^{2+} ratio of the rock. Harte and Hudson (1979) used petrological and geochemical methods to attempt to quantify pressures and temperatures at various stages in the metamorphic history of the eastern Grampian Highlands.

Field excursions that visit this GCR site have been described by Harte (1987) and MacGregor (1996).

9.2 Description

The first three localities are along the banks of the River North Esk; the others are on crags away from the river (Figure 30).

9.2.1 Locality 1, Chlorite Zone: North Esk Gorge (NO 586 733)
The North Esk Fault at this locality separates Dalradian rocks to the north-west from Highland Border Complex rocks to the south-east. The Dalradian rocks consist of compositionally layered, grey-green schistose chlorite-muscovite pelites, semipelites and psammites. Porphyroblasts of magnetite and rare pyrite up to 2 mm across are widely visible. A spaced cleavage developed during D1 is overprinted by an S4 crenulation cleavage, which is only visible in the more-micaceous lithologies.

9.2.2 Locality 2, Biotite Zone: North Esk Gorge (NO 583 736)
This locality is only *c.* 200 m upstream of locality 1. The lithologies are similar to those at locality 1, but also include beds of gritty psammite up to 1 m thick. The rocks look very similar to the chlorite-zone rocks, but a few flakes of brown biotite are visible in some layers. In thin section, the rocks are well-foliated semipelites and pelites with a good fabric formed by the alignment of muscovite and chlorite parallel to an S1 foliation. This fabric has been crenulated during D4. Post-dating the S1 fabric but pre-dating the S4 crenulations, are scattered, randomly orientated biotite porphyroblasts up to 1 mm long by 0.5 mm wide, which are visible on freshly broken surfaces of the more-pelitic rocks.

9.2.3 Locality 3, Garnet Zone: Auchmull (NO 579 744)
One of the few accessible exposures of garnet-zone rocks is *c.* 800 m upstream of locality 2, on the west bank of the River North Esk, near the end of the largely continuous exposures through the chlorite and biotite zones. Here, the rocks are grey-green schistose semipelites and pelites, similar to those at localities 1 and 2, but slightly coarser in grain size. The S1 foliation can be seen to be disrupted locally by a widely-spaced S2 cleavage, which gradually becomes more persistent northwards. The F4 folds are less numerous than at locations 1 and 2, and the S4 crenulation cleavage is only weakly developed. The locally abundant garnet porphyroblasts, up to 5 mm in diameter, are best seen on the south-east side of low exposures that protrude into the river. Elsewhere, where the rocks are more psammitic, garnet is hard to find. The garnets are seen in thin section to be poikilitic, with

inclusions generally smaller than the grain size of the matrix. The folds in the inclusion trails show that the garnets grew post D2 and pre D4. Biotite porphyroblasts up to 3 mm across also occur.

9.2.4 Locality 4, Staurolite Zone: Craig of Weston (NO 583 756)
This is the upper of the two localities described by Harte (1987), in an area where there is much loose rock but little material definitely *in situ*. Staurolite is developed in the more-pelitic layers lying within a dominantly psammitic to semipelitic succession. Here, the dominant fabric in the pelitic rocks is a penetrative schistosity, which is related to the well-developed S2 spaced cleavage in the semipelites and psammites. Relics of S1 are preserved in the microlithons between the S2 cleavages. The S2 cleavage is in places folded by tight minor folds ascribed to D3, but the broad open F4 folds, characteristic of lower Glen Esk, are absent.

The pelites are considerably coarser grained than those at localities 1 to 3. A fabric defined by 2–3 mm-long muscovite and biotite crystals dominates the rock. Randomly orientated porphyroblasts of garnet and staurolite reach 5 mm in size. Some of the rocks contain anhedral porphyroblasts of poorly twinned plagioclase. Much of the coarsening of the fabric of the rocks and the prophyroblast growth probably occurred during D3.

9.2.5 Locality 5, Kyanite Zone: Craigoshina (NO 574 766)
At this locality, the rocks have the same coarse mica fabric as at locality 4, and the dominant fabric is S2, which is folded by minor F3 folds. In the Glen Esk–Glen Lethnot area in general, kyanite is best developed in silvery muscovite-rich pelites, many of which also contain abundant haematite porphyroblasts. These pelites form units up to 100 m thick, extending for up to 2 km along strike, and represent a distinctive lithology with a higher Fe^{3+}/Fe^{2+} ratio than the surrounding rocks. Because of the oxidized nature of the rocks, kyanite is abundant at this locality despite the rocks being below the regional kyanite isograd for less-oxidized rocks (Chinner, 1960; Harte, 1966; Atherton and Brotherton, 1972). The fabric of the rocks is dominated by abundant well-aligned muscovite flakes with relatively little biotite. Porphyroblasts of garnet and staurolite reach 5 mm in size, and kyanite crystals are typically up to 3 cm in length. The kyanite porphyroblasts contain abundant inclusions of fine-grained haematite, and many of them have retrogressed to fine-grained aggregates of white mica. Better crystallized, and more typically blue kyanite is present in some of the numerous quartz veins. Garnet occurs in the haematite-kyanite schists but is fine grained and hence difficult to see (Chinner, 1960).

9.2.6 Locality 6, Sillimanite Zone: Hillock (NO 560 785)
At this locality schistose semipelites and pelites form rough craggy knolls. The rough surface of the more-pelitic rocks displays welts and knots up to several centimetres long, consisting of tiny fibres of sillimanite, usually intimately associated with quartz. Larger upstanding ‘blobs’ of fibrous sillimanite, 1–2 cm across, on weathered surfaces, can be found surrounding garnets.

In this area, the main foliation of the rocks is still the composite S0-S1-S2, but in the cores of the tightest of the abundant flat-lying F3 folds, the axial planar S3 cleavage merges with the earlier composite foliation. Minor folds showing crenulation of the mica fabric are attributed to D4. Between the kyanite-zone exposure and this exposure, the more-feldspathic semipelites and impure psammites show incipient segregations of quartzofeldspathic laminae, typically with biotitic selvedges, indicating the commencement of migmatization in susceptible lithologies.

9.3 Interpretation

The sequence of six typical exposures illustrates the effects of progressive regional metamorphism of pelitic rocks at medium to high pressures. The first five of these exposures occur within the Glen Lethnot Grit Formation, a 1500 m-thick succession of gritty, turbiditic psammites, with interbeds of semipelite and pelite, typically forming graded units 0.5–2.5 m thick (Harte, 1979; Gould, 2001). The sillimanite-zone exposure lies within the older, Glen Effock Schist Formation, which contains more semipelite and less psammite than the Glen Lethnot Formation.

The Barrovian index minerals are typically confined to the pelitic lithologies, although chlorite and biotite also occur in semipelites and impure psammites. Kyanite is best developed in an atypical, highly oxidized type of pelite characterized by silvery mica felts and numerous small haematite porphyroblasts. One of these pelites has been chosen for inclusion in the GCR site.

The local peak of metamorphism occurred progressively later in the higher metamorphic grades (Harte and Johnson, 1969; Robertson, 1994); it was syn to post D2 in the chlorite and biotite zones, post D2 but pre D3 in the garnet zone, and syn D3 in the staurolite, kyanite and sillimanite zones. The migmatization in the highest-grade rocks overlapped D3 in nearby Glen Clova (Robertson, 1991). Retrogressive effects, with alteration of biotite to chlorite and of staurolite and kyanite to sericitic felts, are associated with areas of intense D4 crenulation, and with the post-D4 folds associated with emplacement of the Mount Battock Pluton. Dempster (1985a) has used Rb-Sr and K-Ar dating to plot pressure-temperature paths and to work out the cooling and uplift history of the area. He concluded that the main metamorphism occurred at 520–490 Ma, with peak temperatures occurring progressively later at greater burial depths. After local uplift at 520–490 Ma, two major periods of uplift occurred at 460–440 Ma, associated with D4, and 410–390 Ma, associated with intrusion of the Mount Battock Pluton. Dempster (1985b) also estimated that peak metamorphism in the kyanite and sillimanite zones in nearby Glen Lethnot occurred at a temperature of 630–660 °C and a pressure of 5.7–6.2 kbar.

The temperature and pressure gradients estimated from the compositions of pairs of co-existing minerals is steeper than would be calculated from the exposed outcrop width of the zones in Glen Esk. This probably implies a considerable degree of tectonic thinning within the Glen Lethnot Grit Formation. A clue to the timing of the thinning occurs in areas a short distance to the east, where Phillips and Auton (1997) described blastomylonites within Glen Lethnot Formation rocks south of the Mount Battock Pluton. From their mineral textures, they deduced that most of the mylonitization and accompanying attentuation of the metamorphic zones occurred during D2.

9.4 Conclusions

The Glen Esk GCR site is within the internationally recognized type area for the Barrovian type of regional metamorphism. It was here in 1893 that George Barrow first erected a scheme of metamorphic zones based upon the first appearance of various index minerals with increasing metamorphic grade in pelitic rocks. These zones are typical of regional metamorphism at moderate to high pressures within the greenschist and amphibolite facies and have subsequently been recognized throughout the world. The GCR site provides, within a short distance, examples of Dalradian pelitic rocks from all of the Barrovian metamorphic zones, which are characterized, with increasing grade, by chlorite, biotite, garnet, staurolite, kyanite and sillimanite.

The exposures are all readily accessible and are invaluable for teaching purposes. Only the garnet-zone exposure is of less than excellent quality, and even it is acceptable. The index minerals can mostly be seen with the naked eye, and all are conspicuous under a hand lens. The exposures can also be used to demonstrate the development of folds and cleavages during successive deformation and progressive coarsening of texture within rocks of increasing metamorphic grade.

Thin sections from these rocks have enabled the timing of growth of the various minerals to be worked out with respect to the four regional deformations that affected Dalradian rocks of the eastern Grampian Highlands. Further work could involve electron-microprobe analysis of co-existing mineral phases to work out the temperature and pressure during deformation in different parts of the site. However, such studies would be partly hampered by the effects of retrogression that are particularly associated with the D4 deformation.

10 GARRON POINT TO MUCHALLS (NO 894 877–NO 907 921)

C.W. Thomas

10.1 Introduction

The east coast of the Grampian Highlands, north of Stonehaven, provides a continuously exposed and largely accessible section through Southern Highland Group metasedimentary rocks (Figure 32). The outcrops reveal in outstanding detail, the characteristics of the original sedimentary rocks and their response to metamorphism and deformation. In particular, there is a continuous section across the Tay Nappe, from the Flat Belt, across the Highland Border Downbend, into the Highland Border Steep Belt and the downward-facing complex hinge-zone of the nappe, which is truncated here by the Highland Boundary Fault (Figure 33). In addition, distinctive metamorphic mineral assemblages are developed within the pelitic rocks, which differ from those of the 'Buchan' metamorphism to the north, and the 'Barrovian' metamorphism to the west.

The importance of this coast section has long been recognized. Although the study of the metamorphic mineral assemblages has been an important feature (e.g. Williamson, 1953; Harte and Hudson, 1979), it is the study of the structure that has been particularly important and highly relevant to the regional Dalradian structure. Anderson (1942, 1947a) was the first to describe and interpret the geological structure of the coast, relating this to the structure he observed in the River North Esk. And Stringer (1957) identified the four main phases of deformation, which he traced from the coast along the Highland Border to the south-west. However, it was Shackleton (1958) who recognized the monoformal Highland Border Downbend, and was able to show, by combining way-up evidence in the metasedimentary rocks with the geometrical relationships between first cleavage and bedding, that the first fold structures in the Highland Border Steep Belt are downward-facing. In other words, he showed that the sequence was already inverted prior to folding around the Highland Border Downbend. This inversion was attributed to the emplacement of an early nappe, equivalent to the Tay Nappe of Perthshire. However, the recognition of a right-way-up succession in the Tarfside district to the west led Harte (1979) to propose that the coast section may not lie on the inverted limb of the Tay Nappe, but on the right-way-up limb of an underlying 'Tarfside Nappe'. This interpretation was supported by Booth (1984), who also concluded that the coast section lies on a right-way-up fold limb. But more-recent work by the British Geological Survey during the remapping of 1:50 000 Sheet 67 (Stonehaven, 1999) indicated that this interpretation is difficult to substantiate. Younging evidence in outcrops to the north of the Highland Border Downbend shows that the rocks are generally inverted, which is more consistent with the traditional interpretation that the coast section lies in the lower, inverted limb of the Tay Nappe.

10.2 Description

The GCR site extends for some 5 km from the southern end of Skatie Shore at Garron Point (NO 894 877), to Ritchie Shore (NO 907 921), some 300 m south-east of Muchalls. The coast is dominated by steep cliffs, locally up to 30 m or more in height, above a rock platform that is exposed at mid to low tides.

The metasedimentary rocks are very well bedded. Bedding is generally planar, although beds do wedge out locally. Graded bedding is abundant and is seen particularly well in the south of the site, where the metamorphic grade is lower. The succession is dominated by metasandstone (psammite), with metasiltstone (semipelite) and metamudstone (pelite) common in many places. The metasandstones vary from fine-grained, thinly bedded units to massive, very coarse-grained and sometimes pebbly or microconglomeratic units in excess of 2 m in thickness. To the north of the Highland Border Downbend, calcsilicate-bearing layers commonly occur in the centre of metasandstone beds. These are thought likely to be of diagenetic origin, but now contain garnet, amphibole and plagioclase. Units containing volcanic debris, informally known as 'green beds' and a notable feature of the Southern Highland Group elsewhere, are conspicuously absent from the coast section, exacerbating correlation problems.

The structure of the coast section is complex. Four major phases of deformation are developed between Garron Point and Findon Ness (NO 944 974), to the north of the GCR site, and three of these are readily observed within the site. The site is divided into two structural domains by the Highland Border Downbend (Figures 32 and 33). This major structure cuts the coast at Castle Rock of Muchalls (NO 899 907), where it is very sharply defined, much more so than in many other areas of the Highland Border region. The coast to the north of the downbend is occupied generally by relatively shallow-dipping strata of the Flat Belt. To the south of the downbend, strata dip steeply, generally to the north-north-west, in the Highland Border Steep Belt.

D1 structures dominate the southern part of the GCR site along Skatie Shore and Perthumie Bay, and this early phase of deformation appears to be generally more intense than in some other areas where lithostratigraphically equivalent rocks are exposed (e.g. in the Aberfoyle district; see the *Duke's Pass* GCR site report). It is manifested most obviously as coarsely spaced, anastomising cleavages (S1) in gritty metasandstone beds. Tight to isoclinal F1 folds can be shown to be present on the basis of changes in younging direction, but hinges are very rarely seen. The best example is exposed below mid tide on the rock platform in the southern part of Perthumie Bay. In this example, the S1 cleavage is seen to fan around the hinge. On the basis of the facing of the S1 cleavages observed in the southern part of the site, it is clear that the F1 fold system is not cylindrical, and F1 fold plunges are markedly variable.

D2 structures probably occur throughout the GCR site, but are only readily observable north of Perthumie Bay. In addition, it appears that the D2 deformation is not pervasive. D2 is manifested by complex minor structures that deform the first cleavage in the metasandstones in a very characteristic manner, giving rise to what is most easily described as a very coarse crenulation cleavage. The minor F2 folds formed within this cleavage have axial planes that are approximately parallel to the bedding and have markedly curvilinear hinges. F2 folds to the south of the Highland Border Downbend plunge generally to the south-west. To the north of the downbend they plunge to the north. Larger F2 folds of bedding are developed more commonly in the northern part of the coast section, where they are tight to isoclinal in form. The D2 deformation is probably heavily partitioned into the pelitic rocks, but the fine-grained and recrystallized nature of these lithologies obscures the D1-D2 relationships that are so readily observed in the coarse-grained metasandstones. D2 deformation is generally considered to just pre-date or be synchronous with the peak of metamorphism.

The D3 deformation is not well developed within the GCR site; unequivocal D3 structures are best observed in the Portlethen area about 6 km to the north of Muchalls. Folds just north of Red Man (NO 892 888), ascribed by Booth to D3 (Booth, 1984; see also Harte *et al.*, 1987, locality 6), are thought more likely to have resulted from D1 deformation. Locally developed cleavages of obscure origin might be due to D3 effects, but their relationships to other cleavages are commonly ambiguous and they could well have arisen from local strain partitioning.

The D4 deformation is complex and probably occurred over a protracted period, involving early extension, followed by compression. The observable effects of this phase of deformation are focussed on the Highland Border Downbend. F4 folds are overturned towards the downbend from both the south and the north. They are open to close, parallel fold structures that become more intense towards the downbend. In the Steep Belt, F4 folds are centimetre- to ten metre-scale structures. In the Flat Belt, F4 folds range in scale from small, centimetre-sized structures to large folds on the scale of tens of metres. These larger structures produce local steep zones that form the short limbs of the folds. Crenulation cleavages are best developed in pelitic beds and in laminae within the hinge regions of the folds. F4 folds plunge at shallow angles mainly to the south-west and, less frequently, to the north-east. F4 axial planes dip at shallow angles to the north-west.

Faults and dislocations are a common feature of the coast section. In general, they appear to become more common towards the Highland Border Downbend from the south and are common in the Flat Belt towards Muchalls, where they result in a complex, incised coastline. In broad terms, they can be divided into low-angle and high-angle sets.

The low-angle faults were probably related to D4 compression after the formation of the Highland Border Downbend, probably originating as thrust structures during or after the development of F4 folds. Good examples of low-angle faults are observed in Hall Bay (NO 898 899). One at the northern end of Hall Bay is clearly a thrust, having a thin gouge along the fault plane. Low-angle discontinuities are displaced by a steep fault in the section east of Craigview (NO 9050 9127), about 1 km south of Muchalls. This suggests that the steep faults post-date the low-angle faults.

Two sets of steep faults are identified. A dominant set trending north-west is responsible for the deeply incised coastline north of the Highland Border Downbend, particularly around Doonie Point (NO 903 910) and on the promontory at Grim Haven, south of Muchalls. These faults generally dip steeply to the north-east or south-west and the available field evidence indicates that they are normal faults. The other conjugate set trends north-east and dips steeply to the south-east or north-west, but these faults are relatively uncommon compared to the NW-trending set. They are roughly parallel to the regional strike and the Highland Boundary Fault and might be related to the formation of the Highland Border Downbend.

The metamorphism within the coast section is characterized by a rapid increase in grade northwards from the Highland Boundary Fault. This is manifested by the development of distinctive mineral assemblages in the pelitic rocks, most notably chloritoid + biotite and andalusite, the latter in place of the kyanite that is characteristic of the classic Barrovian assemblages of the Angus glens to the south-west. The presence of chloritoid and andalusite led Harte (1975) to define the 'Stonehavian' metamorphic assemblage sequence, which is intermediate between the relatively high-pressure Barrovian and high-temperature Buchan sequences (Harte and Hudson, 1979). Biotite + chlorite-bearing pelitic rocks at Skatie Shore become garnet-bearing in the northern part of Perthumie Bay. Chloritoid appears first in the northern part of Red Man in highly aluminous pelites (Harte and Hudson, 1979). The main appearance of chloritoid results from the discontinuous reaction between garnet and chlorite to yield chloritoid + biotite, this being the chloritoid isograd in the Stonehavian sequence. Staurolite first appears just to the north of Red Man (NO 892 888), initially resulting from reaction between chloritoid and chlorite to produce staurolite + biotite and then from the terminal breakdown of chloritoid to give staurolite + garnet + biotite. Andalusite is the stable aluminosilicate polymorph throughout the site. The staurolite + biotite assemblages coupled with the presence of andalusite indicate peak metamorphic pressures of no more than about 3 kbar at temperatures in excess of 500°C (Spear, 1993).

