Little Glen Shee, Craig a'Barns, Rotmell

Little Glen Shee [NN 979 346]

Craig a'Barns [NO 019 438]–[NO 014 442]

Rotmell [NO 014 469]–[NO 011 475]

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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 4.23). 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 4.24). 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 (Figure 4.23) and (Figure 4.24)a. 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 (Figure 4.23) and (Figure 4.24). 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 4.24) 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 4.25).

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 4.25), insets 1 and 2; (Figure 4.26)a. 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 4.25), insets 1 and 2; (Figure 4.26)b 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 4.25). Parasitic on these, a smaller pair of modified buckles have wavelengths of *c*. 1 m (Figure 4.26)b, 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 4.26)b.

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 toS0, particularly on the inverted SSE-younging limbs (Figure 4.25). 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 4.26)b.

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 4.24) 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 (Figure 4.23) and (Figure 4.24). The localities are shown on (Figure 4.27). 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 andthe 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 4.28)a 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 4.28)b; 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 4.28)c. At the top of the exposure illustrated in (Figure 4.28)c, 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 4.28)c, 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 4.24) 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 4.29). 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 4.24). 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 (Figure 4.23) and (Figure 4.24). 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^{o}–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

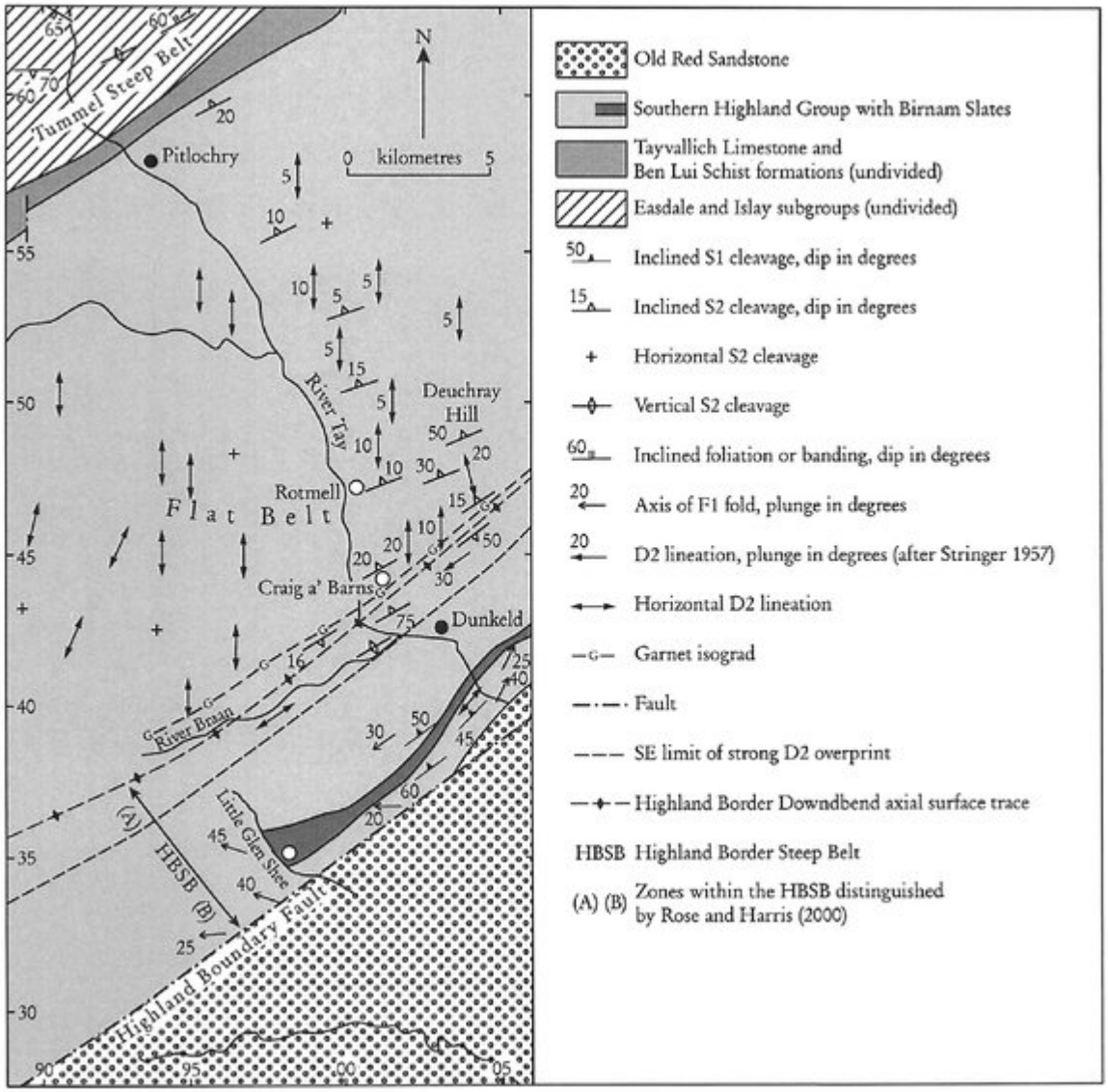
The Little Glen Shee, Craig a'Barns and Rotmell GCR sites together display the best set of exposures in the British Isles to exhibit the sequence of structures developed during the initiation, emplacement and modification of a major recumbent fold (nappe). This fold, the Tay Nappe, is one of the largest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

