Discussion of 'The Highland Boundary Fault and the Highland Border Complex' by B. J. Bluck, *Scottish Journal of Geology*, 46, 113–124

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P.W. Geoff Tanner writes: In this paper, Bluck has failed to provide a balanced and accurate assessment of the progress that has been made over many years to find a robust, modern geological interpretation of the Highland Border. This is no trivial matter, for the rocks exposed in this narrow strip of ground retain many of the clues to understanding the causes, and subsequent development, of the Caledonian *c.* 470 Ma Grampian Event, and the role played by the Highland Boundary Fault in continental-scale plate-tectonic reconstructions (Strachan & Dewey 2003; Tanner 2008).

The Highland Boundary Fault is considered by Bluck to define the contact between the Southern Highland Group (Dalradian) and the 'Highland Border Complex'. However, at outcrop this boundary is variously seen as a fault (North Esk), a lithological transition (Keltie Water), or the sole of an ophiolite (Innellan), and there is no evidence of a major, through-going fault between Arran and Stonehaven, as conventionally depicted (Tanner 2008). Conflicting interpretations of Highland Border geology have generated two diametrically opposed models, essentially summarized below, variations notwithstanding, as A & B.

In **model A** (Curry *et al.* 1984; Bluck 1985), the rocks between uncontested Southern Highland Group (Dalradian) to the NW and the unconformable Old Red Sandstone to the south, were assigned to the 'Highland Border Complex' (HBC). The latter was once 'considerably separated' from the Dalradian block, and acquired a northerly dip and younging direction before the two were amalgamated, following the Grampian Event, by movement on the Highland Boundary Fault.

In **model B** (Tanner & Sutherland 2007), the HBC was divided into two parts: the Trossachs Group (now the youngest part of the Dalradian Supergroup), and an overlying, allochthonous unit, the Highland Border Ophiolite (HBO).

The main differences between the two models are: all of the rocks belonging to the HBC young to the NW in Model A, with the ophiolite being older than, and lying beneath, the rest of the sequence. In Model B, all of the Dalradian rocks from the top of the Southern Highland Group through the Trossachs Group to the ophiolite, essentially young to the SE and are physically overlain by the latter.

Following the 2008 Highland Workshop held at Murchison House, Edinburgh, 23 participants examined some key exposures of the HBC/HBO. Findings were reported (Henderson *et al.* 2009; Leslie 2009), but are not mentioned in Bluck's paper. The omission from the latter of critical references, coupled with a tendency to rely too heavily on work published pre-1920, which was before way-up structures and bedding/cleavage relationships were first used by field geologists in Scotland, undermines any attempt to promote an objective and informed debate on Highland Border geology. This discussion is therefore focused upon assessing the field evidence that has been used by Bluck to support Model A and in particular, the way-up of beds in the Trossachs Group.

Observed younging directions in the Trossachs Group

This author has worked in all of the areas listed below and verified the conclusions. In assessing the overall younging direction in a unit such as the Trossachs Group, local reversals of younging caused by mesoscopic folds, and accompanied by a switch in bedding/cleavage relationships, are excluded. They have been recorded in the Keltie Water and North Esk sections, and possibly, at Stonehaven. 'SHGt' refers to only the topmost part of the Southern Highland Group.

When traced from Arran to Stonehaven, the foliation (and bedding) in the SHGt and Trossachs Group changes from dipping SE, through the vertical, to dipping gently NW. However, although the SHGt and the Trossachs Group are right-way-up between Arran and Innellan and become inverted from Balmaha to the North Esk, neither the overall younging direction (to the SE), nor the D1 facing direction (downwards) change. Accordingly, the ophiolite, which was emplaced on to the Dalradian rocks (Model B), now lies on top of the Trossachs Group in the SW, and beneath it NE from Balmaha.

North Glen Sannox, Arran

The SHGt and Trossachs Group are right-way-up and young consistently SE (Johnson & Harris 1967; Henderson & Robertson 1982; McKerrow & Atkins 1989; Chew *et al.* 2010). The pillow lavas in the Trossachs Group are not inverted, as is stated in the paper by Bluck.

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Innellan & Toward, Cowal; Scalpsie Bay, Bute

Cross-lamination and graded bedding show that the SHGt and Trossachs Group young consistently SSE, to the sole of the ophiolite (Tanner 2007).

Balmaha, Loch Lomond

The lithic arenite at Arrochymore Point (part of the HBO) is inverted (7 examples of inverted beds; none right-way-up), and youngs to the south (e.g. Henderson & Robertson 1982; Bluck 1992). However, Bluck mistakenly quotes Barrow (1901) and Campbell (1913), for evidence that these rocks are isoclinally folded and young to *both* north and south. Their work pre-dated the use of way-up structures, and neither author referred specifically to the Balmaha area.