10.3 Interpretation

There are no precise constraints on the age of the metasedimentary rocks within this GCR site. All are assigned to the Glen Lethnot Grit Formation, in the upper part of the Southern Highland Group. This formation is now generally considered to be broadly equivalent in its lithological character and lithostratigraphical level to the Ben Ledi Grit Formation of the Aberfoyle–Callander area, a correlation first suggested by Anderson (1942). However, the lack of significant marker horizons at this site precludes precise correlation. Although metasiltstones and metamudstones are common locally, metasandstones dominate. Their general sedimentological characteristics indicate deposition within a submarine fan system on a continental margin, generally by turbidity currents; mass-flow mechanisms are thought to have been responsible for the deposition of massive, very thick single units of coarse, gritty rocks.

The metasedimentary rocks were strongly deformed during the Grampian Event of the Caledonian Orogeny and three of the four main phases of deformation generally recognizable in the Dalradian are developed within the GCR site. The pre-D2 way-up of the section is critical to the interpretation of the overall structural setting. Although Harte (1979) proposed, by analogy with the Tarfside succession inland, that the coast section might lie in the right-way-up limb of a nappe lying below the Tay Nappe, all the available younging evidence in the Flat Belt indicates that the rocks are generally inverted. This, coupled with the downward-facing nature of the F1 folds in the Steep Belt, indicates that the rocks are more-readily interpreted as lying within the inverted limb of an early nappe structure most simply correlated with the Tay Nappe.

10.4 Conclusions

The coast between Garron Point and Muchalls contains outstanding exposures of Southern Highland Group metasedimentary strata in an area of the Highland Border region that is otherwise poorly exposed. The site is of national and international importance for the continuous section that it exhibits across the downbent complex hinge-zone of the Tay Nappe, the most intensively studied and, arguably, the most important structure in the Grampian Highlands. The effects of three deformation events (D1, D2 and D4) can be readily discerned and the site contains some of the first localities in the world at which downward-facing geological structures (e.g. synformal anticlines) were deduced from their smaller scale component structures by Robert Shackleton in 1958. The recognition of the facing of the early structures led to a radical re-interpretation of the structure of the south-eastern part of the Dalradian as a whole.

Metamorphism accompanying the deformation resulted in the generation of mineral assemblages in the pelitic rocks that are a distinctive feature of the area around the GCR site and indicate rapidly increasing metamorphic grade northwards from the Highland Boundary Fault. Metamorphic conditions were intermediate between those of the high-temperature Buchan Zones to the north and those of the high-pressure Barrovian Zones to the south-west.

The ready accessibility of the outcrops, the excellent exposure and the nature of the lithologies make this an excellent site within which to demonstrate and teach structural geology and the temporal links between deformation and metamorphism within a classic orogenic belt.

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Figure 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 this regional paper 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 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.
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 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. GCR sites are numbered as on Figure 1.

Figure 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 18.

Figure 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 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 24a).
FF' Glen Shee. (after sections 1, 2 and 4, BGS 1:50 000 Sheet 56W, Glen Shee, 1999).
GG' Stonehaven. (after Figure 33).
Positions of GCR sites, projected onto the nearest equivalent cross-section, are numbered as on Figure 1.

Figure 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).

Figure 6 Map showing the bedding-cleavage relationships in the Dalradian rocks immediately north-west of a splay of the Highland Boundary Fault, north of Ardscalpsie Point, Isle of Bute. A–F, reference points on the line of cross-section shown in Figure 8.

Figure 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 8 A true-scale, NNW–SSE-trending cross-section, prepared from field sketches, of the structures along the line A—F in Figure 6, Ardscalpsie Point GCR site.

Figure 9 Map of the southern end of the Rosneath peninsula, including the Cove Bay to Kilcreggan GCR site, based on BGS 1:50 000 Sheet 30W (Greenock, 1990).

Figure 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 7b).
(Photos: P.W.G. Tanner.)

Figure 11

(a) Location map of the Portincaple GCR site. Bedrock is the Beinn Bheula Schist Formation, cut by the few dykes shown. A–B, C–D, lines of cross-section for (b).
(b) True-scale field sketch of a vertical cross-section, viewed approximately down-plunge for F4, across the southern part of the hinge-zone of the Highland Border Downbend (F4). The main fabric in these rocks is a centimetre-spaced pressure-solution (or dissolution) cleavage (S2).
(c) Equal-area stereographic projection showing poles to the S2 fabric that defines a best-fit great circle whose π axis plunges at 10° to 079°, parallel to the major F4 fold axis of the Highland Border Downbend.

Figure 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 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 3.3b 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 14 Map of the area around Bealach nam Bo, Loch Katrine, Trossachs. Based upon mapping by the British Geological Survey, 1996–1998.

Figure 15 Sedimentological log through 'green beds' in the Loch Katrine Volcaniclastic Formation, exposed in cliffs at Bealch nam Bo. Adapted from Burt (2002).

Figure 16 F1 folds with axial planar cleavage picked out by quartz veins in 'green beds' and cleaner metasandstone in the Loch Katrine Volcaniclastic Formation at Bealach nam Bo (NN 478 075). Lens cap is 50 mm diameter. (Photo: C.W. Thomas, BGS No. P 726593.)

Figure 17 F2 crenulation folds of the first cleavage in the Creag Innich Sandstone Formation at NN 4777 0714, Bealach nam Bo GCR site. Lens cap is 50 mm diameter. (Photo: C.W. Thomas, BGS No. P 726594.)

Figure 18 Map of the area around the Duke's Pass, Aberfoyle. Based upon mapping by the British Geological Survey, 1996–1998.

Figure 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 20 Map of the Keltie Water, Callander GCR site. Locations of photomicrographs (Figure 21, a–e) and the field photograph (Figure 22) are indicated. The position of the putative terrane boundary between the Grampian Terrane and the Highland Border 'exotic terrane' (Brasier *et al.,* 1992) is also shown for reference.
The inset map shows three structural sub-areas sited across the boundary between undoubted Dalradian rocks of the Ben Ledi Grit Formation (A), and the lower part of the Keltie Water Grit Formation, including the Transition Member (B). Sub-area C consists mainly of gritty metasandstones of the Keltie Water Grit Formation, comparable in lithology to the rocks in sub-area A. Equal-area stereographic projections for each of these sub-areas show the poles to the main cleavage, together with their computed mean orientation shown as a great circle (solid line).

Figure 21 Photomicrographs of medium- to coarse-grained metagreywackes from the Keltie Water section, and a related exposure 5 km to the south-west. The photomicrographs illustrate the similarities in petrography and strain state of samples from **(a)** the Ben Ledi Grit Formation, **(b)** the Transition Member, **(c)** the lower part of the Keltie Water Grit Formation, above the Transition Member, **(d)** the Keltie Water Grit Formation above the Keltie Limestone and Slate Member and **(e)** the upper part of the Keltie Water Grit Formation above the Leny Limestone and Slate Member. The selected photomicrographs are representative examples chosen from over 100 thin sections and full details of the petrography were given by Tanner and Pringle (1999). Locations of samples are shown on Figure 20, except for (e) which is located at NN 6037 0858. All photomicrographs are at the same scale with a width equivalent to approximately 4 mm. (Photos: P.W.G. Tanner.)

Figure 22 Spaced S1 cleavage, with microlithons 1–3 cm thick, associated with a minor fold in gritty metasandstones of the Keltie Water Grit Formation. Section viewed to the north-east. This exposure (see Figure 20 for location) was removed totally by a recent flood. (Photo: P.W.G. Tanner.)

Figure 23 Map of the Dunkeld – Pitlochry area to show the main lithostratigraphical units, the main elements of the structure and the locations of the Little Glen Shee, Craig a'Barns and Rotmell GCR sites. Adapted from Rose and Harris (2000, figure 2).

Figure 24
(a) Schematic cross-section from Pitlochry to Dunkeld to show the location of Figure 24b, and the position of the Little Glen Shee, Craig a'Barns and Rotmell GCR sites in relation to the Tay Nappe.
(b) Schematic cross-section across the Flat Belt (FB), the Highland Border Downbend (HBD), the Highland Border Steep Belt (HBSB) and the Highland Boundary Fault (HBF) to show the position of the Little Glen Shee, Craig a'Barns and Rotmell GCR sites in relation to the detailed geology of the district. Adapted from a drawing by P.T.S. Rose.

Figure 25 Geological relationships at the crag that comprises the Little Glen Shee GCR site, to show the geometry of the folds and the general direction of younging of the beds. Insets 1 and 2 show the detail of relations between bedding and the refracted cleavage on alternate fold limbs. Locations of photographs, Figures 26a and 26b, are shown. Adapted from a field sketch by P.W.G. Tanner with insets from P.T.S. Rose.

Figure 26 Detailed sedimentological and structural features of the Little Glen Shee GCR site at locations shown in Figure 25.
(a) Cleavage types and refraction related to rock type. A spaced cleavage (S1p) occurs in metasandstones in the centre of the photo and is refracted as it passes into a slaty cleavage (S1) in metasiltstones on either side. To the right there is a sharp lithological change at the base of the metasandstone unit, but to the left the more gradual refraction brings out grading from one lithology into another. Younging is to the left (north-north-west). Coin is 1.2 cm in diameter.
(b) Detail of the minor fold-pair diagrammatically represented in Figure 25 and discussed in the text. Coin is 1.2 cm in diameter.
(Photos: A.L. Harris.)

Figure 27 Location map of the Craig a'Barns GCR site, showing the position of localities A–D described in the text and the approximate trace of the Highland Border Downbend (HBD).

Figure 28 Detailed structural relationships at the Craig a'Barns GCR site.
(a) Sketch taken from a photograph of the fold at locality B on Figure 27, discussed in the text. A metasandstone bed contains tight F2 folds of S1p showing consistent vergence on opposite limbs of the Highland Border Downbend-related, step-like open fold.
(b) The association between the Highland Border Downbend-related crenulation cleavage (overdrawn straight lines, labelled S4) and folded bedding (S0), seen at or near the core of the downbend at locality C on Figure 27. At the top of the photograph, bedding is essentially parallel to both S1 and S2 but in the bottom left, S1p is at a distinct angle to bedding. Looking north-east, width of exposure about 60 cm. (Photo: A.L. Harris.)

(c) Detail of the crenulation cleavage related to the Highland Border Downbend at locality C on Figure 27. Looking north-east, width of exposure 20 cm. (Photo: A.L. Harris.)

Figure 29 Intense F2 folds of the S1p cleavage at the Rotmell GCR site. Note the contrast in thickness between S1p microlithons in the hinges of the F2 folds and those on the limbs. Top-to-the-right (south-east) shear is inferred. Looking north-east at NO 0128 4118. Field of view is approximately 50 cm high. (Photo: J.E. Treagus.)

Figure 30 Map of lower Glen Esk showing the full range of regional metamorphic zones first erected by Barrow (1893, 1912). Redrawn from Harte (1987), with modifications based on BGS 1:50 000 Sheet 66W (Aboyne, 1995).

Figure 31 Photomicrographs (a–d, f) and one field photo (e) illustrating the sequence of Barrow's Zones, as represented in the Glen Esk GCR site. Rocks photographed come from the localities described in the text, except for the sillimanite zone (f), which is from a locality by Glen Effock (described by Harte, 1987). All photomicrographs are at the same scale with a width equivalent to approximately 4.5 mm. (Photos: B. Harte.)

(a) ***Chlorite Zone***. Principal minerals are quartz, white mica, chlorite and opaques (iron oxide and sulphide). The bedding and main cleavage are approximately parallel to the top edge of photo, and the upper (darker) half of the photo represents a chlorite-rich layer, whilst the lower part is more quartz rich. A later cleavage is visible as pale (white mica-rich) seams cutting obliquely across the chlorite-rich layer.

(b) ***Biotite Zone***. Biotite porphyroblasts (Bt) overgrow a finer grained matrix of quartz, white mica, chlorite and opaque iron minerals. The bedding and main cleavage are roughly parallel to the top edge of the photo.

(c) ***Garnet Zone***. Biotite (Bt) and garnet (Grt) porphyroblasts in a finer grained matrix of quartz, white mica, chlorite and opaque iron minerals. Areas in the matrix richer in chlorite (Chl) have a darker appearance.

(d) ***Staurolite Zone***. Porphyroblasts of garnet (Grt and highest relief), staurolite(St and high relief) and biotite (Bt and moderate relief) in a matrix of quartz and muscovite with a small amount of opaque iron minerals.

(e) ***Kyanite Zone***. Field photo of a vein dominantly of quartz and kyanite; the label is in the centre of a rosette of kyanites. Penknife is 10 cm long.

(f) ***Sillimanite Zone***. A large (2 mm) porphyroblast of garnet (Grt) in the centre, together with smaller porphyroblasts of kyanite (Ky) and staurolite (St). The 'Sill' label is on a cluster of sillimanite fibres (fibrolite). Darker areas to the left and right of the garnet are of biotite intergrown with fibrolite. Pale areas are dominated by muscovite and quartz.

Figure 32 Location of the coast section in Southern Highland Group rocks from Garron Point to Muchalls, north of Stonehaven, showing the principal structural and metamorphic features. After BGS 1:50 000 Sheet 67 (Stonehaven, 1999), with approximate locations of metamorphic mineral isograds based on Harte *et al.* (1987, figure 2a).

Figure 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 27. Section is true scale (no vertical exaggeration). After BGS 1:50 000 Sheet 67 (Stonehaven, 1999).

Figure 34 Cleavage/bedding relationships in Southern Highland Group rocks of the Garron Point to Muchalls GCR site.
(a) Widely spaced S4 cleavage in calcsilicate-rock and psammite at Hall Bay (NO 8994 8985). View to the south-west down the plunge of the F4 folds.
(b) S1 cleavage is steeper than bedding in beds that young south and are therefore inverted and downward facing on S1. Exposure at high-water mark just south of promontory at edge of main part of Perthumie Bay (NO 8908 8811). (Photos: C.W. Thomas, BGS Nos. P 726595 and P 726596.)

