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DISCUSSION

Age of the Grampian event: 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"

A. L. Harris, **D. J. Fettes & N. J. Soper** comment: As a contribution to the current debate on the age of the Grampian Orogeny in the Scottish Dalradian, we comment on the valuable paper by Tanner (1995) that establishes stratigraphical continuity between the 'Dalradian' Ben Ledi Formation and the 'Highland Border' Keltie Water Formation that contains the Lower Cambrian Leny Limestone (Cowie, Rushton & Stubblefield, 1972, p. 17). Tanner's interpretation of the stratigraphy differs in detail from that of Harris & Fettes (1972). We unreservedly accept Tanner's mapping and the stratigraphical changes that follow from it: there are two units of black slate and limestone; that containing the fossiliferous limestone of Leny Old Quarry is the younger.

Our reading of the structure differs from that of Tanner in the matter of structural facing of the cleavages; our interpretation in fact reinforces Tanner's main conclusion, providing stronger evidence of the structural continuity that complements his stratigraphical findings. It is of historical interest that Tanner's interpretation – that the main cleavage faces down in all the rocks – is essentially the initial position adopted by Harris (1962) who subsequently modified it in the light of thin section evidence and further fieldwork (Harris & Fettes, 1972). There is an early cleavage that faces up to the southeast, dipping less steeply to the northwest than the inverted bedding, and a later cleavage that dips more steeply than the bedding and thus faces down. To establish this it is necessary to find bedding, younging evidence, which the turbidite beds provide in abundance, first cleavage and preferably second cleavage, all in the same outcrop. Recently we made a further visit to Keltie Water at exceptionally low water and recorded the observations shown in Figure 1.

The turbidite sandstones of the Keltie Water Formation strike east or northeast and dip gently northwest, inverted, showing delayed grading, sometimes with a few centimetres of cleaved silty mudstone at the top of the beds. The early cleavage is penetrative and is restricted to the slaty tops. It strikes consistently clockwise to bedding, so that the intersection plunges east and the cleavage faces up to the east or southeast. The later cleavage takes the form of a spaced anastomosing 'rough' cleavage in the sandstones and is the dominant macroscopic fabric. It dips to the northwest more steeply than bedding, so it faces down. An important criterion for distinguishing the two cleavages from a single refracting cleavage is the facing, because a single cleavage cannot refract 'through' the plane of the bedding. Style of cleavage and superimposition relationships are less reliable criteria in the field, though useful in thin section.

The geometrical relationships described above are common to the pale Keltie Water Formation sandstones that lie stratigraphically below, and between, the two slate units. In the 'transitional' sandstones and slates towards the base of the formation, the early cleavage is not prominent, the later downward–facing cleavage being dominant. In the green sandstone turbidites of the Ben Ledi Formation in the Allt Breac–nic tributary, both cleavages are present. The bedding steepens through the vertical so that south of Sron Eadar 'a Chinn it dips very steeply southeast, right way up, and the early cleavage dips steeply northwest, still striking clockwise to bedding and facing up across it.

