Geol. Mag. **144** (3), 2007, pp. 597–602. © 2007 Cambridge University Press
doi:10.1017/S0016756807003342 First published online 20 April 2007 *Printed in the United Kingdom*

RAPID COMMUNICATION

The role of the Highland Border Ophiolite in the ~470 Ma Grampian Event, Scotland

P. W. G. TANNER*

Department of Geographical & Earth Sciences, University of Glasgow, Glasgow G12 8QQ, UK

(*Received* 9 August 2006; *accepted* 11 January 2007)

Abstract

Field and petrological studies of the Highland Border Ophiolite demonstrate that it was obducted onto the Neoproterozoic–Ordovician rocks of the Dalradian block, and not emplaced against them by post-orogenic strike-slip movement. It was welded onto the upper, southward-younging limb of the already recumbent Tay Nappe (D1), and deformed by the Downbend Antiform (D4). However, its emplacement was *not* accompanied by significant internal deformation of the Dalradian block. As the ophiolite is correlated with those at Clew Bay, Tyrone and Shetland, this result will necessitate complete revision of the current model for basin closure on the southeastern margin of Laurentia.

Keywords: Ordovician, ophiolite, obduction, Dalradian.

1. Introduction

Ophiolites of early Ordovician age (~ 470–480 Ma) are implicated in Grampian and Appalachian orogenic events along the entire southeastern margin of Laurentia (van Staal *et al.* 1998), and the Highland Border Ophiolite in the Scottish Caledonides (Fig. 1) is no exception. A recent study of the Cambro-Ordovician 'Highland Border Complex' (Tanner & Sutherland, 2007) has demonstrated that it may be divided into two parts: (a) the newly-designated Trossachs Group, which is in stratigraphical and structural continuity with the Dalradian Supergroup, and ranges in age up to at least the earliest Ordovician, and (b) the overlying, lower to middle Arenig Highland Border Ophiolite and its cover sequence, the Garron Point Group. The Trossachs Group includes most of the former 'Highland Border Complex'.

This interpretation replaces earlier ones in which the Highland Border Ophiolite was seen as either (i) the floor of a back-arc basin that, together with the overlying Complex, constituted an exotic terrane that docked by strike-slip motion against the Dalradian block in late Silurian to early Devonian times, following the end of the early Ordovician Grampian Event (Bluck 2002, and references therein), or (ii) a series of nappes or thrust sheets expelled from an ocean basin to the north and transported south during Grampian D2 (Henderson & Robertson, 1982).

The aims of this paper are to document and interpret critical exposures of the basal contact of the ophiolite, unique in the British Isles for their quality, and thereby demonstrate that the ophiolite was obducted on to the Dalradian–'Highland Border Complex' sequence early in the structural evolution of the Scottish Caledonides. The hypothesis that obduction of the ophiolite caused the formation of NW-vergent nappes (D1–3) during the early Ordovician Grampian Event (Dewey & Shackleton, 1984; Dewey & Mange, 1999; Dewey, 2005) is re-examined.

2. Geological setting

The relationship between rocks belonging to the uppermost part of the Dalradian succession in the Scottish Caledonides (Southern Highland Group), and the 'Highland Border Complex' found to the SE, has been a source of controversy for over a century. However, following the seminal work by Johnson & Harris (1967), it has recently been affirmed that most of these rocks share the same structural history (Tanner & Sutherland, 2007) and in total have been affected by up to three phases of deformation belonging to the early Ordovician ~ 470 Ma (see Baxter, Ague & Depaolo (2002), and references therein) Grampian Event (D1–D3), and by a later < 460 Ma event (D4).

Two major structures affect the Dalradian rocks in the southern part of the outcrop, the Tay Nappe (D1–2) and the Downbend Antiform (D4), and may be traced for ~ 300 km parallel to the 'Highland Boundary Fault' (Fig. 1). The Highland Border Ophiolite occurs on the upper limb of the Tay Nappe, immediately north of the fault, where the Dalradian rocks are affected only by D1; the D2 deformation is very localized within the Highland Border Steep Belt, and S2 does not become dominant until well into the lower limb of the Tay Nappe, ~ 5 km north of the Highland Border (Fig. 1).