Figure 4.1

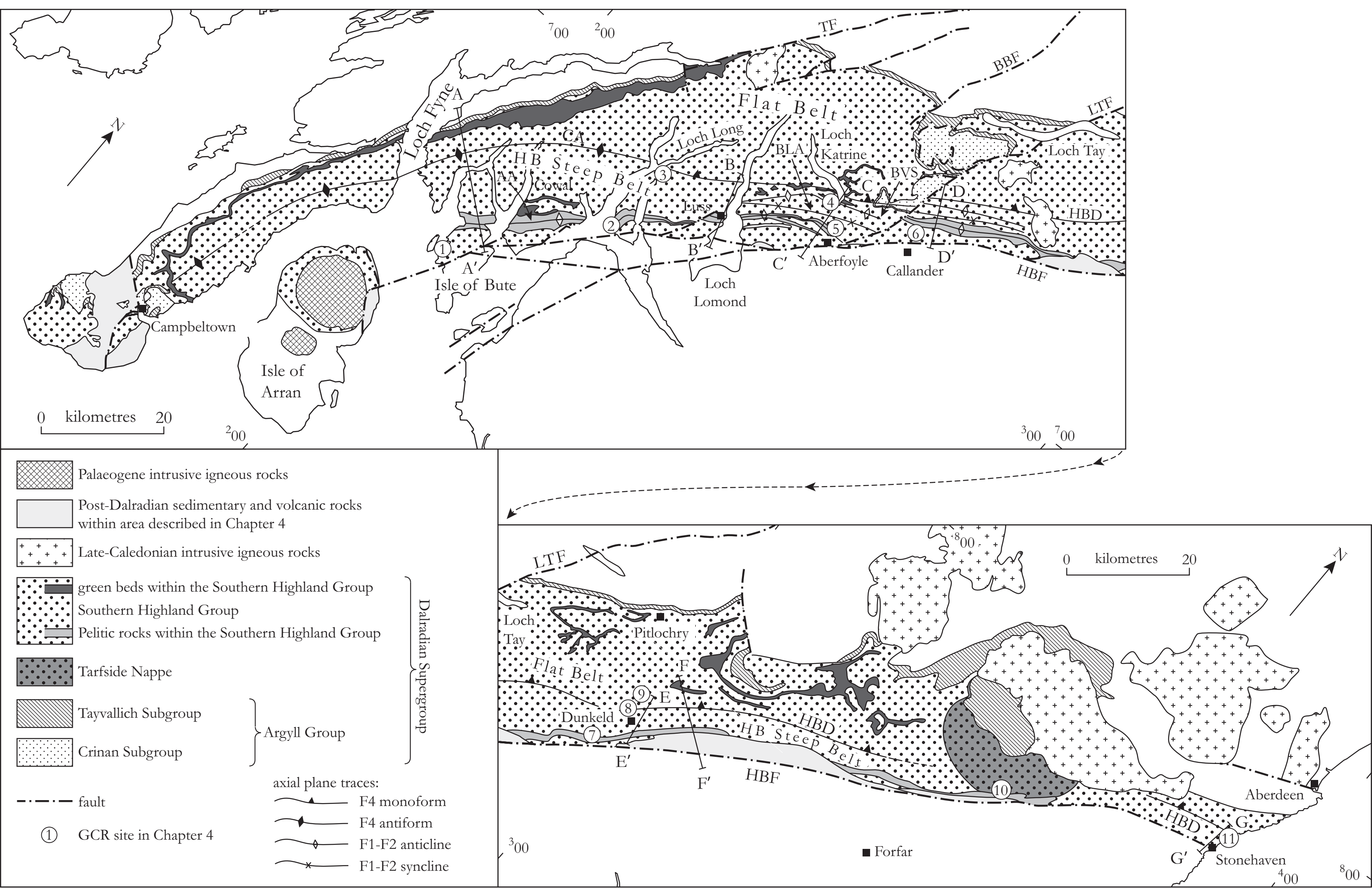
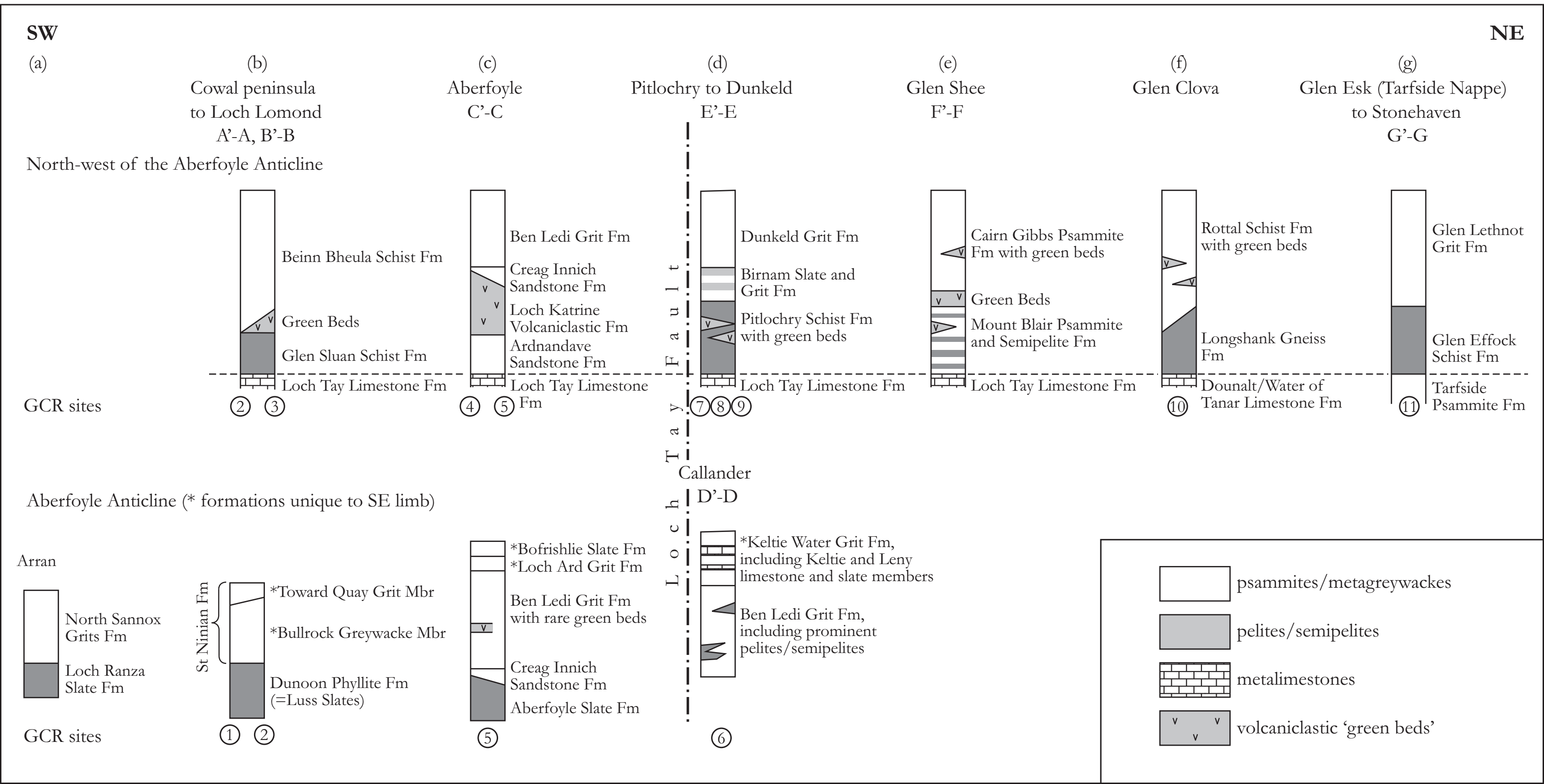
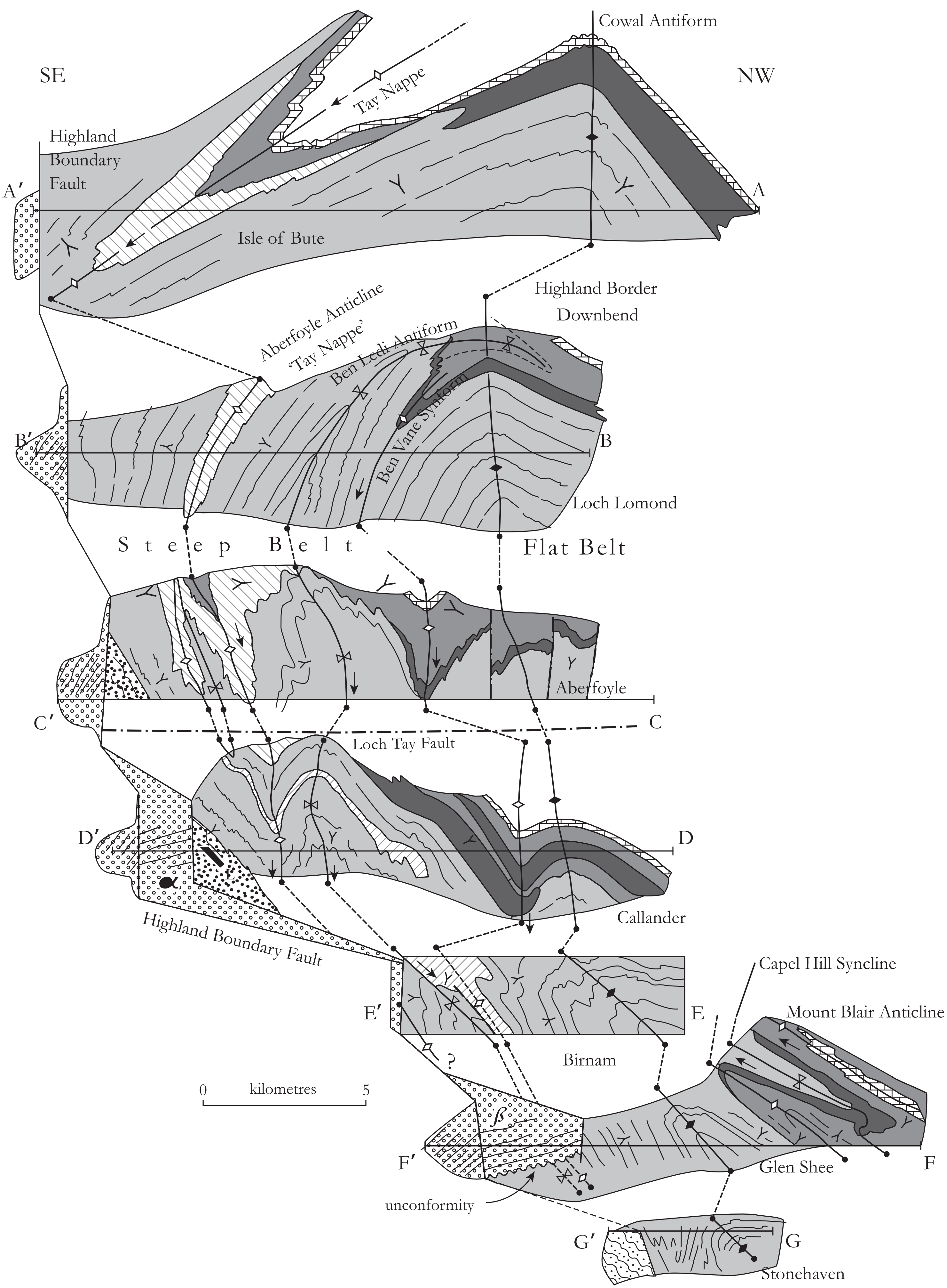

N
TF
BBF
LTF
Flat Belt
Loch Fyne
Loch Long
Loch Katrine
Loch Tay
CA
HB Steep Belt
AA
Cowal
BLA
BVS
HBD
HBF
A
A′
B
B′
C
C′
D
D′
Luss
Aberfoyle
Callander
Loch Lomond
Isle of Bute
Campbeltown
Isle of Arran
0 kilometres 20
^{7}00
^{2}00
^{3}00
Palaeogene intrusive igneous rocks
Post-Dalradian sedimentary and volcanic rocks within area described in Chapter 4
Late-Caledonian intrusive igneous rocks
green beds within the Southern Highland Group
Southern Highland Group
Pelitic rocks within the Southern Highland Group
Tarfside Nappe
Tayvallich Subgroup
Crinan Subgroup
Argyll Group
Dalradian Supergroup
fault
GCR site in Chapter 4
axial plane traces:
F4 monoform
F4 antiform
F1-F2 anticline
F1-F2 syncline
Loch Tay
Pitlochry
Flat Belt
Dunkeld
E
E′
F
F′
HB Steep Belt
Forfar
Aberdeen
Stonehaven
G
G′
^{8}00
^{4}00
1
2
3
4
5
6
7
8
9
10
11

Figure 4.2



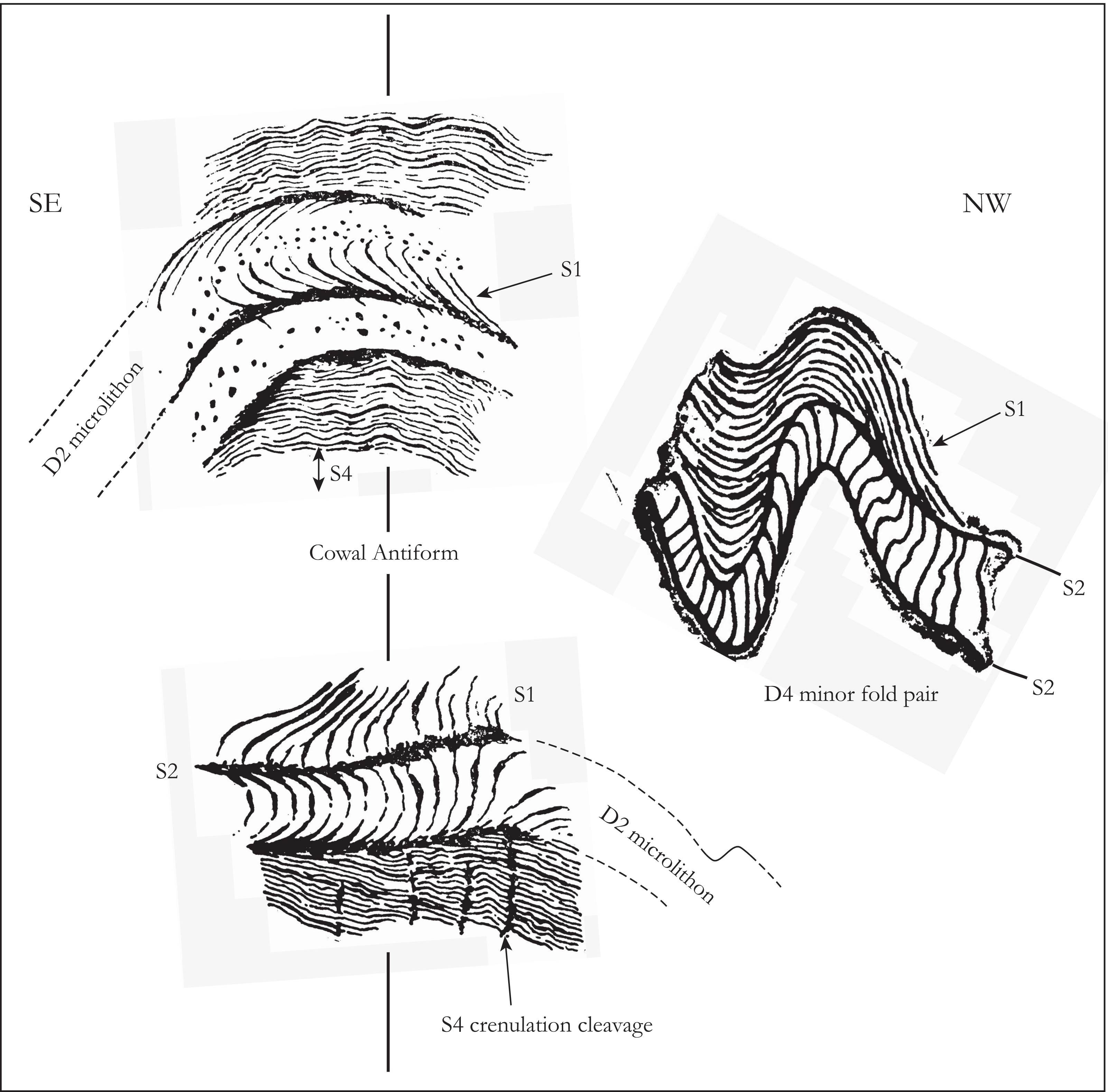
SW
NE
(a)
(b)
Cowal peninsula to Loch Lomond
A'-A, B'-B
(c)
Aberfoyle
C'-C
(d)
Pitlochry to Dunkeld
E'-E
(e)
Glen Shee
F'-F
(f)
Glen Clova
(g)
Glen Esk (Tarfside Nappe) to Stonehaven
G'-G
North-west of the Aberfoyle Anticline
Beinn Bheula Schist Fm
Green Beds
Glen Sluan Schist Fm
Loch Tay Limestone Fm
Ben Ledi Grit Fm
Creag Innich Sandstone Fm
Loch Katrine Volcaniclastic Fm
Ardnandave Sandstone Fm
Loch Tay Limestone Fm
Dunkeld Grit Fm
Birnam Slate and Grit Fm
Pitlochry Schist Fm with green beds
Loch Tay Limestone Fm
Cairn Gibbs Psammite Fm with green beds
Green Beds
Mount Blair Psammite and Semipelite Fm
Loch Tay Limestone Fm
Rottal Schist Fm with green beds
Longshank Gneiss Fm
Dounalt/Water of Tanar Limestone Fm
Glen Lethnot Grit Fm
Glen Effock Schist Fm
Tarfside Psammite Fm
GCR sites
2 3 4 5 7 8 9 10 11
Loch Tay Fault
Callander
D'-D
Aberfoyle Anticline (* formations unique to SE limb)
Arran
North Sannox Grits Fm
Loch Ranza Slate Fm
St Ninian Fm
*Toward Quay Grit Mbr
*Bullrock Greywacke Mbr
Dunoon Phyllite Fm (=Luss Slates)
*Bofrishlie Slate Fm
*Loch Ard Grit Fm
Ben Ledi Grit Fm with rare green beds
Creag Innich Sandstone Fm
Aberfoyle Slate Fm
*Keltie Water Grit Fm, including Keltie and Leny limestone and slate members
Ben Ledi Grit Fm, including prominent pelites/semipelites
GCR sites
1 2 5 6
psammites/metagreywackes
pelites/semipelites
metalimestones
volcaniclastic 'green beds'

Figure 4.4



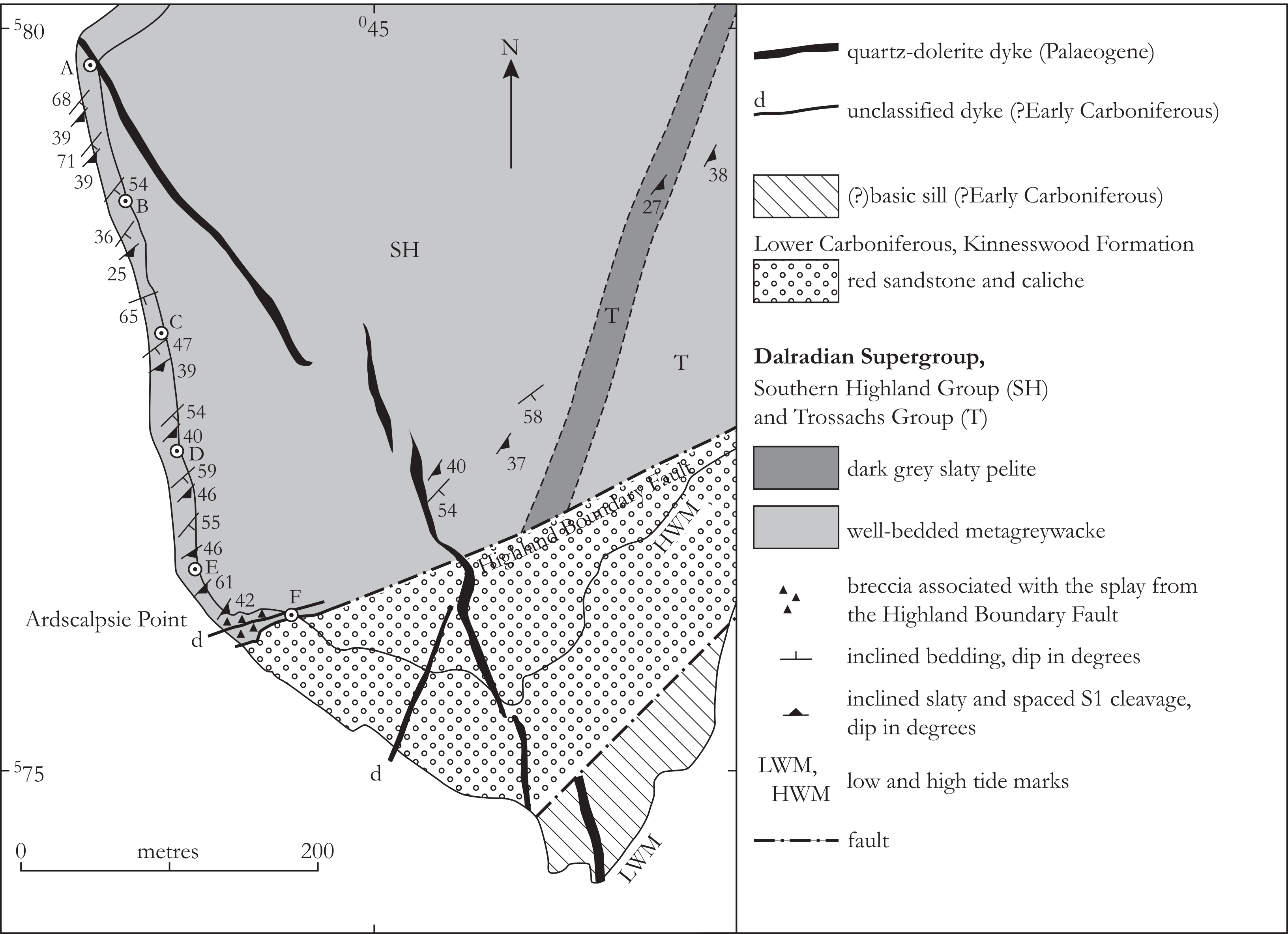
Cowal Antiform
SE
NW
Tay Nappe
Highland
Boundary
Fault
A′
A
Isle of Bute
Highland Border
Downbend
Aberfoyle Anticline
'Tay Nappe'
Ben Ledi Antiform
Ben Vane Synform
B′
B
Loch Lomond
S t e e p B e l t
Flat Belt
Aberfoyle
C′
C
Loch Tay Fault
D′
D
Callander
Highland Boundary Fault
Capel Hill Syncline
Mount Blair Anticline
E′
E
Birnam
?
0
kilometres
5
F′
F
Glen Shee
unconformity
G′
G
Stonehaven

Figure 4.5



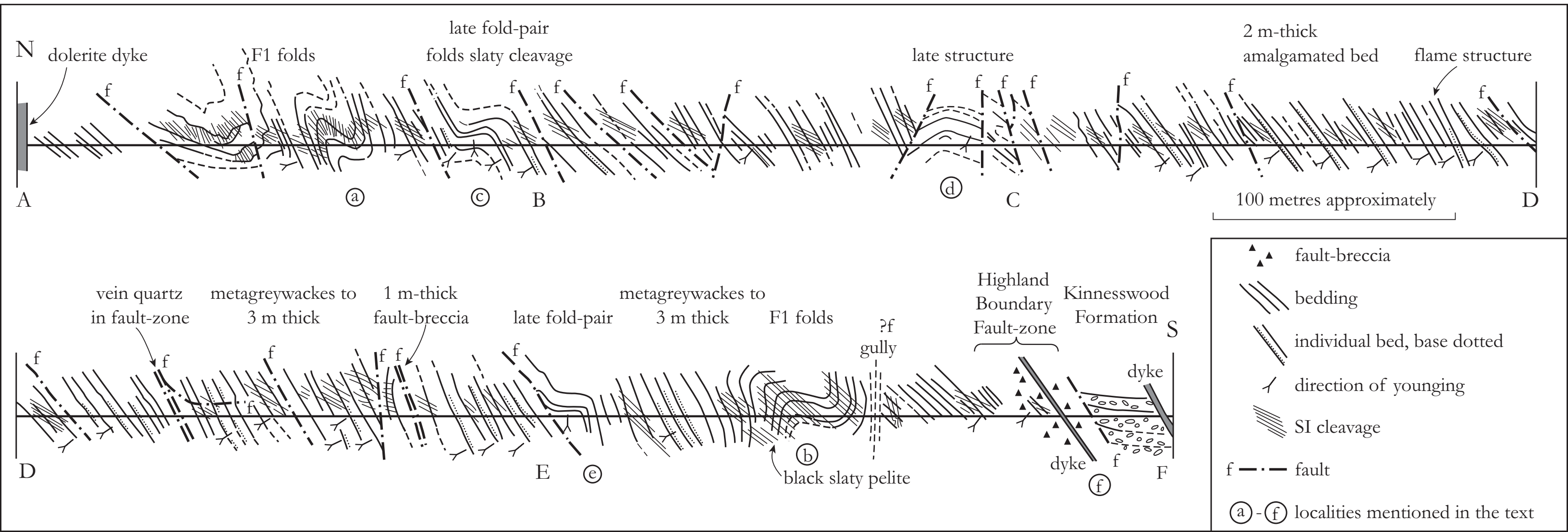
SE
NW
S1
D2 microlithon
S4
Cowal Antiform
S1
S2
S2
D4 minor fold pair
S1
S2
D2 microlithon
S4 crenulation cleavage