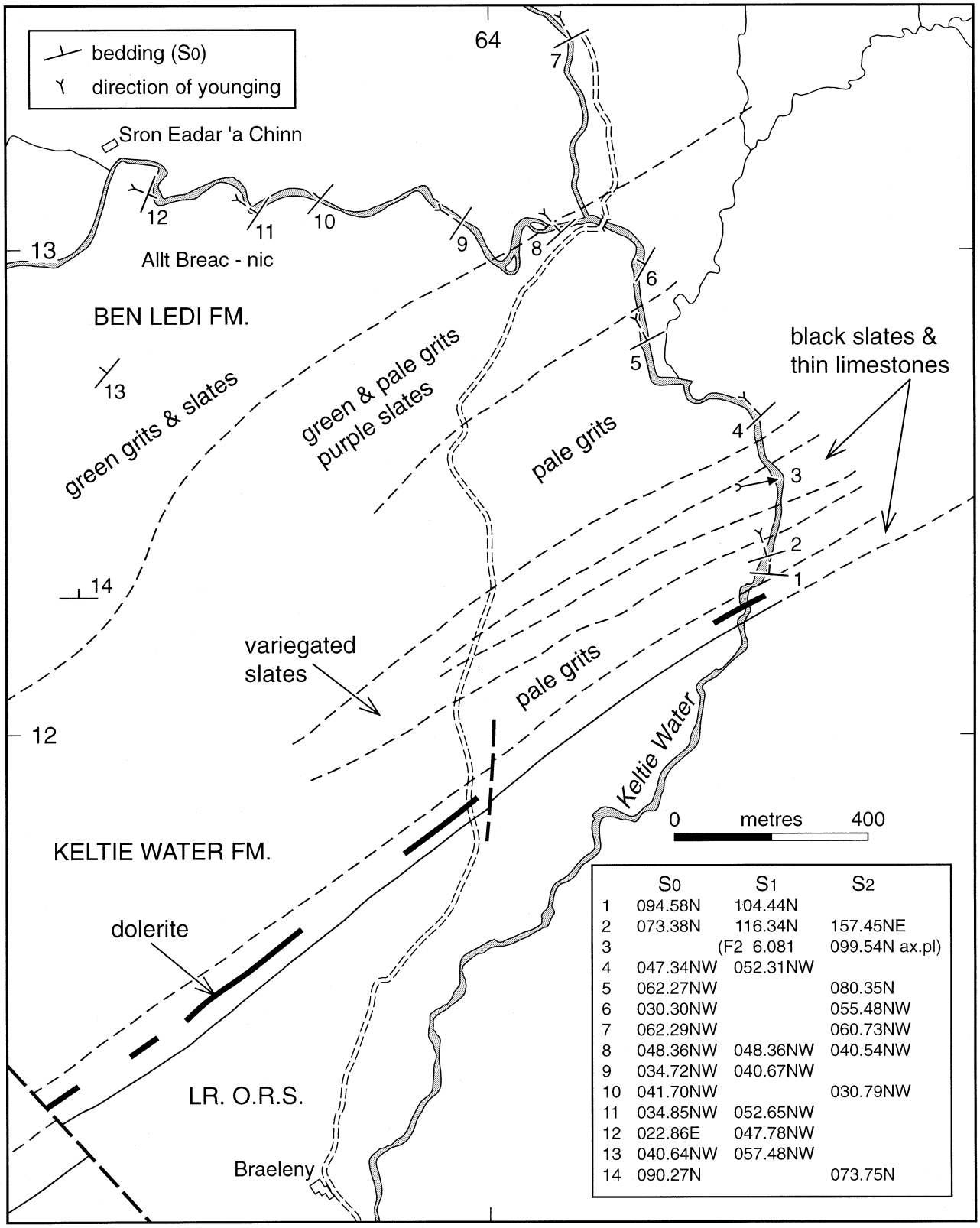
The significance of these data is that the Cambrian rocks share structural as well as stratigraphical continuity with strata that are agreed to be Dalradian. To propose a cryptic suture between them demands a double coincidence. There may well be faults in the section which contains numerous porphyrite dykes with potential displacements. But any such faults merely excise or repeat parts of a continuous stratigraphical sequence, and juxtapose rocks with an identical and quite complex structural history. The conclusion must be that the upper part of the Southern Highland Group is early Palaeozoic in age, and so too is the Grampian Orogeny.

Professor Bluck kindly made his critique of Tanner's paper available to us prior to publication (Bluck & Ingham, 1997). This critique did not discuss the Keltie Water evidence directly but concentrated on the general issue of the relationship of the Highland Border Complex to the Dalradian. We believe Bluck & Ingham's approach to this key issue in Highland geology to be misconceived. They define the question as '... whether theHighland Border Complex has affinities with the Dalradian block or constitutes a separate block ... slivers of which have been caught up along the Highland Boundary Fault'. They see the Highland Border Complex as a coherent stratigraphical sequence, linked by unconformities, that encompasses all the early Palaeozoic rocks in the vicinity of the Highland Border; it has a history that differs from that of the Dalradian, in that it contains strata younger than the Arenig whereas the Dalradian was undergoing post–orogenic cooling by 515 Ma, based on Rb–Sr mica regression ages (Dempster, Hudson & Rogers, 1995).

This model is driven by indirect (isotopic) evidence and involves distortions of the primary (field) evidence, for example by hypothesizing cryptic sutures within sequences that have coherent structure and stratigraphy, as in the Keltie Water. A straightforward evaluation of the field evidence poses quite a different question: 'Which parts of the Highland Border Complex belong to the Dalradian block and which are exotic?' The former provide a maximum age for the Grampian Orogeny, the latter were accreted subsequently and do not.

An early Ordovician age for the orogeny means that the isotopic evidence for pre–Ordovician cooling needs to be re–evaluated, perhaps along the lines suggested by Evans & Soper (1997). If, as we suspect, it emerges that the base of the Cambrian lies well down within the Southern Highland Group, some redefinition of the the Highland Border Complex will be necessary.

