Major nappe-like D2 folds in the Dalradian rocks of the Beinn Udlaidh area, Central Highlands, Scotland

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ABSTRACT: Two regional-scale, recumbent folds control the structure of the Beinn Udlaidh area, Tyndrum, Perthshire. They reached their maximum development during D2, following the regional metamorphic peak, and are part of a stack of larger SE-facing recumbent folds formed during the ~470 Ma Grampian Orogeny. The rocks belong to the Neoproterozoic–Lower Ordovician Dalradian Supergroup, and preserve a sedimentary transition between the Grampian Group and the overlying Appin Group. The latter occupies the core of the S-facing, recumbent Beinn Udlaidh Syncline (D2) which, with the underlying complementary Glen Lochy Anticline, is gently folded by a regional-scale structure, the Orchy Dome. The recumbent folds postdate an early fabric (S1), which is generally obliterated by the D2 imprint, but preserved as inclusion trails in regional metamorphic garnets, that are highly oblique to, and wrapped by, S2. It is concluded that the Dalradian rocks described here from below the Iltay Boundary Slide are in structural continuity with those of the Tay Nappe above, and that the Slide represents a structurally-modified disconformity between the Leven Schist (Appin Group) and the overlying Ben Lui Schist (Argyll Group). The Orchy Dome probably influenced the spatial distribution of minor intrusions and explosion vents of the lamprophyre suite.

KEY WORDS: dome, Grampian orogeny, lamprophyre, recumbent fold, Scottish Caledonides, structure

Major recumbent folds or fold nappes with hinge lines of the order of tens to hundreds of kilometres long, are an important and striking feature of most orogenic belts, but their identification is commonly disputed (i.e. Gessner *et al.* 2002; Okay 2002) and their origin remains largely speculative. Recognition of such structures depends on there being both a distinctive stratigraphic sequence, individual members of which may be traced or correlated over large distances, and considerable topographic relief to expose both limbs of the recumbent fold. Thus, it is not surprising that the first recumbent folds and nappes to be recognised, in the latter half of the 18th century by Escher von der Linth, Heim, and Lugeon (Howarth 1999), were in the European Alps, in a region with high relief and an easily identifiable stratigraphical sequence. Such regional-scale folds are invariably tight to isoclinal structures that developed early in the orogeny. Those formed at relatively high levels in the crust, for example, the Courel recumbent syncline (Fernández & Bastida 2007), the Mondoñado Nappe (Martínez Catalán *et al.* 2003), both in the Iberian Variscan Belt, and an un-named nappe in the Montaign Noire (Aerden & Malavieille 1999), are most readily identified, whereas those formed at deeper levels in the interior of the fold belt are more difficult to recognise because of the effects of later deformation.

In the Grampian Belt in Scotland, as in many orogenic belts word-wide, the 'internal' nappes commonly reach their maximum amplitude during the second regional deformation phase (D2), synchronous with, or immediately following, the peak of the regional metamorphism (i.e. the Tay Nappe in the Scottish Caledonides) (Shackleton 1958; Krabbendam *et al.* 1997; Crane *et al.* 2002). During this process, earlier tectonic structures and fabrics are commonly obliterated due to the intensity of the D2 deformation. This leaves only the stratigraphical carapace and, in rocks of suitable composition and metamorphic grade, inclusion trails in pre-D2 regional metamorphic porphyroblasts (e.g. garnet), as evidence of its early (D1) history. In some instances, minor structures and fabrics of D2 age may in turn be overprinted and made unrecognisable by one or more later phases of folding. Destruction of the porphyroblastic minerals during these later events may leave stratigraphical repetition as the sole clue to the presence of the original D1 fold.

The Beinn Udlaidh massif is situated a few km NW of Tyndrum in the Central Highlands of Scotland (Fig. 1). It consists of metasedimentary Dalradian rocks of Neoproterozoic age, namely the topmost part of the Grampian Group and the lowermost portion of the Lochaber Subgroup (Appin Group), which underwent polyphase deformation (D1–D4) during the Lower Ordovician (~470 Ma) Grampian Orogeny (for review, see Oliver 2001). All of the rocks have been affected by amphibolite facies regional metamorphism: garnet is commonly developed in the pelitic rocks, but no aluminosilicate minerals have been recorded. Intense and widespread chloritisation has affected these assemblages and fresh garnet is rare. The structure of the area consists of two major, isoclinal, originally flat-lying, south-facing folds, the Beinn Udlaidh Syncline and the underlying Glen Lochy Anticline (Fig. 2), folded by what is named here as the Orchy Dome. The latter is a slightly elliptical, asymmetrical km-scale structure centred on the Beinn Udlaidh massif. Sills, dykes and irregularly-shaped

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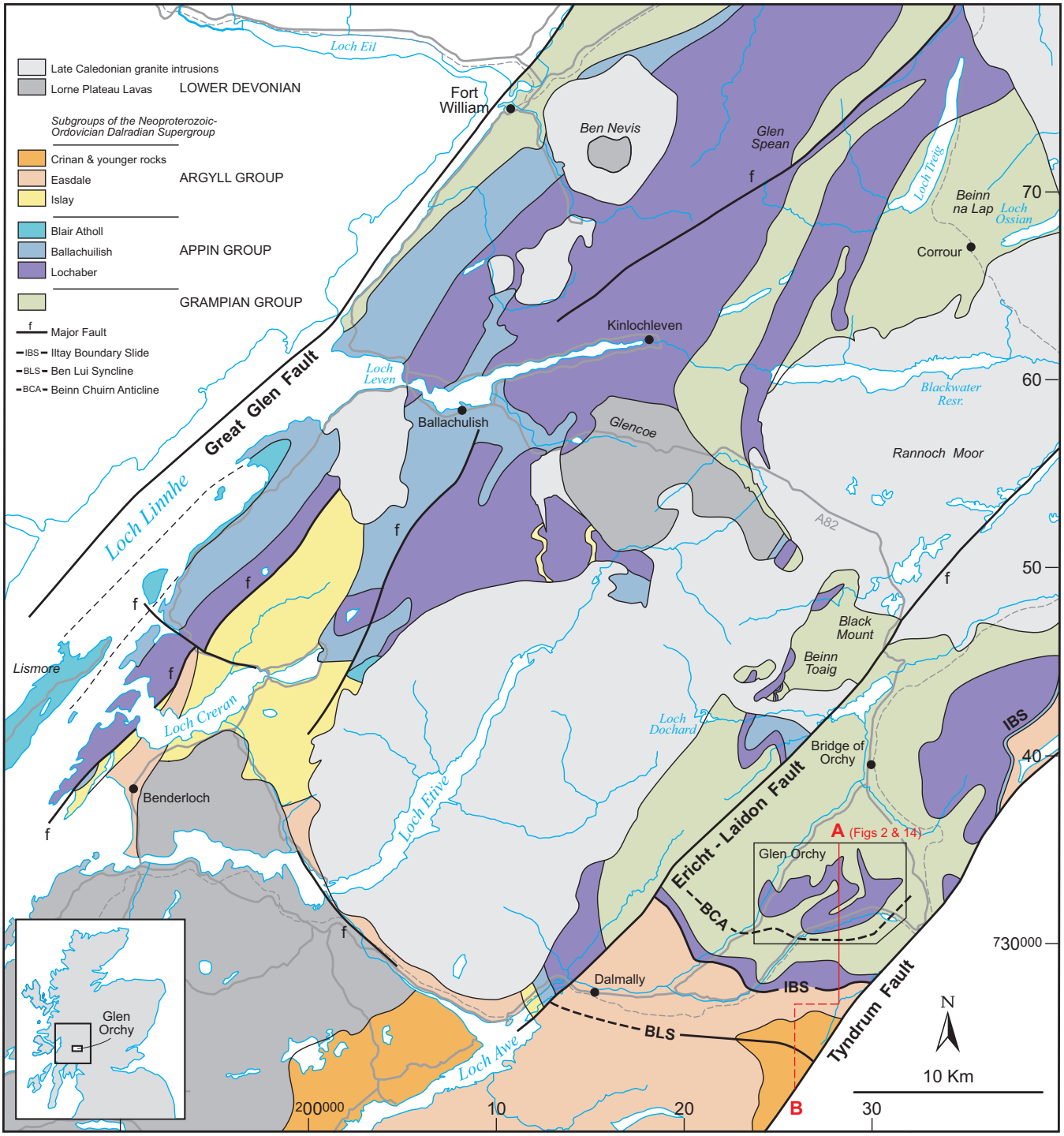

Figure 1 Geological setting of the Beinn Udlaidh area in the Central Highlands of Scotland. The area covered by Figures 4, 5 and 6 is labelled 'Glen Orchy'; line A–B refers to Figures 2 and 14.

minor intrusions belonging to the lamprophyre suite (mainly vosgesite), including explosion breccia pipes, are common in part of the area and the possibility that their distribution was controlled by the Orchy Dome is examined. The main bodies are shown on the maps presented in this present paper, but small, <2 m-thick sills etc. have been omitted for clarity. The geometry and origin of the network of faults and associated quartz-breccia veins will be described elsewhere.

Looking farther afield, Roberts & Treagus (1975) followed Bailey (1922) in dividing the Dalradian rocks in this region into two SSW-dipping units, separated by the Iltay Boundary Slide (Figs 1 & 2). The latter, also referred to simply as the 'Boundary Slide', was initially considered to be a major tectonic discontinuity, but has been reinterpreted more recently as a structurally-modified disconformity separating the Leven Schists (Appin Group) below, from the Ben Lui Schist (Argyll Group) above (Krabbendam *et al.* 2002). The term 'Iltay Boundary Slide' is a misnomer in several respects, but is retained until the feature is correctly named and described with reference to a type section. Roberts & Treagus (1975) interpreted the Beinn Udlaidh folds as D1 structures that were separated from the overlying Iltay Boundary Slide by a major D2 fold, the Beinn Chuirn Fold. They inferred that the Beinn Udlaidh Syncline was folded by the D2 fold and cut out against the slide (Fig. 2).

The folds described here, in particular the Beinn Udlaidh Syncline, satisfy the criteria mentioned above for recognising major, early recumbent folds. The syncline has a hingeline

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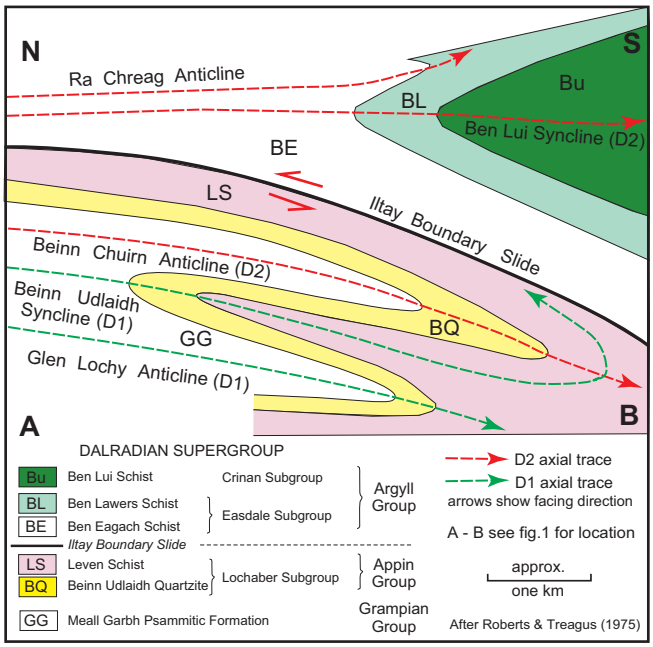

Figure 2 Schematic cross-section through the Beinn Udlaidh area and the region to the south, based upon Roberts & Treagus (1975, fig. 4B), and flipped horizontally. The section is located approximately along line A–B on Figure 1.

traceable for over 20 km and an inverted limb width of 3–4 km, being equivalent to the Morcles Nappe Complex (Dietrich & Casey 1989) in size. It folds a well-defined tripartite stratigraphical sequence (psammite/quartzite/mica-schist), and is dissected by steep-sided glaciated valleys, such as the two north-facing glens headed by Coire Daimh [NN 275 330] and Coire Ghamhain [NN 290 340]. These glens provide sufficiently deep cuts into the massif, to make it an ideal setting for a 3-D study of the structures. Indeed, the Beinn Udlaidh Syncline was described, pre-forestation, as "the best-exposed example of a recumbent fold in the British Isles, and must rank for clarity alongside those of similar size in the European Alps" (Bailey & Macgregor 1912, p. 171).

