Geol. Mag. **134** (*4*), *1997, pp. 563–570. Printed in the United Kingdom*

DISCUSSIONS

The Highland Border controversy: a discussion of "New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex"

B. J. Bluck & J. K. Ingham comment: The status of the fossiliferous rocks at the Highland Border (the Highland Border Complex) has been a matter of speculation for over a century. The question has been whether the Highland Border Complex has affinities with the Dalradian block or constitutes a separate block, a sliver or slivers of which have been caught up along the Highland Boundary Fault.

Tanner (1995) has revived an older idea of Johnson & Harris (1967) that a degree of structural similarity between the Dalradian and the Highland Border Complex blocks implies that the complex is in stratigraphical continuity with the Dalradian. Although the Cambrian rocks at Leny Quarry form the core of his evidence (Tanner 1995 fig 3), the rocks in other parts of the Highland Border Complex also have a structural similarity to the Dalradian, and he quite logically includes them as part of the Dalradian sequence (Tanner, 1995, fig.6).

This view introduces a welcome rethinking of the history of the northern margin to the Midland Valley of Scotland. There are many direct, radical implications of his conclusions, two of which are:

(a) If there is stratigraphical continuity between the Dalradian and the Highland Border Complex, then as the contact between the Highland Border Complex and the Old Red Sandstone is an unconformity (Campbell, 1913; Bluck *et al*. 1984; Ingham, Curry & Williams, 1986; Fig. 2), all contacts from the Dalradian to the Old Red Sandstone are stratigraphical. There is no need for a major structural break at the Highland Border, implying there is no Highland Boundary Fault in Scotland in the sense of Anderson (1947) and Kennedy (1958) and earlier workers, i.e. no major structural break along the Highland Border (and its continuation westward into Ireland) which brings together rocks of different affinities.

(b) If there is continuity in succession between the two units then as Dalradian sedimentation began substantially before 595 Ma (Halliday *et al.* 1989) and continued substantially after mid Arenig time (*c.* 480 Ma), then this was an unusually long-lived sedimentary basin of at least 130 Ma or >25% of Phanerozoic time. If this new sequence is accepted then it fails to qualify as a long-lived passive margin succession which terminated with the Highland Border Complex. Ophiolitic rocks, including pillow lavas, serpentinite and even an amphibolite, are not the usual end *stratigraphical* members of an unbroken passive margin sequence.

We believe there is no need to resort to such radicalism and offer the simpler alternative that the structural similarity between Dalradian and Highland Border Complex is either coincidental or the result of late stage deformation. Our selected objections rest on five points, all of which the Tanner view has to refute before it can be accepted.

1. The Dalradian and Highland Border Complex were folded at different times

The steeply dipping Dalradian rocks at the Highland Border acquired their structure before 415 Ma. There are two prominent outliers or groups of outliers of Lower Old Red Sandstone rocks along the southern edge of the Dalradian and north of the Highland Boundary fault zone (Fig. 1) which, often with gentle dip, rest unconformably on it (Allan, 1928, 1940). Both these outliers contain horizontal to gently dipping basaltic andesites and locally derived conglomerates containing Dalradian clasts and sandstones typical of the Lower Old Red Sandstone of the Strathmore Syncline and Ochil–Sidlaw hills. The outlier at Lintrathen contains an ignimbrite from which Thirlwall (1988) obtained an age of 415 Ma (late Silurian, mid Ludlow Epoch), and at West Cult the Lintrathen Ignimbrite rests directly 'on an eroded surface, at present inclined at a low angle towards the south, of Dalradian slates and schists' (Paterson & Harris, 1969, p. 1).

The attitude of the Highland Border Complex was acquired during the formation of the Strathmore Syncline, i.e. post 380 Ma**.** Lower Old Red Sandstone of the northern limb of the Strathmore Syncline locally rests unconformably on various stratigraphical divisions of the Highland Border Complex (Figs 1, 2). The attitude of this complex, or at least a good deal of it, was therefore at a relatively low angle at the time of Lower Old Red Sandstone sedimentation (*c.* 415–380 Ma). Since the north limb of the syncline is either vertical, near vertical or occasionally overturned the rotation has to be up to or exceeding 90°. The youngest rocks in the syncline are at the top of the Lower Old Red Sandstone (Emsian; Scott, Edwards & Rolfe, 1976), dating the structure to late early Devonian or more realistically to middle Devonian time(*c.* 380–370 Ma).

The possibility of individual block rotations within the Highland Border Complex accounting for this problem appears to have been ruled out by the uniformity of structural orientations from outcrops spaced widely along the Highland Border, as demonstrated by Tanner (his fig. 6) and used as the basis of his premise.

It therefore follows that the general attitude of the Highland Border Complex was radically different from that of the Dalradian at 415 Ma and, as argued above, there is no reason to see continuity in these structures and therefore no reason to see continuity of succession.

2. Problems of deposition on a cooling block

Cooling ages, following thickening and regional metamorphism, for the Dalradian begin at *c.* 515 Ma (mid–late Cambrian) in the Angus region (Dempster, 1985) and are at least as old as 505 Ma (earliest Ordovician) in the eastern areas of the Buchan metamorphism (Dempster, Hudson & Rogers, 1995). Cooling reached a peak at 470–460 Ma (mid Ordovician, Llanvirn Epoch) and continued to 440 Ma (latest Ordovician) or younger (Dempster, 1985). As the Highland Border Complex rocks are at least as young as 480 Ma and probably as young as *c.* 450 Ma, partly comprising black shales, pillow lavas and cherts, it is most improbable that these predominantly deep water sediments were laid down on a metamorphic block which was cooling and presumably rising at the time.