Figure 4.6



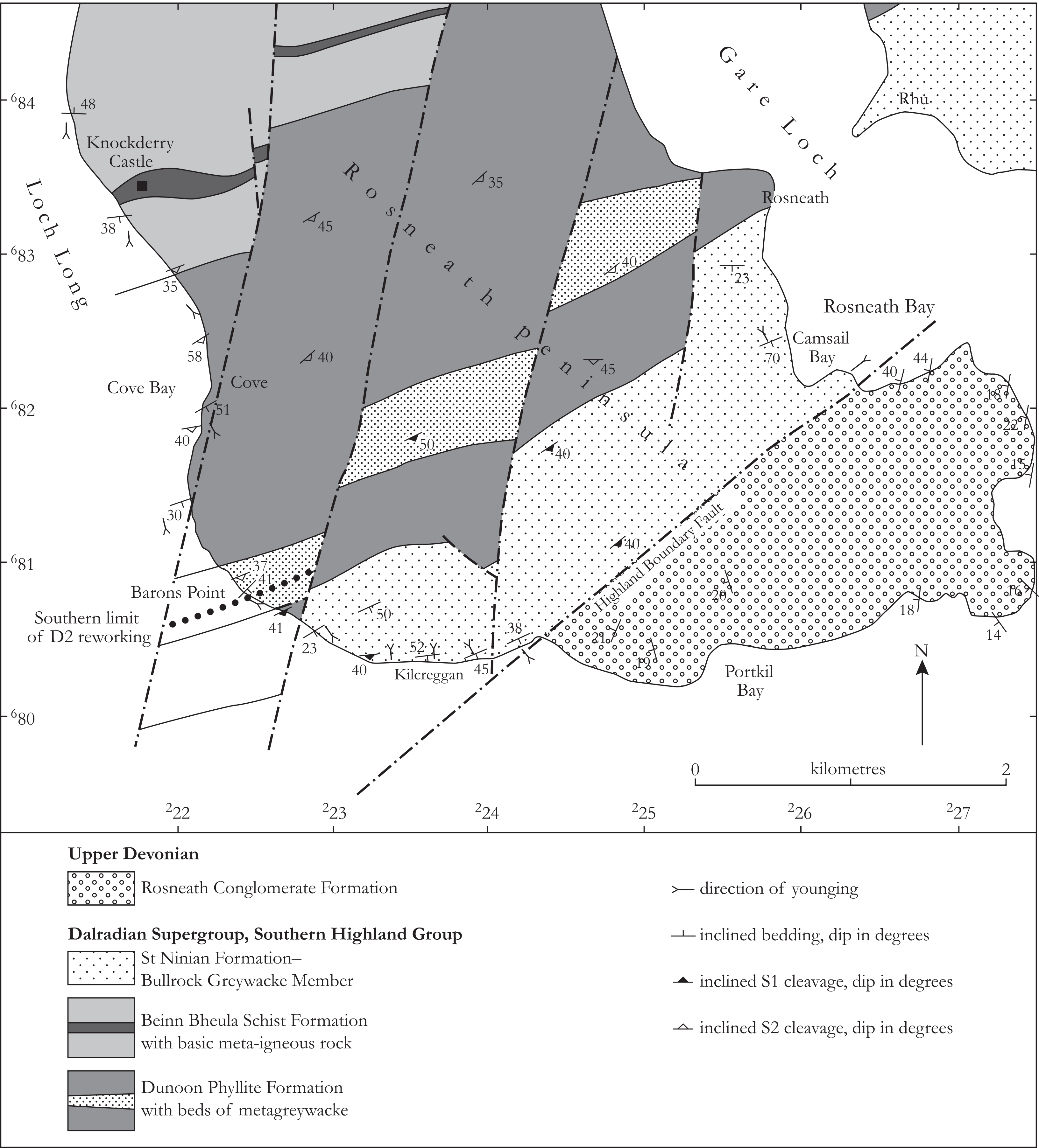
580
045
575
N
A
B
C
D
E
F
68
39
71
39
54
36
25
65
47
39
54
40
59
46
55
46
61
42
40
54
58
37
27
38
SH
T
T
Ardscalpsie Point
d
d
Highland Boundary Fault
HWM
LWM
0
metres
200
quartz-dolerite dyke (Palaeogene)
d
unclassified dyke (?Early Carboniferous)
(?)basic sill (?Early Carboniferous)
Lower Carboniferous, Kinnesswood Formation
red sandstone and caliche
Dalradian Supergroup,
Southern Highland Group (SH)
and Trossachs Group (T)
dark grey slaty pelite
well-bedded metagreywacke
breccia associated with the splay from the Highland Boundary Fault
inclined bedding, dip in degrees
inclined slaty and spaced S1 cleavage, dip in degrees
LWM, HWM
low and high tide marks
fault

Figure 4.8



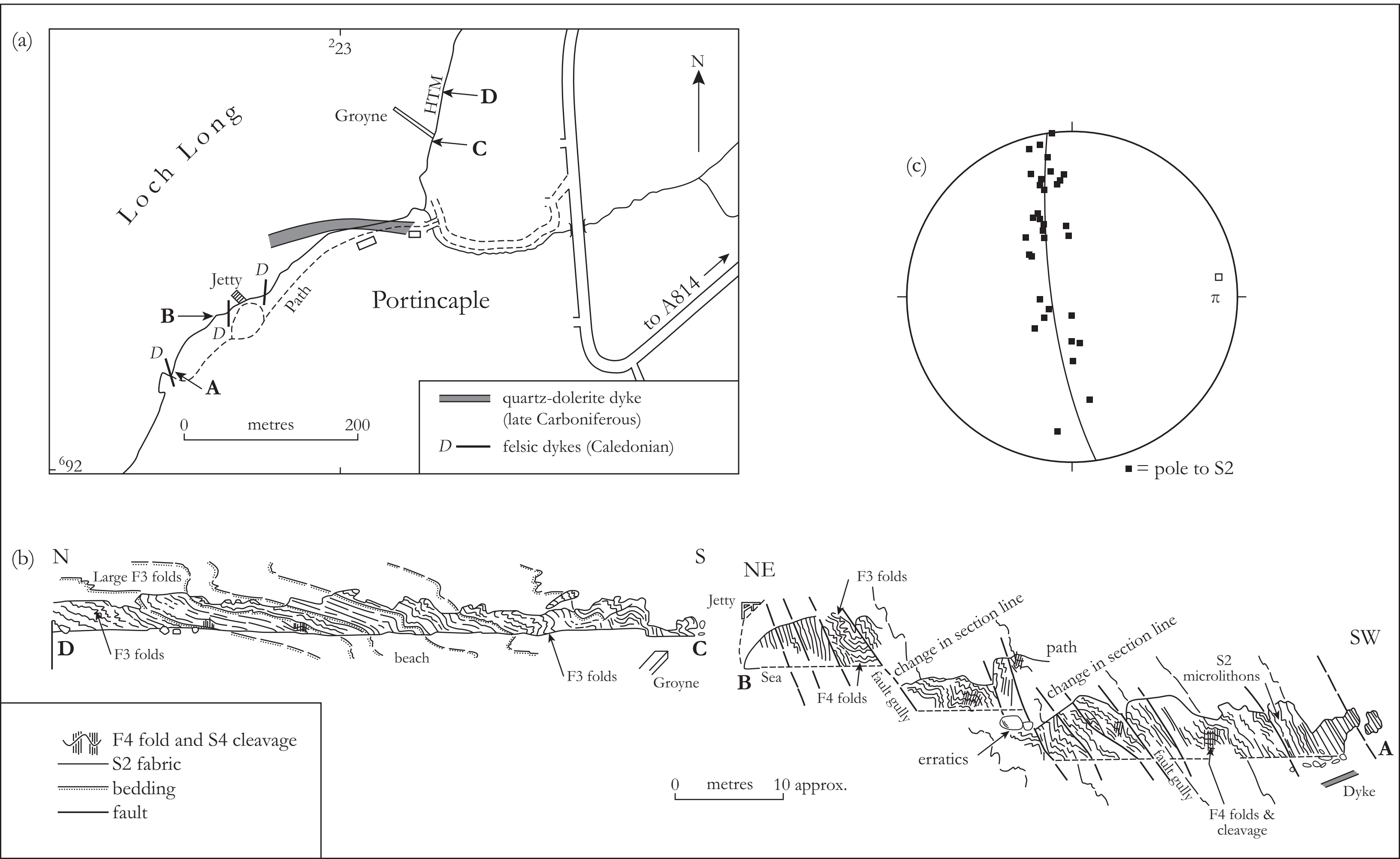
N
dolerite dyke
F1 folds
late fold-pair
folds slaty cleavage
late structure
2 m-thick
amalgamated bed
flame structure
f
A
a
c
B
d
C
100 metres approximately
D
vein quartz
in fault-zone
metagreywackes to
3 m thick
1 m-thick
fault-breccia
late fold-pair
metagreywackes to
3 m thick
F1 folds
?f
gully
Highland
Boundary
Fault-zone
Kinnesswood
Formation
S
dyke
D
E
e
b
black slaty pelite
dyke
f
F
fault-breccia
bedding
individual bed, base dotted
direction of younging
SI cleavage
fault
a - f localities mentioned in the text

Figure 4.9



Gare Loch
Rhu
Loch Long
Knockderry Castle
Rosneath peninsula
Rosneath
Rosneath Bay
Camsail Bay
Cove Bay
Cove
Barons Point
Southern limit of D2 reworking
Kilcreggan
Highland Boundary Fault
Portkil Bay
N
0 kilometres 2
684
683
682
681
680
222
223
224
225
226
227
Upper Devonian
Rosneath Conglomerate Formation
Dalradian Supergroup, Southern Highland Group
St Ninian Formation–Bullrock Greywacke Member
Beinn Bheula Schist Formation with basic meta-igneous rock
Dunoon Phyllite Formation with beds of metagreywacke
direction of younging
inclined bedding, dip in degrees
inclined S1 cleavage, dip in degrees
inclined S2 cleavage, dip in degrees

Figure 4.11



(a)
²23
Loch Long
N
HTM
D
Groyne
C
Jetty
D
B
D
Path
Portincaple
D
A
to A814
0 metres 200
quartz-dolerite dyke (late Carboniferous)
D felsic dykes (Caledonian)
⁶92
(c)
π
■ = pole to S2
(b) N
S
Large F3 folds
D
F3 folds
beach
F3 folds
C
Groyne
NE
Jetty
F3 folds
change in section line
path
change in section line
SW
S2 microlithons
B
Sea
F4 folds
fault gully
erratics
fault gully
F4 folds & cleavage
A
Dyke
0 metres 10 approx.
F4 fold and S4 cleavage
S2 fabric
bedding
fault

Figure 4.12b

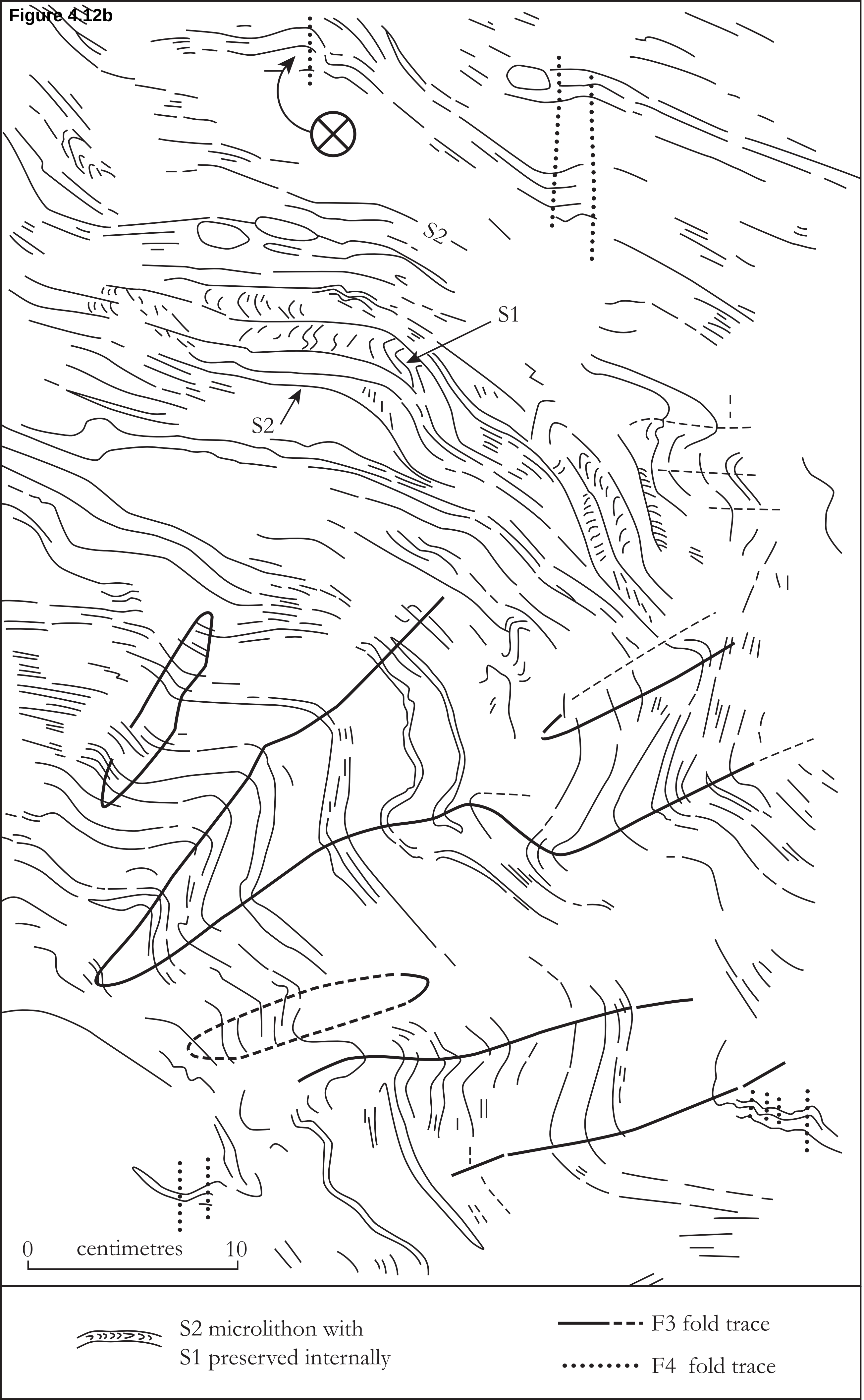

S2
S1
S2
0 centimetres 10
S2 microlithon with
S1 preserved internally
F3 fold trace
F4 fold trace