The current work was initiated in 1984 by the authors as an unfunded research project, and by the early 1990s most of the area had been covered and a map compiled. Lithological and structural field mapping was carried out at 1:7000, partly on printed maps and partly using aerial photo overlays, augmented in recent years by a GPS receiver. Over 300 rock samples were studied in thin section.

The aims of this paper are to confirm the presence of these major recumbent folds, demonstrate their geometry with respect to the regional structure, interpret their age with respect to the regional D1–D4 sequence (Tanner 1992) and comment briefly on their possible origin.

1. History of previous research

The primary survey of the area by Officers of the Geological Survey of Scotland (Sheet 46, Balquhidder), published in 1872 and currently under revision, yielded little information, the rocks being shown as undifferentiated schists of 'Moine type'. Subsequently, two members of the Survey made a pioneering reconnaissance of the Beinn Udlaidh massif "in their holiday-time" (Bailey & Macgregor 1912, p. 167), and recognised that the structure consisted of three stratigraphical units, namely pelite, quartzite, and psammite, repeated by a major recumbent structure, the Beinn Udlaidh Fold. They also identified a later structure that warps this fold, and named it the Glen Orchy Anticline. However, having presented convincing evidence in 1912 for correlating the pelitic schist in the core of the Beinn Udlaidh Fold with a readily recognisable member of the Appin Group, the Leven Schist, Bailey then did a volte-face and assigned the Beinn Udlaidh Quartzite and the 'Leven Schist' to a 'Sub-Eilde (i.e. pre-Moine) Complex' (Bailey 1922).

The situation was confused further by Gregory (1931), who rejected the evidence for the existence of the Beinn Udlaidh Fold, and concluded that all of the rocks belonged to the Moine and were in normal stratigraphical sequence. The survey by Bailey & Macgregor (1912) was carried out before the methods for using sedimentary structures to determine way-up in rocks had become generally known, and it was Cummins & Shackleton (1955) who first reported cross-bedding from the area, and demonstrated that the Beinn Udlaidh Fold is a syncline.

Thomas & Treagus (1968) prepared detailed maps of two parts of the Beinn Udlaidh area and showed that Bailey's 1922 'sub-Eilde' correlation for the Beinn Udlaidh succession was incorrect, and that the rocks were of Dalradian age. They concluded that the Beinn Udlaidh Syncline and the Glen Lochy Anticline are primary (D1) folds that face down to the SE, and that the dome is a primary (i.e. D1) feature of the architecture. Roberts & Treagus (1975), amplified this work and placed the structures in a regional context.

2. Dalradian stratigraphy of the Beinn Udlaidh area

The stratigraphy of the Beinn Udlaidh area is easily read, for the Quartzite outcrop can be traced as a continuous ribbon throughout the whole area and, from the evidence of way-up structures, separates the older Meall Garbh Psammite Formation from the younger, Coire Daimh Pelite Formation (Figs 3, 4). Evidence for the order of succession is given by trough cross-bedding and cross-lamination in the Quartzite: in clean exposures on the east bank of the River Orchy above Eas a' Chaithaidh waterfall (Cummins & Shackleton's (1955) locality) at [NN 247 331]; in the Allt Broigleachan at [NN 248 330]; in extensive exposures on the An Grianan ridge west of Coire Daimh at [NN 266 334]; and in Glen Lochy at [NN 279 313]. Thus, the tripartite succession reported by Bailey & Macgregor (1912) and Thomas & Treagus (1968) is confirmed. Three formations are proposed (with present thicknesses) as follows:

Coire Daimh Pelite Formation	>250 m		
---------- transitional contact ----------		Lochaber Subgroup	APPIN GROUP
Beinn Udlaidh Quartzite Formation	7–80 m		
---------- transitional contact ----------		----------	----------
Meall Garbh Psammitic Formation	>1000 m		GRAMPIAN GROUP

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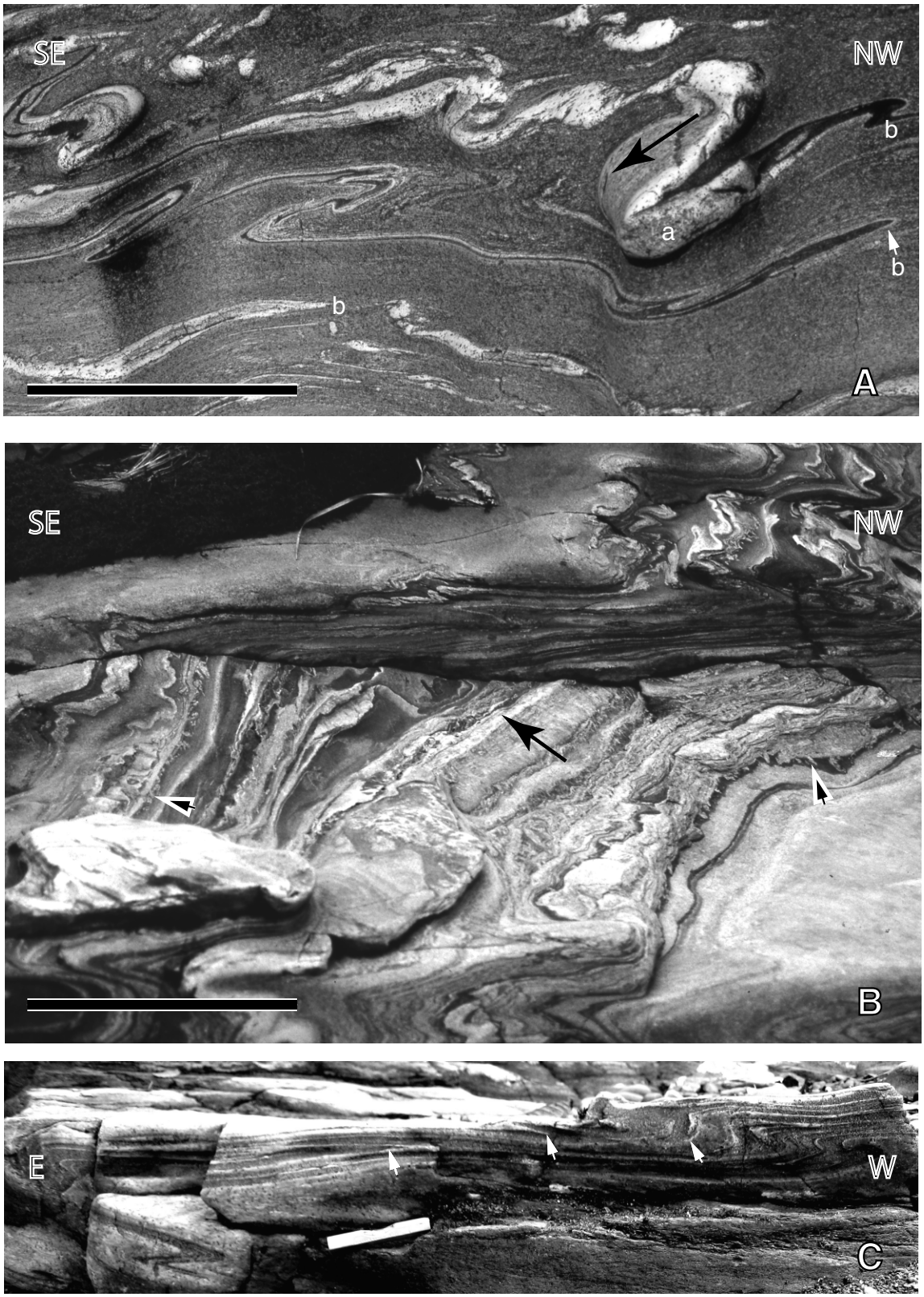

Figure 3 Sedimentological and structural features of the Coire Daimh Pelite–Beinn Udlaidh Quartzite transition zone. (A) Minor D2 folds affecting quartz veins (a) and lithological layering in the Coire Daimh Pelite on the lower limb of the Beinn Udlaidh Syncline (D2), viewed to the SW. The stripes in the country rock have a dark carbonate-rich centre rimmed on both sides by quartzose psammite and, in this case, represent the cores of early minor folds (D1), several of whose fold closures are preserved (b) (see text for discussion). The quartz veins are folded and boudinaged and commonly preserve the D2 stretching lineation (large arrow) on their outer surface. The scale bar is approximately 4 cm long. River Orchy at Eas Urchaidh [NN 244 323]. (B) Symmetrical minor D2 folds from the hinge zone of the Beinn Udlaidh Syncline. Small-scale sand-filled apophyses (dewatering structures) occur consistently along one side of thin sandstone beds and probably, but not necessarily (Tanner 1998), mark the base of these beds (small arrows). Also shown are thin discontinuous, wedge-shaped beds with the D2 stretching lineation on some of the surfaces (large arrow). The scale bar is approximately 5 cm long, and the viewing direction is to the SW. Allt Broighleachan [NN 244 326]. (C) Centimetre-scale, S-shaped D1 isoclinal fold pairs (arrowed) refolded by S-shaped D2 minor folds on the lower limb of the Beinn Udlaidh Syncline. The spirit level is 5 cm long, and the section is viewed to the S. River Orchy at Eas Urchaidh [NN 244 323].

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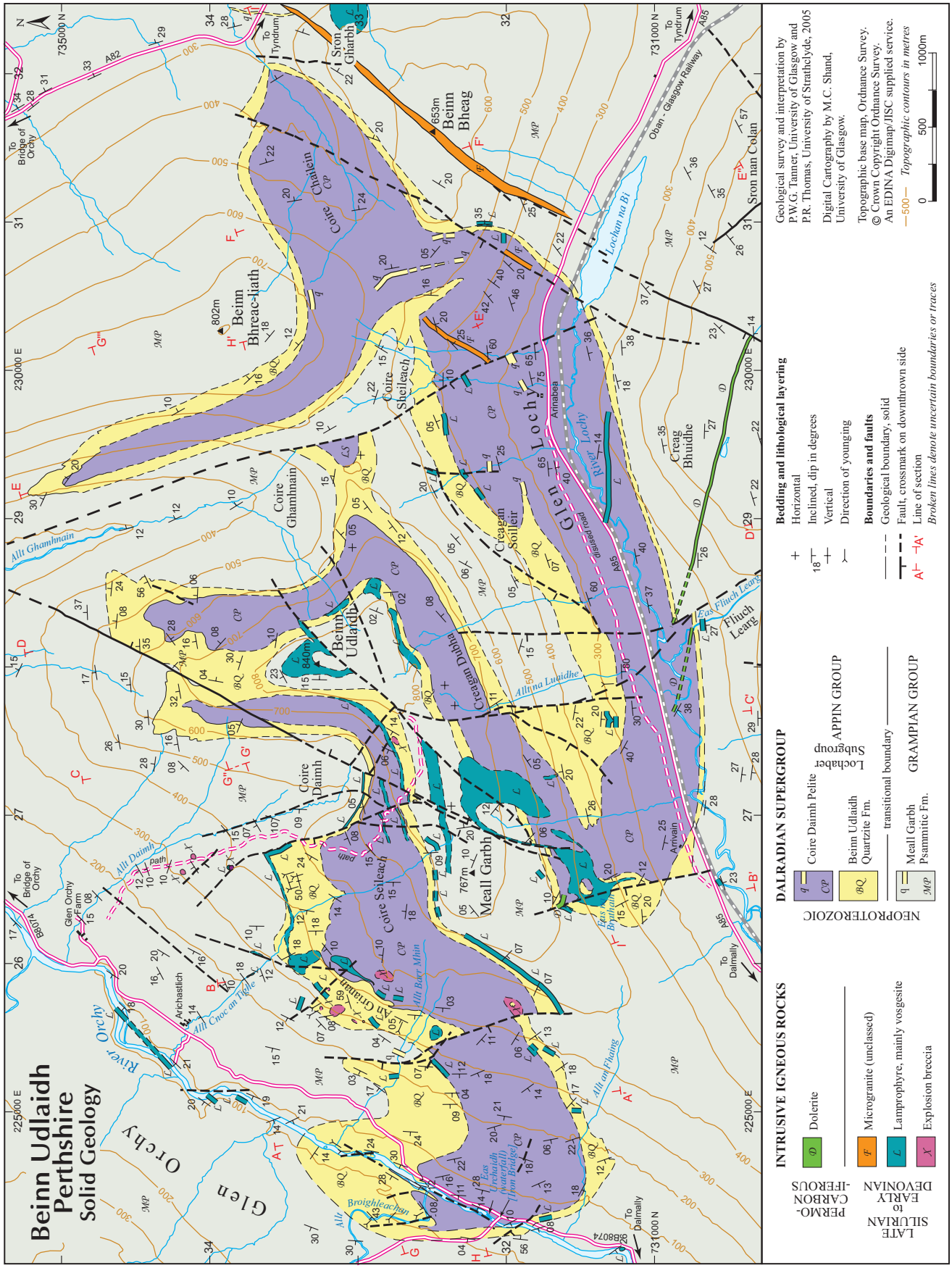

Figure 4 Geological map of the Beinn Udlaidh massif, Perthshire, Scotland.