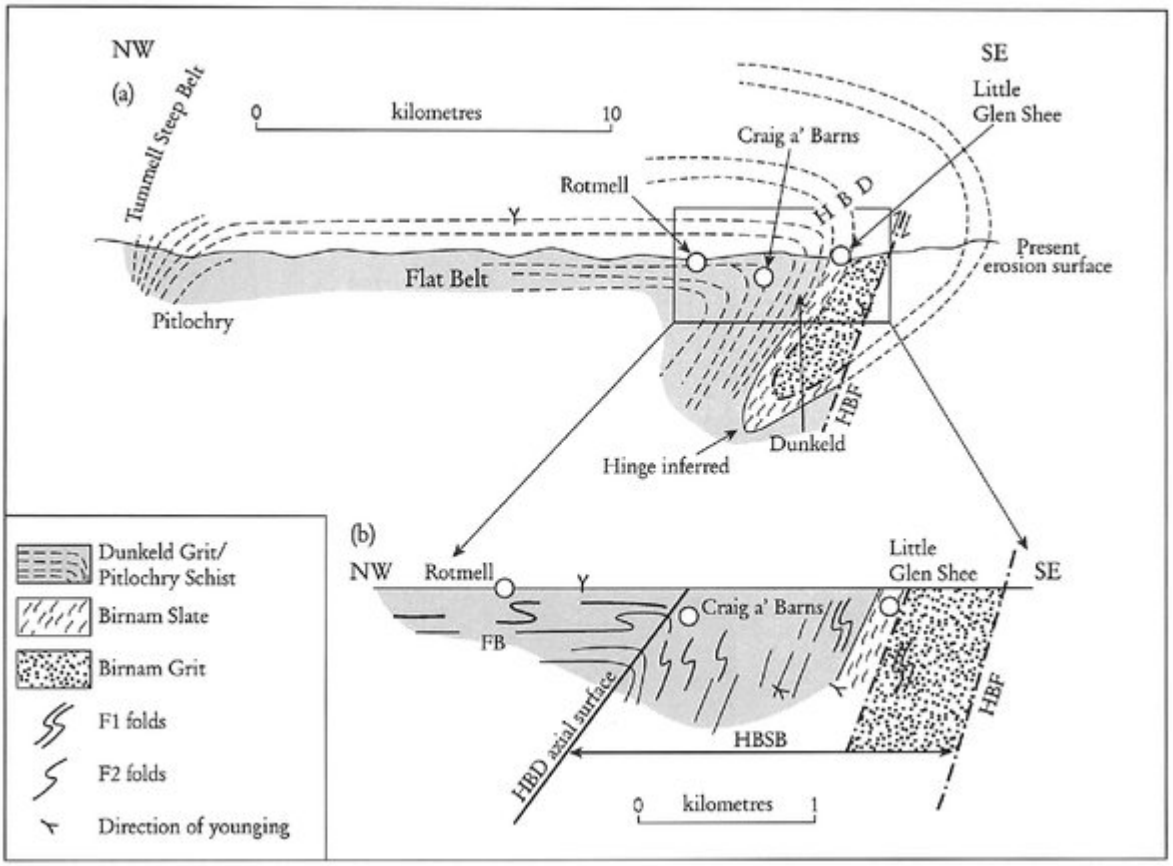
The rocks of the *Craig a'Barns* GCR site once occupied deeper levels of the Tay Nappe than those of the Little Glen Shee site. Consequently, the original sedimentary bedding characteristics, and the small-scale folds and cleavages that formed during the initial stage of nappe formation, have all been 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.