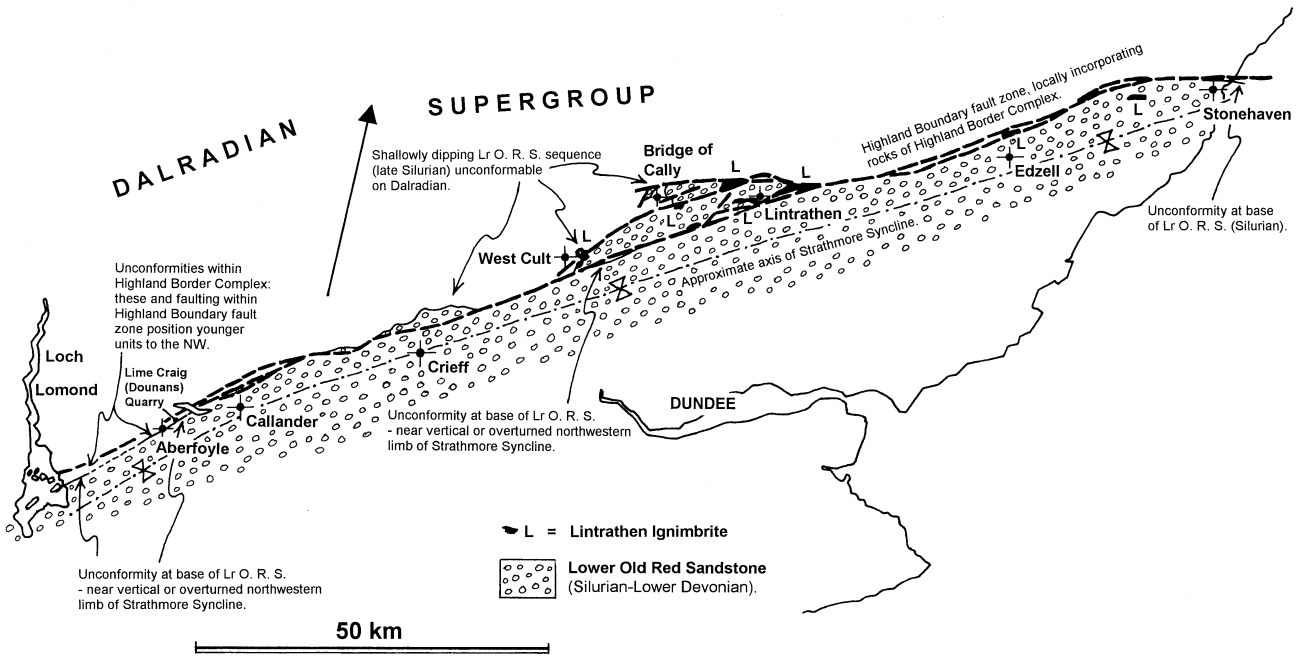

Figure 1. Simplified geological map of the Highland Boundary Fault zone, from Loch Lomond to Stonehaven, showing the position of the main sites discussed in the text and locating the positions of known unconformable relationships between the Lower Old Red Sandstone, either with rocks of the Highland Border Complex along the steep northern limb of the Strathmore Syncline, or at a low angle, north of the Highland Boundary Fault zone, where Lower Old Red Sandstone rests on steeply dipping Dalradian strata.

With the base of the Cambrian being *c.* 544 Ma (Brasier, Cowie & Taylor, 1994), it is possible within this framework of ages for the Lower Cambrian Leny limestone to have been deposited on the Dalradian before its uplift. This would presumably also apply to the Bute amphibolite, a component of the Highland Border Complex in that region. This amphibolite, dated (cooled) at *c.* 540 Ma (earliest Cambrian; Dempster & Bluck, 1991), is difficult to fit into a situation where there is stratigraphical continuity from Dalradian (Proterozoic) into Cambrian.

3. Folding events within the Highland Border Complex

The Highland Border Complex has an intricate stratigraphy yet to be thoroughly appraised: it has a great diversity in rock type ranging in age from early Cambrian to ?Caradoc. It is not surprising therefore that within the complex there are at least two unconformities (Bluck *et al.* 1984 and references therein), one of which divides a tightly folded black shale and chert sequence from the serpentinite breccias and conglomerates already sheared and folded before the shales were laid down. This relationship is exposed in a small island in Loch Lomond [NS 415913]. The other, photographed and described from near Aberfoyle by Jehu & Campbell (1917, plate V), marks the boundary between the black shale and cherts and the Achray Sandstone Formation, thought to be of late Ordovician age. Blocks of the black shales and cherts, found as clasts in the the basal Achray Sandstone breccia, are highly deformed indicating a phase of deformation prior to the deposition of the sandstone.

4. The stratigraphical order in the Highland Border Complex

With respect to the unconformities within the Highland Border Complex, the basal beds of the younger sequence in each case contains clasts of the older near to the contact. For many of the outcrops in the complex the younger beds lie to the northwest of the older, so the stratigraphical order in the Highland Border Complex is generally seen to be to the northwest, even though local sequences may young to the southeast. There are exceptions where there is structural repetition, and the exposures at Callander and the North Esk are examples.

There are two points which emerge from **3** and **4**:

(a) Regardless of local younging directions, the direction of the stratigraphical order in the Highland Border Complex is commonly towards rocks which are supposedly older and opposite to the general direction of younging in the Dalradian (Shackleton, 1958) so it seems highly improbable that both sequences are in structural continuity.

(b) With the Highland Border Complex having quite an intricate structural history with lithologies repeated in different stratigraphical and structural assemblages, lithological correlation to demonstrate structure is not possible without a tight palaeontological and stratigraphical control. Moreover, the three main limestones at the Highland Border (Leny, Dounans and Margie) are all divided from each other by unconformities or major structural breaks, suggesting each to have been involved in folding events at different times. Any attempt to map out the structure of the ground using continuity of lithologies, without being able to indentify clearly the affinity and age of each, results in the imposition of a uniform, single structural interpretation on a sequence of rocks which have undergone a multiple structural history.

On the other hand, if structures of similar orientation are found pervading all stratigraphical and structural units within the Highland Border Complex (i.e. they ignore unconformities) then it seems probable that these structures post-date the folding events within the Highland Border Complex, and are therefore late stage.