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2.1. The Meall Garbh Psammitic Formation

The flaggy psammitic rocks, which underlie the quartzite, can be equated with quartz–plagioclase–biotite schists found throughout the Central Highlands. They were previously called the Eilde Flags and correlated with the Moine rocks of the Northern Highlands (Bailey & Macgregor 1912; Thomas & Treagus 1968; Roberts & Treagus 1975), but are now recognised as belonging to the Grampian Group. Typical examples of this lithology are seen at the summit of Meall Garbh [NN 266 323] and on the slopes below Creagan Dubha in Glen Lochy [NN 285 323].

There is a considerable lateral variation in lithology in a <100 m-thick package that occurs immediately below the Beinn Udlaidh Quartzite. The boundary between the Grampian Group and the Quartzite is generally transitional over several tens of metres, and is marked by a unit of interbedded psammite and semipelite, with quartzite ribs. Bailey & Macgregor (1912) identified this 'Banded Series' at the contact between the Grampian Group and the Quartzite on the northern spur of Beinn Udlaidh, and below the weir 200 m downstream from the 'Iron Bridge' near Eas a' Chathaidh. At the latter locality [NN 242 318], Thomas & Treagus (1968, p. 127) reported a 10 m-thick 'passage group' of mixed psammite, semipelite, and pelite with some calcareous and graphitic bands.

Further examination of the transitional assemblage on clean exposures in the River Orchy shows that it is mainly of finely banded to laminated psammite, semipelite and pelite, much of which contains chloritised garnets. Also present are distinctive zoned sedimentary units consisting of chocolate brown-weathering calcareous bands a few cm thick, separated from the pelitic country rock by a thin rind of steel grey quartzose psammite or quartzite.

Elsewhere, as on An Grianan, individual quartzite bands up to 10 m in thickness occur in the psammites below the main quartzite outcrop, making it difficult to define a mappable boundary to the quartzite. Farther east, along the same contact on the north side of Coire Daimh, the psammitic top of the Grampian Group passes laterally into a mixed semipelitic facies.

2.2. The Beinn Udlaidh Quartzite Formation

The Beinn Udlaidh Quartzite generally varies from pale grey to white, or even acquires a pinkish colour where it is coarse-grained and feldspathic. In places it contains gritty horizons, and is sometimes pebbly near to the base (Bailey & Macgregor, 1912, p. 172), as at [NN 249 314], but this is not a widespread feature. The Quartzite is generally flaggy in units 0·15–1·0 m thick, as in the hinge zone of the major fold at [NN 248 332]. It shows an order of magnitude change in thickness across the area from >100 m thick in the north, to <10 m thick in the south and south-east. This variation in thickness is due to a combination of lateral facies change, tectonic thinning on the upper limb, and marked thickening in the hinge zone, of the Beinn Udlaidh Syncline. For example, on the upper limb of the fold it is 22 m thick in the Allt nan Faing [NN 249 314] in Glen Orchy, decreasing to only 7 m thick on the south side of Glen Lochy at [NN 295 312].

2.3. The Coire Daimh Pelite Formation

The youngest metasediments in the area lie in the core of the Beinn Udlaidh Syncline and are well exposed in the 300 m-high crags at the back of Coire Daimh [NN 275 329], where they are both underlain and overlain structurally by the Beinn Udlaidh Quartzite. As a result of this structural repetition, only the lower part of the formation is seen in the Beinn Udlaidh area.

The Coire Daimh Pelite is very uniform in lithology and consists mainly of finely banded to lustrous, dark grey, biotite–muscovite–quartz–plagioclase–garnet–graphite-bearing schist with thin layers of psammite and semipelite. It also contains a few thin bands of quartzite, especially in the western part of the outcrop. The pelitic schists are characterised by a strong bedding-parallel schistosity, and by abundant, folded, lineated and boudinaged lenticular quartz veins, up to 10 cm thick, which contain some calcite ± white mica, and commonly show a stretching lineation (Fig. 3A). Porphyroblasts of partially to completely chloritised garnet, up to 0·5 cm across, commonly occur in the schists, together with mm-sized randomly orientated flakes of variably chloritised biotite. Non-retrogressed garnet is most common in the thin siliceous bands.

Significantly, in the exceptionally clean exposures above the Iron Bridge at [NN 243 323], 1–3 cm-thick striped and laminated units are found in the pelite, close to its contact with the Beinn Udlaidh Quartzite. It contains zoned units identical to those described from the transitional assemblage at the top of the Grampian Group. They generally appear parallel-sided over long distances and some are isoclinal D1 folds, but others could be of sedimentary origin, with a symmetrical repetition of layers (Fig. 3A). Diagenetic carbonate bands and pods are commonly enclosed in a thin sheath of quartzose psammite or quartzite, which was depleted in carbonate during their formation. Similar units were reported from the Leven Schist in the Glen Roy area (Fig. 1) as "calcareous beds, which may form the cores of quartzose beds" (Key *et al.* 1997), and as lenses of dolomitic limestone (Stephenson & Gould 1995, plate 4).

Sedimentary structures are rarely preserved in the pelite, but thin sandy layers found in the core of the syncline on the Allt Broleachan [NN 2439 3256] show water-escape structures and wedging-out of beds (Fig. 3B).

3. Structure of the Beinn Udlaidh area

3.1. Introduction

The distinctive outcrop pattern formed by the Dalradian rocks of the Beinn Udlaidh massif west of Tyndrum in the Central Highlands of Scotland is readily recognisable on a small-scale geological map (Fig. 1). It results from the dissection of a pair of large, gently warped recumbent folds by a series of ridges and valleys that have a combined topographic relief of up to 830 m.

Two major recumbent folds control the structure of the Beinn Udlaidh massif: the Beinn Udlaidh Syncline, which is well exposed and can be traced throughout the map area; and the Glen Lochy Anticline, which is largely hidden and whose lower limb is only exposed over an area of <2 sq km (Fig. 5). The Beinn Chuirn Anticline, argued here to be another fold of the same generation, is seen in the south of the area (Fig. 1).

The Beinn Udlaidh Syncline has a gently curvilinear axis and plunges at a low angle to either the NE or SW, except in the extreme west of the area where, due to an intensification of D2 strain, it turns to plunge due south (Figs 5 & 6). Together with the Glen Lochy Anticline, it has been arched over a major late domal structure, which is of unknown absolute age relative to the regional D1–D4 sequence. Although it is nearly isoclinal and has minimum amplitude of several km, it would be incorrect to refer to this structure as a fold-nappe, as the stratigraphy can be followed around it without a break, and the syncline does not lie on a thrust plane.

The hinge zone of the Beinn Udlaidh Syncline is exposed in four places, but none of the previous workers recognised the two closures within the quartzite immediately north of the Beinn Udlaidh summit, where the major fold axis passes

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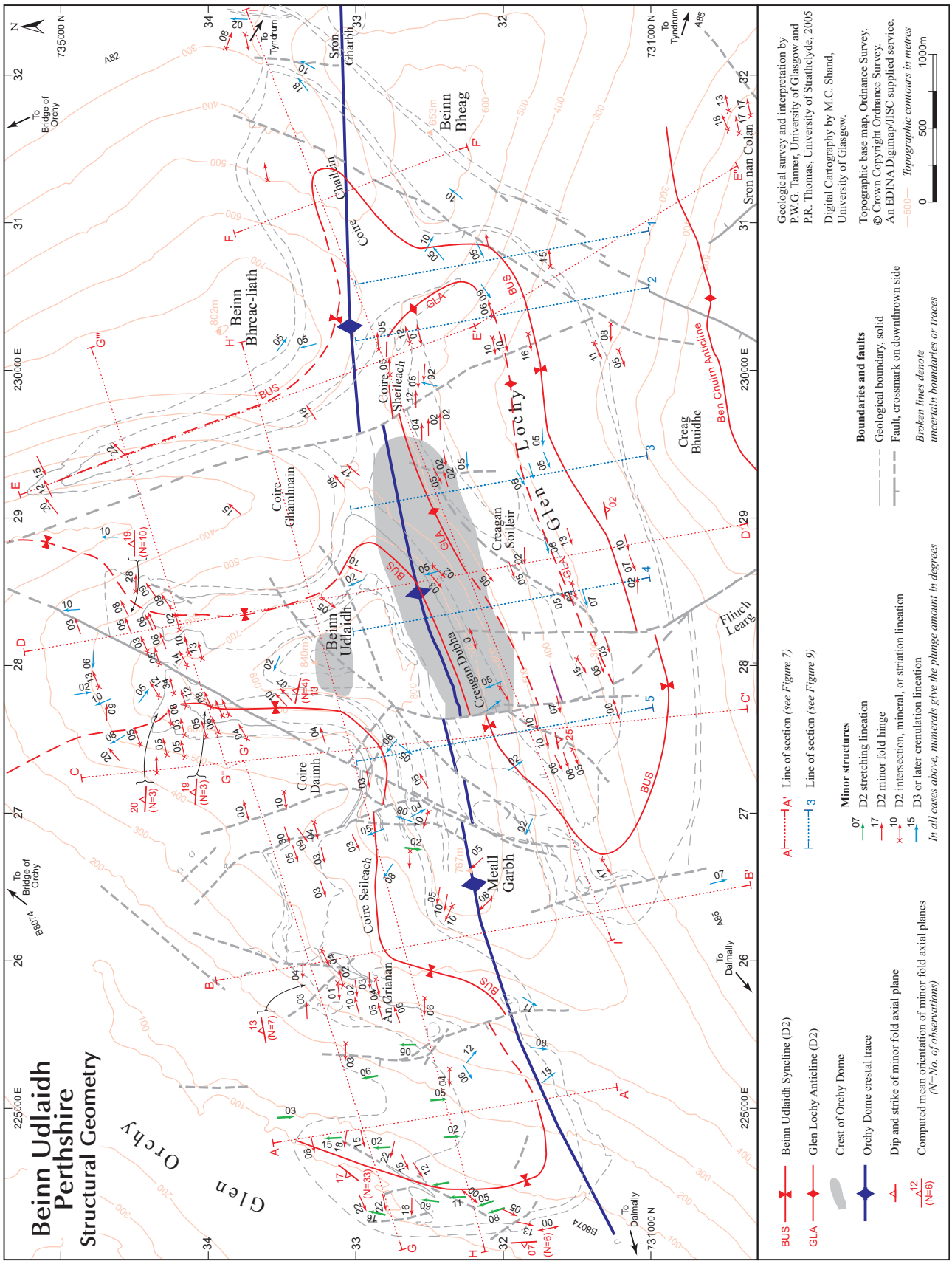

Figure 5 Structural map of the Beinn Udlaidh area, Perthshire, showing the axial traces of major D2 folds (red) and of the crestal trace of the Orchy Dome (blue), together with the geometry of the minor D2 and D3 structures. Lines of cross-section: A–I, red dots, Figure 7; 1–5, blue dots, Figure 9.

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through the ridge. The closure of the underlying Glen Lochy Anticline, whose presence was inferred by Thomas and Treagus (1968), has now been located in several places (Figs 4 & 5). Way-up structures, mainly cross-lamination, show that both folds face SSE across the dome.

It is not customary to use the terms 'Anticline' and 'Syncline' for second-phase major folds, as this would require a change in name each time that the axial trace crosses that of a major D1 fold. It is however acceptable in the present case, as no major D1 folds have been recognised in the area, and the Glen Orchy Syncline, for example, maintains its relationship to the stratigraphy as it changes from a synform to an antiform southwards across the Orchy Dome.

3.2. Detailed geometry of the D2 structures

3.2.1. Construction of cross-sections. In order to display the precise 3-D structure of the area, a set of true-scale cross-sections was drawn on a 6 × 4 gridiron pattern locked to the D2 geometry. The area was divided into 16 homogeneous sub-areas with respect to the second phase linear structures (L2) and the computed mean for each sub-area was then plotted on the map (Fig. 6). A set of regularly spaced lines at right angles to the L2 mean was selected for drawing the cross-sections, thereby giving near-perfect profile sections of the major folds. A second set of regularly spaced cross-sections was then drawn parallel to the L2 means to generate the gridiron pattern. In all cases the true-scale cross-sections were made more precise by projecting (calculated) fold axes into the plane of the section, and by the local use of structure contours. The representation of faults on the cross-sections was controlled, where possible, by structure contours drawn on the fault in map view.