Figure 4.13

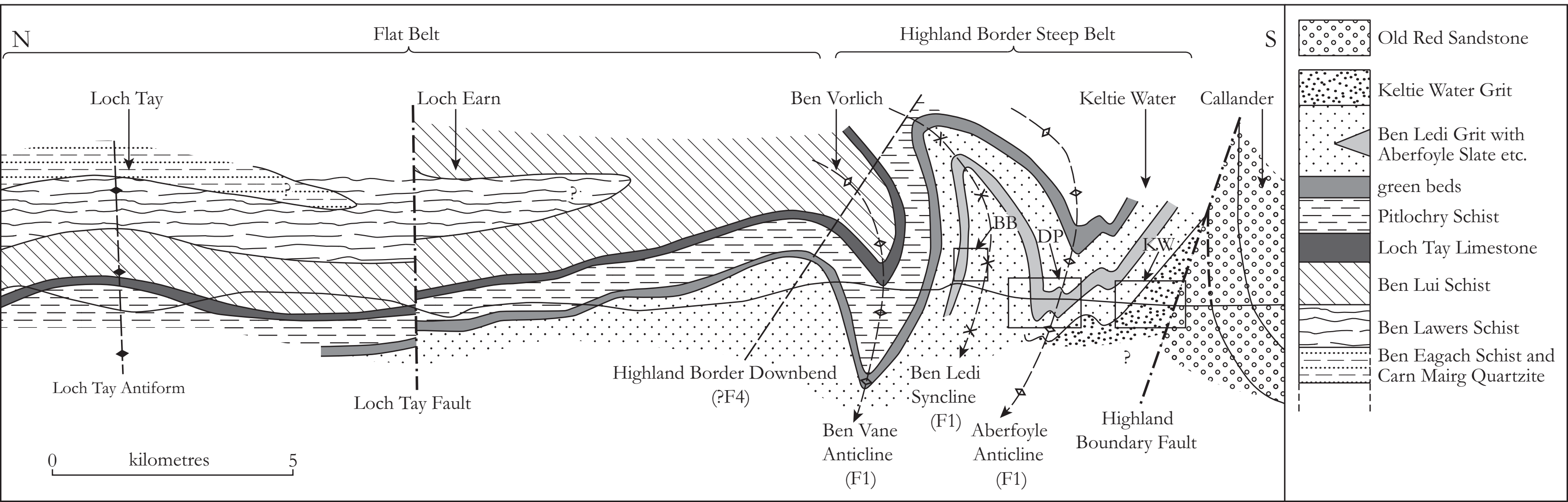
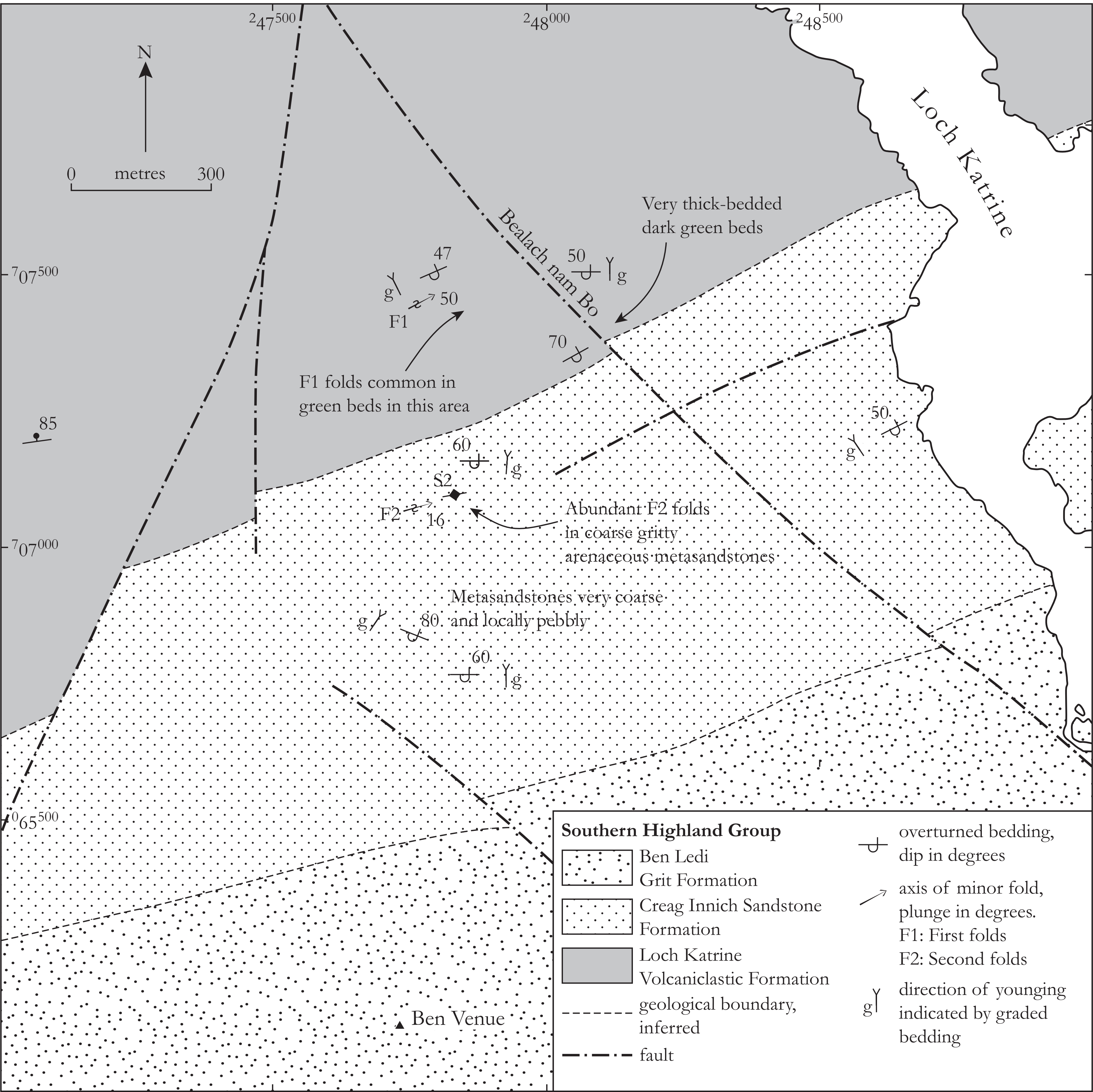
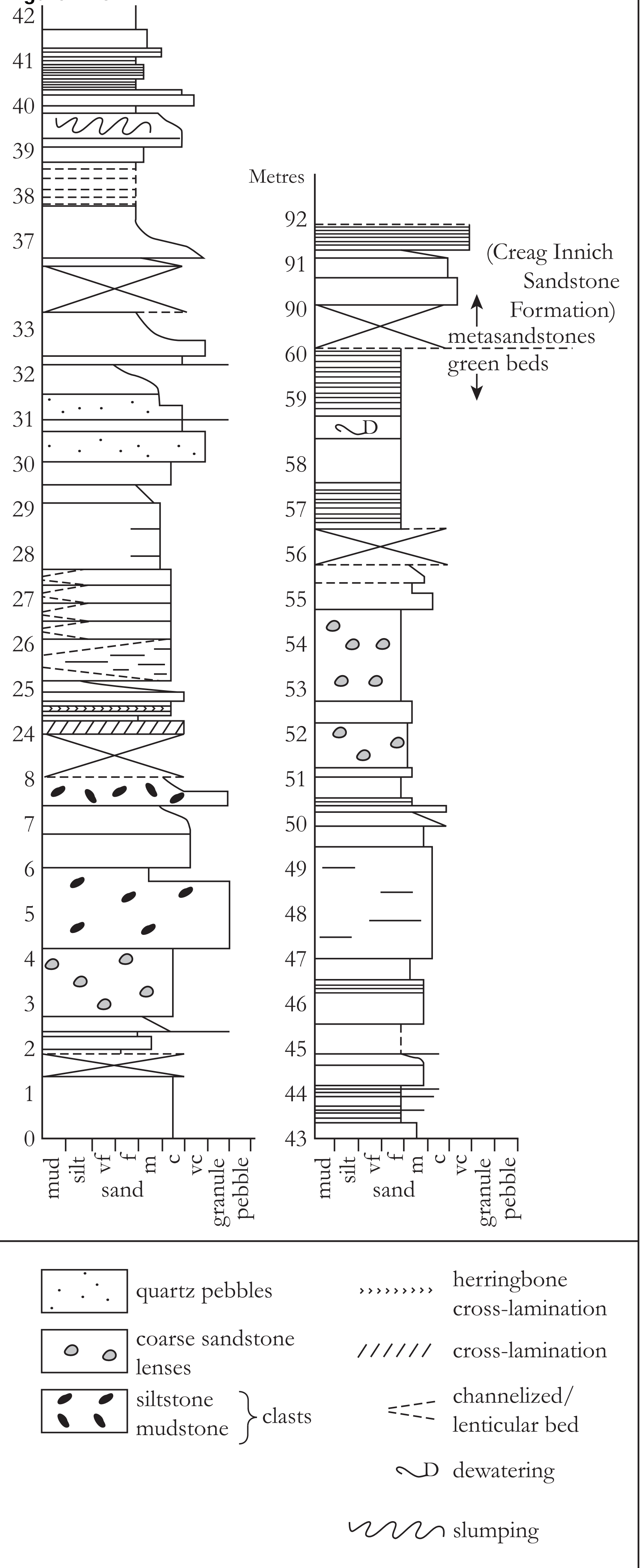

N
Flat Belt
Highland Border Steep Belt
S
Loch Tay
Loch Earn
Ben Vorlich
Keltie Water
Callander
BB
DP
KW
Loch Tay Antiform
Loch Tay Fault
Highland Border Downbend
(?F4)
Ben Vane
Anticline
(F1)
Ben Ledi
Syncline
(F1)
Aberfoyle
Anticline
(F1)
Highland
Boundary Fault
0
kilometres
5
Old Red Sandstone
Keltie Water Grit
Ben Ledi Grit with
Aberfoyle Slate etc.
green beds
Pitlochry Schist
Loch Tay Limestone
Ben Lui Schist
Ben Lawers Schist
Ben Eagach Schist and
Carn Mairg Quartzite

Figure 4.14



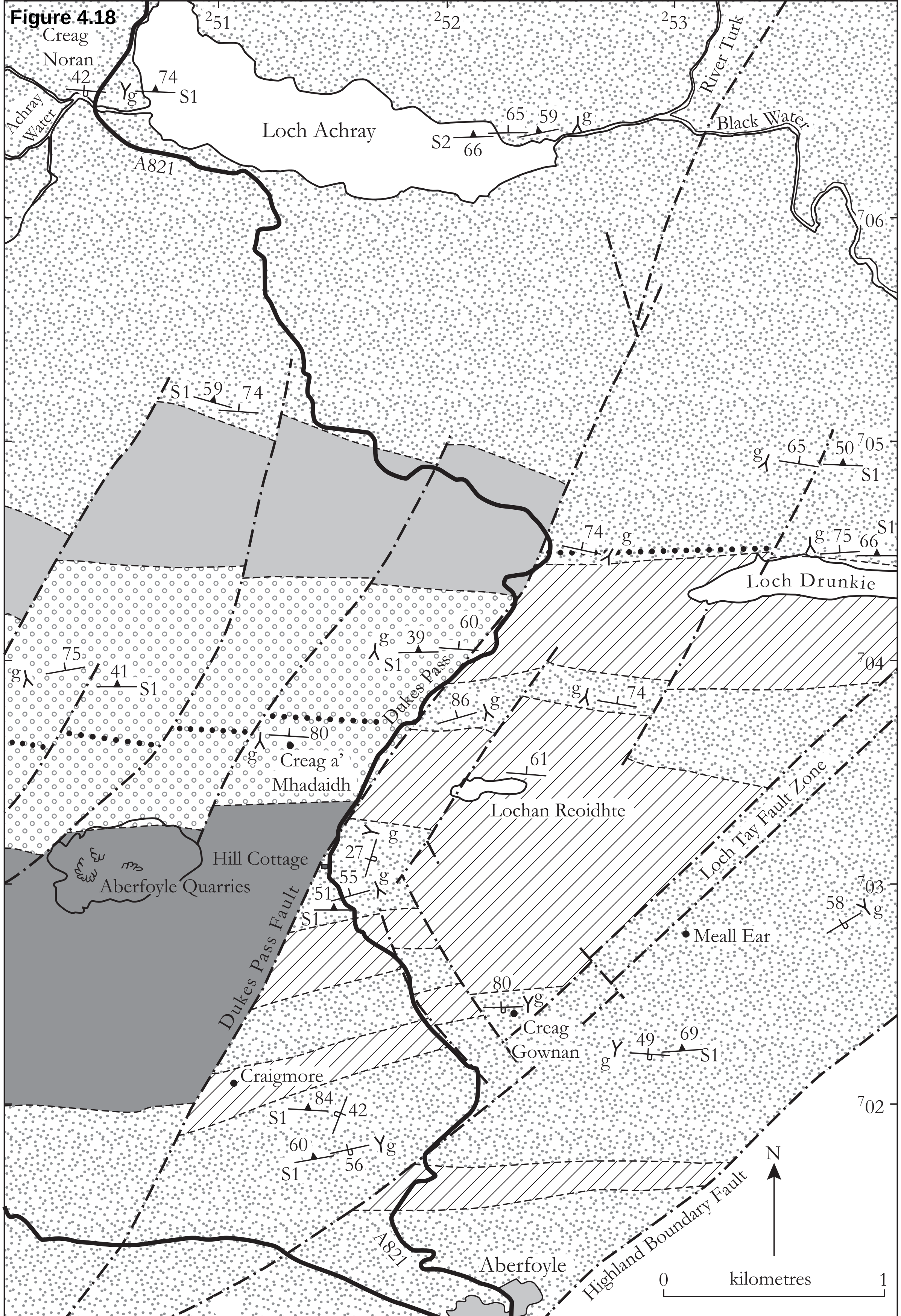
N
0 metres 300
²47⁵⁰⁰
²48⁰⁰⁰
²48⁵⁰⁰
⁷07⁵⁰⁰
⁷07⁰⁰⁰
⁷065⁵⁰⁰
Loch Katrine
Bealach nam Bo
Very thick-bedded dark green beds
F1 folds common in green beds in this area
Abundant F2 folds in coarse gritty arenaceous metasandstones
Metasandstones very coarse and locally pebbly
Ben Venue
S2
F1
F2
47
50
70
60
80
16
85
g
Southern Highland Group
Ben Ledi Grit Formation
Creag Innich Sandstone Formation
Loch Katrine Volcaniclastic Formation
geological boundary, inferred
fault
overturned bedding, dip in degrees
axis of minor fold, plunge in degrees.
F1: First folds
F2: Second folds
direction of younging indicated by graded bedding

Figure 4.15



Metres
(Creag Innich
Sandstone
Formation)
metasandstones
green beds
D
mud
silt
vf
f
m
c
vc
granule
pebble
sand
quartz pebbles
coarse sandstone
lenses
siltstone
mudstone
clasts
herringbone
cross-lamination
cross-lamination
channelized/
lenticular bed
dewatering
slumping

Figure 4.18



Southern Highland Group

- Ben Ledi Grit Formation
  - pelite and semipelite
- Ledard Burn Member
- Creag Innich Sandstone Formation
- Aberfoyle Slate Formation

Symbols:

- inclined bedding, dip in degrees
- inclined overturned bedding, dip in degrees
- direction of younging; g: graded bedding
- S1 inclined first cleavage, dip in degrees
- approximate southern limit of D2 deformation in metasandstones
- road
- geological boundary, inferred
- fault

Figure 4.4 key

Dalradian Supergroup: key units in approximate stratigraphical order, formed by combining the different sequences found on the limbs of the Tay Nappe (see Fig 4.2 for details).

- Keltie Water Grit Formation (with Leny Limestone, L)
- Birnam Slate and Grit Formation
- Aberfoyle Slate Formation (=Luss Slates and Dunoon Phyllites)
- Beinn Bheula Schist Formation, St Ninian Formation, Ben Ledi Grit Formation etc.
- green beds
- Glen Sluan Schist Formation etc.
- Loch Tay Limestone Formation
- fault-bounded panels of Lower Old Red Sandstone strata north-west of the Highland Boundary Fault.

- Lower Devonian, Upper Devonian and Lower Carboniferous (ORS facies)
- Highland Border Ophiolite
- younging direction
- generalized younging direction
- facing direction of early (F1) major fold
- form line (generally bedding)
- axial plane trace of early fold
- axial plane trace of later fold
- correlation tie-line
- minor fault

Figure 4.20

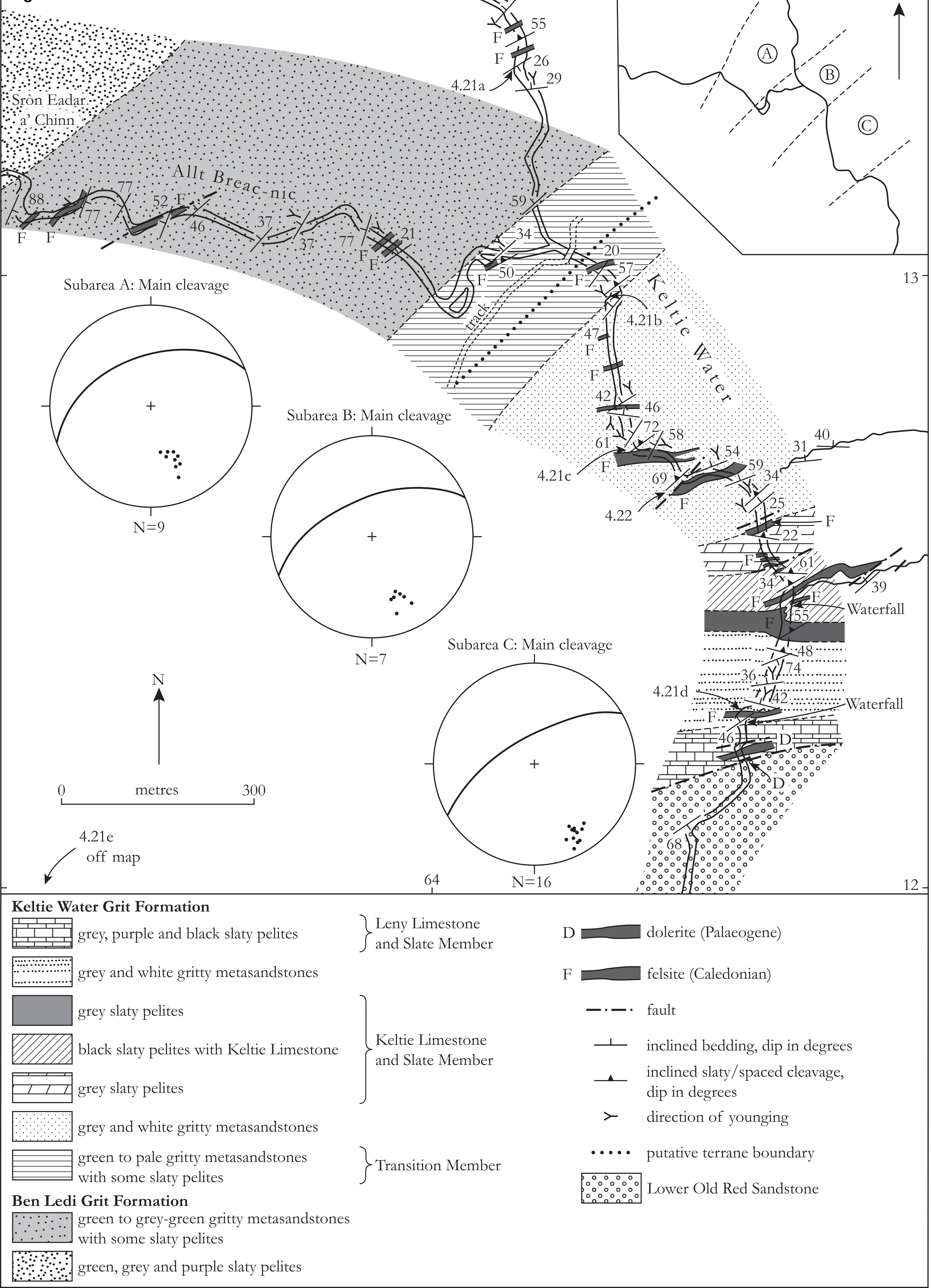
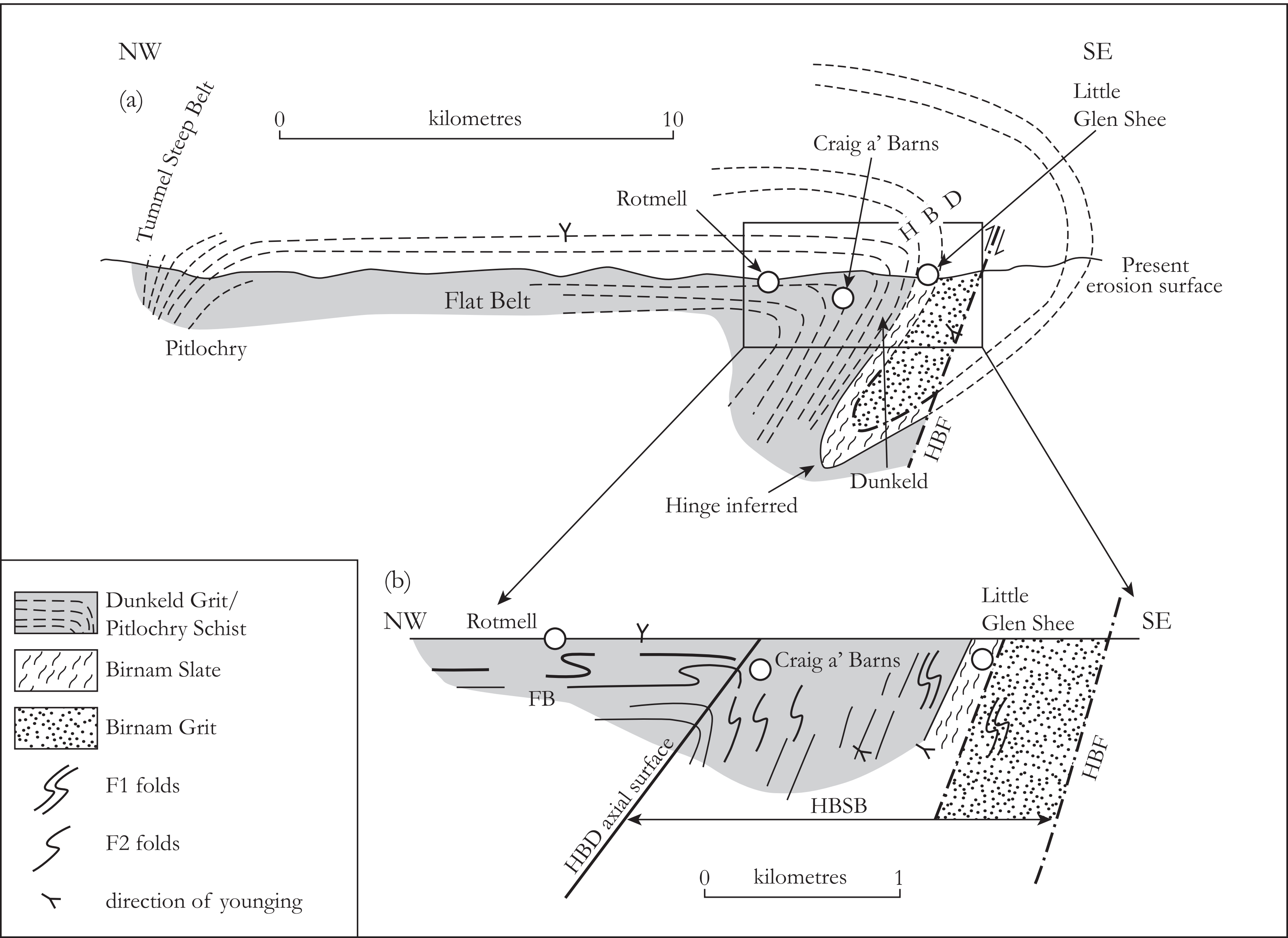