3. The Highland Border Ophiolite

This varied assemblage of mafic and ultramafic rocks forms a discontinuous outcrop < 1 km wide, along the Highland Border from Bute to Stonehaven (Fig. 1). It has a thick, locally developed 'sole' of finely banded amphibolite at Scalpsie Bay (Henderson & Robertson, 1982), and at Lime Hill (Henderson & Fortey, 1982) (Fig. 1A,I). In each case the underlying rocks have been affected by contact metamorphism. The main body includes thick units of serpentine conglomerate (du Toit, 1905), together with spinel-bearing harzburgite (Ikin, 1983), massive ultramafic rock, and jasper. The most consistent member of the assemblage is a thick sheet of orange–brown-weathering, carbonated serpentinite, or ophicarbonate. The serpentine conglomerate is seen in all stages of alteration to ophicarbonate, and is locally

*Email: geoff.tanner@virgin.net

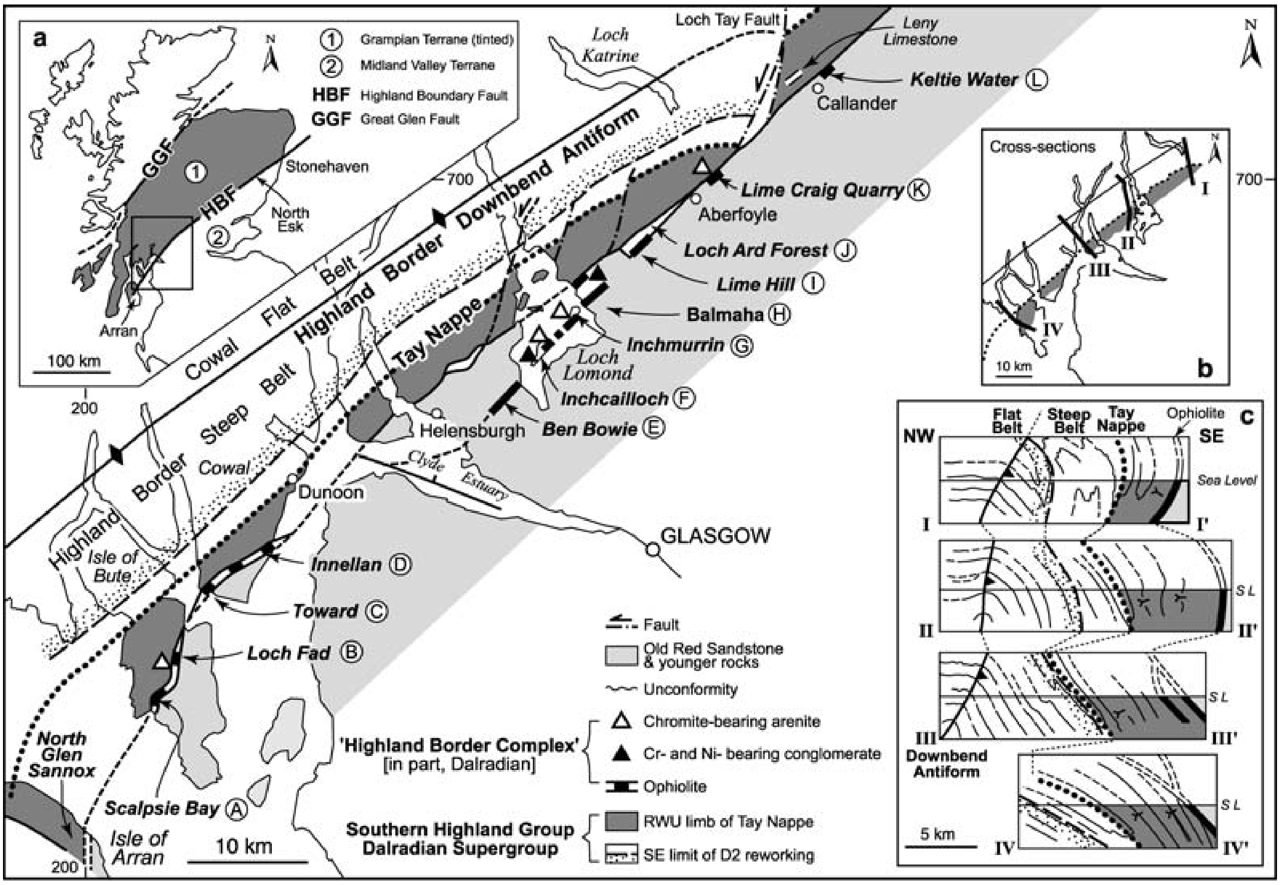

Figure 1. Geological setting of the Highland Border Ophiolite in Scotland. A–L, locations referred to in the text. (a) Location of the main map (boxed). (b) Locations of cross-sections I–IV. (c) True-scale cross-sections along I–IV in (b).

associated with Ni- and Cr-rich conglomerates (Fig. 1, F, G, K) (Henderson & Fortey, 1982).