The cross sections (Fig. 7) show the Beinn Udlaidh Syncline–Glen Lochy Anticline as a S-shaped fold pair, but it is the *upper* limb of the syncline that is consistently thinned. This limb is common to the overlying Beinn Chuirn Anticline, indicating that the sense of shear is top-to-S. The complementary sets of cross-sections GG′–II′ (Fig. 7) show the symmetrical shape of the Glen Orchy Dome in an E–W direction, but sections BB′–EE′ show that it has a steeper southern limb.

3.2.2. Major D2 fold geometry. The complex outcrop patterns on Figure 4, resulting from the interaction of flat-lying major folds with an irregular topographic surface, are not easy to interpret and are now explained briefly with reference to Figure 8. The axial trace of the Beinn Udlaidh Syncline (BUS) forms two closed loops, the northern parts of which are outwith the area studied (Fig. 8). The enclosed areas are windows exposing the common limb of the BUS and Beinn Chuirn Anticline, beneath the eastern of which erosion has exposed part of the lower limb of the Glen Lochy Anticline.

At locality A (Fig. 8) the trend of the fold axis of the BUS, given by the D2 lineations and minor fold hinges, rotates through almost 90° as it is traced from north to south for a distance of <1 km (Fig. 6, plot IJ, to plot N, to plot M), from the hinge zone and lower limb of the fold to the top limb (Fig. 7 AA′). The strain increases from that shown in Figure 7B to that in Figure 7C, and the geometry of the process has been described in detail by Tanner (in press). The stretching direction shows little variation in orientation (Fig. 6, plot NM) with a mean of 02°/360° (N=41). Because of the change in plunge direction, the fold closure also appears in section GG′ (Fig. 7).

On the north limb of the Orchy Dome, the BUS hinge line or axis lies above ground level at B (Fig. 8) on An Grianan, but a plunge culmination brings it back to ground level at C where the fold core of pelite enclosed in quartzite passes through the ridge to emerge at D on the eastern loop (Fig. 7, section CC′, DD′). It then crosses the deep valley that runs north from Coire Ghamhnain, to plunge into the hillside at locality E (section EE′). The upper limb appears thicker at this location on section G″ G‴ as it is close to the hinge zone of the BUS. The tongue of pelite with quartzite to the east of it at locality F, where the F2 axis plunges due east (Fig. 6, plot A) is due to the intersection of the bottom limb of the BUS with the ground surface, and the semi-circular patch of pelite with quartzite to the west of it, at locality G, is part of the lower limb downthrown to the west, as shown on section HH′ (Fig. 7).

On the south limb of the Dome, from locality H to locality I, the F2 axis plunges consistently west at 1–7° (Fig. 6, plots C and D). The BUS closure is in the pelite (section II′). The closure at locality I is due to a W-plunging warp of the BUS (Fig. 7, section CC′) the latter being the continuation of the fold core which passes through Coire Daimh.

The lower limb of the Glen Lochy Anticline is seen as an elliptical area on the south side of the Dome, as shown in sections CC′ and DD′ (Fig. 7). A clear understanding of the relationship between structure and topography is required in order to appreciate the outcrop shape that results when the angle of dip and the angle of terrain slope are similar. Confirmation of the closure of the Glen Lochy anticline has been found during the current mapping of Coire Sheileach, where the Beinn Udlaidh Quartzite is infolded several times with the Meall Garbh Psammite. The contact of the Coire Daimh Pelite Formation occurs at a low angle both above and below the quartzite in the larger eastern burn at [NN 3047 3266] (Fig. 4) and [NN 3036 3259] respectively, and the quartzite itself closes in the forest to the SE (Fig. 9, section 2). The lower topography to the west exposes only the pelite (Fig. 9, section 3) but the tip of the sharp hinge of this downward-facing anticline reappears in the quartzite close to the pelite boundary near the old military road. The closure in Allt na Luaidhe [NN 2792 3138] has been plotted on section 4 of Figure 9. Less than 100 m to the west, the hinge in quartzite has been down-faulted so that only the upper limb is exposed (Fig. 9, section 5).

3.3. The early folds (D1 & D2): their structural geometry and associated fabrics

3.3.1. Relative ages of the major structures. The Beinn Udlaidh Syncline has the hallmark of a primary fold. No earlier major folds have been recognised (i.e. from a folded repetition of stratigraphical units), and there is a notable lack of minor folds refolded by the main phase structures congruous to the syncline. The minor folds associated with the syncline have a penetrative axial-planar schistosity, do not fold an earlier lineation, and in the field do not appear to deform an earlier planar fabric apart from bedding. However, several examples of refolded isoclines have been found in the River Orchy at [NN 244 323] (Fig. 3A, C), and microscopic examination of the axial-planar fabric associated with the main phase folds, and its relationship to the internal fabrics of regional metamorphic garnets, shows that these folds are of D2 age.

3.3.2. Internal fabrics in garnet porphyroblasts. Non-retrogressed garnet is rare in this area (Roberts & Treagus 1975), but occurs at several places in the Coire Daimh Pelite on the lower limb of the Beinn Udlaidh Syncline in Glen Orchy. The rocks consist of alternating dark (biotite- and chlorite-rich) and light coloured (quartz-rich) laminae averaging 1–3 mm in thickness. These laminae have been strongly deformed and disrupted (Fig. 10), and it is not clear whether they represent the original lithological layering or a spaced D1 fabric. Features such as occasional grey laminae rich in disseminated graphite; a gradation in the amount of chlorite in some of the quartz-rich bands (? muddy tops to beds); and the presence of

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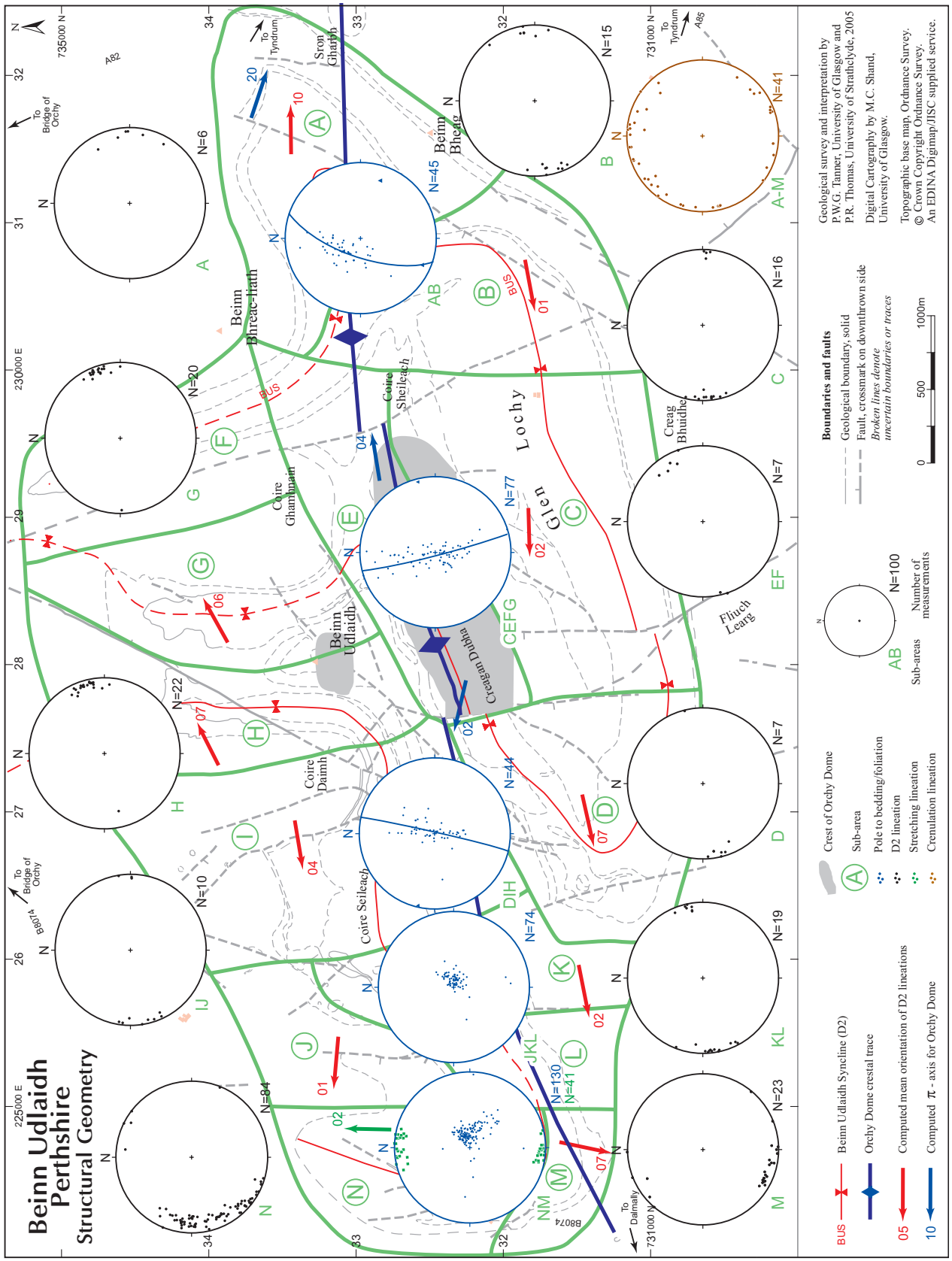

Figure 6 Structural sub-areas A–M of the Beinn Udlaidh area (delimited by dark green lines), with corresponding equal area stereographic projections (labelled according to sub-area(s); N = number of readings). The plots show the orientation of one of the following: poles to bedding (blue dots); D2 lineations (black dots); and D2 stretching lineations (green dots; the green arrow in sub-area N refers to this feature); together with crenulation lineations (brown dots). The background geological information is taken from Figure 4.

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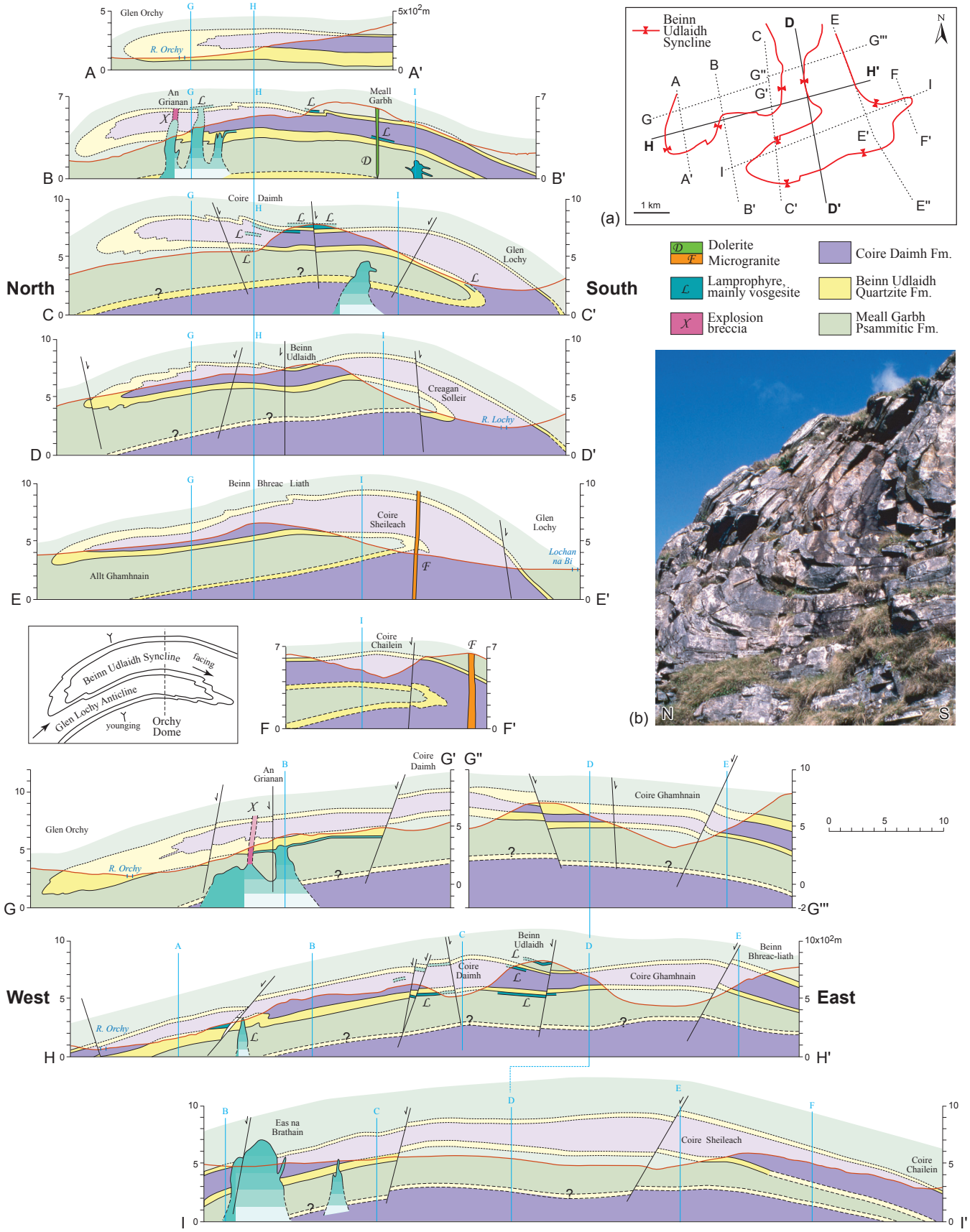

Figure 7 Serial true-scale cross-sections across the Beinn Udlaidh area: A–F (north–south) and G–I (east–west). The topographic surface is shown by a red line and the positions of intersections with other lines of cross-section are shown by thin vertical blue lines. The black-and-white sketch shows the general structure of the area as seen in a north–south cross-section. Inset (a) shows the map relationship between the axial trace of the Beinn Udlaidh Syncline and the lines of cross-section, and (b) shows a mesoscopic D2 fold above the hinge zone of the major structure north of Beinn Udlaidh at [NN 278 340]. The hammer shaft marking the axial trace of the fold is 37 cm long. Lines of cross-section are shown on Figures 4, 5, and 12.