P. W. G. Tanner replies: I thank Harris, Fettes & Soper for contributing new structural data which help to confirm



	S0	S1	S2
1	094.58N	104.44N	
2	073.38N	116.34N	157.45NE
3		(F2 6.081	099.54N ax.pl)
4	047.34NW	052.31NW	
5	062.27NW		080.35N
6	030.30NW		055.48NW
7	062.29NW		060.73NW
8	048.36NW	048.36NW	040.54NW
9	034.72NW	040.67NW	
10	041.70NW		030.79NW
11	034.85NW	052.65NW	
12	022.86E	047.78NW	
13	040.64NW	057.48NW	
14	090.27N		073.75N

Figure 1. Sketch map of the Keltie Water section discussed in the text, lithostratigraphy following Tanner (1995, fig. 3), with a selection of our structural data.

beyond any reasonable doubt that the Dalradian Supergroup and Keltie Water Grit Formation have shared the same, complex, structural history. As the Lower Cambrian Leny Limestone is part of the Keltie Water Grit Formation (Tanner, 1995), this strengthens the conclusion that the Grampian orogenic event, to which these structural events belong, is of early Palaeozoic (probably early Ordovician) age.

In the Keltie Water section (located on Fig. 2), the 'main cleavage' of Tanner (1995) (S_2 of Harris, Fettes & Soper) is the downward north- to northwest-facing cleavage seen in the field to be associated with the formation of a number of

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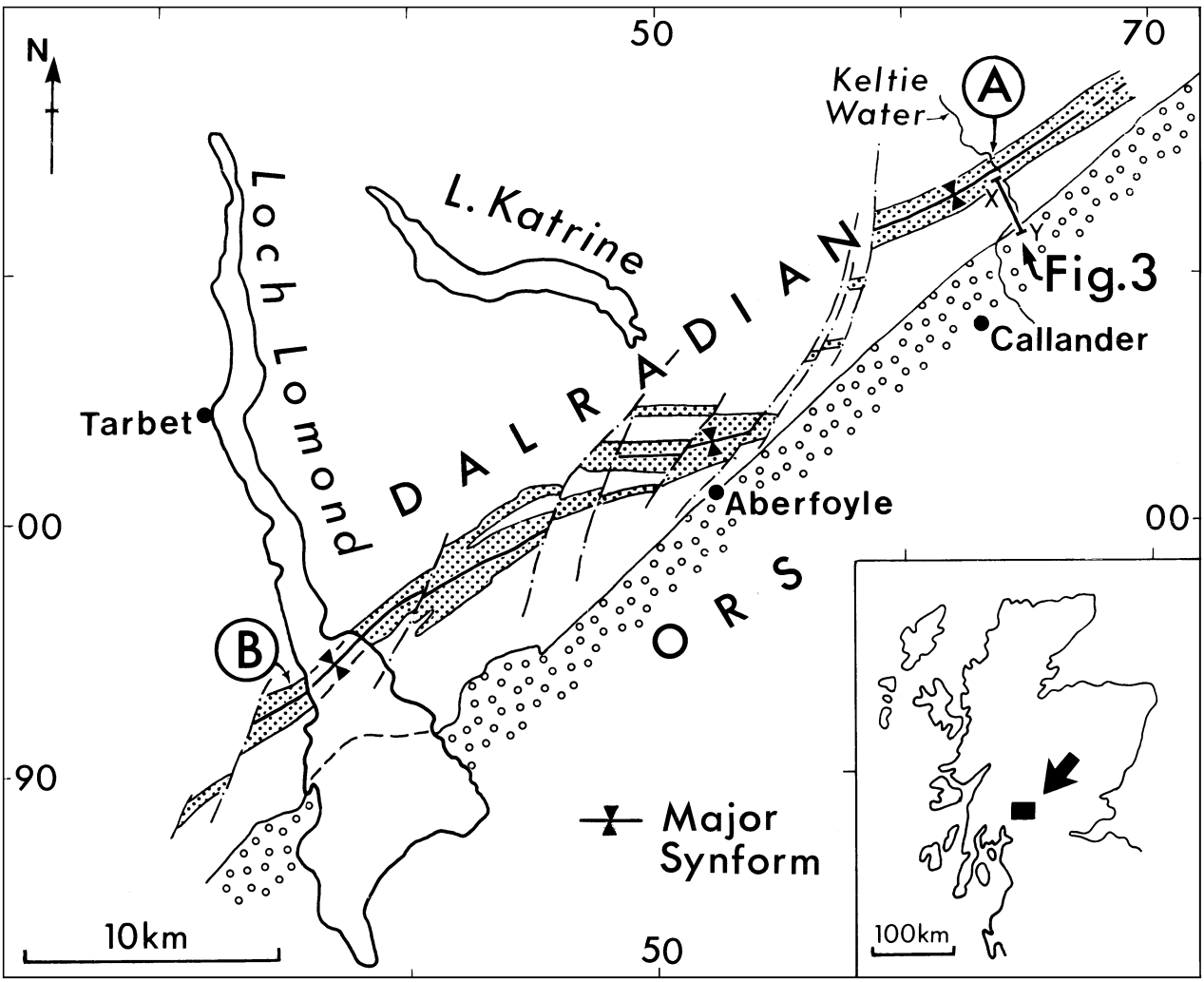