Between Innellan and Aberfoyle, the ophiolite comprises two bodies of serpentine conglomerate (du Toit, 1905) separated by a thick unit of Ni- and Cr-rich lithic arenite (Fig. 1) (Henderson & Robertson, 1982). The northern, stratigraphically lower, body is the more highly sheared and is associated with jasper and grey chert, whereas the southern body is of carbonated serpentine conglomerate containing pebbles and boulders of metasandstone and metaquartzite, as well as of ultramafic rocks. The latter can be traced across Loch Lomond to Ben Bowie (Fig. 1, E), but the northern sheet is hidden beneath a cover of Upper Old Red Sandstone in this area. The two sheets probably combine to form a single body NE of Balmaha at British National Grid reference NS 484975; likewise, a single ophiolite body is seen SE of Innellan.

Neither a sheeted dyke complex nor a pillow lava sequence accompany the ophiolite, except at Stonehaven (Fig. 1a), which is unique in that the pillow lava sequence overlying the ophicarbonate includes varicoloured cherts, graphitic slates and umbers (Williams, Harkin & Rice, 1997). The pillow lavas in North Glen Sannox on Arran (Fig. 1) belong to the autochthonous part of the 'Highland Border Complex' below the ophiolite (Trossachs Group; Tanner & Sutherland, 2007), and there is no evidence to link the pillow lavas (Jasper and Green Rock Formation) (Johnson & Harris, 1967, and references therein) in the River North Esk section (Fig. 1a) with the ophiolite. In summary, the standard ophiolite sequence is not developed, and an unknown portion of the body is hidden under the unconformable cover of younger strata to the SE, or has been removed subsequently by extensional faulting.

4. Age of the ophiolite

The maximum stratigraphical age for ophiolite emplacement is constrained by the following: (i) it lies above the Lower Cambrian ($\sim$ 519 Ma) Leny Limestone at Callander (Tanner, 1995) and, critically, above the Tremadoc–Arenig Margie Limestone (R. L. Ethington, pers. comm. *in* Tanner & Sutherland, 2007) in the River North Esk; (ii) the Arenig Dounans Limestone at Aberfoyle (Curry *et al.* 1984) (Fig. 1, location K) lies above the ophiolite, and is overlain by the Lower Old Red Sandstone. It is a pale grey, calcite-veined rock that could be examined until recently in an exposure < 1 m across on the extreme NE corner of Lime Craig Quarry, the remainder having been quarried-out long ago. Mapping at 1:5000 shows that these exposures are separated from those to the SW by a major fault, and that the remainder of the exposures labelled as 'Dounans Limestone' on figure 7 of Curry *et al.* (1984) are of carbonated serpentinite, not Dounans Limestone, and have a transitional contact with the overlying Dounans Conglomerate. As no correlation is possible between rocks on either side of the fault, it can only be inferred that the limestone is part of the succession that overlies the ophiolite, and was deposited prior to the obduction event. *In toto*, the above information constrains the ophiolite to being of Arenig (480–470 Ma) age.

https://doi.org/10.1017/S0016756807003342 Published online by Cambridge University Press

5. Radiometric age of emplacement

The amphibolite sole at Scalpsie Bay, Bute (Fig. 1, A) has given an Sm–Nd age (garnet) of 546 ± 42 Ma, and a K–Ar (hornblende) age of 537 ± 11 Ma (Dempster & Bluck, 1991). As these ages are difficult to reconcile with above, the K–Ar age was possibly affected by excess Ar, and the Sm–Nd age by contamination from inclusions in the garnet. Titanite is abundant in the amphibolite but attempts to date this mineral by TIMS (J. Evans, NIGL) failed due to its very low uranium content.

6. Regional ophiolite–Dalradian relationships

In one of the most perceptive and informative papers written on the 'Highland Border Complex', Henderson & Robertson (1982) concluded that the Highland Border Ophiolite is in contact with Dalradian rocks in Cowal and Bute, and cuts up-section to rest on different members of the 'Highland Border Complex' (now Trossachs Group) farther to the NE. This important finding, disregarded for two decades, is here confirmed from the results of unpublished mapping of most of the outcrop of the Complex shown on Figure 1.

From Bute to Aberfoyle, the ophiolite lies on the upper S-younging limb of the downward-facing Tay Nappe (Fig. 1, b, c) in contact with rocks affected by the first deformation (D1), and the same relationship probably holds for the remaining distance to Stonehaven. The base of the ophiolite transgresses from typical Dalradian gritty sandstones on Bute, to graphitic black slates and sandstones younger than the Lower Cambrian Leny Limestone at Callander (Fig. 1, L). It is clearly folded, together with the Tay Nappe, by the D4 Downbend Antiform (Fig. 1c), and is unconformably truncated to the SE by rocks ranging in age from late Silurian to early Carboniferous. The question is whether the ophiolite was emplaced onto the Dalradian block before, during, or after the formation of the D1 Tay Nappe. The top of the ophiolite is not exposed, but the base is seen at four localities and these are described in detail.

