Chapter 2 Early Ordovician volcanic rocks and associated ophiolitic assemblages of Scotland

Introduction

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At the beginning of the Palaeozoic Era the continental masses of Laurentia, Avalonia and Baltica were separated by large oceans. The Iapetus Ocean separated Laurentia from Eastern Avalonia and Baltica while the two latter continents were divided by the Tornquist Sea. Volcanic activity occurred within and at the margins of these oceans. The rocks described in this chapter all originated as varieties of Iapetus oceanic crust and upper mantle which were caught up in the orogenic fold belt produced as the ocean closed. This is the Caledonian–Appalachian Orogen which, prior to the Mesozoic and later opening of the Atlantic Ocean, formed a sinuous deformation belt extending from what is now northern Scandinavia, through Britain and Ireland, and on into maritime Canada, the eastern seaboard of the USA and possibly beyond. A pre-Atlantic continental reconstruction is shown in (Figure 2.1).

The Iapetus Ocean probably reached its maximum width during the Late Cambrian or early Ordovician. Closure of the ocean then followed during the Ordovician and Silurian with continental suturing complete by the Early Devonian. Along the length of the orogen are preserved vestiges of the original ocean in the form of ophiolite complexes, assemblages variously comprising spilitic lava, sheeted mafic dykes, gabbros and ultramafic plutonic rocks; the ophi-olite concept is discussed in more detail below. The distribution of the principal ophiolite complexes within the orogen is shown in (Figure 2.1). Those now seen in Britain and Canada were obducted onto the continental margin of Laurentia, the Norwegian examples were obducted onto the margin of Baltica on the other side of the closing ocean. Despite their wide geographical range there is a surprising uniformity of age with most apparently being generated in the Late Cambrian or early Ordovician and then obducted shortly after. Of the Scottish ophiolites, the early Ordovician, Ballantrae Complex has much in common with those now exposed in Newfoundland, whereas the Shetland ophiolite is probably a little older with similar generation and obduction ages to some of the Norwegian examples. The broad coincidence of ages probably reflects the initiation of ocean closure when intra-oceanic subduction zones were formed adjacent to both continental margins. The volcanic products of these zones would have had greater obduction potential than the oceanic crust that was subsequently consumed by subduction at the continental margin. At that time the margins of the Iapetus Ocean were probably similar in character to the modern west Pacific Ocean with a complicated pattern of inter-related volcanic island arcs and back-arc basins.

The ophiolite model

The common association of serpentinite, gabbro, spilitic pillow lava and pelagic sedimentary rock has long been recognized by geologists and the idea of a kindred genetic relationship was introduced by Steinmann (1927). However, it was the later development of the plate tectonic theory that allowed a coherent interpretation as oceanic crust, generated at a constructive plate margin but subsequently accreted or thrust onto continental crust at a destructive margin. Until then the term *ophiolite* (from the Greek *ophi* meaning snake or serpent, hence serpentinite) had been used in a variety of ways but in 1972 the Geological Society of America convened a conference to formalize both its use and the underlying concept; the resulting proposals have been generally adopted. *Ophiolite,* as now defined (Anon, 1972), refers to a distinctive assemblage of mafic to ultramafic rocks which, in a complete development (Figure 2.2), consists of rock types in the following sequence, starting from the top and working down:

- *Mafic volcanic complex,* commonly of pillowed lava.
- *Mafic sheeted dyke complex.*
- *Gabbroic complex,* commonly with cumulus textures.
- *Ultramafic complex,* consisting of variable proportions of harzburgite, lherzolite and dunite (ultramafic rock names are defined in (Figure 2.3)), commonly serpentinized and with a tectonic fabric.

Associated rock types include: overlying pelagic sedimentary rocks such as chert, podiform chromite bodies in dunite, sodium-rich felsic intrusive rocks. The definition stresses that although *ophiolite* is generally interpreted to be oceanic crust and upper mantle, the use of the term should be independent of the supposed origin. As this terminology has been applied it has become common practice to refer to the whole assemblage as an *ophiolite complex.*

The comparison with oceanic crust relates the ultramafic rocks to the upper mantle and the gabbroic rocks and sheeted dykes to seismic layer 3 of the oceanic crust; the pillow lavas form layer 2 and the overlying pelagic strata form layer 1 (Figure 2.2). On this basis the geophysically defined Moho (occurring in the 5–10 km depth range beneath oceanic crust) coincides with the base of the gabbroic unit in an ophiolite complex. Beneath this level in many ophiolites, there is a transition zone of dunite and interlayered gabbroic and ultramafic lithologies passing down into harzburgite. The base of the transition zone has become known as the petrological Moho, which may lie up to several kilometres beneath the geophysical Moho. This zone is preserved within the Punds to Wick of Hagdale and Skeo Taing GCR sites on Shetland.