Structural sub-areas
A
B
C
N
Sròn Eadar a' Chinn
Allt Breac-nic
Keltie Water
track
4.21a
4.21b
4.21c
4.22
4.21d
4.21e off map
Waterfall
Waterfall
Subarea A: Main cleavage
N=9
Subarea B: Main cleavage
N=7
Subarea C: Main cleavage
N=16
0 metres 300
64
13
12
Keltie Water Grit Formation
grey, purple and black slaty pelites
grey and white gritty metasandstones
Leny Limestone and Slate Member
grey slaty pelites
black slaty pelites with Keltie Limestone
grey slaty pelites
Keltie Limestone and Slate Member
grey and white gritty metasandstones
green to pale gritty metasandstones with some slaty pelites
Transition Member
Ben Ledi Grit Formation
green to grey-green gritty metasandstones with some slaty pelites
green, grey and purple slaty pelites
D dolerite (Palaeogene)
F felsite (Caledonian)
fault
inclined bedding, dip in degrees
inclined slaty/spaced cleavage, dip in degrees
direction of younging
putative terrane boundary
Lower Old Red Sandstone

Figure 4.23


Tummel Steep Belt
Pitlochry
N
0 kilometres 5
Flat Belt
River Tay
Deuchray Hill
Rotmell
Craig a' Barns
Dunkeld
River Braan
Little Glen Shee
HBSB (A) (B)
Highland Boundary Fault
55
50
45
40
35
30
90
95
00
05
Old Red Sandstone
Southern Highland Group with Birnam Slates
Tayvallich Limestone and Ben Lui Schist formations (undivided)
Easdale and Islay subgroups (undivided)
inclined S1 cleavage, dip in degrees
inclined S2 cleavage, dip in degrees
horizontal S2 cleavage
vertical S2 cleavage
inclined foliation or banding, dip in degrees
axis of F1 fold, plunge in degrees
L2 lineation, plunge in degrees (after Stringer 1957)
horizontal L2 lineation
garnet isograd
fault
SE limit of strong D2 overprint
Highland Border Downbend, axial surface trace
HBSB Highland Border Steep Belt
(A) (B) zones within the HBSB distinguished by Rose and Harris (2000)

Figure 4.24



NW
SE
(a)
Tummel Steep Belt
0
kilometres
10
Little
Glen Shee
Craig a' Barns
Rotmell
H B D
Present
erosion surface
Flat Belt
Pitlochry
HBF
Dunkeld
Hinge inferred
Dunkeld Grit/
Pitlochry Schist
Birnam Slate
Birnam Grit
F1 folds
F2 folds
direction of younging
(b)
NW
Rotmell
Little
Glen Shee
SE
Craig a' Barns
FB
HBD axial surface
HBSB
HBF
0
kilometres
1

Figure 4.25

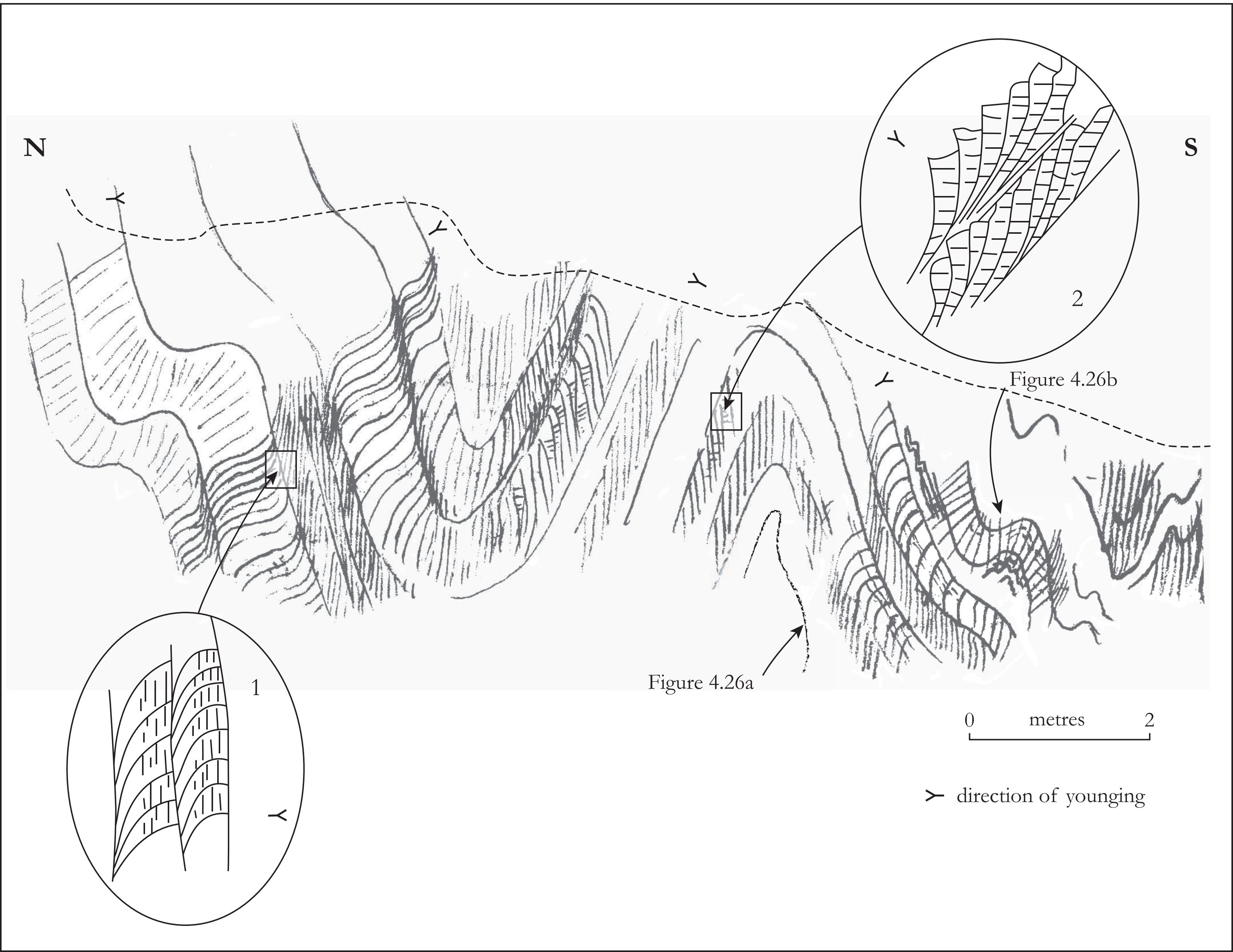
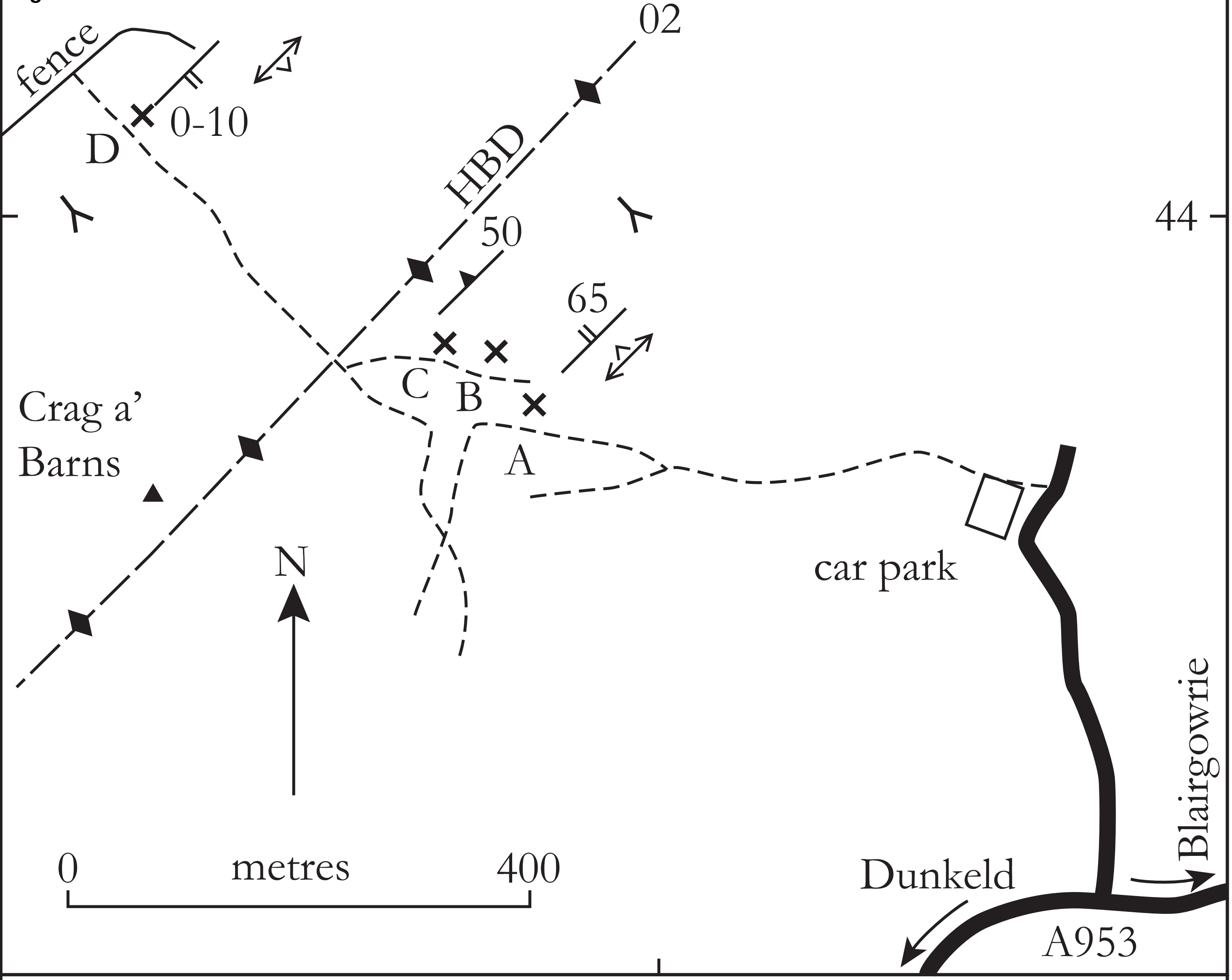

N
S
1
2
Figure 4.26b
Figure 4.26a
0 metres 2
direction of younging

Figure 4.27



inclined composite foliation of SØ, S1 and S2 on long limbs of F4 folds, generalized dip in degrees

inclined S4 crenulation cleavage at Highland Border Downbend hinge-zone, generalized dip in degrees

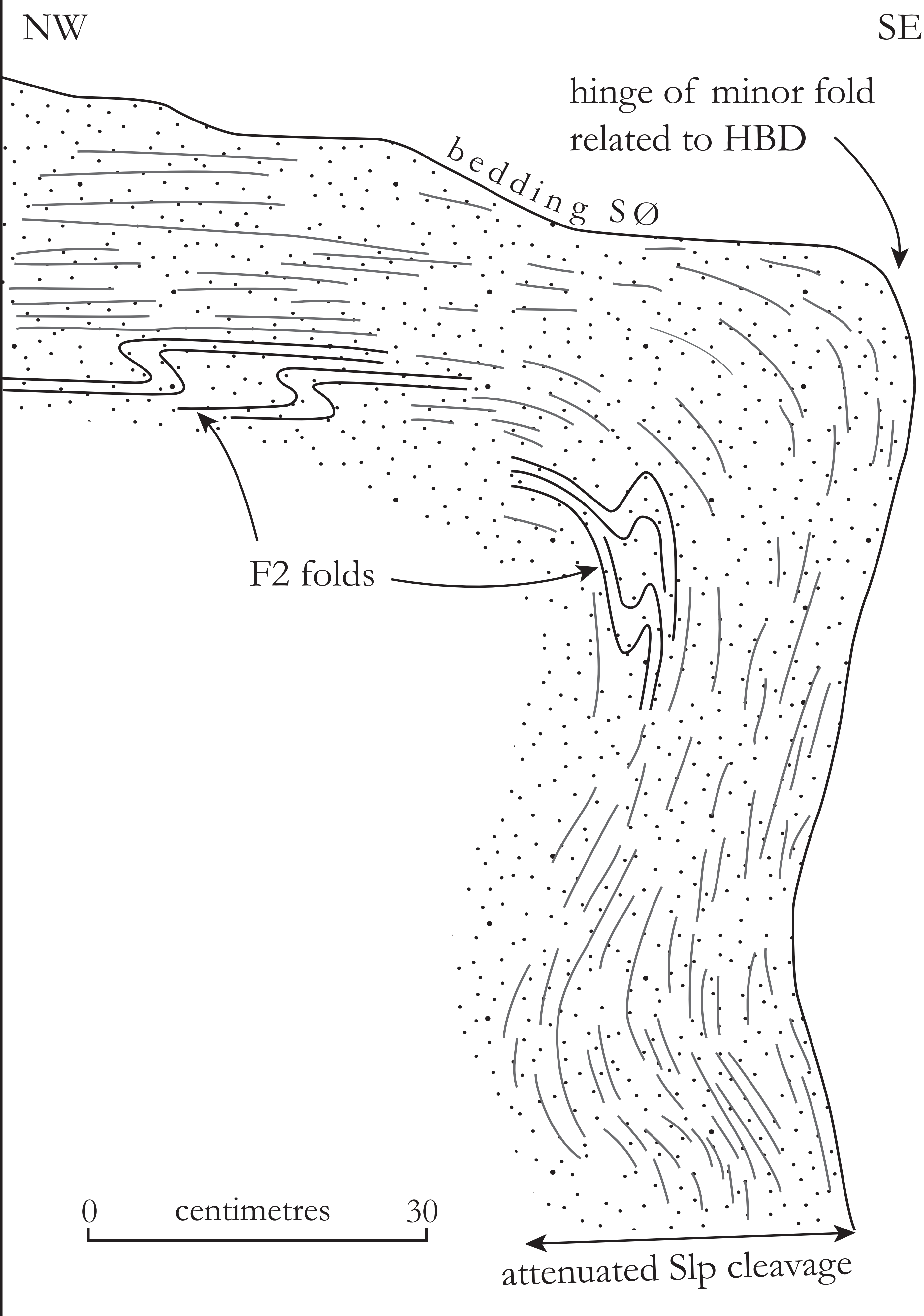
subhorizontal axis of F4 minor fold, showing direction of vergence