7. Local ophiolite–footwall relationships

At localities A–D (Fig. 1) in Cowal and on Bute, the ophiolite sheet rests upon right-way-up Dalradian rocks comprising the upper limb of the Aberfoyle Anticline ('Tay Nappe') (Fig. 1c, section IV). The field relationships are summarized in the form of schematic vertical columns in Figure 2, together with equal area stereographic projections of some of the data. Bedding is consistently steeper than cleavage in all of these sections, and the basal plane of the ophiolite is oblique to both surfaces (Fig. 2).

At Scalpsie Bay on Bute, the base of the ophiolite is represented by tens of metres of banded amphibolite (Henderson & Robertson, 1982), which is separated from the rocks to the NW by an unexposed gap of 25–35 m (Figs 1, 2a), probably occupied by sheared serpentinite, as found in the equivalent position on the nearby coastal section. The base of the ophiolite is marked by several metres of green–black recrystallized mylonite underlain by a sheet of distinctive, pale-coloured granitoid up to 4 m thick (Fig. 2a). Undeformed, cross-cutting stilpnomelane veins, in places altered to chlorite, are characteristic of the contact zone.

The granitoid sheet has a gradational contact over a horizontal distance of up to 8 m through partially melted Dalradian country rock, to gritty sandstones and slates with clear bedding–cleavage relationships. In places, a sheet-like structure is developed in the granitoid body, parallel to the Dalradian contact. The basal contact has a mean orientation of dip 40° SE, strike 020°, lies within 10° of the D1 cleavage, and cuts right-way-up bedding at a mean angle of 36° ($n = 10$) (Fig. 2a,b). Close to this contact, the granitoid body is lineated parallel to the regional D1 stretching lineation, for which a mean direction of 33° to 100° was quoted by Simpson & Wedden (1974) for the coastal section 1.5 km SW of Scalpsie Bay. Sheared gritty sandstones found immediately below the footwall contact display a strong stretching lineation.

At Loch Fad (Fig. 1, B), the basal amphibolite forms a slab dipping at 43° SE, underlain by a 5–6 m thick granitoid sheet, that surmounts several metres of what appears to be grey flinty recrystallized mylonite (Fig. 2c). The Dalradian country rock is finer grained than at Scalpsie Bay, bedding is not evident, and the amphibolite is in direct contact with the granitoid sheet.

Critical evidence for the mode and timing of ophiolite obduction is found at Toward and Innellan (Fig. 1, C, D). At Innellan (Fig. 2d), serpentine conglomerate is separated from the 'normal' Dalradian rocks by a 1–3 m thick contact zone having a foliation (S_{cz}) that appears to be parallel to the base of the ophiolite. The latter is clearly oblique to both S1 and bedding (Fig. 2e). The contact zone consists of finely banded and laminated rocks, largely recrystallized mylonite, with dark stilpnomelane-rich bands, that is cross-cut by small, pink–white granitoid bodies, each surrounded by a halo of pale, bleached-looking rock. Most of the granitoids have rectilinear margins, cross-cut S_{cz}, and appear to be undeformed (Fig. 3a), but some were deformed at their margins during D1 and locally exhibit the D1 stretching lineation (Fig. 2e). Undeformed, randomly orientated black stilpnomelane veins occur throughout, and cross-lamination is preserved in the country rock within 0.5 m of the ophiolite contact.

The most important feature of the contact zone is the development of randomly orientated chlorite pseudomorphs. These spots are 1–3 mm across, and commonly have a diamond-shaped cross-section (Fig. 3b), with a few concentric internal zones and a quartz-rich core. Clough (*in* Gunn, Clough & Hill, 1897, p. 77) reported that some of the pseudomorphs had hexagonal outlines and contained relic garnet, whereas Henderson & Robertson (1982) inferred that the pseudomorphs were altered andalusite or cordierite. None of these interpretations has been confirmed and the parent mineral is unknown. The pseudomorphs overgrow, without displacement, a very fine-grained fabric (S_{cz}) in the matrix, which is defined largely by small, aligned opaque grains (Fig. 3c).

Farther south at Toward, four individual slices of ophiolite are exposed in a cross-strike distance of 150 m. The larger body has a faulted contact with the Dalradian rocks but the smaller sheets are associated with small granitoid bodies and/or spotted rocks that are restricted to the footwall (NW) side of each slice (Fig. 2f). This configuration suggests that the sequence consists of a number of slices each consisting of Dalradian footwall rock + contact zone + ophiolite separated either by thrusts (as shown in Fig. 2d), or by extensional faults. The contact metamorphic spots, although rare, are undeformed close to the serpentinite, whereas farther away from it, streaks and small bodies of chlorite are elongated parallel to the D1 stretching lineation (Fig. 2g), and develop pressure-solution tails. Clough (in Gunn, Clough & Hill, 1897) first reported deformed spots from this locality, and Henderson & Robertson (1982)

https://doi.org/10.1017/S0016756807003342 Published online by Cambridge University Press