Keltie Water (not Kelty), Callander

Numerous graded beds demonstrate that the Trossachs Group from the SHGt to the Leny Limestone, youngs to the south, and is inverted (Stone 1957; Harris 1962; Tanner 1995; Tanner & Pringle 1999).

River North Esk, Edzell

Although limited, outcrop evidence, which includes repeated finely graded beds in the 'Margie Grits' (Henderson, *pers. comm*. 2010) favours southward-younging and supports the findings of Johnson & Harris (1967) that the SHGt and the Trossachs Group, although separated by the North Esk Fault, are both inverted, young to the south, and display downward-facing D1 structures (Pringle 1942; Shackleton 1958; Henderson & Robertson 1982; Harte & Booth *in* Gould 2001).

Craigeven Bay, Stonehaven

The NW-younging shown by the pillow lavas in figure 2 is well known (Henderson & Robertson 1982; Trewin *et al*. 1987, plate 17). The sequence includes brecciated lava (not agglomerate) and is part of the HBO.

Summary

None of the examples quoted by Bluck of northward-younging from the Trossachs Group are confirmed.

Breccias and conglomerates as way-up indicators

Loch Lomond conglomerates

The serpentine conglomerates at Balmaha belong to the HBO and are of sedimentary origin (du Toit 1905; Henderson & Fortey 1982; Tanner 2007). They have a history separate from that of the Trossachs Group (see Conclusions).

Basement Breccia, Aberfoyle

This is a debris flow deposit, not a basal conglomerate and it consists of a north–south transition over several metres, from massive arenite; to arenite with wisps, then rafts, of black shale; to black shale with angular fragments of arenite; to black shale. The angular arenite fragments and blocks are affected by soft-sediment deformation, including water-escape structures. There is no evidence for a major unconformity, as envisaged by Jehu & Campbell (1917, fig. 2). The debris flow deposit youngs to the SE towards the black shale.

Green Conglomerate, North Esk

Bluck follows Barrow (1901), who inferred that the sequence in the North Esk youngs to the NW, based on the assumption that the Green Conglomerate represents a basal conglomerate to the 'Margie Series', derived from the structurally underlying lavas. Subsequently, Pringle (1942) concluded that there was no evidence for an unconformity, and Shackleton (1958) observed that three graded beds 2 m north of the Margie/Green Conglomerate contact, young south, and that a single bed 2 m south of this contact also youngs to the south. Thus the evidence indicates southward younging.

Summary

None of the above examples quoted by Bluck, of northward-younging from the Trossachs Group are supportable from observations on the ground.

Related matters

1. The lack of Dalradian detritus in the HBC, has been persistently emphasized as one of the tenets of the Bluck model, but it is axiomatic that such detritus will not be found in a Trossachs Group that is part of the Dalradian (Model B).
2. Tanner & Sutherland (2007) did not 'ignore' the Chitinozoan mentioned by Bluck: the mounted specimen was absent from the collection. A fresh rock sample was collected from the original location, and processed, but nothing recognizable was found.
3. Bluck refers to garnet and biotite at Innellan, presumably quoted from Clough (in Gunn *et al.* 1897, p. 73). The 'spots' are pseudomorphs after stilpnomelane (misidentified by Clough as biotite), not garnet.

Conclusions

The considerable body of data summarized above unequivocally demonstrates that, along the length of the Highland Border in Scotland, both the Trossachs Group and the underlying older, Southern Highland Group (Dalradian) young in the same direction (to the south or SE). Where the D1 facing direction can be determined, it is the same in both groups of rocks, demonstrating structural continuity. These carefully researched findings support Model B, and provide the basis for confirming the Trossachs Group as being the youngest unit in the Dalradian Supergroup, thereby extending its upper age limit to at least the topmost Tremadocian. The putative Highland Boundary Fault lies somewhere SE of the outcrop of the Trossachs Group.

In addition, taking into account work published over the past 20 years, it is concluded that the HBO is a dismembered Ligurian-type 'ophiolite' that formed part of the seafloor during the later stages of Dalradian sedimentation in an ocean–continent transition setting. The architecture developed at this time was subsequently modified structurally during emplacement of the 'ophiolite', and finally overprinted by the Grampian deformation. Thus the 'ophiolite' should be considered as a separate stratigraphical and structural entity, with no predictable geometrical relationship to way-up or D1 facing within the Trossachs Group.

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Reply to the discussion by Tanner on 'The Highland Boundary Fault and the Highland Border Complex' Bluck (2010) *Scottish Journal of Geology*, 46, 113–124

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B.J. Bluck replies: Many plates were shown in the paper by Bluck (2010, figs 2,3,4,5,7,) which illustrate quite clearly the stratigraphy and direction of younging of the rocks involved. These figures, not exhaustive, were taken from outcrops which span almost the entire length of the Highland Border Complex from Cowie, north of Stonehaven to Bute in the SW. As a sedimentologist I have disregarded 'graded bedding' in sheared quartzose sandstones of indeterminate origin and indifferently exposed, as a reliable way-up criterion (for example in the North Esk and elsewhere).