5. Exposure of the fault

The fault contact between the Highland Border Complex rocks and the Dalradian is clear where the exposure is good, namely

https://doi.org/10.1017/S0016756897007292 Published online by Cambridge University Press

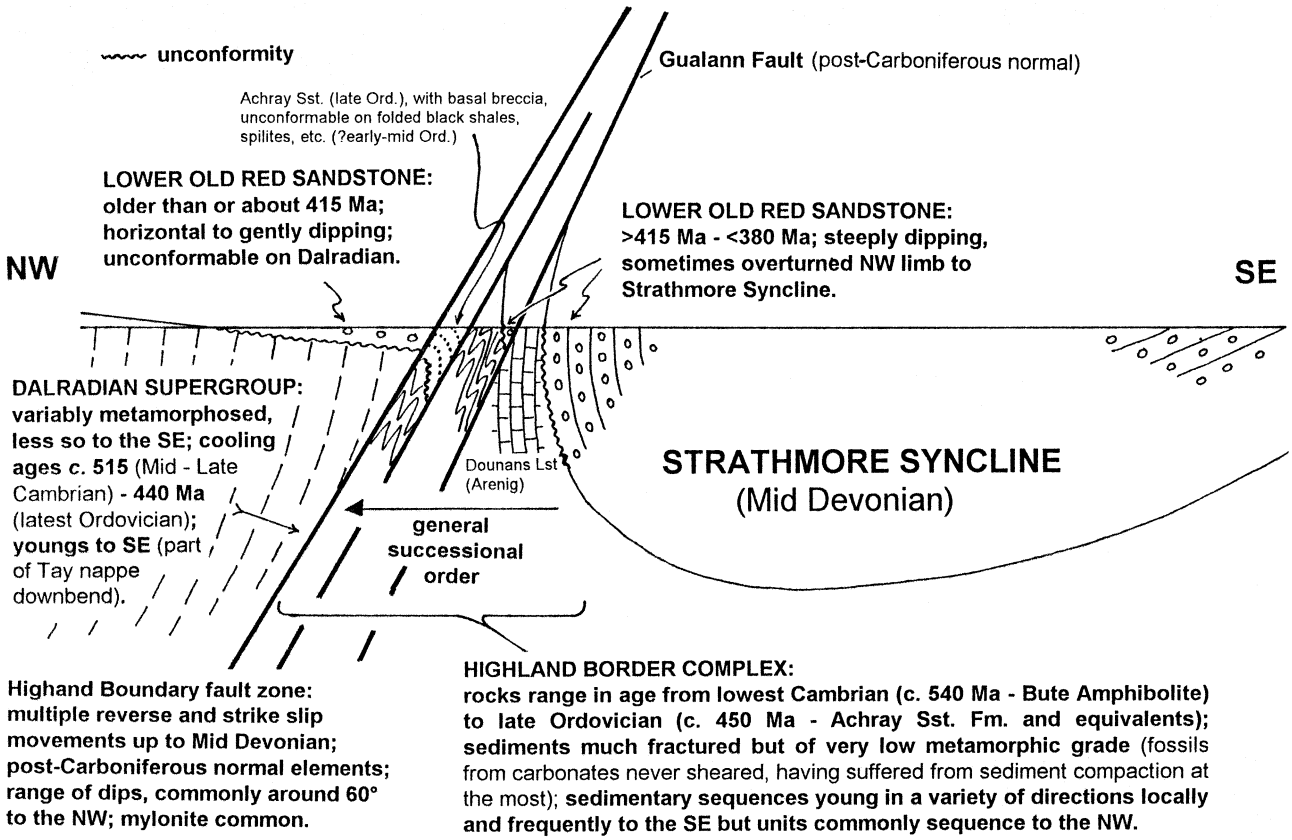

Figure 2. Diagrammatic composite cross-section from the Dalradian block of the Grampian Highlands, through the Highland Border Complex (incorporating generalized Aberfoyle, West Cult and Bridge of Cally data), to the Strathmore Syncline of the Midland Valley of Scotland. Part of the section is simplified from Allan (1928,1940); Armstrong *et al.* (1982); Bluck (1992). Other data are discussed in text or are in the listed references.

Craigeven Bay, near Stonehaven. There and in Bute and Arran the boundary is marked by a mylonite (Henderson & Robertson, 1982), implying a substantial movement between the two blocks. It is therefore surprising to have continuity in the orientations of a pre-fault fabric across this boundary.

In view of the evidence presented above, the thick mylonites at the contact between Dalradian and Highland Border Complex on Arran and Bute, the presence of the Bute amphibolite and the clear intensity of fracturing in this zone, we fail see that some structural similarities between groups of rocks in an area of indifferent exposure can challenge the evidence for the existence of a major fault at this boundary.

P. W. G. Tanner replies: I welcome the opportunity to discuss further the relationship between the Highland Border Complex and the Dalradian Supergroup, and to clarify a number of critical issues which have been raised by Bluck & Ingham. However, before responding to the numerous specific points which they raise, I would like to place the discussion in a broader context for those not familiar with the details of the fundamental dispute over the interpretation of Highland geology which underpins this dialogue. The two current hypotheses which have been proposed to explain the relationship between the Dalradian rocks and the Highland Border Complex, and hence the nature and timing of the Grampian orogeny in Scotland, may be summarized as:

Hypothesis A. The Dalradian and Highland Border rocks were deformed together (Johnson & Harris, 1967) during a single orogenic event of early to middle Ordovician age. Part of the 'Highland Border Complex', including the Lower Cambrian Leny Limestone, was deposited in continuity with the Dalradian (Harris, 1969; Tanner, 1995), but most of the Ordovician portion originated as an arc complex which docked with the Dalradian block during mid-Ordovician time, resulting in the Grampian orogeny (Ryan *et al.* 1995; Dewey, Ryan & Soper, 1995).

Hypothesis B. The Dalradian block has been affected by two orogenies: a late Proterozoic event, followed over 80 Ma later by a late Cambrian–early Ordovician event. The Cambrian–late Ordovician Highland Border Complex (which includes the Leny Limestone) developed in a back-arc basin setting well away from the Dalradian block. It docked with the latter in Devonian times, and thus does not share any major deformation events with the Dalradian (Curry *et al.*, 1984; Rogers *et al.*, 1989; Bluck, 1990; Bluck & Dempster, 1991).

These hypotheses differ radically in their interpretation of the structural history of the Dalradian block; the degree to which the Highland Border Complex developed as a separate unit; and the time(s) at which part, or all, of the Highland Border Complex docked with the Dalradian.

I would like to extend and modify the views expressed in Tanner (1995), and hypothesis A above, to propose the following as the best working model for explaining most of the data available at present. The presence of at least one ophiolite body in the Highland Border Complex sequence is of particular significance and, unless it was obducted passively without causing deformation of the Dalradian and other underlying strata, there must be a cryptic suture which divides the Highland Border Complex into two parts: one part in sequence with the Dalradian rocks, and the other forming an exotic unit.