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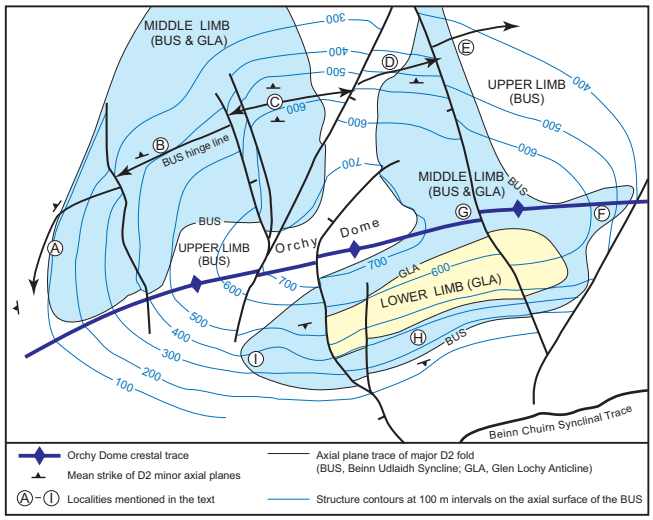

Figure 8 Synthesis of the geometry of the Beinn Udlaidh Syncline (D2) in the Beinn Udlaidh area. The map shows structure contours drawn on the axial surface of the fold, areas occupied by the lower and upper limbs, and the hingeline of the fold at the boundary between the Coire Daimh pelite and the Beinn Udlaidh Quartzite, with plunge direction arrowed. Locations A–I are referred to in the text.

recognisable quartz clasts in some layers, all support a sedimentary origin for many of the layers.

The samples studied here were collected from the River Orchy section at [NN 2442 3240] where the gross lithological layering is folded by cm- to m-scale D2 folds, which have an S-shaped profile, and are congruous to the Beinn Udlaidh Syncline. The axial surfaces of these minor folds dip at a shallow angle to the W–NW, and are marked by a strongly developed, penetrative fabric (Fig. 11); their hinges change progressively in trend from 280° to 190° as they are traced south along the section (Thomas & Treagus 1968, p. 131) and become, with increasing strain, nearly parallel to the D2 stretching lineation (Tanner, in press).

At this locality, biotite occurs in a variety of forms, as: bands intergrown with garnet (Fig. 10A); stubby biotite laths lying in S2 oblique to the lithological layering (Fig. 10B), which in some cases form a fanned axial planar array; and, most commonly, as randomly orientated crystals. The latter 'spearing' laths are the most obvious feature of the pelitic rocks because they are commonly unaffected by the chloritisation that has destroyed the accompanying garnets.

Biotite grew at a late stage of, or following, the D2 deformation. The upper time limit for biotite growth is constrained by the fact that the laths are deformed by the D3 crenulation cleavage.

Garnet occurs as subhedral to rounded crystals, up to 4 mm across, which are crowded with included trails of opaque material and minute elongated quartz grains (Fig. 10), and are in part chloritised. The crystals have irregular margins as the garnet has grown around, and enclosed, elements of the D2 fabric. The internal trails (Si) in garnet are commonly slightly curved and make a high angle with the axial trace of the minor D2 folds on whose limbs they occur (Fig. 10B). The external S2 fabric is bowed around the garnet crystals, many of which have pressure-solution tails of quartz. The rocks shown in Figure 10A & B were taken from different folds, and have been sectioned normal to the D2 hinge and oblique to the D2 stretching lineation. In many cases it is difficult to distinguish between pressure-solution tails of non-fibrous quartz (?re-crystallised) and original quartz-rich laminae (either bedding or S1 microlithons).

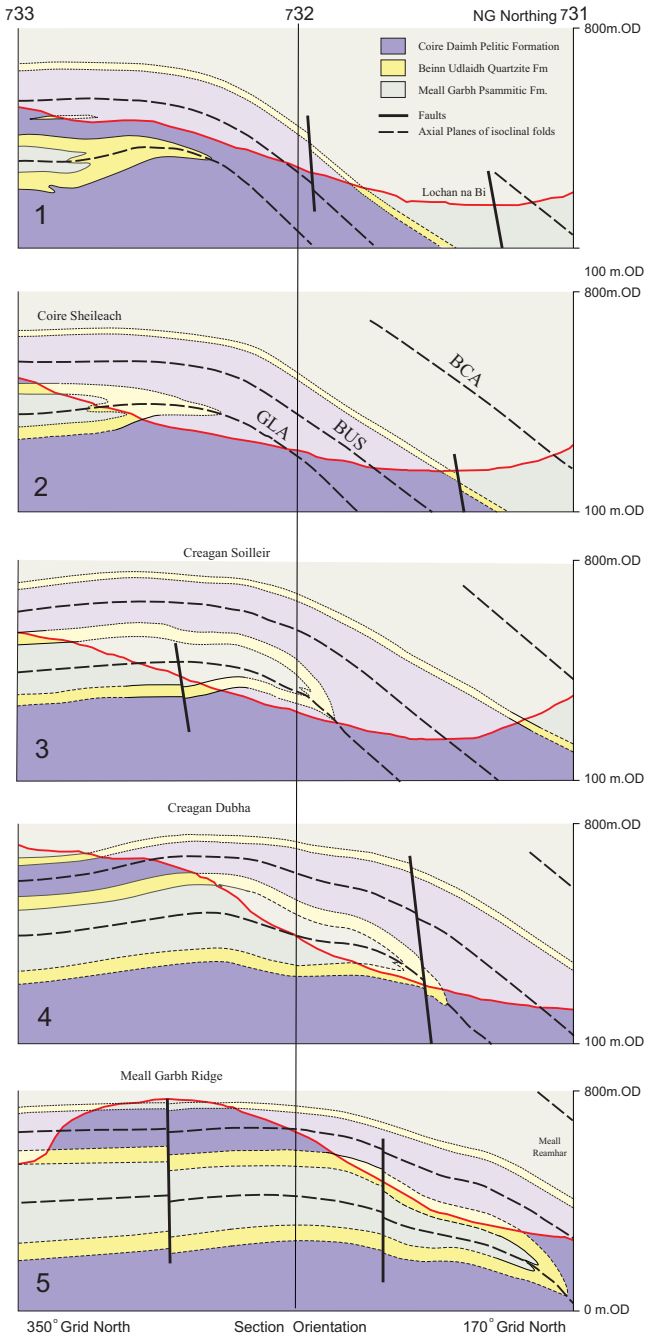

Figure 9 True-scale serial sections 1–5 of the Glen Lochy Anticline (GLA) and Beinn Udlaidh Syncline (BUS) in Glen Lochy, show the critical relationship between the topographical slope and the GLA axial plane. BCA, Beinn Chuirn Anticline. Each section is 2.05 km in length. See Figure 5 for location of the cross-sections.

The observations that the garnets contain inclusion trails that make a high angle with the external D2 fabric, and have developed pressure-solution tails lying parallel to S2, provide irrefutable evidence that garnet growth took place in the interval between D1 and D2, and that the minor folds, and hence the Beinn Udlaidh syncline, are of D2 age. What is not clear is the absolute shear sense represented by these structures. The δ-porphyroclasts divide into two populations, with the apparent sense of shear changing from limb-to-limb (top-to-S on the upper limb in Figure 10A, and top-to-N on the equivalent lower limb in Figure 10B. However, the translation of these into absolute senses of rotation is dependant upon whether the garnets or the matrix rotated during deformation, a topic that has been much debated (e.g. the memorable

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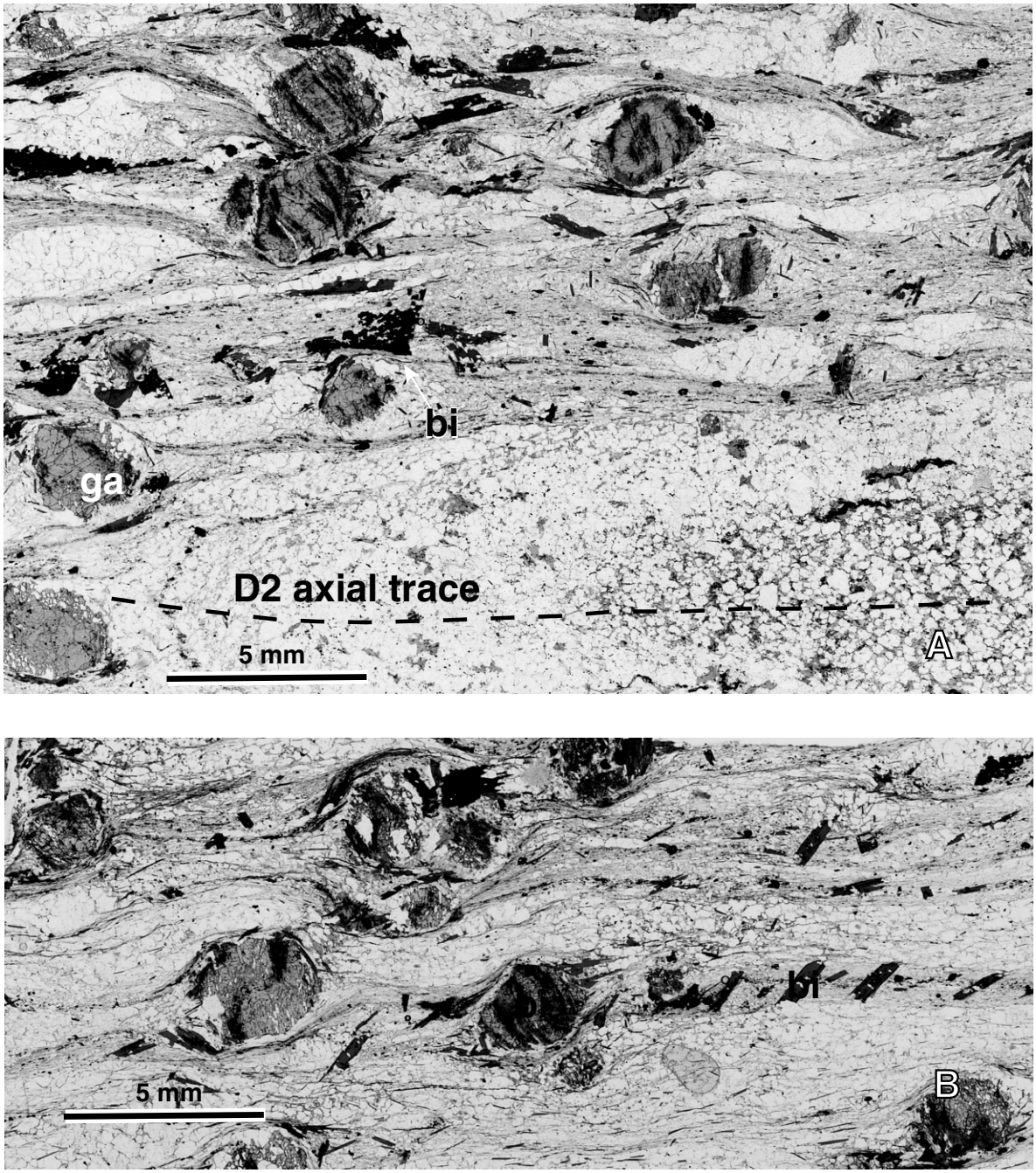

Figure 10 (A, B) Digitally scanned images of garnet–biotite–muscovite schist from two separate folds in the Coire Daimh Pelite–Beinn Udlaidh Quartzite transition zone. The direction of view is W–SW in both cases. See text for discussion. bi = biotite; ga = garnet. River Orchy at [NN 244 323].

interchange between Bell *et al.* 1992, Passchier *et al.* 1992, and Johnson 1993), and requires further investigation

3.3.3. D2 minor structures. The change in vergence of minor D2 folds, which are locally abundant in the Beinn Udlaidh Quartzite and the Grampian Group psammites, was used to locate the position of major fold traces. Bedding/S2-schistosity relationships are rarely seen, and minor folds are not common on the attenuated, parallel-sided major fold limbs. Some minor folds have a highly strained long limb, which mimics the geometry of the Beinn Udlaidh Syncline–Beinn Chuirn Anticline fold-pair and indicates top-to-the-SSE simple shear (Fig. 11A).