Figure 2. Geological sketch map, based on BGS Sheet 38W, Harris (1962), Mendum & Fettes (1985), and Stone (1957), showing the location of the Keltie Water cross-section XY in Figure 3, and localities A and B mentioned in the text. At A, a downward-facing synform occurs within the Aberfoyle Slate Formation (stippled), and at B a downward-facing synform (Aberfoyle Anticline) occurs within the Luss Slate Formation. The unit marked by small open circles consists of younger rocks belonging to the Highland Border Complex and the Lower Old Red Sandstone (ORS).

mesoscopic fold pairs with $\lambda/2$ of <10 m (Fig. 3, a–c). This cleavage invariably dips more steeply north than the inverted bedding on the long limbs of these structures and occurs as a spaced cleavage (0.5–2 cm) in the grits; a 'rough' cleavage in sandstones; and a penetrative cleavage in mudrocks. It is marked by the growth of aligned flakes of white mica, the development of pressure-solution seams, and by mica-quartz 'beards' on detrital grains. This fabric has a closely similar, computed mean orientation in the Dalradian rocks, the Keltie Water Grit Formation, and in the transition group between them, and is the main unifying structural element in the whole package.

Because both arenaceous and argillaceous rocks in all three of the above units contain abundant detrital white mica, sometimes accompanied by biotite, the main cleavage commonly takes on the appearance of a (micro)crenulation cleavage, and in most cases it is difficult under the microscope to be certain whether or not an earlier penetrative cleavage is also present. A clue that such a fabric may be present is given by the rare development in grit bands in each of the units, of a centimetre-spaced pressure solution cleavage at a low angle, or parallel, to bedding. The S_1 cleavage reported from the thin, muddy tops of some grit bands by Harris, Fettes & Soper, which dips more gently north than bedding and faces up to the east or southeast, belongs to this early generation of structures. Although one could dispute some of the evidence given by these authors to identify this early cleavage at individual localities (for example, I would interpret the 'S_1' cleavage at localities 11–13 (Fig. 1) as a late cleavage facing up to the southeast), I agree with their conclusion that there is clear evidence in some of these rocks for a tectonic fabric which predates the main cleavage.

A major point of great interest, not considered by Harris, Fettes & Soper, is how these two fabrics, upward-facing to the southeast succeeded by downward-facing to the north, correlate with the D_1–D_4 structural sequence widely reported from the Dalradian rocks of the Highland Border Zone in Scotland. Throughout this zone, for a few kilometres north of the Highland Boundary Fault between Loch Lomond and Dunkeld, there is a widespread downward-facing, spaced or slaty early cleavage (S_1) (Shackleton, 1958; Harris, Bradbury & McGonigal, 1976; Mendum & Fettes, 1985). It is the dominant tectonic fabric in these rocks and is associated with the development of several large D_1 folds, including the northward- and downward-facing Aberfoyle Anticline. When Harris & Fettes (1972) first reported the

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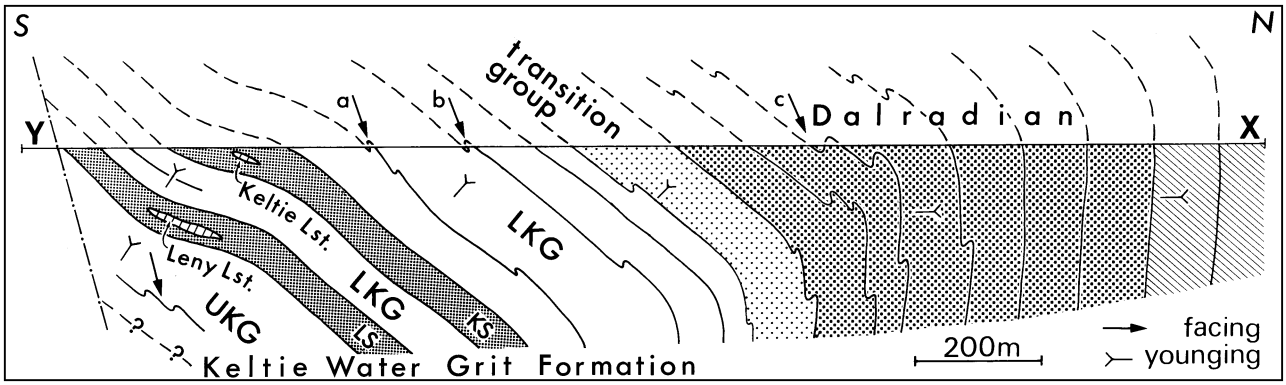