The preferred model is that Dalradian deposition continued

https://doi.org/10.1017/S0016756897007292 Published online by Cambridge University Press

until at least the Lower Cambrian, with the Keltie Water Grit Formation at Callander (and possibly other similar pale grit–black shale sequences in the Highland Border between Callander and the Isle of Bute) being of Dalradian affinity. The Highland Border Complex was assembled from the Arenig onwards as an arc complex (linked with Midland Valley crust?) outboard of the Dalradian basin, and collision of this complex with the Dalradian block in mid-Ordovician time (Llandeilo–Llanvirn) resulted in major deformation of the Dalradian rocks, and probably also of the pre-Caradoc part of the Highland Border Complex.

If the presence of a late Proterozoic orogenic event in the Dalradian block *is* confirmed subsequently by radiometric dating, then this fact could be reconciled with data from the Highland Border Zone (and hypothesis A) only if (i) Proterozoic deformation and metamorphism did not affect the highest levels in the Dalradian pile, and (ii) Cambrian rocks were brought into contact with these Dalradian rocks along a presently unidentified tectonic break, before both sequences were deformed during Ordovician times.

6. General remarks

In an area where field investigation stretches back for over a century, and some of the older published 'facts' are inevitably wrong, it is more than usually important to check each item of stratigraphic, structural, and palaeontological data, so that spurious hypotheses are not erected upon flawed data. This is what I have attempted to do at Callander, Glen Sannox, and the North Esk, and I am disappointed that Bluck & Ingham have not commented upon or challenged the new data presented in the paper under discussion, but have chosen to argue mainly on the basis of data from elsewhere in the Highland Border Complex.

Bluck & Ingham refer several times in their discussion to the 'structural similarity' of the Dalradian and Highland Border Complex as though this were the sole point at issue. They ignore the singular feature that has impressed all previous workers in the Callander area, including Clough (*in* Geikie, 1897): that there is a progressive change in *lithology* from the Dalradian sequence with its green, chlorite–feldspar-bearing grits and grey, green, and purple slates, southwards over 300 m or so, to the brown-weathering, white grits and black 'shales' characteristic of the Highland Border Complex. This transition is mirrored in the detailed petrography of the rocks. There is no single place in the succession at which a dividing line can be drawn and I believe that this is the most important single feature of the sequence at Callander; structural continuity, here as elsewhere in the Highland Border Complex, is only one aspect of the evidence.

7. Detailed response to points a and b in Comment

(a) There is much confusion in the literature as to what constitutes the Highland Boundary Fault, as exemplified here by Bluck & Ingham's reference to Anderson (1947) and Kennedy (1958). Anderson (1947, p. 487) actually defined the 'Highland Boundary Fault proper' as the break between the 'Serpentine Belt' (Highland Border ophiolite) and the Lower Old Red Sandstone, which is now generally recognized to be an unconformable contact, as at Aberfoyle (Curry *et al.* 1984). On the other hand, Kennedy (1958, p. 114) used the term to refer to a 'steeply-inclined thrust plane' on which the Dalradian rocks were inferred to have been driven southwards over what is now known as the Highland Border Complex, and it is obviously this latter definition that Bluck & Ingham have in mind. The concept of a thrust fault separating the Dalradian from the Highland Border Complex was introduced by Barrow (1912), and applied by Jehu & Campbell (1917) in the Aberfoyle area, but evidence for such a fault contact is not exposed anywhere in the Highland Border today (see Tanner, 1995, p. 475), and the structure must be considered non-proven.

Other faults, either entirely within the Highland Border Complex or cutting the Lower Old Red Sandstone, are common, and some are related to a sinistral displacement along the Highland Boundary Fault Zone during the Acadian (mid-Old Red Sandstone) event which gave rise to the Strathmore Syncline to the southeast (Jones & Tanner, 1995). Later fault movements displace either the Upper Old Red Sandstone or Carboniferous rocks. Thus I would agree with Bluck & Ingham's inference from my conclusions, that no known single fault, which can be followed for even a fraction of the total length of the Highland Border Zone, can given the status of *the* Highland Boundary Fault. The most structurally significant contact is that between the Highland Border ophiolite and the other rocks in the Highland Border Zone, but the exact position of that cryptic boundary is not known at present.

(b) I agree that 130 Ma is an unusually long time for the development of a sedimentary basin. The possible significance of the ophiolite was discussed above.

8. Detailed response to sections 1 to 5 in Comment

Below, I address Bluck & Inghams's five selected objections:

(1) The fundamental point raised here, that structures in the Highland Border Complex differ in both age and orientation from those found in the adjacent Dalradian rocks, is best tested by looking at the actual relationships seen at a number of localities between Stonehaven and Arran (Fig. 3, A–E). What is seen at each of these places, where it is possible adequately to map the structures in both groups of rocks within a short distance of their mutual contact (Fig. 4a, A, C–E), is that (a) sedimentary structures show that the sequence youngs consistently from the Dalradian to the Highland Border Complex, and (b) the attitude of bedding and cleavage in the two groups of rocks is remarkably similar at any one place, and that this similarity persists along the whole belt, although the actual orientation of the structures varies systematically from west to east. Thus whatever structural events have affected the Dalradian have also affected the Highland Border Complex.

Untilting the beds at each locality to bring the Lower Old Red Sandstone to the horizontal in sectional view (Fig. 4b) removes the structural effect of the Strathmore Syncline to the southeast (Fig. 3) and shows that the Highland Border Complex was *moderately to steeply dipping* (not gently dipping as deduced by Bluck & Ingham) in Lower Old Red Sandstone times. This was therefore the attitude assumed by both groups of rocks as a result of the development of the Downbend structure (D4) in the Dalradian block (see Tanner, 1995, for references). It can be inferred from this result that the Highland Border Complex has been 'welded' to the Dalradian since before D4, and that the southern margin of the Dalradian block was locally affected by the formation of the post-Lower Old Red Sandstone Strathmore Syncline. Evidence supporting the latter is provided by the fact that the anomalous gentle southward dip adopted by the Dalradian rocks adjacent to the Highland Boundry Fault Zone changes as the rocks are traced northwards (i.e. along a 2–3 km cross-strike section along the A82 west of Loch Lomond, and northwards for >2 km from the northern margin of the Keltie Water Grit Formation at Callander) and passes smoothly without any discontinuity into the steep attitude characteristic of beds in the Highland Border Zone on the south limb of the Highland Border Downbend, immediately south of the axial trace of the Aberfoyle Anticline (Tay Nappe).