Mineral, rodding and striation lineations are developed parallel to the local minor fold hinges, especially in the quartzite (Figs 5 & 6). The D2 schistosity is commonly parallel to the lithological banding in the pelitic rocks, generally absent in the quartzite, and forms a distinct axial planar fabric to minor folds in the Meall Garbh Psammite. As the parent rock seldom splits parallel to the schistosity, reliance has to be placed on measuring the axial planes of the minor folds. However, this is no easy matter, as these usually dip at <20° (Fig. 5), and a board/spirit level mounted on a tripod was used for the purpose.

A stretching lineation is only seen clearly in the western one-third of the area (Figs 5 & 6), and is of D2 age. It is seen as a faint striation lineation, commonly with a silky appearance in fine-grained rocks, defined by minute micas and elongated quartz grains, and characterised by aligned dark specks <1 mm long, of indeterminate origin. The stretching lineation is weakly developed on the lower limb of the Beinn Udlaidh Syncline (Fig. 11B), whereas on the upper limb of the fold in Glen Orchy, the quartzite is reduced to a thickness of

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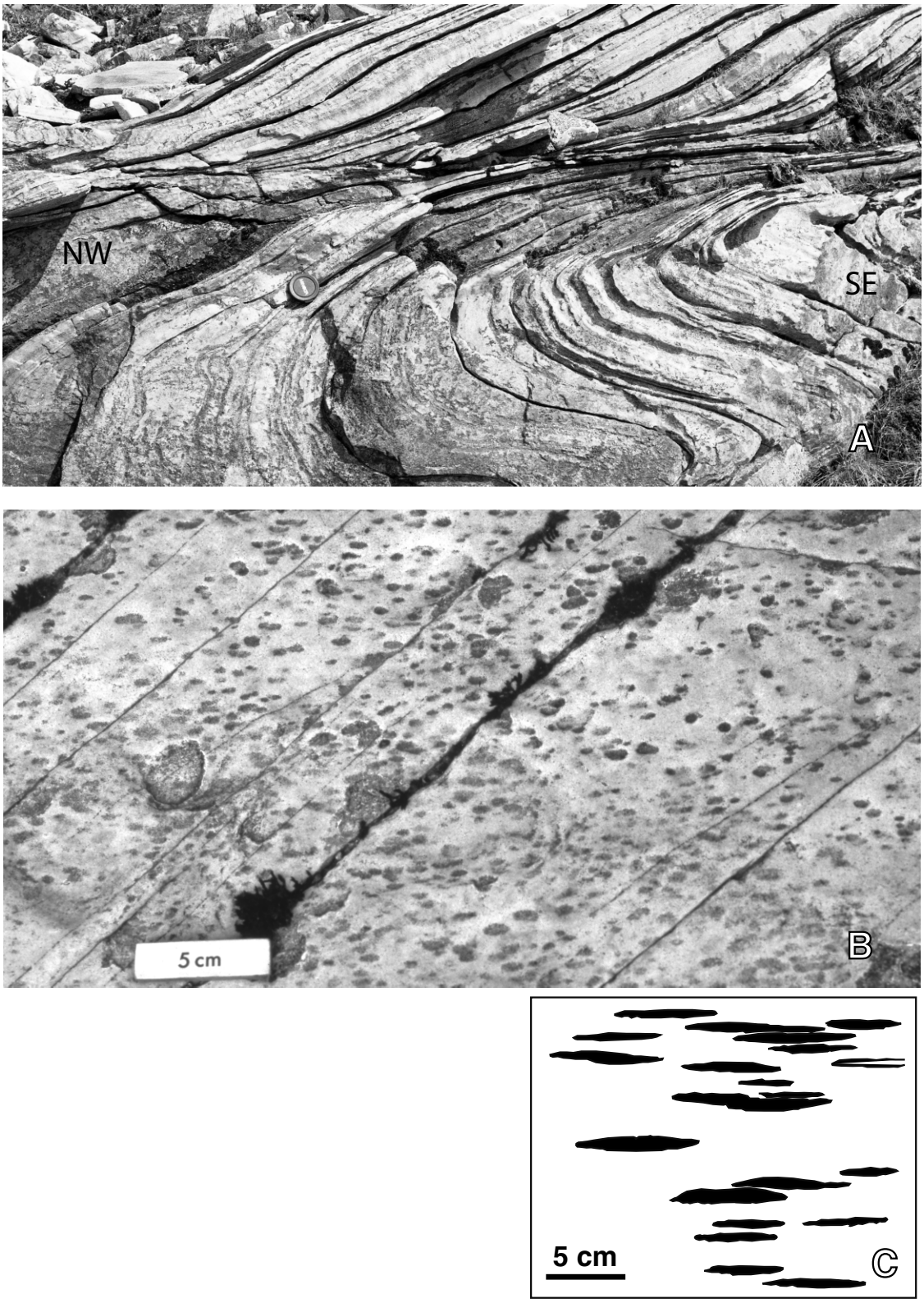

Figure 11 Features of the D2 deformation. (A) Minor D2 folds from the upper limb of the Beinn Udlaidh Syncline. The geometry of the lower fold is analogous to that of the major syncline, having a strongly sheared and thinned upper limb and normal lower limb. The lens cap is 5 cm across, and the direction of view is to the NE. North flank of Beinn Udlaidh [NN 278 341]; (B) D2 stretching lineation on the lower limb/hinge zone of the Beinn Udlaidh Syncline in the Beinn Udlaidh Quartzite Formation, defined by weathered feldspar-rich clasts (aligned N–S, approximately parallel to the 5 cm scale). Bed of River Orchy at [NN 2474 3333]; (C) Inset showing a field tracing of the shapes of deformed pebbles whose long axes trend N–S and lie on a bedding surface in the Beinn Udlaidh Quartzite Formation on the upper limb of the Beinn Udlaidh Syncline. Allt an Fhaing [NN 249 314].

22 m and pebbles lying on the bedding plane are highly elongated parallel to the stretching lineation (Fig. 11C).

Small clasts in the Beinn Udlaidh Quartzite are generally flattened in the foliation plane, and define a fabric (S1), which may be traced around the hinge zones of close to tight D2 minor folds. However, in more highly deformed quartzite, feldspathic clasts in particular are flattened in S2. Where the D2 strain is low, the stretching lineation is symmetrical to the

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curvilinear D2 fold hinges (Fig. 3A, B), and west of Allt na Luaidhe [NN 2768 3157] the two are almost at right angles. Where the D2 strain is high, the D2 hinges and stretching lineation are virtually parallel.

3.4. The later structures (D3 & D4)

Several sets of crenulation cleavages and lineations occur in the area (Figs 5 & 6, combined plot A–M) but are not accompanied by any mesoscopic structures and probably pre-date the only late major structure, the Orchy Dome.

Minor D3 folds associated with a crenulation cleavage are seen locally within the area. For example, they occur on the upper limb of the Beinn Udlaidh Syncline south of the dam below the Iron Bridge at [NN 2419 3177], as described above. This is an important locality historically, as these D3 structures were regarded by Roberts & Treagus (1975) as being of D2 age in their chronology.

Minor asymmetrical folds, locally refolding isoclinal D2 structures, have also been found north of the summit of Beinn Udlaidh [NN 2796 3357] and on the summit of Meall Garbh [NN 2670 3237]. A strong axial planar spaced cleavage (S3) has developed at a higher angle than the (S2), and dips at 20–40°SW. A late N-trending crenulation cleavage associated with minor upright folds, which plunge at low angles to the N and NW is locally well developed in pelitic rocks on the Glen Orchy side of the Orchy Dome, whilst on the Glen Lochy side, similar crenulation lineations have a mean plunge of 15°WSW.

3.4.1. The Orchy Dome. The presence of a regional-scale dome affecting the rocks of the area was first recognised by Bailey & Macgregor (1912), who named it the Glen Orchy Anticline. In this present project, the shape of the structure has been quantified by drawing separate sets of structure contours on the pelite/quartzite contact on the upper limb (Fig. 12) and lower limb (Fig. 12, inset), respectively, of the Beinn Udlaidh Syncline. These contours were based on both the intersection of the contact with the topographic contours, and its position in the true-scale cross-section(s). The result is an internally consistent set of structure contours based on an actual, mapped contact. The contour pattern (Fig. 12), shows that the dome has a mean trend of 077°, plunges at 0–20°, to either E or W, has a steeper southern limb dipping at 26°, and an inter-limb angle varying from 146° (N–S) to 150° (E–W). On Figure 6, poles to bedding/foliation for groups of sub-areas transverse to the dome are plotted as a series of five equal area projections in blue, and show that the eastern part of the dome plunges at 4–20°E, whereas the western half of the dome, beyond the horizontal crest, plunges 5–18°WSW. The structure is at least 5 km across and >800 m high, with the long axis of the dome trending parallel to the hinge lines of the BUS and GLA. A 3-D representation of the structure is shown in Figure 13. Minor structures associated with the Orchy Dome are difficult to recognise, but there are many m-scale open warps of the foliation in the quartzite and Meall Garbh Psammite that are probably of this generation.

3.4.2. Age of the Dome. The age of the doming has been controversial for some time. Thomas & Treagus (1968) and Thomas (1979,1980) considered the dome to be contemporaneous with the collapse of upright primary major folds, but Roberts & Treagus (1975,1979) reinterpreted the dome as being formed by a combination of later deformation events.

In order to test the possibility that emplacement of the lamprophyre suite in the area was structurally controlled, and hence raise the possibility of using radiometric dating to constrain its age, the locations of all of the minor igneous intrusions were plotted on Figure 12.

The igneous rocks consist of sheets and bosses of olivine-pyroxene-biotite-?-bearing lamprophyre, up to 700 m across. The larger intrusions probably fed a set of sills and dykes, and are associated with explosion breccia pipes (Fig. 7, sections BB′ & GG′). The sills are most commonly found along either margin of the Beinn Udlaidh Quartzite, and some are linked by dykes, which themselves follow fault planes. However, fracture zones are also found to 'disappear' into the intrusions without trace, which would suggest that the dykes and faults developed contemporaneously.

Several near-cylindrical explosion breccia pipes up to 50 m across occur on the northern flank of Meall Garbh. They consist of randomly orientated, angular blocks of metaquartzite and psammitic schist up to 60 cm across, with little or no matrix separating them. One such pipe clearly cuts an appinite intrusion running along a NNW-trending fault on the west side of Coire Daimh at [NN 2665 3384].

Although the greatest concentration of lamprophyre intrusions and pipes lies some 2 km W of the crest of the dome, as defined by structure contours (Fig. 12), it does coincide with the section of the dome where the mean bedding/foliation is near horizontal (Fig. 6, plot JKL). Within this limited area, large irregularly-shaped intrusions pass outwards into sills, with dykes being most common around the periphery. This relationship between dome geometry and the distribution of minor intrusions suggests that the lamprophyre magma was emplaced into a pre-existing domal structure. Thus the crystallisation age of the lamprophyre suite should provide a minimum age for the formation of the Orchy Dome.

No radiometric data are available for the Beinn Udlaidh lamprophyre suite, but other neighbouring complexes such as those in Appin, 30 km to the NW, and Garabal Hill and Arrocher, 15–30 km to the south, give remarkably consistent U–Pb (titanite & zircon) ages in the range, 422–429 Ma (mid-Silurian) (Rogers & Dunning 1991).