axial plane trace of major F4 antiform

general direction of younging, inferred from regional structure

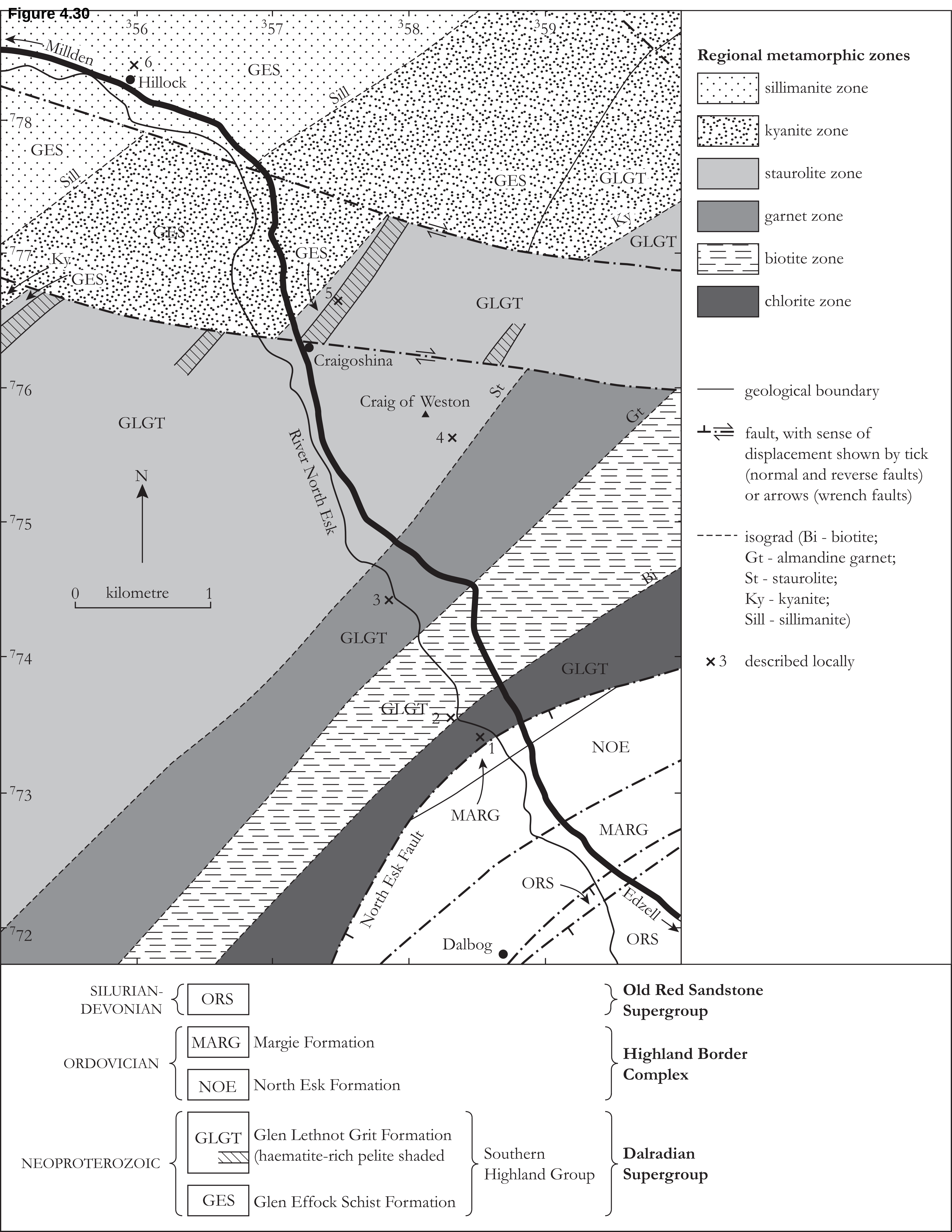
path

Figure 4.28a



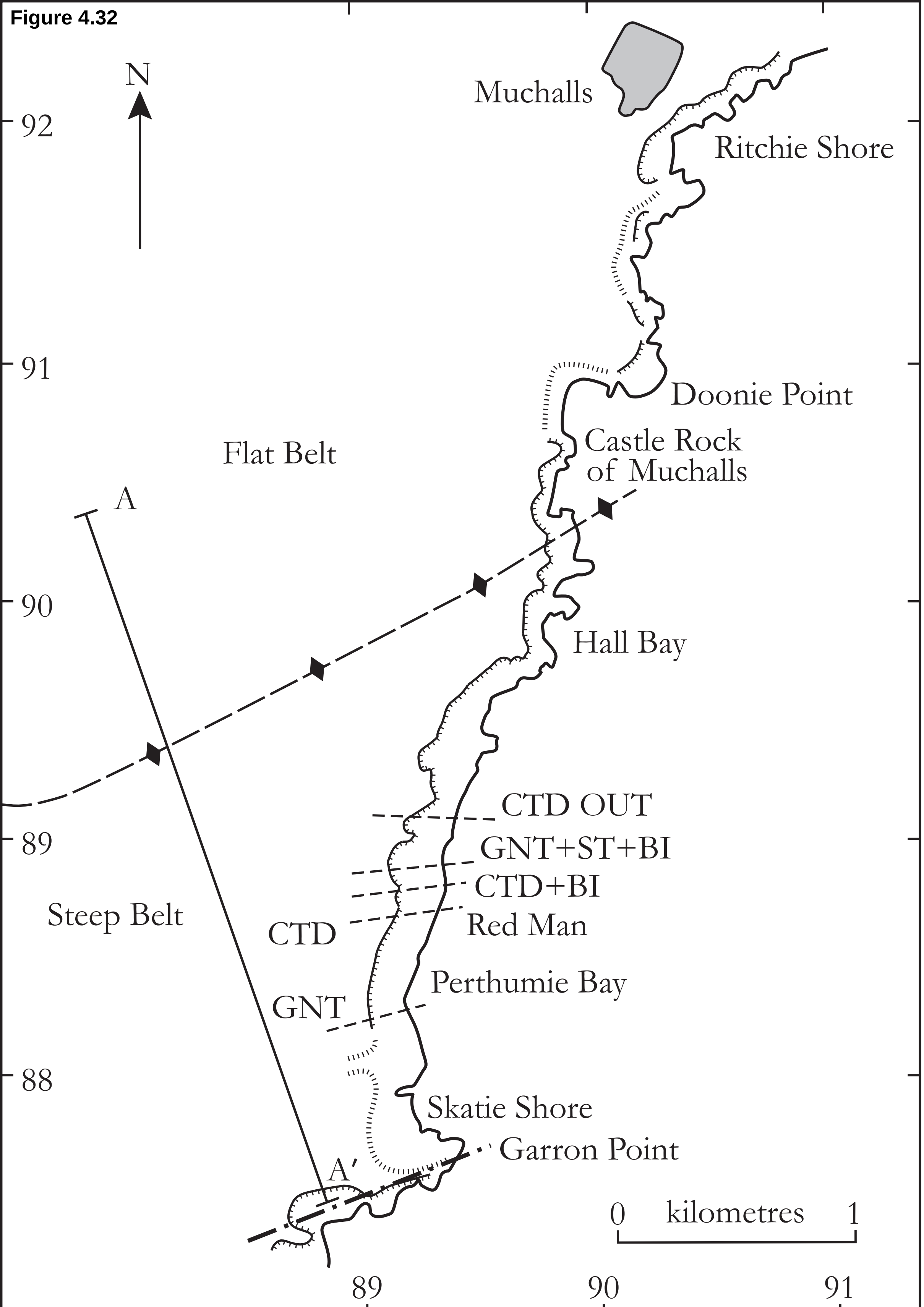
NW
SE
hinge of minor fold
related to HBD
bedding SØ
F2 folds
0
centimetres
30
attenuated Slp cleavage

Figure 4.30



356
357
358
359
778
777
776
775
774
773
772
Millden
Hillock
Craigoshina
Craig of Weston
Dalbog
Edzell
River North Esk
North Esk Fault
GES
GLGT
NOE
MARG
ORS
Sill
Ky
St
Gt
Bi
N
0 kilometre 1
1
2
3
4
5
6
Regional metamorphic zones
sillimanite zone
kyanite zone
staurolite zone
garnet zone
biotite zone
chlorite zone
geological boundary
fault, with sense of displacement shown by tick (normal and reverse faults) or arrows (wrench faults)
isograd (Bi - biotite; Gt - almandine garnet; St - staurolite; Ky - kyanite; Sill - sillimanite)
3 described locally
SILURIAN-DEVONIAN
ORS
Old Red Sandstone Supergroup
ORDOVICIAN
MARG Margie Formation
NOE North Esk Formation
Highland Border Complex
NEOPROTEROZOIC
GLGT Glen Lethnot Grit Formation (haematite-rich pelite shaded
GES Glen Effock Schist Formation
Southern Highland Group
Dalradian Supergroup

Figure 4.32



Highland Boundary Fault

axial plane trace of Highland Border Downbend (F4)

metamorphic mineral isograds, GNT: garnet, CTD: chloritoid, BI: biotite, ST: staurolite

approximate line of section in figure 4.33

Figure 4.33

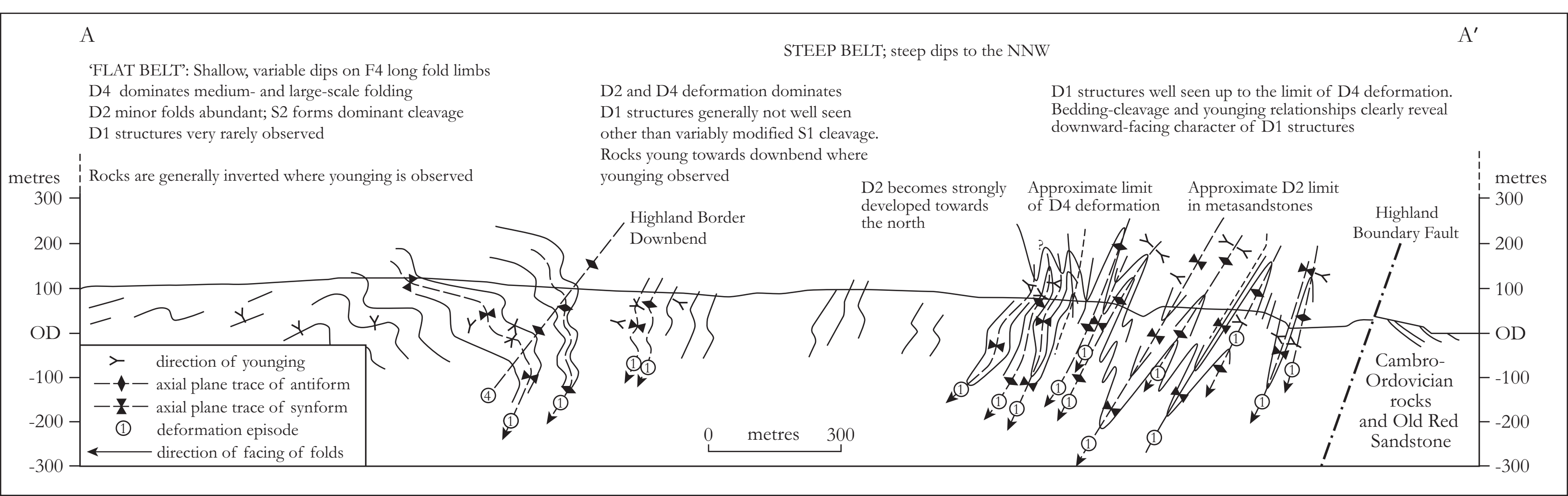

A
A′
STEEP BELT; steep dips to the NNW
'FLAT BELT': Shallow, variable dips on F4 long fold limbs
D4 dominates medium- and large-scale folding
D2 minor folds abundant; S2 forms dominant cleavage
D1 structures very rarely observed
Rocks are generally inverted where younging is observed
D2 and D4 deformation dominates
D1 structures generally not well seen
other than variably modified S1 cleavage.
Rocks young towards downbend where
younging observed
D1 structures well seen up to the limit of D4 deformation.
Bedding-cleavage and younging relationships clearly reveal
downward-facing character of D1 structures
metres
300
200
100
OD
-100
-200
-300
Highland Border
Downbend
D2 becomes strongly
developed towards
the north
Approximate limit
of D4 deformation
Approximate D2 limit
in metasandstones
Highland
Boundary Fault
Cambro-
Ordovician
rocks
and Old Red
Sandstone
direction of younging
axial plane trace of antiform
axial plane trace of synform
deformation episode
direction of facing of folds
0 metres 300

Figure 4.3 colour

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Figure 4.7 colour
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Figure 4.10 colour
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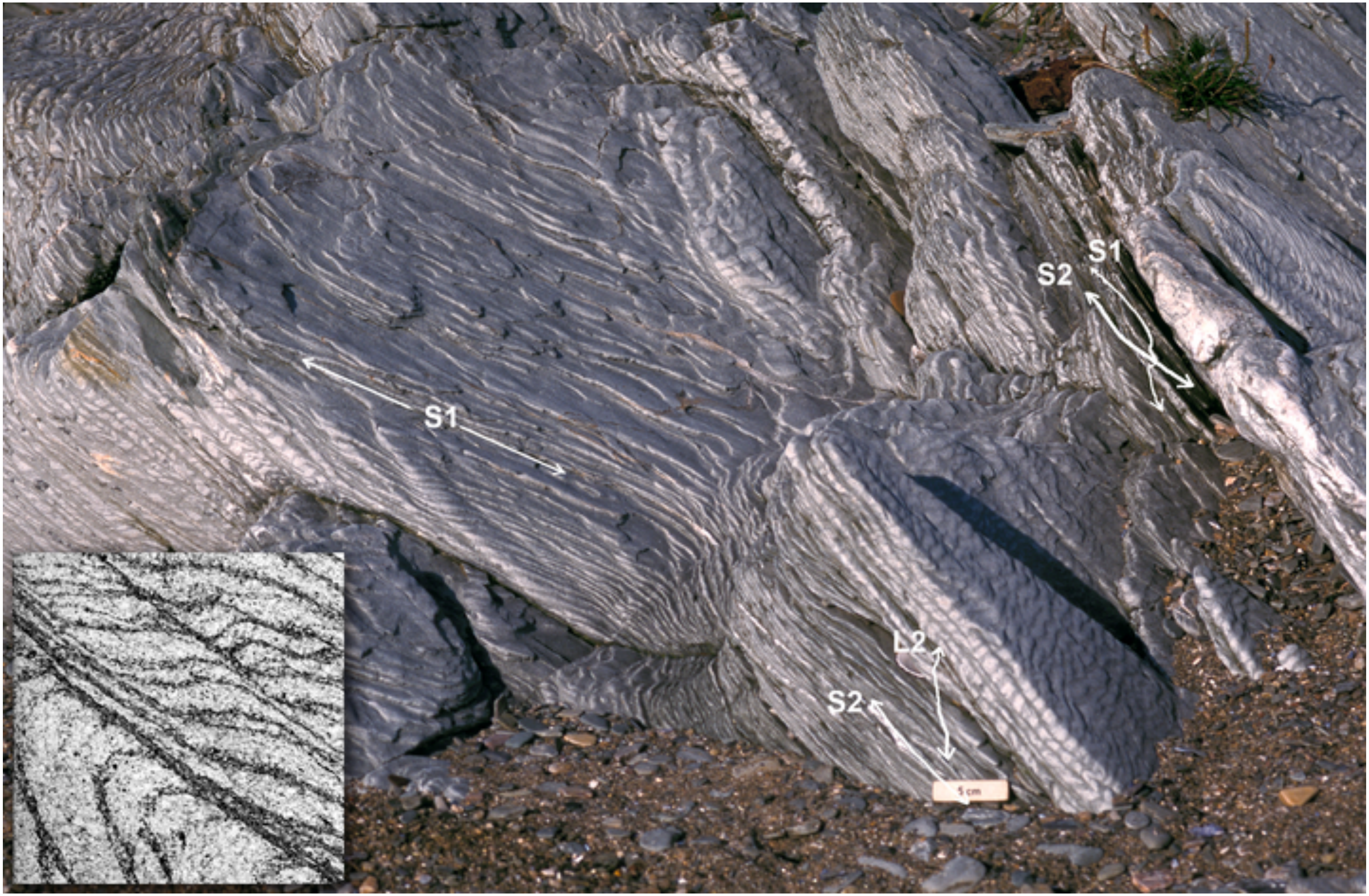

Figure 4.12a + c

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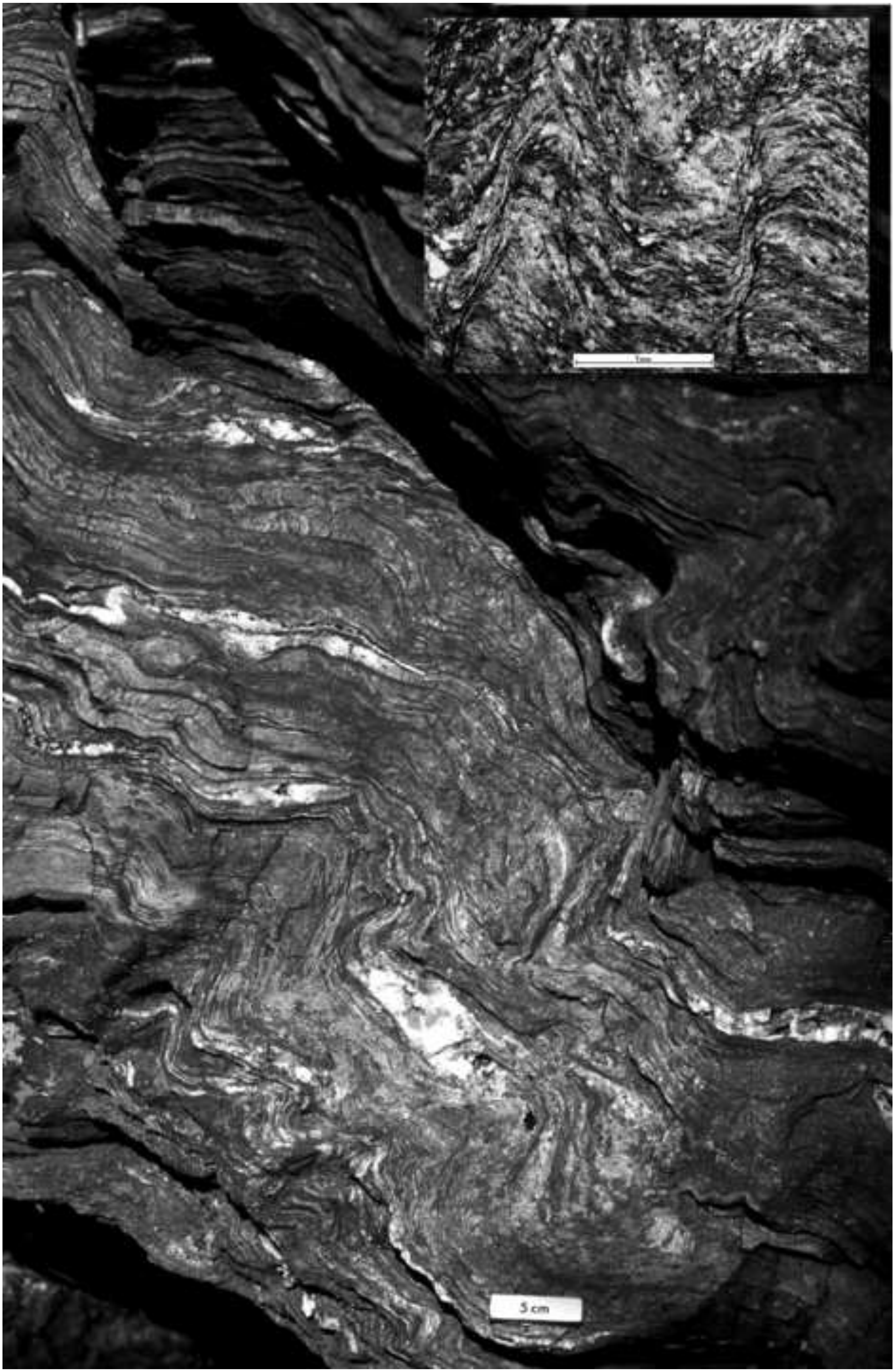

Figure 4.16 colour
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Figure 4.17 colour

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Figure 4.19 colour
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Figure 4.21a
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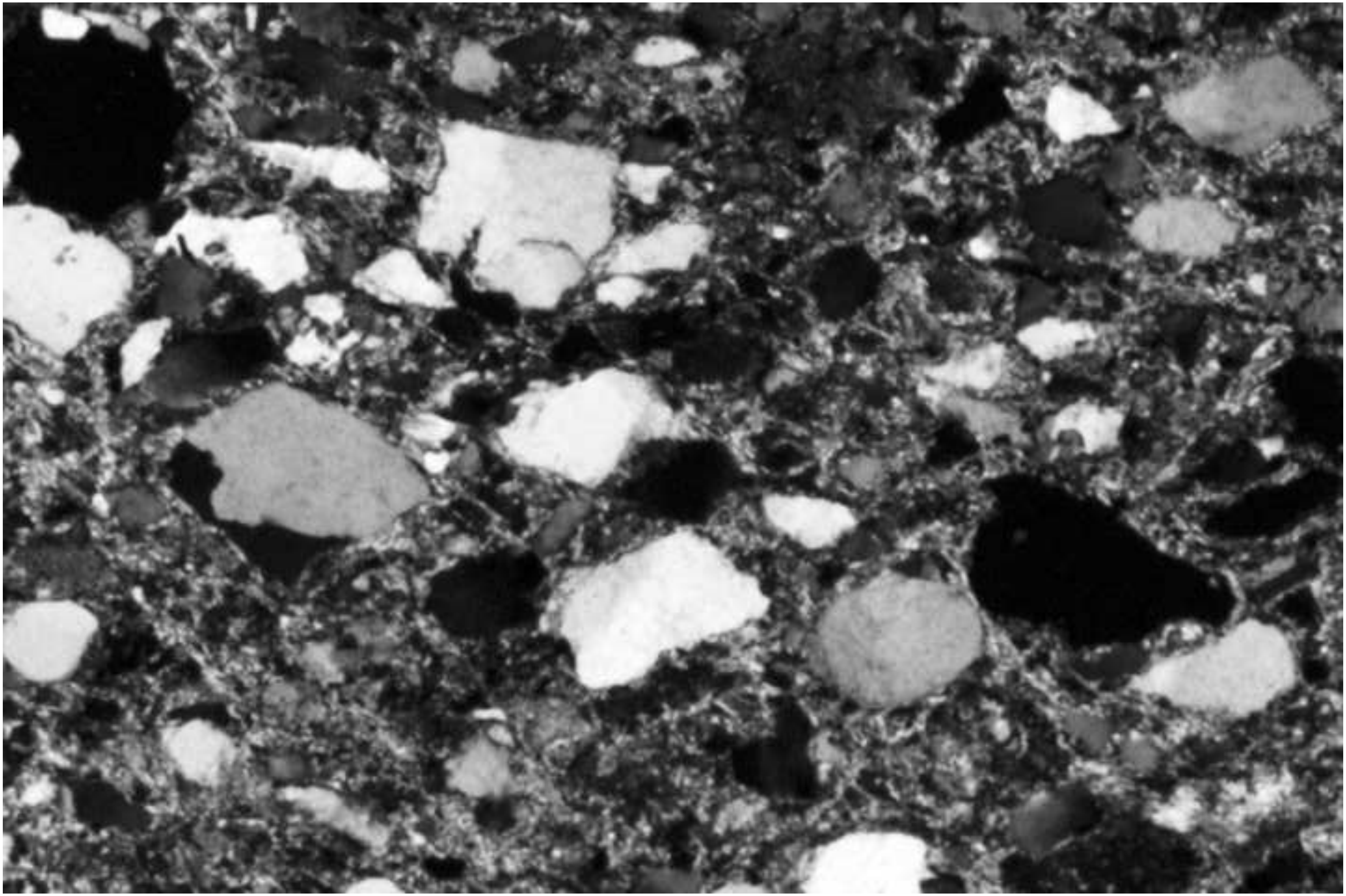