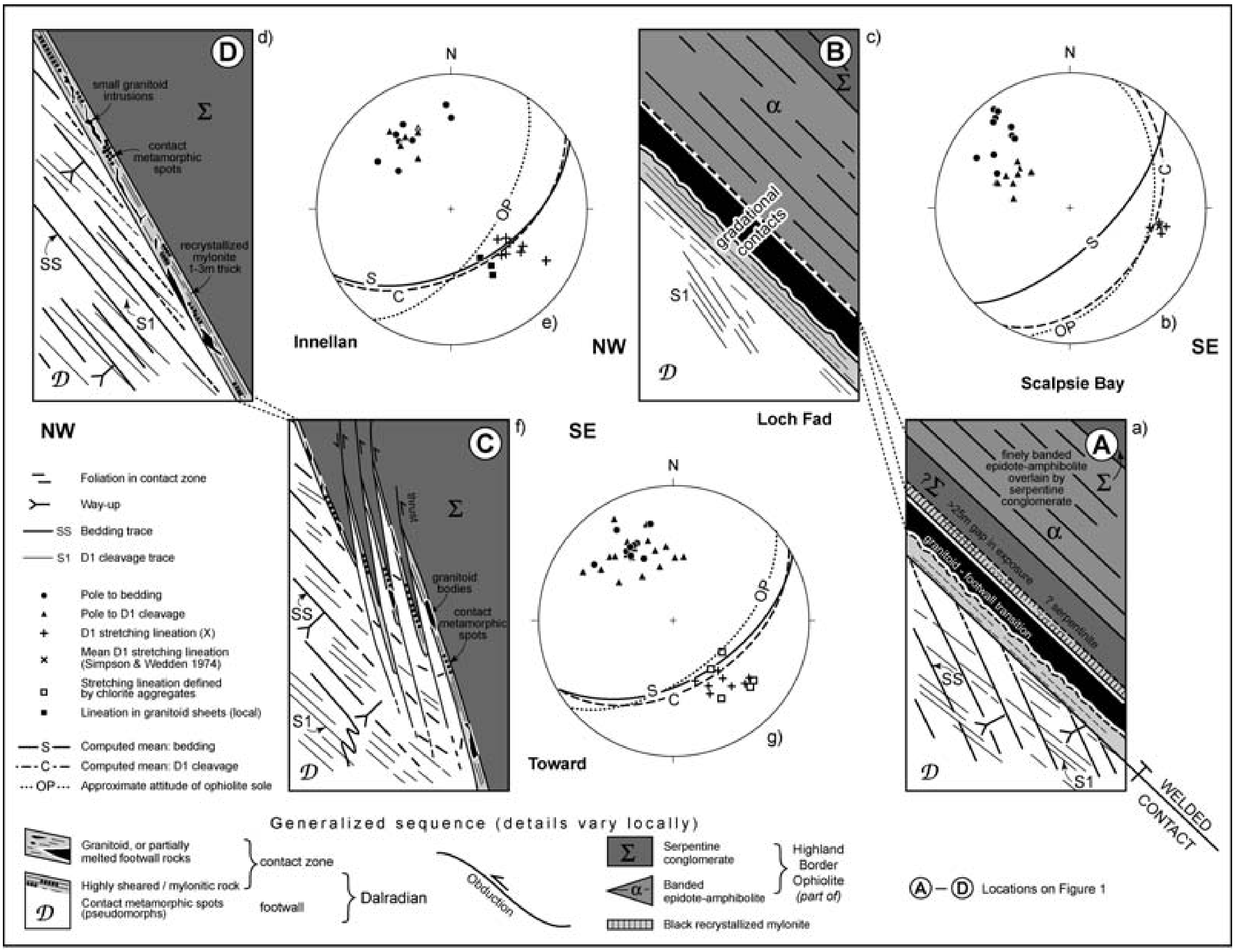

Figure 2. (a, c, d, f) Schematic, non-scaled, vertical sections through the base of the Highland Border Ophiolite at localities A–D, Figure 1. (b, e, f) Equal-area stereographic projections of data from three localities. A colour version of this figure is available from the author on request, or online at GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/).

concluded that the spots were elongated parallel to the D2 stretching direction.

NE of Balmaha (Fig. 1, H) the basal contact of the ophiolite is poorly exposed but, as in Cowal, the footwall rocks (Trossachs Group; Tanner, 2007) for a few metres below the contact are strongly sheared and locally affected by contact metamorphism. In the Loch Ard Forest (Fig. 1, J), Jehu & Campbell (1917, pp. 199–200) first reported contact metamorphic knots *(sic)* (two of which contain relic garnet) that had grown prior to the regional deformation and metamorphism in schists in the immediate footwall to the ‘Highland Border Ophiolite’. Henderson & Robertson (1982, p. 442) confirmed the occurrence of such spots, and recorded the presence of ‘altered cordierite porphyroblasts’ from close to the base of the ophiolite. Away from this narrow zone, the geometrical pattern of bedding and D1 cleavage in the footwall is undisturbed by the presence of the ophiolite sheet.