Stratigraphic evidence

The pattern of stratigraphical evidence is shown in photographs in Bluck (2010).

1. This is presented in Bluck (2010) fig. 4 where clasts of the rocks to the SE, which are made of tuffs, pillow lavas and cherts, occur in a conglomerate immediately overlying them to the NW. Clasts of chert and lava are also found in the basal parts of the quartz-arenite sequence immediately to the NW.
2. In the Prosen Water and Carity Burn clasts of serpentinite, many of which are rounded, occur immediately to the NW of a large outcrop of serpentinite to be followed by the Margie Series.
3. At Aberfoyle Jehu & Campbell (1917, plate V, fig. 4) show a breccia, with clasts of black shales and lavas overlying black shales to the NW the rocks above an unconformity. That the rocks may be a slide breccia is inconsequential to the fact that they contain fragments of the underlying lithologies.
4. A conglomerate with rounded clasts of serpentinite is found to the NW of a band of sheared and heavily altered serpentinite rock immediately to the SE (see Bluck 2010, fig. 5). This conglomerate is immediately followed to the NW by black shales which are periodically exposed beneath the Old Red Sandstone (Bluck 2010, fig. 8A).
5. A conglomerate with clasts of sheared and altered serpentinite occurs in a cherty shale to the NW in outcrops (now covered with water) in Loch Lomond. This outcrop (Bluck 2010, fig.7) is followed by outcrops of black shales. The northern serpentinite in this outcrop is also followed on the shores of Loch Lomond by a conglomerate (see Bluck 2010, fig. 8A).
6. In addition petrographic evidence from Cowie, Prosen Water and Aberfoyle all show the Margie group in its very lowest beds contain fragments of ophiolite—all indicating that these Margie beds formed after serpentinite and associated rocks. These stratigraphic way-up criteria are regionally found within the Highland Border Complex and stand in stark contrast to the statement by Tanner & Sutherland 2007 p.112 that 'way-up structures, although uncommon, invariably show that the Highland Border Complex youngs away from the Dalradian' which I regard as totally false.

OTHER WAY-UP CRITERIA

Bluck (2010, figs 2 & 3) also list other criteria for the direction of younging of the outcrop. The pillow lava at Cowie (fig. 2) and the stratified tuffs and agglomerates infill the intersticies between the pillow lavas. Tanner (above) regards these breccias as tectonic in origin; however they have bands of stratified tuffs and agglomerates and show, in thin section, show no evidence at all of shearing. So I strongly dispute this statement and reconfirm my original view that they show the sequence to young towards the NW.

The lithic arenite at Loch Lomond varies between being a totally unsheared rock to one which is heavily sheared. It has cross-bedding which is both inverted and the right way up and is therefore regarded as folded. Parts of the sequence include a conglomerate, the composition of which includes many igneous fragments and cherts. The Lomondside exposures include chert and the fragments in the conglomerates are thought to have a source in them making them younger than the chert beds.

The metamorphic rocks found at Aberfoyle and Bute are part of an ophiolite sole (see also Chew *et al.* 2010) and dated by them as *c.* 500 Ma. Such rocks are produced when hot and thick oceanic crust is obducted. In this instance the highest metamorphic grade is usually found immediately below the serpentinite (originally peridotite) then very rapidly declines. All but the highest grade rocks are found on the NW of the outcrop which are amphibolites and like other soles grade very quickly to the SW through epidote rocks and finally to very contorted black shales—all within a distance of *c.* 50–70 metres. The peridotite mass at *c.* 500 Ma either came from the north or from the south as its protolith,

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serpentinite, is well exposed along the Highland Boundary Fault. At this age, when sedimentation was taking place in the Dalradian block it almost certainly derived from the south where much of this type of activity took place. Here at 505 ±11 Ma a garnet metapyroxenite formed during the obduction of the Ballantrae ophiolite (Hamilton *et al*. 1984) and which is very near to the age of the Bute sole at *c*. 500 Ma (Chew *et al*. 2010) but the serpentinite is missing from Bute, so it is either beneath the present outcrop of Dalradian rocks or occupied a space between the southern margin of the Dalradian and the ophiolite sole. With respect to the folding related to cleavage it is important to point out that the deformation in the Highland Border Complex is highly variable: there are unsheared pillow lavas and volcanic agglomerates, conglomerates with extremely well rounded clasts in an unsheared matrix and there are also examples in which shearing has distorted the rocks (as pointed out by Bluck 2010, p.118).

The sequence is established by tracing the petrography of the rocks with earliest being the ophiolite extending its sediments to the later so called Margie Series. It is for these reasons that the of part of the Highland Border rocks belonging to the Dalradian sequence of Tanner & Sutherland (2008) with very little or doubtful evidence given, is rejected and the view of Curry *et al*. (1984) and Bluck (2010) is restated with the clear evidence shown in photographs.

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