Figure 3. True-scale cross-section showing the relationship between the Dalradian rocks (Ben Ledi Grit Formation, heavy stipple; Aberfoyle Slate Formation, cross-hatched) and members of the inverted Keltie Water Grit Formation. The latter consists of, in ascending order: the 'transition group'; the Lower Keltie Water Grits (LKG), which include the Keltie Limestone and Slate unit (KS); the Leny Limestone and Slate unit (LS); and the Upper Keltie Water Grits (UKG). The line of section is shown on Figure 2. Localities a, b and c are referred to in the text.

early, southeast-facing cleavage from the Callander area they correlated it with the 'primary', (presumably S_1) Dalradian fabric, and concluded that the major fold contained within the outcrop of the Aberfoyle Slates to the north (A on Fig. 2) was a secondary structure which had folded the inverted limb of the Tay Nappe. However, this interpretation does require the Callander area to be unique in several respects: the grits, sandstones, and siltstones for several kilometres north of the Highland Boundary Fault would lack the spaced D_1 cleavage and minor folds characteristic of this zone elsewhere along strike; the Aberfoyle Slates would be contained within the core of a late fold, not a D_1 structure as elsewhere; and if the main cleavage is designated S_2, then the D_2 structural event would appear much farther south than in adjoining areas, and does not show the development of spaced microlithons reworking S_1 which are a reliable fingerprint for the S_2 fabric in the entire Southern Highland area.

The alternative interpretation proposed here, based on work in the Aberfoyle Slates and Ben Ledi Grits north of Callander as well as in the Keltie Water, is that the 'main cleavage' at Callander (Tanner, 1995) (S_2 of Harris, Fettes & Soper) *is* equated with the regional Dalradian S_1 fabric, and that the vergence of minor structures of this age is related to a major downward-facing synformal D_1 fold contained with the Aberfoyle Slates to the north (Fig. 3). The corollary is that the earlier, southeast-facing cleavage is a pre-D_1 fabric not previously recognized in the Highland Border region. This conclusion needs thorough testing by means of a detailed examination of the fabrics in rocks in the southernmost part of the Dalradian outcrop, but there is evidence from ongoing work on Lochlomondside 35 km southwest of Callander, where a major downward-facing synformal D_1 fold (the Aberfoyle Anticline) occurs in the Luss Slates (B on Fig. 2), that the steeply southward-dipping S_1 cleavage on the south limb of this structure near to the contact with the Old Red Sandstone overprints an earlier south- or southeast-facing slaty cleavage. If confirmed, this would support the interpretation that the early cleavage reported here by Harris, Fettes & Soper (and initially by Harris & Fettes, 1972) from Keltie Water represents a deformation episode not previously recognized on a regional scale. It may only be preserved in the lowest grade rocks and is obliterated by D_1 strain and mineral growth within a short distance from the southern margin of the Dalradian outcrop.

Regarding the overall stratigraphy at Callander, I agree with Harris, Fettes & Soper that any strike-parallel faults that may be present (such as are seen in Leny Quarry and in the Keltie Water section) are of minor importance and not relevant to the main argument, as the Leny Limestone–black slate unit is itself overlain stratigraphically by a further sequence of pale grits and slates (Fig. 3) (Tanner, 1995, fig. 3) which show the same detrital mineralogy and tectonic structures as the rocks below the Leny Limestone. The sequence from the Dalradian to the top of the exposed Keltie Water Grit Formation has a sedimentological and structural unity that shows no evidence of having been disrupted by major faults of any type.

The Highland Border Complex must therefore be divisible into that part to the north which is in stratigraphical continuity with the Dalradian, such as at Callander, and that part which although generally younging to the south (Tanner, 1997), includes the Highland Border ophiolite, and must have been brought into structural contact with the northern block. If, as seems likely, all of the components of the Complex which are associated with the Highland Border ophiolite can be shown to be no younger than Llanvirn, then their emplacement may also be *causally* related to some part of the Grampian event.

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