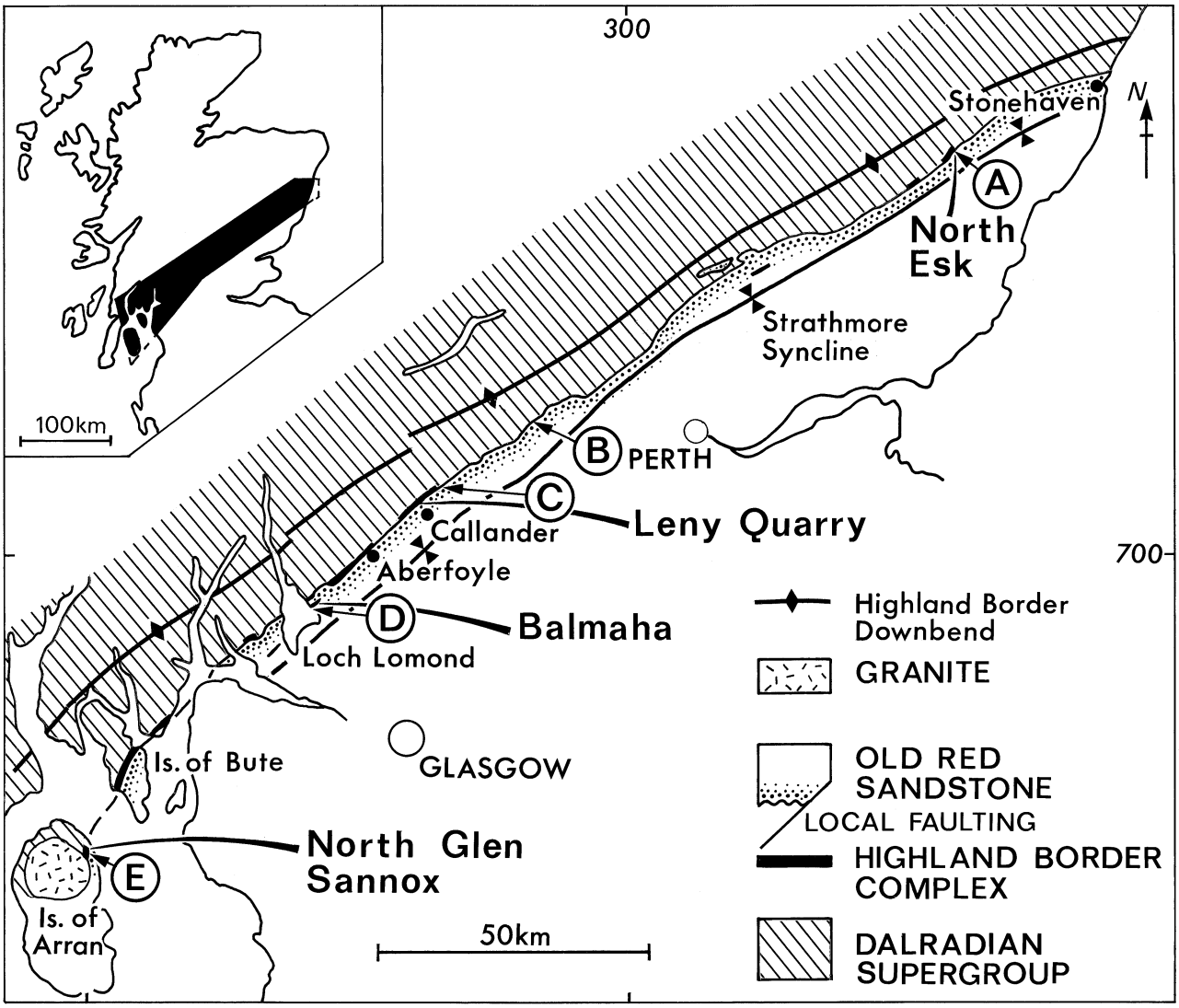

Figure 3. Simplified geological map of the Highland Border Zone in Scotland showing the positions of the Highland Border Downbend (D4) and the Strathmore Syncline, with respect to the outcrop of the Highland Border Complex (solid black). Locations A–E are discussed in the text, and northwest–southeast cross-sections at these places are shown in Figure 4. The inset shows the location (solid black) of the Highland Border Zone in Scotland.

These relationships suggest that the Highland Border Complex had docked with the Dalradian before 460 Ma ago, and that the two were deformed together, firstly during the development of the Downbend structure, and secondly, during the formation of the Strathmore Syncline.

In the areas of gently dipping Lower Old Red Sandstone sediments north of Crieff and northeast of West Cult (Fig. 1) mentioned by Bluck & Ingham, the underlying Dalradian schists have a *steep* attitude (Fig. 4b, B), as predicted above, which in the *restored* section is comparable to that seen elsewhere along the belt (Fig. 4b, A, C–F). These areas of flat-lying Lower Old Red Sandstone strata are separated by a major fault (called the Highland Boundary Fault by Allan, 1940) from steeply dipping Old Red Sandstone beds to the southeast which are affected by the Strathmore Syncline. Thus in some places the northern limit of pronounced Acadian deformation is marked by a brittle fracture, whereas in others it is marked by a progressive decrease in deformation within a zone a few kilometres wide affecting the southern margin of the Dalradian outcrop.

Both the restored and unrestored cross-sections in Figure 4 demonstrate that no single section can be drawn which is characteristic of Old Red Sandstone/Highland Border Complex/Dalradian relationships as a whole. As they acknowledge, Bluck & Ingham's Figure 2 is a composite section largely based on Dounan's Quarry (Curry *et al.* 1984, fig. 8) combined with relationships recorded over 30–100 km to the northeast by Allan (1928, 1940). Another problem with the Bluck & Ingham section is that the actual orientation of bedding in the carbonate rocks is not known: the only indication of possible stratification is given by aligned pebbles and cobbles in the Dounan's Conglomerate (Henderson & Fortey, 1982, p.237). A more reliable indication of the attitude of the beds in the Highland Border Complex is given by the Achray Sandstone found in the cutting just to the north (dip 50–65°N); restoration of the Lower Old Red Sandstone unconformity (dip 55–60°S) to the horizontal, gives a residual dip for the Achray Sandstone, which is in accordance with the restored dips for the Highland Border Complex seen elsewhere (Fig. 4b).