Figure 4.21b
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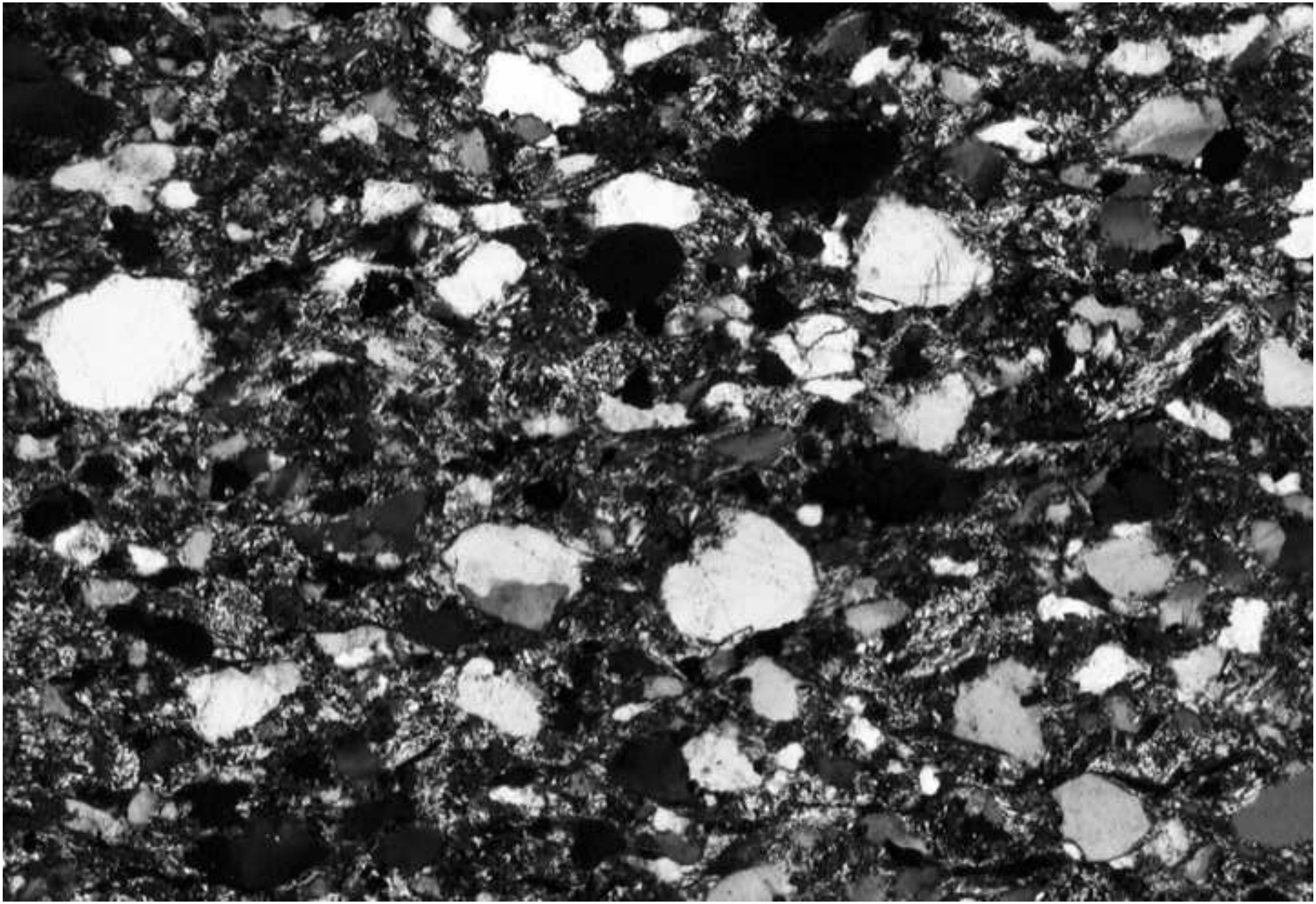

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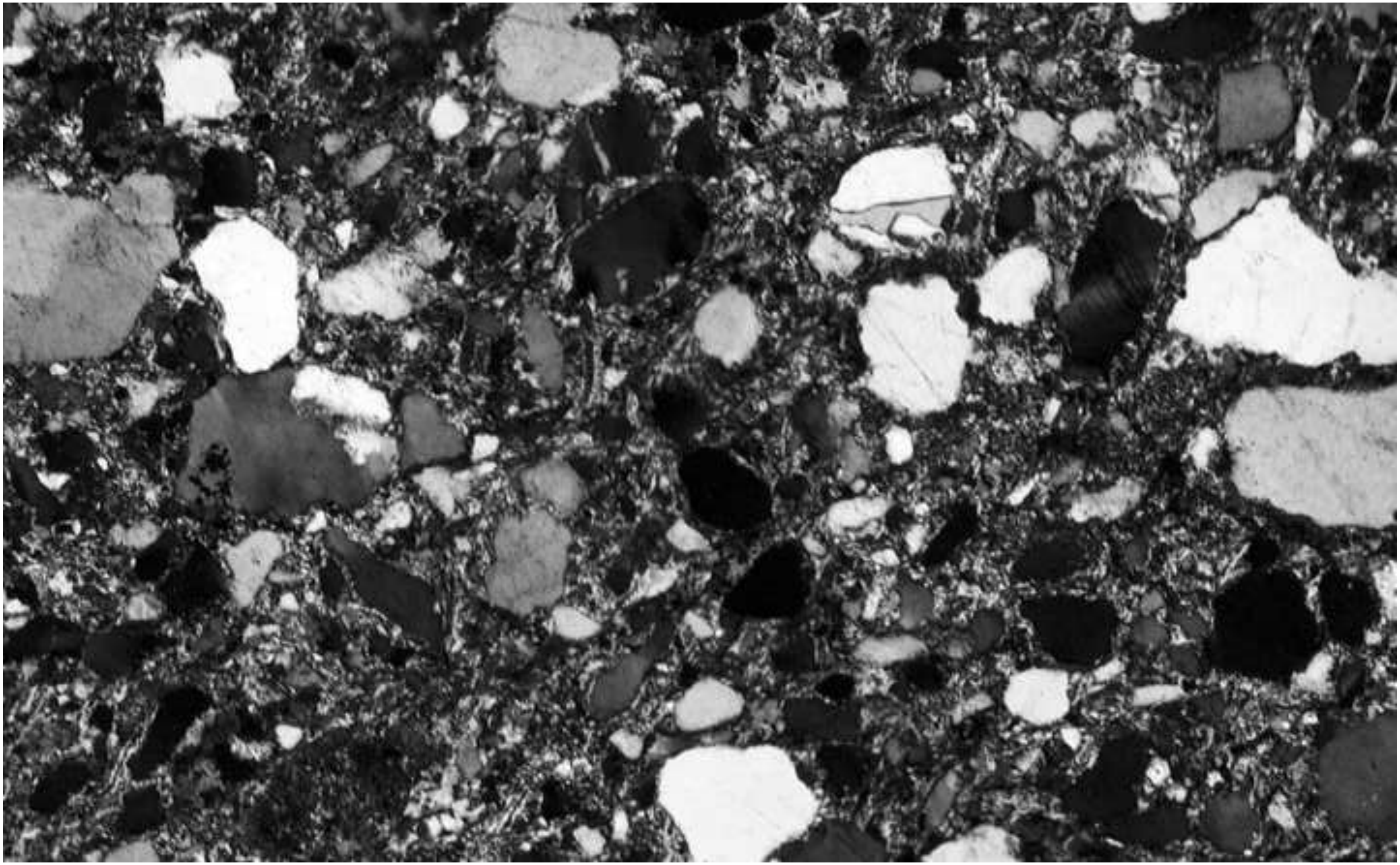

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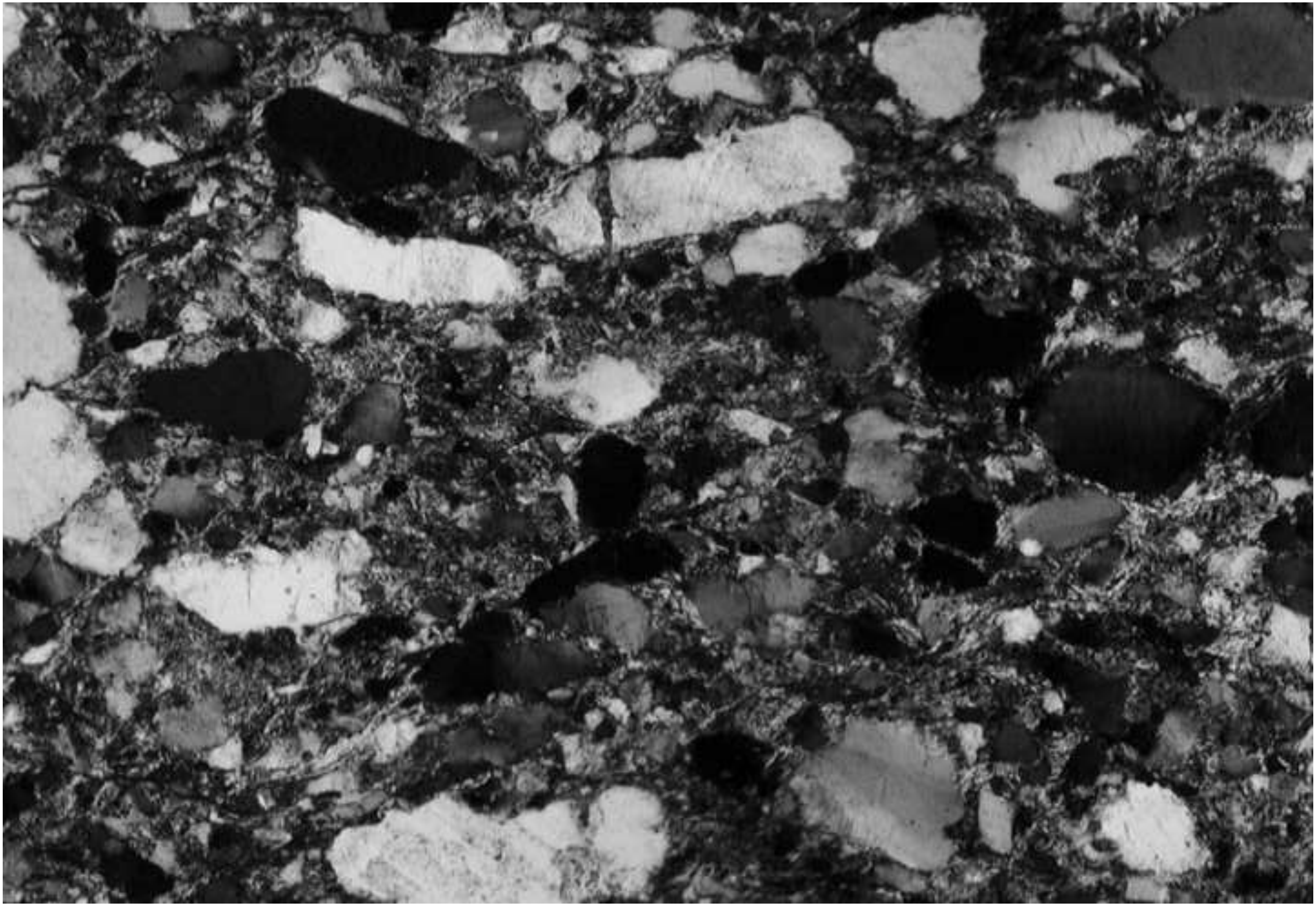

Figure 4.21e
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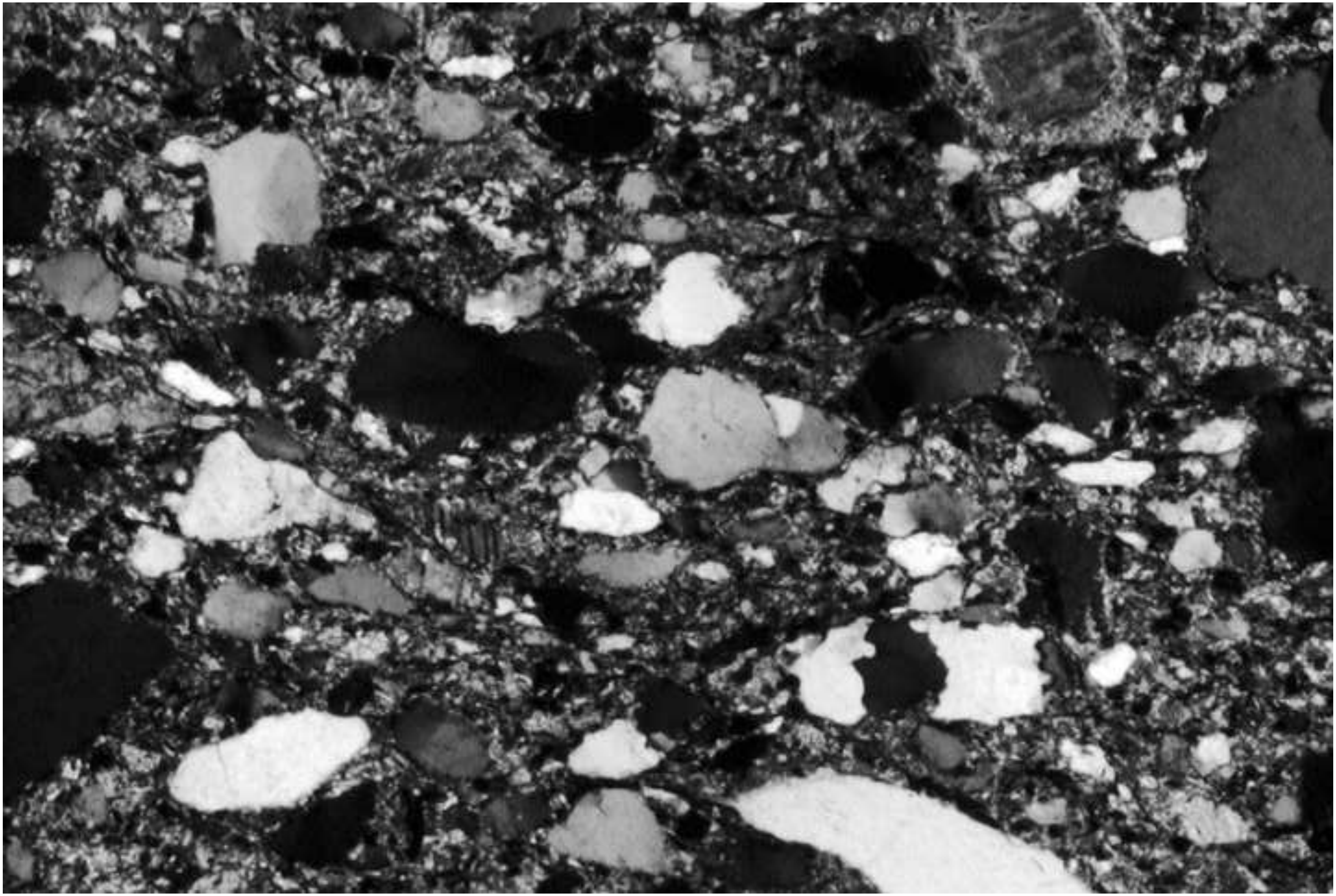

Figure 4.22 colour
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Figure 4.26a
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Figure 4.26b colour

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Figure 4.28b
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Figure 4.28c
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Figure 4.29 colour
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Figure 4.31 a-f

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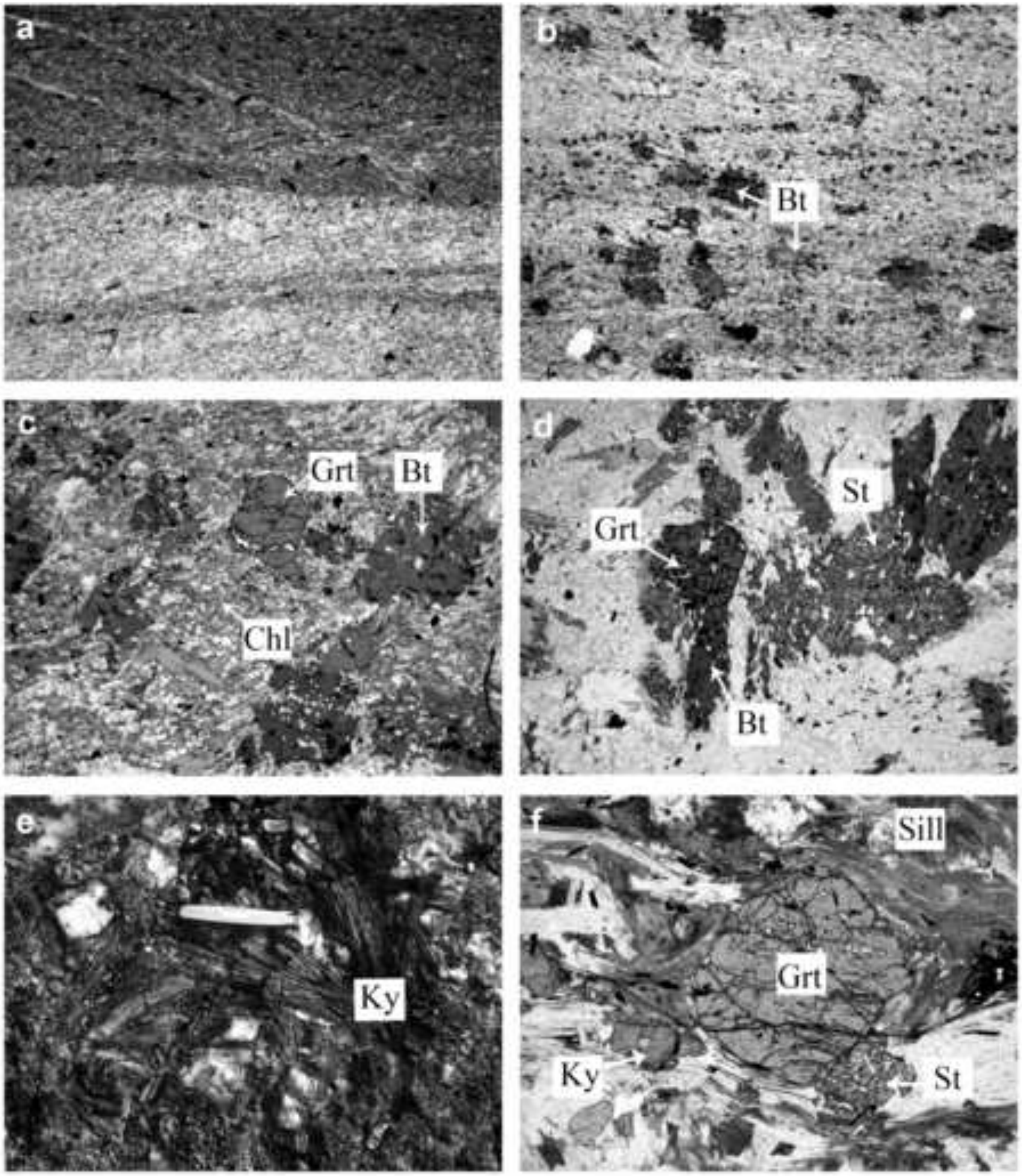

Figure 4.34a colour
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Figure 4.34b colour
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Figure 4.3 B&W

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Figure 4.10 B&W
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Figure 4.16 B&W
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Figure 4.17 B&W

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Figure 4.19 B&W

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Figure 4.22 B&W
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Figure 4.26b B&W
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Figure 4.29 B&W
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Figure 4.34a B&W

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Figure 4.34b B&W
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