

Border skirmish

Are remnants of an Ocean-Continent-Transition Zone preserved at the Highland Border in Scotland? Graham Leslie* reports from the 2008 Highland Workshop and takes a fresh look at a long-standing controversy in Scottish Geology.

The geological significance of the boundary between the Midland Valley and the Highlands of Scotland, known traditionally as the Highland Border, has been a source of controversy and debate since the beginning of the last century. The 'Highland Line' is one of Scotland's most iconic and readily visible landscape features, linked intimately with the Highland Boundary Fault Zone.

That structure separates Dalradian metamorphic rocks of Neoproterozoic to Lower Palaeozoic age in the NW from Silurian-Devonian sedimentary rocks to the SE. The Dalradian rocks have been affected by early Ordovician (Arenig-Llanvirn) Grampian orogenesis, whereas only mid-Devonian (Emsian) Acadian and late-Carboniferous deformation affects the rocks of the Midland Valley. Geoff Tanner has now revived debate on the significance of the Highland Border with a number of published papers, most recently in the *Journal of the Geological Society, London*^{1,2,3,4}.

The Highland Border zone is generally less than a kilometre across, but displays a remarkable diversity of rock types, including highly altered ultramafic rock, amphibolite, basaltic pillow lava, conglomerate, arenite, black graphitic mudstone, limestone and chert - all formerly assigned to the *Highland Border Complex (HBC)*. Geoff Tanner and Stuart Sutherland argued³ that this assemblage should be divided into a *Trossachs Group*, in stratigraphical and structural continuity with the Dalradian Southern Highland Group, and an overlying suite of ultramafic and mafic rocks belonging to the *Highland Border Ophiolite (HBO)*.

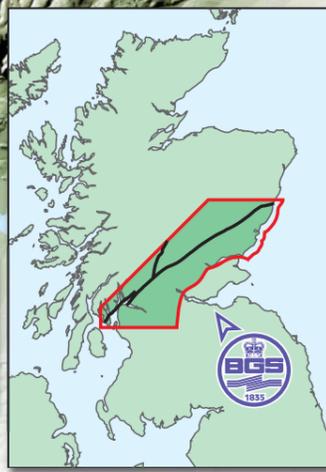
This proposal extends the known age of 'Dalradian' sedimentation on this margin of Laurentia into the Arenig. Geoff has also speculated that the HBO consists largely of rocks of sedimentary origin derived ultimately from exhumed serpentinised sub-continental lithospheric mantle, in the manner of the ophiolitic rocks exposed in Liguria in northern Italy. These derived mafic and ultramafic rocks would then have been obducted onto the Dalradian block subsequent to the formation of the Tay Nappe. Serpentinite, possibly derived from exhumed sub-continental lithospheric mantle rocks, has also been reported from the Dalradian of Ireland by David Chew⁵. It was timely then, that the Highland Workshop 2008 should address and discuss these issues, prior to spending three days examining some of the critical field relationships.

The Highland Workshop is an informal field-focused gathering of geologists motivated strongly by the philosophy that 'the answer resides in the rocks'. The meeting this year was convened in April at the British Geological Survey Murchison House in Edinburgh. In presentations devoted to the Highland Border, David Chew reported new radiometric data for the Bute ophiolite, which were interpreted as giving an emplacement age of 490Ma. Geoff Tanner described the field relationships and setting of the HBO, stressing the contrasts with the 1972 Penrose Conference definition of an ophiolite suite and instead, the close similarities to Mediterranean ophiolites of Ligurian-type.

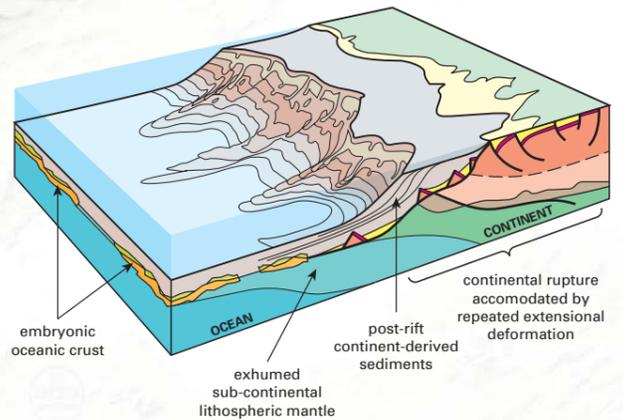
Geoff Tanner (centre, with staff) makes his point to John Dewey. Grahame Oliver and Con Gillen look on (L, R).



The dramatic contrast between the Highlands and the Midland Valley of Scotland is clear in this illuminated surface relief model of the Highland Border, (NEXTMap Britain™ elevation data from Intermap Technologies). Inset shows the extent of the larger map, the BGS logo marks the city of Edinburgh.



A modern view of an Ocean-Continent transition zone, where the Continental and Oceanic crust are separated by a zone of exhumed sub-continental lithospheric mantle.





Banded amphibolite layer of the HBO, in sheared thrust contact with right-way-up Dalradian rocks. Dun Scalpsie, Isle of Bute.