4. Regional correlations

4.1. Regional stratigraphical correlations

The main features of interest are the systematic regional changes in lithology and thickness of the Lochaber Quartzite Formation and the nature of the transitional assemblages found between it and adjacent formations.

4.1.1. The Grampian Group. The lithological changes observed at the top of the Meall Garbh Psammite in the Beinn Udlaidh massif, are interpreted as facies variations analogous to those previously recorded at this stratigraphical level (Thomas 1979,1980; Glover & Winchester 1989; Glover 1993). The Grampian Group banded psammites of the Beinn Udlaidh area continue northwards across the Ericht–Laidon fault to Beinn Toaig [NN 263 456] (see Fig. 1) where the psammitic schists are rich in dune bedding and ripple laminations (Thomas 1979; Glover & Winchester 1989) and young consistently into the overlying quartzite of the Lochaber Subgroup. Sedimentary structures in the intervening rocks are sparse, so that the possible continuation of the Beinn Chuirn Anticline north of Bridge of Orchy is uncertain (Fig. 1) (Thomas & Treagus 1968). However, farther north, in the Black Mount area [NN 2748], psammitic rocks are similarly overlain by a quartzite attributed to the Lochaber Subgroup (Fig. 1).

At a similar stratigraphical level in Glen Spean (Fig. 1), Glover & Winchester (1989) reported a local facies (the Uilleim Semipelite) at the top of the Grampian Group, which appears to be similar to the semi-pelitic facies underlying the Beinn Udlaidh Quartzite Formation in part of the Beinn Udlaidh area. Likewise, in the Ossian Steep Belt, 20 km NE, near Corrour [NN 338 667] (Fig.1), and on Beinn Na Lap [NN 380 699], thin bands of quartzite and semipelite may

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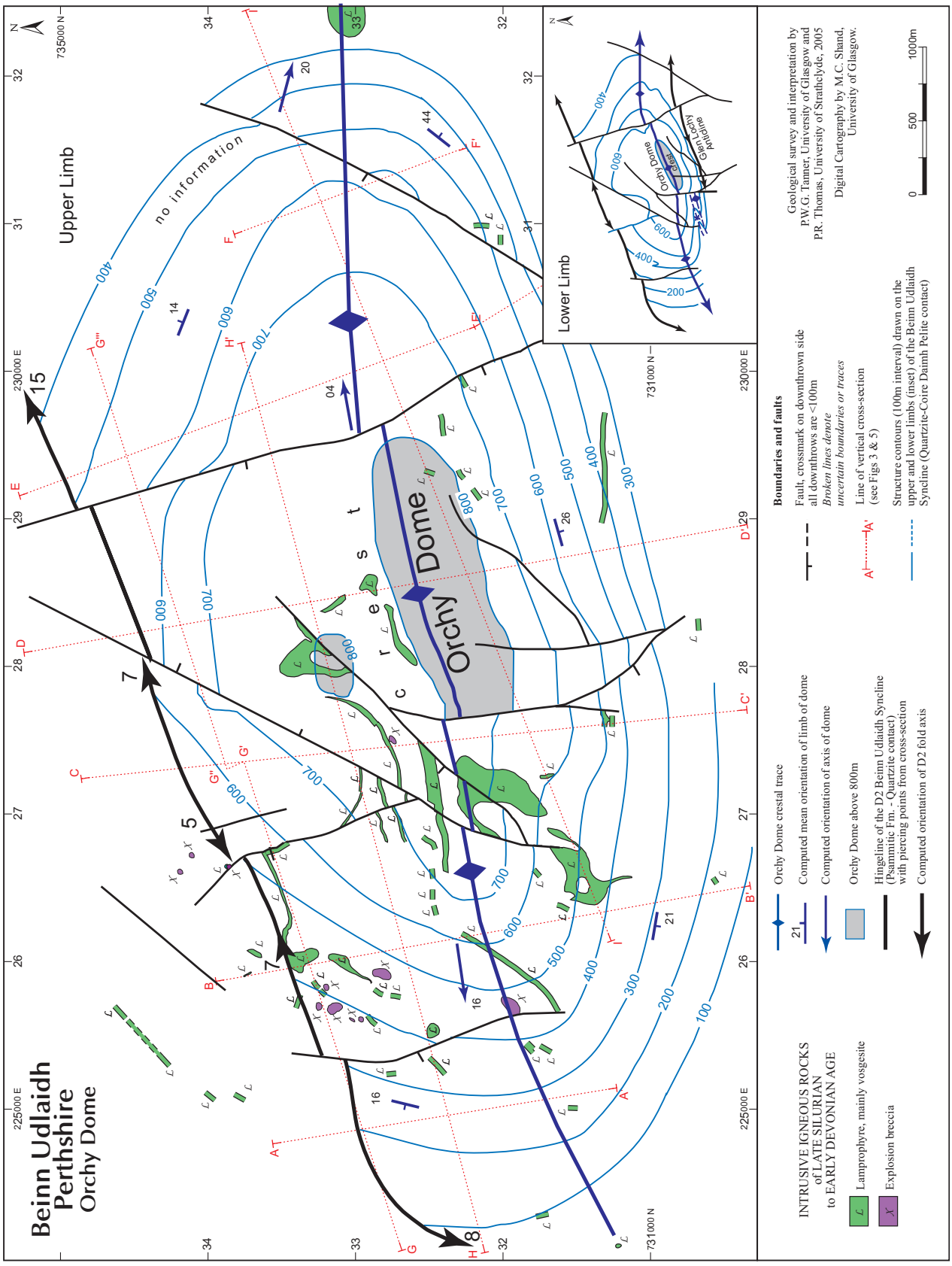

Figure 12 Geometry of the Orchy Dome, and the distribution of outcrops of the lamprophyre suite. The geometry of the Dome is based on structure contours drawn on the upper limb of the Beinn Udlaidh Syncline (hingeline shown by the bold black line) at the Beinn Udlaidh Quartzite–Coire Daimh Pelite contact). The inset diagram shows the corresponding set of contours drawn on the same contact, but on the lower limb of the Syncline, together with the orientation of the hingeline of the Glen Lochy Anticline.

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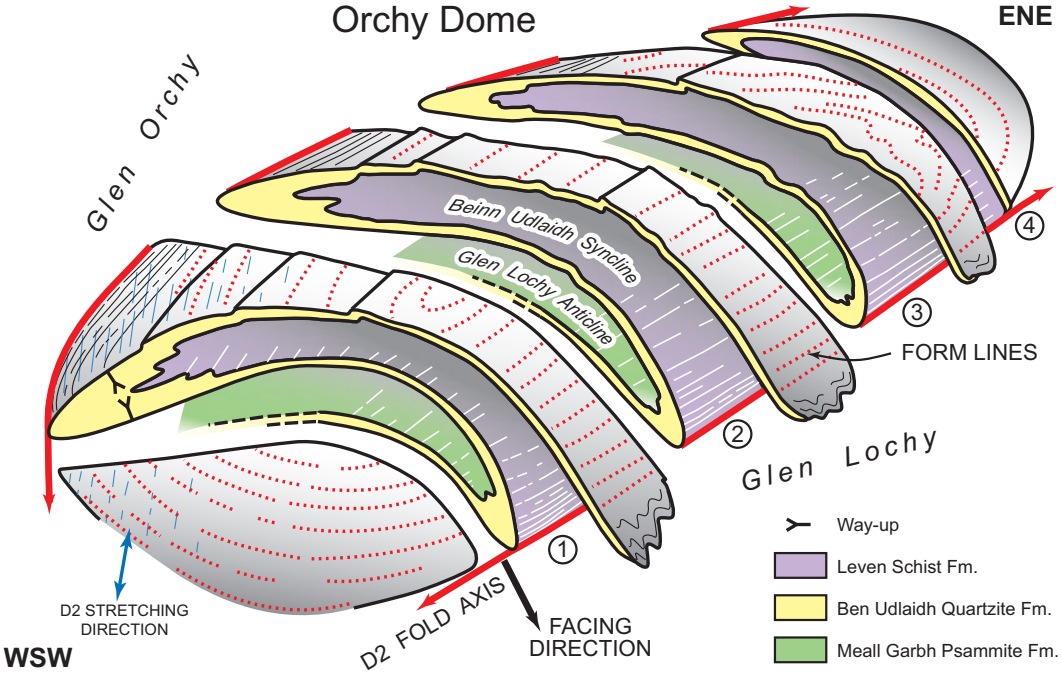

Figure 13 3-D schematic diagram showing the geometry of the major D2 folds refolded by the Orchy Dome in the Beinn Udlaidh Massif, Perthshire. Form lines are drawn schematically.

represent this transition. Farther east in the Strathtummel area (Thomas 1980; Treagus 2000), quartzite bands occur within the psammite for up to 1000 m below the base of the Lochaber Subgroup.

4.1.2. The Lochaber Subgroup. The boundary between the Grampian Group and the Appin Group, at the base of the Lochaber Subgroup, is difficult to delineate in the west Central Highlands due to the multiplicity of quartzites at this stratigraphical level. In the Kinlochleven area (Fig. 1), three distinct, major quartzite formations, separated by banded pelitic schists, overlie the Grampian Group. The purest and uppermost of the quartzite formations, the Glencoe Quartzite, most closely resembles that of Beinn Udlaidh, and was correlated with it by Bailey & Macgregor (1912) and by Thomas & Treagus (1968). The present authors can see no good reason to change that view. However, in the intervening ground east of Loch Dochard [NN 215 425] (Fig. 1), only two quartzites have been mapped, with a semipelitic formation below the upper, thinner quartzite.

The Coire Daimh Pelite Formation is correlated with the Leven Schist, which is a widespread formation with a characteristic striped appearance that tops the Lochaber Subgroup, and is overlain by the first calcareous formation of the Dalradian, the Ballachulish Limestone.

4.2. Regional structural correlations

The regional geological setting of the Beinn Udlaidh area is shown in Figure 1, and a section across the major structures is given in Figure 14.

South of Beinn Udlaidh, the Glen Lochy Anticline and the Beinn Udlaidh Syncline are succeeded structurally upwards by the Beinn Chuirn Anticline, the Iltay Boundary Slide and the Ben Lui Syncline (Roberts & Treagus 1975) (Fig. 2). All previous workers concur that, on the south limb of the structure here named the Orchy Dome, all of the major folds face downwards to the SE (Cummins & Shackleton 1955; Roberts & Treagus 1964; Thomas & Treagus 1968; Roberts & Treagus 1975), although the interpretation of their *relative* ages has changed as structural techniques have evolved over the period. For example, Cummins & Shackleton (1955, fig. 2) considered that all of the major structures were of primary (D1) age, but Roberts & Treagus (1975), following Thomas & Treagus (1968), interpreted the Beinn Udlaidh Syncline and Glen Lochy Anticline as D1 structures which were refolded by a major D2 fold (Beinn Chuirn Anticline), and progressively excised by syn-D2 movement on the Iltay Boundary Slide. These three folds lie structurally below the Ben Lui Syncline, which has also been recognised to be a D2 fold (Roberts & Treagus 1964). Now that the two major recumbent folds in the Beinn Udlaidh area have been shown to be of D2 age, and not D1, it is important to discuss how this conclusion may be reconciled with those previous interpretations, and the fact that the Iltay Boundary Slide is considered by some workers to represent a stratigraphical onlap surface, modified by later deformation, and not a major tectonic break as previously thought (Krabbendam *et al.* 2002).

Roberts & Treagus (1975) reported that the D1 minor folds around the southern end of section A–B in the Ben Lui Schist (Fig. 1) are relatively open structures with a clearly defined, penetrative, axial planar cleavage that is commonly crosscut by a closely-spaced D2 crenulation cleavage. Tracked northwards to the Iltay Boundary Slide, the minor D1 folds become isoclinal and difficult to detect (Roberts & Treagus 1975) and, in conjunction with this change, the D2 structures become progressively dominant in the vicinity of the Beinn Chuirn Anticline (Fig. 14). The final stage in this process, as seen in the Beinn Udlaidh area, is that the D1 fabric is destroyed by recrystallisation and the development of a penetrative D2 schistosity (Fig. 14). This process is so complete that no elements of the earlier fabric (S1) are recognisable in the field, even under the hand lens, and it is not surprising that Thomas & Treagus (1968) recorded it as the earliest tectonic fabric (S1).