Individual block rotations and displacements within the Highland Border Complex are not ruled out by these data as structural information is available only from a few key areas, and I would stress again that it is not the uniformity of structural orientations across large areas that is important, but the *detailed comparison*, at a number of separate localities, of the attitude of

https://doi.org/10.1017/S0016756897007292 Published online by Cambridge University Press

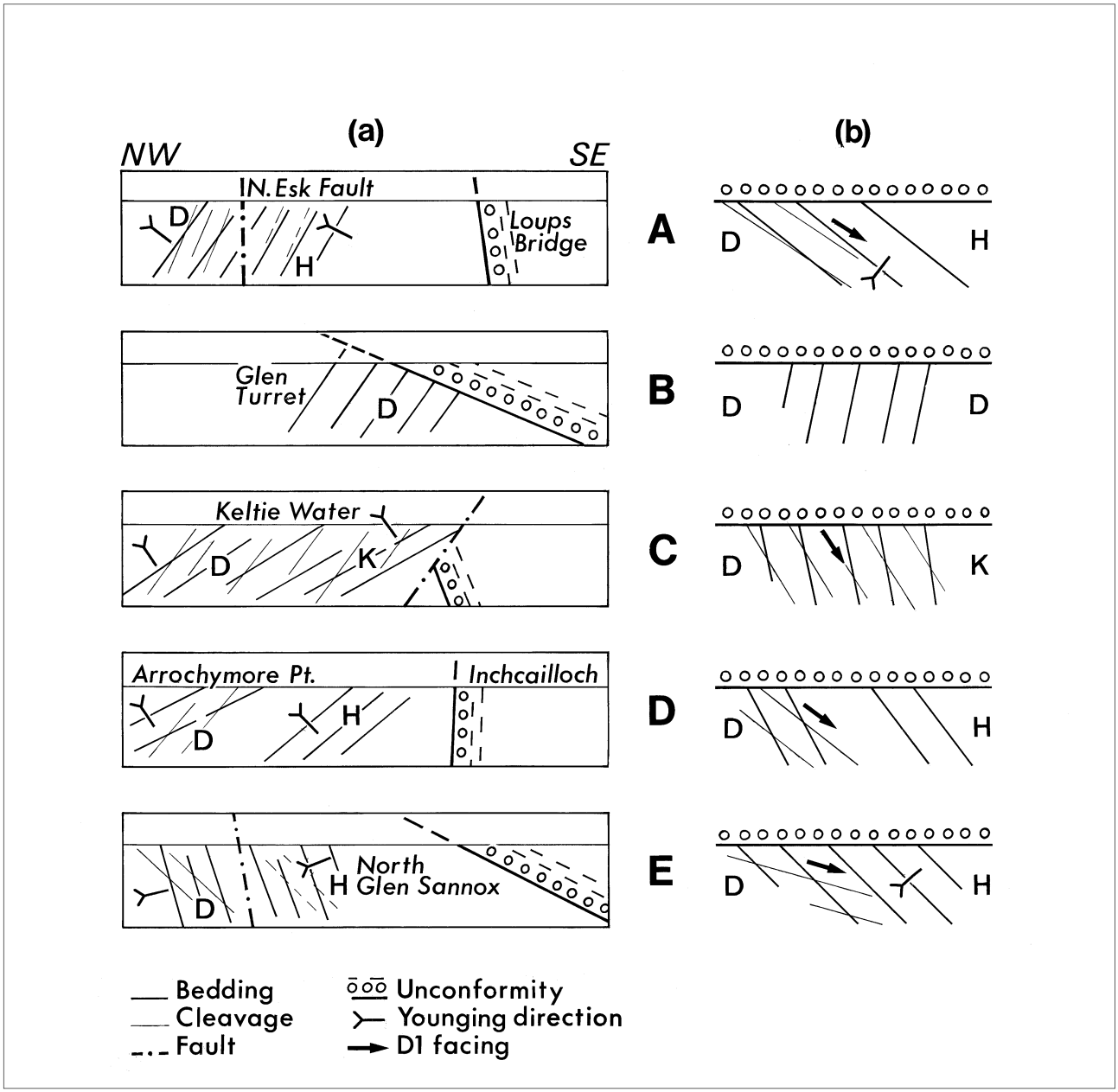

Figure 4. (a) Schematic northwest–southeast cross-sections showing the measured orientations of the Dalradian and Highland Border rocks near, or at, their mutual contact, compared with the orientation of the nearest exposure of the unconformity at the base of the Lower Old Red Sandstone. Details of other rocks occurring in the sections, such as the Highland Border ophiolite, have been omitted for clarity, and the sections are not drawn to scale. The sections are located as follows (see Fig. 3): A, River North Esk near Edzell; B, Turret Burn northwest of Crieff; C, Keltie Water north of Callander; D, island of Inchcailloch and shore north of Balmaha, Loch Lomond; E, North Glen Sannox, Isle of Arran. D, Dalradian; H, Highland Border Complex; K, Keltie Water Grit Formation.
(b) Sections resulting from a simple body rotation of the Dalradian and Highland Border Complex during restoration of the Lower Old Red Sandstone unconformity to the horizontal.

structures in the Dalradian with those in the Highland Border Complex.

(2) I agree that the radiometric data quoted by Bluck & Ingham appear to provide a good reason for concluding that the Dalradian block and the Ordovician arc complex did not amalgamate until mid-Ordovician time. Further evidence for pre-480 Ma events in the Dalradian block is being sought as part of an intensive Rb–Sr and U–Pb radiometric study of the Dalradian block with Drs T. J. Dempster, R. D. Muir, and G. Rogers, and discussion of the existing pre-480 Ma radiometric data would not be fruitful at this stage. An unrelated project will test the Cambrian age obtained by Dempster & Bluck (1991) for the Bute ophiolite, as the latter appears to correlate with the ophiolite at Aberfoyle for which an early Ordovician age would seem more likely. It is difficult to reconcile the radiometric age of *c.* 540 Ma for the ophiolite with a younger age of around 530–520 Ma (based on the revised Lower Cambrian time-scale of Isachsen *et al.* 1994) for the Cambrian trilobite shelf edge assemblage at Leny Quarry.