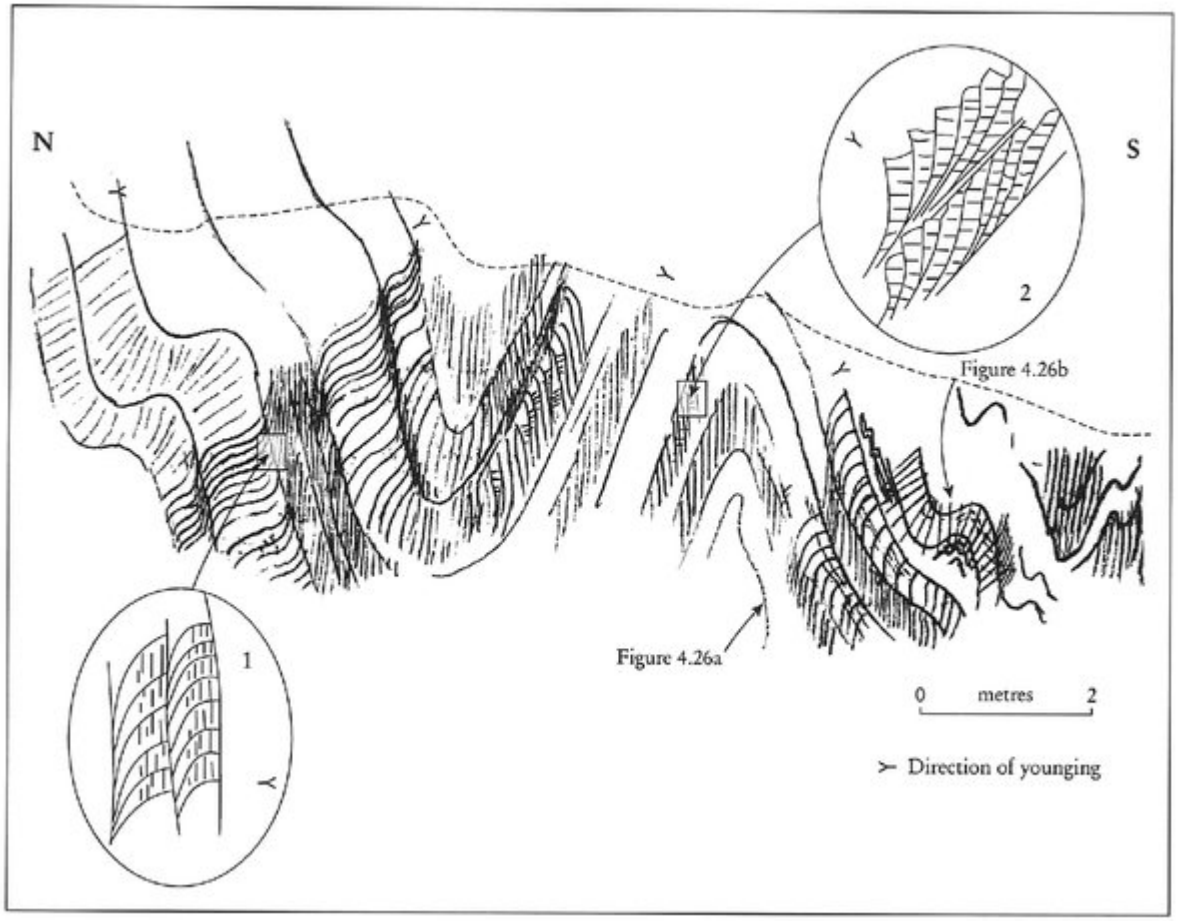
References



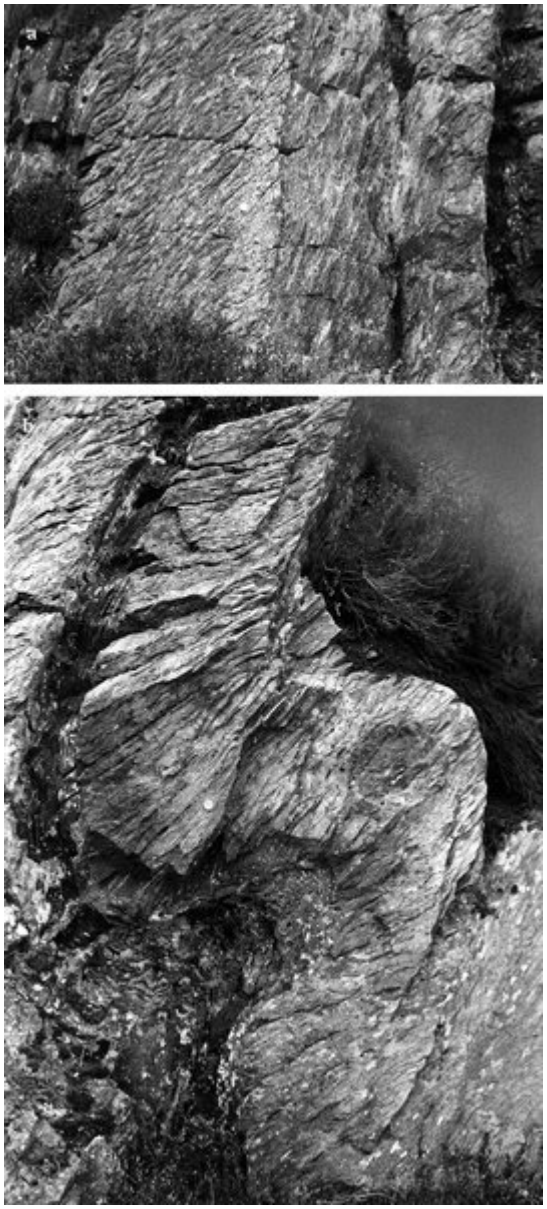
(Figure 4.23) Map of the Dunkeld–Pitlochry area to show the main lithostratigraphical units, the main elements of the structure and the locations of the Little Glen Shee, Craig a'Barns and Rotmell GCR sites. Adapted from Rose and Harris (2000, figure 2).



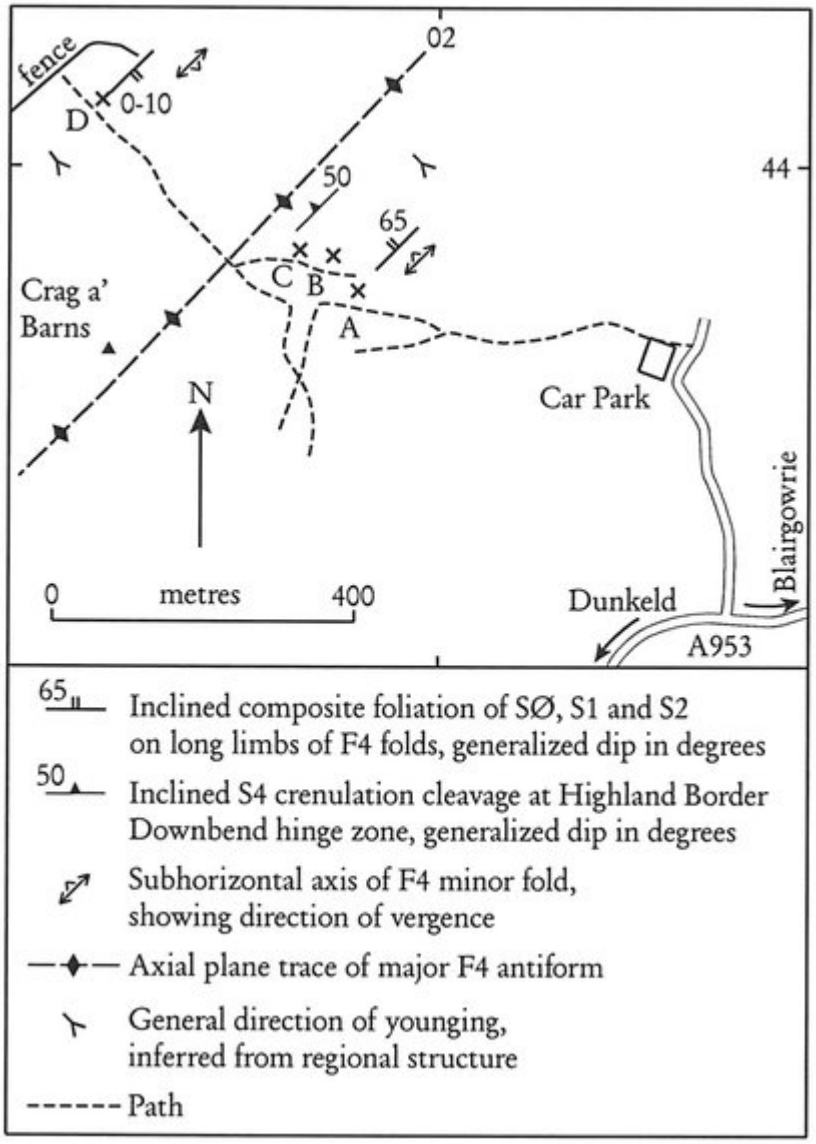
(Figure 4.24) (a) Schematic cross-section from Pitlochry to Dunkeld to show the location of (Figure 4.24)b, and the position of the Little Glen Shee, Craig a'Barns and Rotmell GCR sites in relation to the Tay Nappe. (b) Schematic cross-section across the Flat Belt (FB), the Highland Border Downbend (HBD), 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.