A critical locality for illustrating this structural correlation problem is that described by Roberts & Treagus (1975) 100 m downstream of the Orchy weir [NN 2419 3177]. The rocks here lie on the upper limb of the Beinn Udlaidh Syncline and comprise thinly banded psammites and semipelites of the Grampian Group. Z-shaped minor folds plunging at 0–11° to 177–195° that are congruous to the major structure are overprinted by a strongly developed crenulation cleavage

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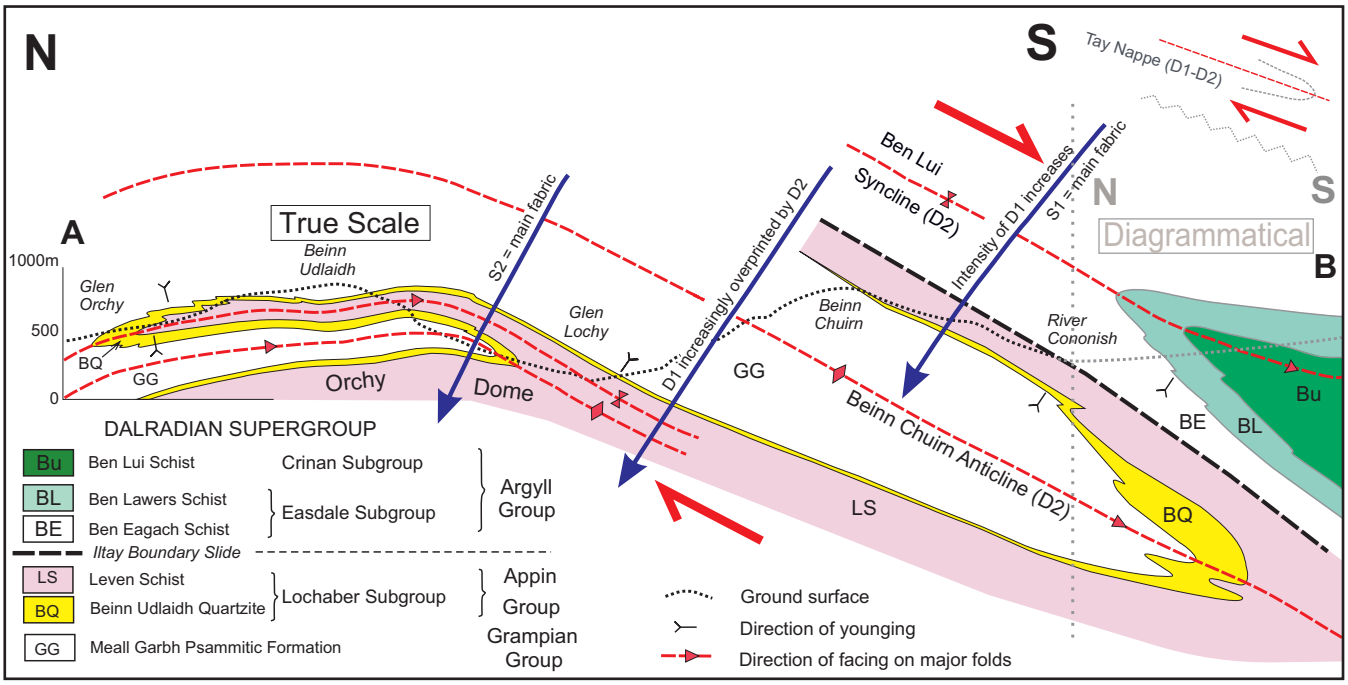

Figure 14 Part true-scale (after Fig. 7 and unpublished mapping by PWGT) and part-diagrammatical, N–S cross-section across the major D2 folds in the Beinn Udlaidh area, and in the ground to the south (data from Roberts & Treagus 1975). A–B=line of cross-section shown on Figure 1.

associated with an almost coaxial suite of minor folds plunging at 5–15° to 155–180°, having the opposite vergence. For the reasons given above, Roberts & Treagus (1975) identified the Z-shaped minor folds as D1 structures overprinted by the D2 crenulation cleavage, whereas in thin-section it can be seen that the axial planar fabric associated with each set has features characteristic of S2 (axial-planar biotite laths) and S3 (biotite laths folded), respectively.

The criteria for distinguishing between the minor structures characteristic of D1–D3 are as follows: (i) the abundant minor folds seen in the field and especially in the quartzite, show by their change in vergence and geometry that they are of the same age as the Beinn Udlaidh Syncline; (ii) their axial planar fabric is correlated with the main fabric seen throughout the inlier; (iii) in thin section, this foliation is seen to postdate the growth of garnet porphyroblasts, which enclose an internal fabric (S1) that is at >75° to the main fabric; (iv) rare isoclinal folds (see Fig. 3C) are refolded by minor D2 folds and transected by S2; (v) both the matrix biotite, together with larger biotite laths found in the garnet-bearing rocks, are commonly orientated parallel to S2 (Fig. 10a); (vi) the main fabric and the biotite laths are crenulated in S3.

Forty kilometres to the NE, the structure of the Beinn Udlaidh area, underlying the Iltay Boundary Slide, is repeated in the Strathtummel area of the Central Grampian Highlands, where the Meall Reamhar Synform is now thought to be D2 in age, and occupies a position analogous to the Beinn Chuirn Anticline (Treagus 2000). More recently, the British Geological Survey (Leslie *et al.* 2006) working a further 20 km to the NE in the Gaick region, within the same original sedimentary environment (Strathtummel Basin), and the same structural corridor (bounded by the Ericht–Laidon and Loch Tay faults), have reported major S-facing D2 folds accompanied by a N–S stretching lineation. No major D1 folds were recognised and D3 is only represented by minor structures.

Until recently, recognition of a single, pre-D2, amphibolite facies regional metamorphism in the Beinn Udlaidh area, marked by the growth of biotite and garnet porphyroblasts, would have been considered anomalous by some authors (e.g. Dempster & Harte 1986) with respect to the timing of regional metamorphism in the overlying Tay Nappe. However, Roberts and Treagus (1975) reported pre- to syn-D2 growth of garnet from rocks *above* the Iltay Boundary Slide, and a recent detailed study of the timing of regional metamorphism in the area north of Loch Lomond (10–20 km S of Beinn Udlaidh) shows a very similar, albeit slightly later, sequence of mineral growths (Mathavan & Bowes 2004). In the latter area, garnet growth occurred from pre- to syn-D2 and, as at Beinn Udlaidh, biotite is post-D2 in age.

Some of the major aspects of the new interpretation for the region south of Beinn Udlaidh discussed above, are shown in Figure 14. These are as follows:

1. D1 minor structures, that are dominant at high structural levels, are reworked and obliterated with increasing structural depth. For example, the D1 cleavage is a cm-spaced pressure solution fabric in most of the greenschist facies rocks near the Highland Border, but becomes a penetrative cleavage with depth, and is overprinted and ultimately destroyed by an increasingly intense, penetrative D2 fabric;
2. S2 changes from a spaced crenulation cleavage, to a spaced cleavage, to a penetrative, generally non-striped schistosity with an increase in confining pressure and T;
3. The stretching lineation trends NW–SE at a high level in the section, where it results mainly from the D1 deformation (Roberts & Treagus 1975, p. 63), and changes to a N–S direction at depth, in conjunction with an increase in D2 deformation;
4. There is evidence of a top-to-S shear sense across the three lowermost major D2 folds;
5. The Iltay Boundary Slide is a modified unconformity located within the common limb to the Ben Lui and Beinn Chuirn folds, along which some bedding-parallel slip possibly occurred during the folding, together with shear strain resulting from the viscosity contrast across this boundary.

The data presented in the present paper, supplemented by that from earlier publications on the Dalradian stratigraphy

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and structure south of the Iltay Boundary Slide, indicate that a single unified sequence of structural and metamorphic events pertains for rocks on both sides of the Slide. Thus, it can be demonstrated on both stratigraphical and structural grounds that there is no evidence for an orogenic unconformity in this region (Dempster *et al.* 2002; Hutton & Alsop 2004; but see Tanner *et al.* 2005), either at the base of the Appin Group, or between the Central Highlands and the Tay Nappe, at the line of the slide.

5. Discussion and conclusions

The Beinn Udlaidh area in the Central Highlands of Scotland consists of strongly folded Neoproterozoic–Lower Ordovician Dalradian rocks, which form a concordant stratigraphical sequence. Interbedded psammites and semipelites belonging to the Grampian Group are overlain by the Beinn Udlaidh Quartzite, which is the basal member of the Appin Group, and succeeded by characteristically striped pelites belonging to the Leven Schist. These units are linked by an unusual sedimentary transition found at both the top and the base of the Beinn Udlaidh Quartzite. Lateral facies changes from psammite to semipelite occur at the top of the Grampian Group on both a regional and a local scale. The changes are more marked on a regional scale, for example the quartzite members at the base of the Appin Group decrease in number southward from three at Kinlochleven (Fig. 1), to the single member on Beinn Udlaidh, which is only a few metres thick farther south on Beinn Chuirn (Tanner, unpublished data).

The structure is dominated by two, major SE-facing, isoclinal recumbent D2 folds, the Beinn Udlaidh Syncline and the Glen Lochy Anticline, which masquerade as D1 structures. However, they post-date an earlier fabric, which was virtually destroyed by a strong S2 overprint and is only preserved as internal inclusion trails in rare, non-chloritised regional metamorphic garnets. The internal trails are at a high angle to the external D2 fabric, and the garnets have developed pressure-solution tails in the S2 fabric.

The intensity of the overprinting is an important feature of the structural evolution and explains why the major folds have been previously misidentified as D1 structures. The D2 fold axes trend NE–SW at about 70° to the stretching direction, across most of the area. However in the east, the axis of the Beinn Udlaidh Syncline has been rotated into near parallelism with the N–S-trending stretching lineation, due to a local increase in D2 deformation. The shear sense recorded parallel to this lineation on the long limbs of D2 folds is top-to-S.

No major D1 folds are present, and there is a close analogy with the Connemara Dalradian inlier in the west of Ireland where the major early structure is of D2 age (Tanner & Shackleton 1979). The S2 fabric is dominant throughout the inlier, and there are no D1 major folds; minor D1 folds have not been recognised; and S1 is only preserved as inclusion trails in garnet. Similarly, the Dalradian rocks of NW Ireland are affected by a regional D2 fabric but there is "no evidence of associated F1 folding or bedding cut across by S1, and the vergence and facing of D1 is thus indeterminable" (Alsop *et al.* 2001, p. 201).

The Beinn Udlaidh Syncline and Glen Lochy Anticline are comparable in size to the smaller of the nappes mentioned in the Introduction, such as the Morcles Nappe. Indeed, they can be considered as parasitic folds on the lower inverted limb of the much larger Beinn Chuirn Anticline (Fig. 14), which lies structurally beneath a fold of comparable size, the Ben Lui Syncline. However, all of the folds in this recumbent D2 stack are dwarfed by the overlying Tay Nappe, which can be traced for over 200 km parallel to the Highland Border, and is an order of magnitude larger than the Beinn Udlaidh Syncline. All of these folds reached their maximum amplitude following the peak of the regional metamorphism. Their mode of origin is uncertain but it seems most likely that they were preceded by open, upright D1 major folds, which resulted in the crustal thickening that was a major factor in causing the post-D1 to pre-D2 lower amphibolite facies regional metamorphism in the area. As in the case of the Tay Nappe, these folds were rotated to the SE by non-coaxial shear (Treagus 1987; Krabbendam *et al.* 1997); this occurred during the later stages of D1, during D2, or possibly during a D1–D2 continuum (Tanner 2007, 2008). The recumbent major D2 folds were then gently warped by the formation of a regionally important structure, the Orchy Dome. Structure contours drawn separately on the folded limbs of the Beinn Udlaidh Syncline reveal the slightly asymmetrical, elongated shape of the 076°-trending dome. There is a concentration of lamprophyric dykes, sills, and explosion breccia pipes in an area close to, but offset by ~2 km, from the crest of the Orchy Dome, suggesting either that the intrusive activity was coeval with the formation of the Dome, or that its location was controlled by the existing structure. The lamprophyre suite is probably of the same age (c. 426 Ma; mid-Silurian) (Rogers & Dunning 1991) as the complexes to the N and S of it, in either of the above two cases this provides a possible minimum age for the doming. A D3 crenulation cleavage is locally developed and is not accompanied by mesoscopic folds: together with other sets of crenulation cleavages it appears to pre-date the development of the Dome.

A synthesis of the new information from Beinn Udlaidh and that of the adjoining area to the south, demonstrates that there is continuity of structural, regional metamorphic, and probably kinematic, events between rocks of the Central Highlands, structurally below the Iltay Boundary Slide, and those of the Tay Nappe above. In addition, it demonstrates an increase in the dominance of the D2 deformation with depth (Fig. 14), which is an important element in understanding the driving force for the Grampian Orogeny (Tanner 2008).

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