(3) I believe that one has to be careful in assigning too much importance either to the Caradoc–Ashgill ages from chitinozoa until these have been independently confirmed, or to the

https://doi.org/10.1017/S0016756897007292 Published online by Cambridge University Press

presence of putative unconformities from the Highland Border Complex, until these have been fully described and documented. It is extremely difficult to decide whether a conglomerate (or breccia) is of intra-formational origin, or marks an unconformity between two groups of rocks of different ages, when the conglomerate and the strata on either side of it are strongly folded and/or sheared. In addition, the putative unconformities are very poorly exposed. That reported from Loch Lomond is not found on an island – it is underwater and is only exposed in conditions of exceptional drought, such as obtained in the summer of 1982 (B. J. Bluck, pers. comm.); it was not even exposed in the dry summers of 1995 and 1996 when the water level fell to 3m below normal. The other, the 'Basement Breccia' described and illustrated by Jehu & Campbell (1917, Plate V), has only recently been rediscovered by the author after a long search in the Loch Ard Forest, and is now completely obscured by vegetation. It has yet to be demonstrated that blocks of *previously cleaved or folded* black shale or siltstone are present in the Achray Sandstone found above the latter 'unconformity' at Aberfoyle.

(4 and 4a) I strongly dispute the contention that the Highland Border Complex generally youngs *towards* the Dalradian, for the following reasons: (i) Where sedimentary structures such as cross-bedding or graded bedding are preserved in the Highland Border Complex, they show, without exception, in the sections that I have examined in detail, that the Complex youngs southeastwards in the same direction as the adjacent Dalradian rocks (i.e. at Glen Sannox, Balmaha, Callander, and the North Esk). 'Structural repetition' has been taken into account by considering the facing direction of folds which affect both sequences in each case. (ii) Second-order evidence given by putative unconformities is suspect (see above). (iii) The high-temperature assemblages preserved at the 'sole' of the Highland Border ophiolite (Henderson & Robertson, 1982) are always on the northwest side of the outcrop.

(4b, paragraph 1) I agree entirely with the general principle outlined here and have never attempted to establish lateral correlations (either stratigraphical or structural) over large areas within the Highland Border Complex. Instead key areas such as that at Callander have been mapped in great detail and a comprehensive field and laboratory study has been made of the Dalradian and Highland Border Complex independently *at each of these places*. No correlation between the sets of structures found at each locality has been implied. However, it is abundantly clear that the structural history of the Complex at each locality is comparable in terms of the number of deformation phases, their geometry, and the metamorphic grade at which they took place, with that of the local, immediately adjacent, Dalradian rocks. These are a series of structural snapshots taken laterally along the contact: no temporal correlations have been assumed, and no attempt has been made to impose a 'uniformitarian' structural regime upon the Highland Border Complex. The structural interpretation is not based on lithological correlation, as implied by Bluck & Ingham; indeed where clear lithological repetition might be thought to suggest the presence of a major fold in the Keltie Water section (Tanner, 1995, fig. 3, loc. A), way-up, facing, and bedding/cleavage relations show that no such fold is present. Conversely, quantitative evidence to support the notion that the unconformities in the Highland Border Complex separate packages of rock with different structural histories is lacking.

However, the corollary to Bluck & Ingham's statement that long-range correlation in the Highland Border Complex should not be attempted *per se* is also true: it must not be *assumed* that the rocks have undergone a 'multiple structural history', and that lateral correlations of any sort are impossible, for these are the very things which we have set out to test. Let us keep an open mind on these matters and see what facts emerge.

(5) The fault at Craigeven Bay is almost certainly a late normal fault of the type found elsewhere along the Highland Border Zone, and there is no evidence from this locality to show that the Dalradian rocks have been thrust southwards over the Highland Border Complex.

The mylonite on Bute occurs in a zone at the base of the ophiolite, and that on Arran occurs within the outcrop of the latter, and not at the junction of the Highland Border Complex and Dalradian. These zones of high shear strain are related to the emplacement of the ophiolite (Henderson & Robertson, 1982) and developed either at the same time as, or before, the penetrative fabric which affects both the Dalradian and the Highland Border Complex. It is therefore not surprising that this fabric shows a similar orientation in both groups of rocks. Contrary to Bluck & Ingham's description of the Highland Boundary Fault Zone on Figure 2, mylonitic rocks are rare or absent from the major part of the Highland Border Zone.

In conclusion, there *is* continuity in the structures which affect the Dalradian and the Highland Border Complex, the general attitude of the Highland Border Complex was *not* radically different to that of the Dalradian when the Lower Old Red Sandstone was deposited some 415 Ma ago, and the stratigraphical and structural data from the Highland Border Complex support the hypothesis that the Grampian orogeny was entirely of early Palaeozoic age.

Acknowledgements. BJB & JKI wish to thank Dr J. Treagus and Professor D. Ramsay for their constructive comments, and other members of staff at Glasgow for much disussion.

References

ALLAN, D. A. 1928. The geology of the Highland Border from Tayside to Noranside. *Transactions of the Royal Society of Edinburgh* **56**, 57–88.

ALLAN, D. A. 1940. The geology of the Highland Border from Glen Almond to Glen Artney. *Transactions of the Royal Society of Edinburgh* **60,** 171–93.

ANDERSON, J. G. C. 1947.The geology of the Highland Border: Stonehaven to Arran. *Transactions of the Royal Society of Edinburgh* **61**, 479–515.

ARMSTRONG, M., BISHOP, A. C., FORSYTH, I. H., FRANCIS, E. H., HARRIS, A. L. & READ, W. A. 1982. *Stirling Sheet 39.1969*. London: Institute of Geological Sciences.

BARROW, G. 1912. On the geology of Lower Deeside and the Southern Highland Border. *Proceedings of the Geologists' Association* **23**, 274–90.