8. Interpretation

The following points are relevant when considering the timing of ophiolite obduction with respect to structural events in the Dalradian block: (i) A single, laterally discontinuous, ophiolite complex was obducted on to the Dalradian block. (ii) On a regional scale, the base of the ophiolite cuts across the boundary between the Dalradian *sensu stricto* and the former ‘Highland Border Complex’, and was welded to the footwall, as witnessed by the occurrence of undeformed contact metamorphic spots in both groups of rocks. (iii) The ophiolite lies on the upper limb of the D1 Tay Nappe but is not folded around that structure (Fig. 1c). (iv) A contact zone of sheared metasediments found immediately below the ophiolite sole carries a penetrative fabric (S_{cz}) that follows the base of the ophiolite sheet, and is oblique to bedding and S1. (v) The S_{cz} fabric is cut by undeformed granitoid sheets formed by partial melting during the obduction process, and is preserved within undeformed chlorite pseudomorphs, which replace a contact metamorphic mineral(s). (vi) Chlorite-rich spots and blebs in rocks on the periphery of the contact zone (equated with those above) are elongated parallel to the local D1 stretching directions, and some of the granitoid sheets develop this lineation at their margins.

From points (iv) and (v) alone it could be deduced that the ophiolite was pre-tectonic, but points (ii) and (iii) strongly favour post-D1 obduction, with some renewed deformation (vi). The deciding factor is the angular relationship between the ophiolite basal plane and S1, as it is generally agreed that the Tay Nappe was recumbent immediately prior to the formation of the D4 Downbend Antiform (Rose & Harris,

https://doi.org/10.1017/S0016756807003342 Published online by Cambridge University Press