Strongly tectonised serpentinite and ophicarbonate-rock of the HBO. Innellan foreshore, Isle of Bute. The hammer shaft is 37cm long.

Strongly sheared brown-weathered ophicarbonate-rock of the HBO enclosing rounded clasts of continent-derived pale grey gritty quartzite. Lime Hill, near Aberfoyle.



workshop to consider the impact of Iberia-type margins in our interpretation of other collisional orogens, not least in the Caledonian of the UK and Ireland. Informed and stimulated by these presentations, the Workshop promptly decamped to Dunoon in the SW Highlands to examine the evidence contained within the rocks of the HBO (and HBC) at close quarters. A 23-strong excursion group scrutinised and argued over several critical Highland Border localities between Aberfoyle and Bute, guided throughout by Geoff Tanner.

Four hypotheses

During the field excursion, four radically different hypotheses, erected to explain the relationships seen at the Highland Border, had to be borne in mind (with one (at least) of their authors present in each case!). These are listed below, together with their proponents.

The four main theories suggest that the Highland Border Ophiolite (HBO):

- consists of the floor of an intra-Dalradian oceanic basin, thrust southwards during Grampian orogenesis⁶
- comprises remnants of oceanic lithosphere obducted north-westwards onto the Dalradian rocks, consequently generating major structures (including the Tay Nappe) and metamorphism, during Grampian orogenesis⁷.
- lies at the base of a group of rocks younging towards the Dalradian sequence, (the Highland Border Complex), that forms part of an exotic terrane docked laterally against the Dalradian block in late Silurian-early Devonian times⁸.
- consists largely of rocks of sedimentary origin derived from serpentinised sub-continental mantle, which were obducted onto the Dalradian block subsequent to the formation of the Tay Nappe. The HBO did not provide the driving force for any of the

principal Grampian deformation episodes'. The available exposures are typically discontinuous, variably accessible, and challenging to interpret. The most striking unit of the HBO seen by the group in the field, is an orange-brown-weathered carbonated serpentinite conglomerate (or ophicarbonate-rock) together with lithic arenite (Ni and Cr-enriched) and jasper. All stages of carbonation, from massive ultramafic rock to fragmental and sheared ophicarbonate-rock, were seen. The HBO rests tectonically above cleaved gritty sandstone and slaty mudstone, limestone and volcanic rocks of the Trossachs Group. If Tanner & Sutherland are correct that the latter is in stratigraphical continuity with the cleaved mudstones and gritty sandstones of the upper Dalradian Southern Highland Group, the following issues remain live:

- When did the HBO form in relation to Dalradian deposition in the latest Neoproterozoic and earliest Palaeozoic?
- Was the HBO derived from north or south of the Highland Boundary, and by what means?
- Did *emplacement* occur before or during the Grampian orogenesis or did the HBO (as part of the HBC) dock still later as part of an exotic terrane in the mid-Palaeozoic?

The Workshop was then galvanised by the keynote contribution of Gianreto Manatschal (CGS-EOST, Strasbourg), who illustrated new discoveries in deep-ocean research, including the mafic and ultramafic rocks that occur in modern ocean-continent transition settings (e.g. in Iberia and Newfoundland). In short, serpentinised peridotite, derived from sub-continental lithospheric mantle exhumed during continental breakup, is observed at the seafloor in 'Iberia-type', magma-poor, rifted passive margins. Here, continent-derived sediments are deposited directly onto, and sheared into, the ultramafic rocks. Geologists now believe that serpentinised sub-continental mantle rocks exhumed in these Iberia-type passive margins can survive orogenic collision and obduction - to occur, for example, within the 'Ligurian-type' ophiolites of the Western Mediterranean Alpine regions⁵.

In such Alpine settings, relict mantle-derived rocks were originally exhumed by extension in a rupturing Tethyan ocean-continent transition zone. Taking things a stage further, Gianreto invited the

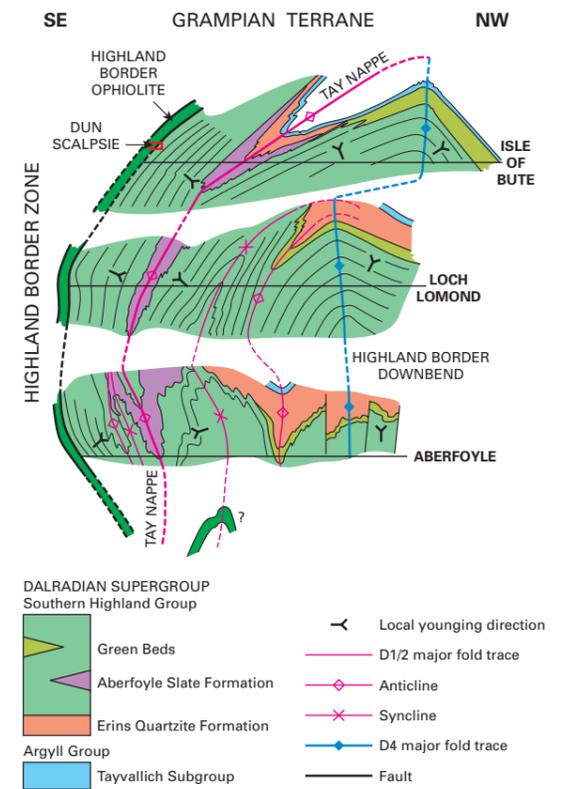
The workshop achieved considerable progress on these and other issues, and a report has been communicated to the *Scottish Journal of Geology*. The principal findings were:

- Widespread existence of fragmental ophicarbonate-rock was confirmed from Aberfoyle to Bute, many examples showing a striking resemblance to material recovered from modern Iberia-type ocean-continent transitions. The more tectonised examples of HBO serpentinites and ophicarbonate-rock are also remarkably similar to examples from Ligurian-type ophiolites. Clasts of continent-derived gritty sandstone and quartzite, enclosed within a serpentinite matrix in conglomerates at Lime Hill near Aberfoyle, generated considerable discussion.
- No firm evidence was found for the existence of hot ophiolitic sole rocks (in contrast to the situation at Ballantrae in the SW Midland Valley, for example).
- The Dalradian rocks and the HBO were juxtaposed prior to generation of the late-Grampian Highland Border Downbend fold. No significant obduction or emplacement-related deformation could be recognised at the contact of HBO ophicarbonate-rock or serpentinite, and the Dalradian rocks. Indeed the earliest Grampian deformation in Dalradian rocks appeared to pass directly into the ultramafic rocks of the HBO. All the structural evidence observed indicates that emplacement of the HBO occurred *before* the Dalradian rocks were deformed during Grampian orogenesis, and thus did not cause any significant deformation of the Dalradian block.
- David Chew's current research implies that the Bute amphibolite is most likely associated with the early stages of Iapetus' closure in the latest Cambrian, rather than its opening. This amphibolite may be similar to supra-subduction zone ophiolitic rocks in Newfoundland, Western Ireland and Shetland. Thus, while most of the HBO could be slices of serpentinised continental mantle that formed part of the floor of an extended Dalradian basin, it would be overdoing it to presume that all of it formed in that way.

The field observations broadly support a model in which the sheared and fragmental ophicarbonate-rocks and associated sediments of the HBO originated in a stretching ocean-continent transition setting, now preserved as a fragment of Ligurian-type ophiolite, at the southern edge of the Grampian orogen. Such an oceanic depositional setting is consistent with the occurrence of spilite, black mudstone and chert in the Trossachs Group. Isolated intra-Dalradian ultramafic bodies in Perthshire and Aberdeenshire, as well as the Dalradian of Ireland, may be linked to exhumation of sub-continental mantle rocks, as indeed could the ultramafic rocks of Glen Urquhart in the Great Glen.

The proposal that the HBC (and HBO) originated as an exotic terrane that finally docked with the Grampian Terrane in the late Silurian could not be substantiated in the field by the Workshop. While most of the HBO could indeed be composed of small slices of exhumed serpentinised sub-continental mantle that originally formed part of the floor of an extended Dalradian basin during the opening of Iapetus, it seems that not all of it may have formed in that way. The evidence from Bute emphasises the fragmentary and challenging nature of the geological record on this margin of Iapetus.

The current hypothesis can therefore be summed up as follows:



Geoff Tanner's composite NW-SE cross-sections constructed for the Highland Border Zone on the Isle of Bute (top), at Loch Lomond (middle) and at Aberfoyle; for locations see main map. This composite shows the folding and rotation of the Highland Border Ophiolite that occurred along with the Tay Nappe structure, 480-460Ma.

Gianreto Manatschal (R) gets to grips with Highland Border geology in the company of (L-R) Paul Smith, Rob Strachan, Stephen Daly, John Dewey, Geoff Tanner and John Mendum. David Stephenson and Tony Prave below.



"The Highland Border Ophiolite is a slice of exhumed serpentinised sub-continental mantle and associated sedimentary rocks, that formed part of the floor of an extended Dalradian basin, and was thrust onto the sedimentary sequence immediately before the start of Grampian orogenesis."

Existing models for the tectonic evolution of the (Scottish) Laurentian margin of Iapetus will need to be modified in order to capture these new observations and ideas. It seems that the HBO may not, after all, represent a remnant of obducted Iapetan oceanic lithosphere. Iberian-type, magma-poor, ocean-continent transitions are now recognised as increasingly common in modern ocean environments by Manatschal and others. Hence, re-examination of the Neoproterozoic to early Palaeozoic events preserved in the Scottish Grampian Highlands may well reveal a more comprehensive record, albeit cryptic, of continental break-up through repeated episodes of (aborted) rifting. What traces now remain in the rock record?

Next year, the Workshop will visit Ireland, where the Ordovician ophiolitic Tyrone Plutonic Group did, apparently, sample Iapetan lithosphere - so providing further evidence of the geometrical complexity that results from the progressive development of an ocean and its subsequent destruction at a subduction margin. 

Interested in Ireland 2009?

If you are interested in participating in the 2009 Irish excursion of the Working Group, contact Mark Cooper (GSNI), mrco@bgs.ac.uk.



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Selected further reading

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