BLUCK, B. J. 1990. Terrane provenance and amalgamation: examples from the Caledonides. *Philosophical Transactions of the Royal Society, London* **331**, 599–609.

BLUCK, B. J. 1992. Balmaha. In *Geological excursions around Glasgow and Girvan* (eds J. D.Lawson and D. S.Weedon), pp 110–29. Geological Society of Glasgow.

BLUCK, B. J. & DEMPSTER, T. J. 1991. Exotic metamorphic terranes in the Caledonides: Tectonic history of the Dalradian block. *Geology* **19,** 1133–6.

BLUCK, B. J., INGHAM, J. K., CURRY, G. B. & WILLIAMS, A. 1984. Stratigraphy and tectonic setting of the Highland Border Complex. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **75,** 124–33.

BRASIER, M., COWIE, J. W. & TAYLOR, M. 1994. Decision on the Precambrian–Cambrian boundary stratotype. *Episodes.* **17,** 3–8

CAMPBELL, R. 1913. The geology of south-eastern Kincardineshire. *Transactions of the Royal Society of Edinburgh* **48,** 932–60.

CURRY, G. B., BLUCK, B. J., BURTON, C. J., INGHAM, J. K., SIVETER, D. J. & WILLIAMS, A. 1984. Age, evolution and tectonic history of the Highland Border Complex, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **75**, 113–33.

DEMPSTER, T. J. 1985. Uplift patterns and orogenic evolution in the Scottish Dalradian. *Journal of the Geological Society, London* **142,** 111–28.

DEMPSTER, T. J., HUDSON, N. F. C. & ROGERS, G. 1995. Metamorphism and cooling of the NE Dalradian. *Journal of the Geological Society, London* **152**, 383–390.

DEMPSTER, T. J. & BLUCK, B. J. 1991. Age and tectonic significance of the Bute amphibolite, Highland Border Complex, Scotland.*Geological Magazine* **128**, 77–80.

DEWEY, J. F., RYAN, P. D. & SOPER, N. J. 1995. Middle Ordovician; the first orogenic event on the Laurentian margin of Iapetus; arc–continent collision. *Abstract. Tectonic Studies Group Annual Meeting, Dublin.*

GEIKIE, A. 1897. *Annual Report of the Geological Survey of the United Kingdom for the year ending December 31, 1896*. p. 28.

HALLIDAY, A. N., GRAHAM, C. M., AFTALION, M. & DYMOKE, P. 1989. The depositional age of the Dalradian Supergroup: U–Pb and Sm–Nd isotope studies of the Tayvallich volcanics, Scotland. *Journal of the Geological Society, London* **146,** 3–6.

HARRIS, A. L. 1969. The relationships of the Leny Limestone to the Dalradian. *Scottish Journal of Geology* **5**, 187–90.

HENDERSON, W. G. & FORTEY, N. J. 1982. Highland Border rocks at Loch Lomond and Aberfoyle. *Scottish Journal of Geology* **18**, 227–45.

HENDERSON, W. G. & ROBERTSON, A. H. F.1982. The Highland Border rocks and their relationship to marginal basin development in the Scottish Caledonides. *Journal of the Geological Society, London* **139,** 433–50.

INGHAM, J. K., CURRY, G. B, & WILLIAMS, A. 1986. Early Ordovician Dounans Limestone fauna, Highland Border Complex, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **76** (part 4 for 1985, published February 1986), 481–513.

ISACHSEN, C.E., BOWRING, S.A., LANDING, E. & SAMSON, D. 1994. New constraint on the division of Cambrian time. *Geology* **22**, 496–8.

JEHU, T. J. & CAMPBELL, R. 1917. The Highland Border rocks of the Aberfoyle district. *Transactions of the Royal Society of Edinburgh* **52,** 175–212.

JONES, R. R. & TANNER, P. W. G. 1995. Strain partitioning in transpression zones. *Journal of Structural Geology* **17**, 793–802.

JOHNSON, M. R. W. & HARRIS, A. L. 1967. Dalradian–?Arenig relations in parts of the Highland Border, Scotland, and their significance in the chronology of the Caledonian orogeny. *Scottish Journal of Geology* **3**, 1–16.

KENNEDY, W. Q. 1958. Tectonic evolution of the Midland Valley of Scotland. *Transactions of the Geological Society of Glasgow* **23**, 106–33.

PATERSON, I. B. & HARRIS, A. L. 1969. *Lower Old Red Sandstone Ignimbrites from Dunkeld, Perthshire*. IGS Report **69/7,** 1–6.

ROGERS, G., DEMPSTER, T. J., BLUCK, B. J. & TANNER, P. W. G. 1989. A high precision U–Pb age for the Ben Vuirich granite: implications for the evolution of the Scottish Dalradian Supergroup. *Journal of the Geological Society, London* **146**, 789–98.

RYAN, P. D., SOPER, N. J., SNYDER, D. B., ENGLAND, R. W. & HUTTON, D. H. W. 1995. The Antrim–Galway Line: a resolution of the Highland Border Fault enigma of the Caledonides of Britain and Ireland. *Geological Magazine* **132,** 171–84.

SHACKLETON, R. M. 1958. Downward-facing structures of the Highland Border. *Quarterly Journal of the Geological Society of London* **113,** 361–92.

SCOTT, A. C., EDWARDS, D. & ROLFE, W. D. I. 1976. Fossiliferous Lower Old Red Sandstone near Cardross, Dunbartonshire. *Proceedings of the Geological Society of Glasgow* **117**, 4–5.

TANNER, P. W. G. 1995. New evidence that the Lower Cambrian Leny Limestone at Callander, Perthshire, belongs to the Dalradian Supergroup, and a reassessment of the 'exotic' status of the Highland Border Complex. *Geological Magazine* **132,** 473–83.

THIRLWALL, M. F. 1988. Geochronology of Late Caledonian magmatism in northern Britain. *Journal of the Geological Society, London* **145,** 951–67.

BLUCK, B. J., Department of Geology and Applied Geology, University of Glasgow, Glasgow, G12 8QQ, UK

INGHAM, J. K., Hunterian Museum, University of Glasgow, Glasgow, G12 8QQ, UK

TANNER, P. W. G., Department of Geology and Applied Geology, University of Glasgow, Glasgow, G12 8QQ, UK