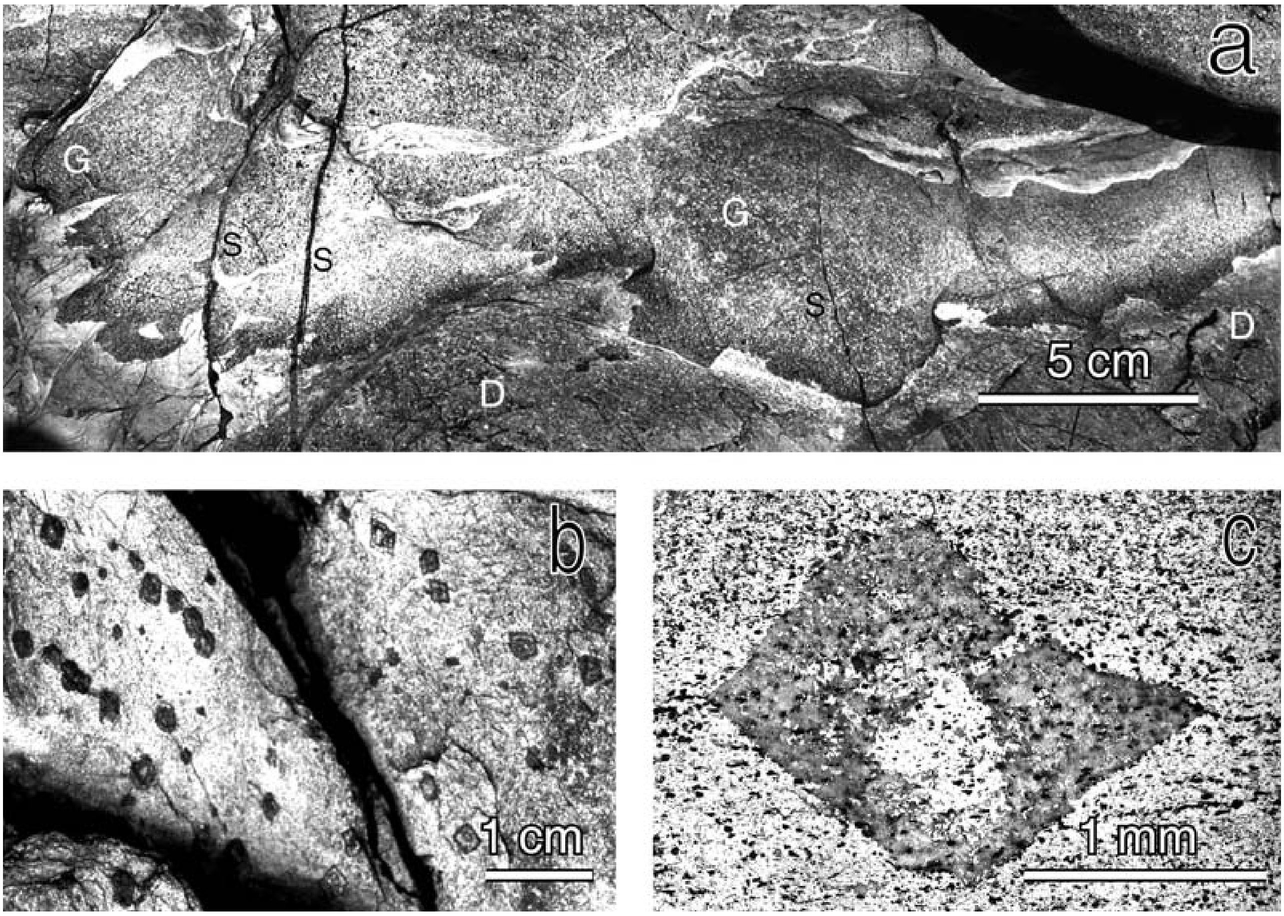

Figure 3. (a) Irregularly-shaped granitoid bodies (G), rimmed by narrow zones of bleached-looking Dalradian rock (D). Innellan, British National Grid Reference NS 1535 7075. (b) Contact metamorphic porphyroblasts, now entirely pseudomorphed by chlorite, from the contact zone at Innellan [NS 1535 7070]. (c) Photomontage of a chlorite pseudomorph from the above locality.

2000). In the present case, if the structure is unfolded to bring the base of the ophiolite to the horizontal, S1 has a residual dip of 10–29° NW. Thus the Tay Nappe had already evolved from an initial upright state to become a gently dipping, south-facing anticline, prior to emplacement of the ophiolite. The inferred sequence of events is therefore as follows:

The Tay Nappe formed during D1 as an upright structure, and was then rotated by over 70° SE. The ophiolite was emplaced across the right-way-up limb of the now gently inclined major fold and a mylonitic fabric (S_{cz}) formed within a narrow zone of intense deformation at its base. Cessation of movement was followed by partial melting of the adjoining country rock, the formation of small granitoid intrusions, and the growth of contact metamorphic spots that preserve S_{cz} as an internal fabric. Further deformation then occurred, with some minor granitoid bodies and spots remaining unaffected due to the shielding effect of the competent ophiolite sheet, and hornfelsing of rocks in the contact zone. Away from this protected area, the spots were deformed and elongated in the D1 stretching direction and the granitoid bodies were both foliated and lineated. This scenario differs from that of Henderson & Robertson (1982) who considered that the ophiolite had been emplaced from the north during D2, because (a) the (S_{cz}) fabric was equivalent to S1; (b) the regional fabric was S1/S2; and (c) the possibility that obduction had taken place from the SE was excluded due to the Highland Border Ophiolite being part of a Highland Border exotic terrane (see Bluck, 2002).

9. Discussion

The Highland Border Ophiolite consists largely of carbonated serpentine conglomerates and fragmental rocks, with the local development of chert, black graphitic shales and umbers. It has a narrow contact metamorphic aureole in which stilpnomelane is ubiquitous in the metasediments, occurs as millimetre-sized radial aggregates in granitoid lenses, and forms cross-cutting veinlets. The footwall rocks had been already affected by greenschist facies metamorphism at the time of ophiolite emplacement, and stilpnomelane could have formed from the breakdown of chlorite and white mica (both of which are stable in D1 mineral assemblages) in the presence of oxidizing metasomatic fluids, as reported by Stevens & Preston (1999) from greenschist facies Precambrian rocks of the Witwatersrand Basin. As stilpnomelane forms under a wide range of *P–T* conditions, its presence cannot be used to provide even a qualitative estimate of these parameters for the Scottish occurrence.

The model proposed here considerably simplifies the plate tectonic setting of the Highland Border Ophiolite, and it can now be compared with ophiolites of similar age (Dewey, 2005) such as the Clew Bay, Tyrone, and Shetland ophiolites. There is no longer a need to invoke the presence of a unique exotic terrane at the Highland Border in Scotland. Likewise, although the description of the 'Highland Border Complex' in the British Isles, as 'a range of unrelated and casually-related rock assemblages swept up at the leading subduction edge of the arc' by Dewey & Mange (1999) may apply to other ophiolites, such as the Deer Park Complex in the west of Ireland, most of the Complex in Scotland lies below this structural level and is in structural and stratigraphical continuity with, and indeed belongs to, the Dalradian Supergroup.