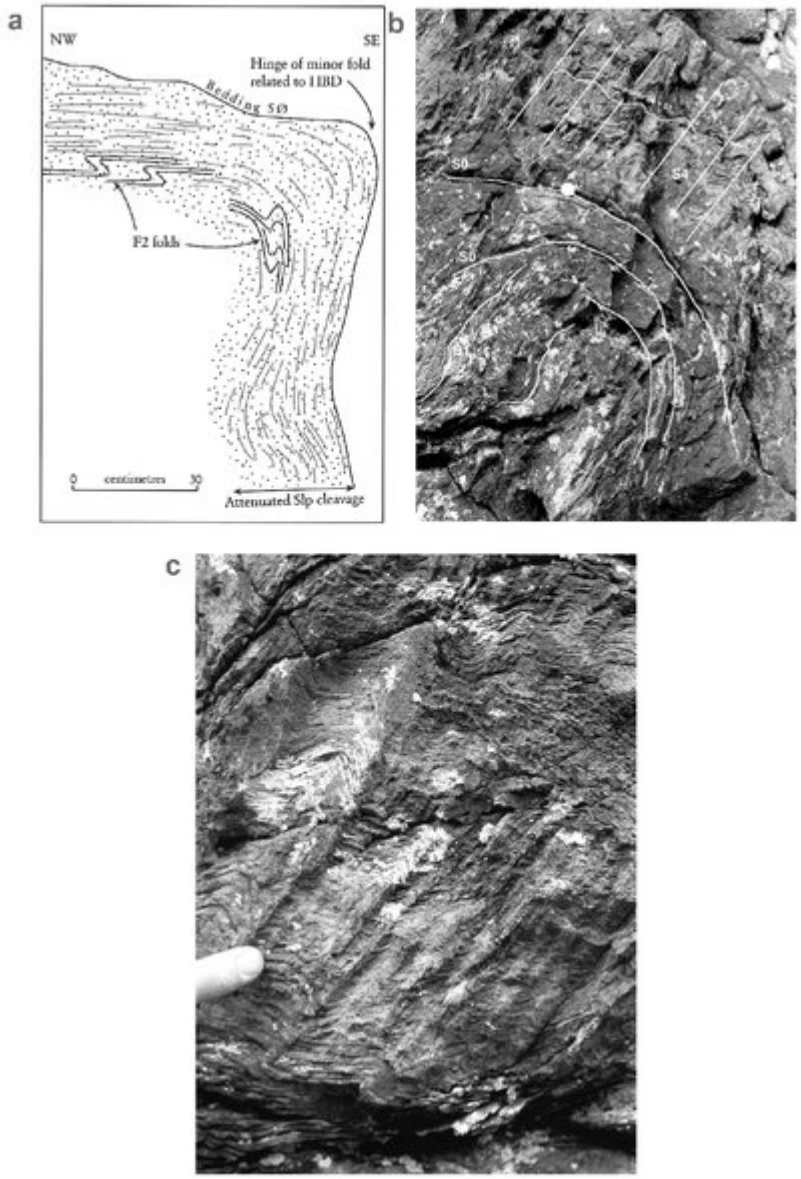
(Figure 4.25) Geological relationships at the crag that comprises the Little Glen Shee GCR site, to show the geometry of the folds and the general direction of younging of the beds. Insets 1 and 2 show the detail of relations between bedding and the refracted cleavage on alternate fold limbs. Locations of photographs, (Figure 4.26)a and (Figure 4.26)b, are shown. Adapted from a field sketch by P.W.G. Tanner with insets from P.T.S. Rose.



(Figure 4.26) Detailed sedimentological and structural features of the Little Glen Shee GCR site at locations shown in (Figure 4.25). (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 4.25) and discussed in the text. Coin is 1.2 cm in diameter. (Photos: A.L. Harris.)



(Figure 4.27) 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 4.28) Detailed structural relationships at the Craig a'Barns GCR site. (a) Sketch taken from a photograph of the fold at locality B on (Figure 4.27), 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 4.27). 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 4.27). Looking north-east, width of exposure 20 cm. (Photo: A.L. Harris.)

(Figure 4.29) 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.)