The hypothesis that obduction of such a laterally extensive, and possibly thick, ophiolite sheet was the driving force behind the Grampian Event (Dewey & Shackleton, 1984; Dewey & Mange, 1999; Dewey, 2005) is, however, called into question. In Scotland, the major architecture of this orogenic belt appears to have been established before the emplacement of the ophiolite, a process that seems to have had very little effect on the local or regional structure of the previously-deformed rocks lying beneath it. In addition, the top-to-SE vergence of the D2 structures over a major part of the inverted limb of the Tay Nappe (Rose & Harris, 2000) is the opposite to the shear couple that would result from obduction from the SE; D3 structures are of negligible importance in the overall framework; and D4 structures fold the ophiolite sheet. The importance of the Highland Border Ophiolite, and its cover rocks, to the Grampian event lies in its loading and blanketing effect, and in supplying hydrothermal fluids to the deforming rock mass.

These conclusions reopen the debate concerning the age of emplacement of the Highland Border Ophiolite (currently Cambrian); the age of the Tay Nappe (a major element of which had developed before the obduction); and the mechanism by which the Grampian structures including the Tay Nappe were formed, as ophiolite obduction was not directly involved in this process.

Acknowledgements. The author is grateful to the Leverhulme Trust for the award of an Emeritus Fellowship and financial support to assist with the writing up of this work; to referees John Dewey, Tony Harris and Rob Strachan for their encouraging comments; and to Mike Shand for the digital cartography.

References

BAXTER, E. F., AGUE, J. J. & DEPAOLO, D. J. 2002. Prograde temperature–time evolution in the Barrovian type-locality constrained by Sm/Nd garnet ages from Glen Clova, Scotland. *Journal of the Geological Society, London* **159**, 71–82.

BLUCK, B. J. 2002. Chapter 5. The Midland Valley terrane. In *The Geology of Scotland* (ed. N. H. Trewin), pp. 149–66. Geological Society of London.

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. & BLUCK, B. J. 1991. The age and tectonic significance of the Bute Amphibolite, Highland Border Complex, Scotland. *Geological Magazine* **128**, 77–80.

DEWEY, J. F. 2005. Orogeny can be very short. *Proceedings of the National Academy of Sciences, USA* **102**, 15286–93.

DEWEY, J. F. & MANGE, M. 1999. Petrography of Ordovician and Silurian sediments in the western Irish Caledonides: tracers of a short-lived Ordovician continent–arc collision orogeny and the evolution of the Laurentian–Appalachian–Caledonian margin. In *Continental Tectonics* (eds C. Mac Niocaill & P. D. Ryan), pp. 55–107. Geological Society of London Special Publication no. 164.

DEWEY, J. F. & SHACKLETON, R. M. 1984. A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. *Nature* **312**, 115–21.

DU TOIT, A. L. 1905. The Lower Old Red Sandstone rocks of the Balmaha–Aberfoyle region. *Transactions of the Geological Society of Edinburgh* **8**, 315–25.

GUNN, W., CLOUGH, C. T. & HILL, J. B. 1897. The Geology of Cowal. In *Memoirs of the Geological Survey, Scotland*. 333p.

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 relation to marginal basin development in the Scottish Caledonides. *Journal of the Geological Society, London* **139**, 433–50.

IKIN, N. K. 1983. Petrochemistry and tectonic significance of the Highland Border Suite mafic rocks. *Journal of the Geological Society, London* **140**, 267–78.

JEHU, T. J. & CAMPBELL, R. 1917. The Highland Border rocks of the Aberfoyle District. *Transactions of the Royal Society of Edinburgh* **52**, 175–12.

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

ROSE, P. T. S. & HARRIS, A. L. 2000. Evidence for the Lower Palaeozoic age of the Tay Nappe: the timing and nature of Grampian events in the Scottish Highland sector of the Laurentian Margin. *Journal of the Geological Society, London* **157**, 381–92.

SIMPSON, A. & WEDDEN, D. 1974. Downward-facing structures in the Dalradian Leny Grits of Bute. *Scottish Journal of Geology* **10**, 257–67.

STEVENS, G. & PRESTON, R. F. 1999. The metamorphic and alteration history of West Rand Group shales from distal portions of the Witwatersrand Basin. *Mineralogy and Petrology* **66**, 123–47.

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.

TANNER, P. W. G. & SUTHERLAND, S. 2007. The Highland Border Complex, Scotland: a paradox resolved. *Journal of the Geological Society, London* **164**, 111–16.

VAN STAAL, C. R., DEWEY, J. F., MAC NIOCAILL, C. & MCKERROW, W. S. 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In *Lyell: the Past is the Key to the Present* (eds D. J. Blundell & A. C. Scott), pp. 199–242. Geological Society of London Special Publication no. 143.

WILLIAMS, D. M., HARKIN, J. & RICE, A. H. N. 1997. Umbers, ocean crust and the Irish Caledonides: terrane transpression and the morphology of the Laurentian margin. *Journal of the Geological Society, London* **154**, 829–38.