As work on ophiolites has progressed it has been established that many are in fact atypical of oceanic crust and many have been generated above subduction zones, i.e. at a destructive plate margin, rather than at a constructive mid-ocean ridge. Interpretation difficulties are also caused by the incomplete and fragmentary nature of most preserved ophiolites. The Scottish Caledonian examples of Shetland, the Highland Border and Ballantrae illustrate many of these problems and are of international importance in the overall assessment of the relationship of ophiolites to oceanic crust.

The Shetland Ophiolite

The Shetland Ophiolite forms a large part of the islands of Unst and Fetlar in the NE of Shetland (Gass *et al,* 1982; Flinn, 1996). It is one of the series of ophiolite fragments distributed along the Caledonian orogenic belt from North America to Norway (Figure 2.1), most of which, including Shetland, were formed and obducted around 500 Ma or soon thereafter. Radiometric age data from Shetland suggests intrusive activity at 492 ± 3 Ma (U-Pb on zircon in a 'plagiogranite', *sensu* albite-granite, vein; Spray and Dunning, 1991) and the initiation of obduction at 498 ± 2 Ma (Ar-Ar on hornblende in amphibolite; Flinn *et al,* 1991). The nearest to Shetland of the other Caledonian ophiolites is Karmoy in Norway, 400 km to the ESE across the orogen, while the nearest in the UK (excepting the small fragmentary vestiges of the Highland Border Complex) is Ballantrae, 600 km to the SSW along the orogen. The upper part (layers 1 and 2) of the characteristic ophiolite sequence (Figure 2.2) is not preserved in Shetland but the lower part is exceptionally well developed and exposed. Overall, the Shetland Ophiolite is among the finest and most accessible examples of ophiolitic rocks in Europe.

The ophiolite complex is composed of two tectonic units, the Upper and Lower nappes (Flinn, 1958), separated and underlain by imbricate zones composed of metasedimentary strata containing ophiolitic erosional debris from the nappes, acid and basic metavolcanic rocks and hornblende schist, all interleaved with tectonic slices of ophiolitic rocks. (Figure 2.4)a shows the distribution of these units together with that of the gneissose metasedimentary basement to the complex which crops out farther west; (Figure 2.4)b summarizes the lithological outcrop.

The *Upper Nappe* occurs as a series of widespread klippen composed largely of meta-harzburgite of mantle origin; it rests either directly on the Lower Nappe or on the Middle Imbricate Zone separating the two nappes. The Upper Nappe is made of highly magnetic rocks, which enable it to be traced under the sea by means of positive aeromagnetic anomalies. The main Vord Hill Klippe occupies the centre of Fetlar and extends north under the sea to the island of Haaf Gruney. The nappe extends northwards to Hill of Clibberswick and westwards to the island of Sound Gruney via a series of small klippen, several of which also occur along the western edge of the complex in Unst. The Virva GCR site reveals that the Upper Nappe is underlain by hornblende schist derived from basic magma intruded into the thrust plane beneath the nappe and later cut into tectonic slices by the thrusting, while in the Tressa Ness to Colbinstoft GCR site the unusual lithology rodingite (a Ca-rich metasomatic rock) is present in the base of the Upper Nappe.

The *Lower Nappe* is widely exposed in Unst but is overlain by the Middle Imbricate Zone in the extreme north (Norwick) and the south-east (Muness). It is bound to the west by an eastward-dipping thrust and separated from the metamorphic basement farther west by the Lower Imbricate Zone. The Lower Nappe extends under the sea into the north of Fetlar on either side of the Vord Hill Klippe.

Unlike the Upper Nappe, the Lower Nappe is composed of a conformable series of vertically orientated layers each several kilometres thick. The layers represent much of the conventional ophiolitic pseudo-stratigraphical succession (Figure 2.2). A thick layer of metaharzburgite, very similar to that forming the Upper Nappe, forms the northern part of the Lower Nappe ((Figure 2.4)b). It is followed to the south (up the ophiolitic succession) by a thick metadunite layer. The Punds to Wick of Hagdale GCR site presents evidence that the metaharzburgite is serpentinized infertile mantle whereas the metadunite is a serpentinized intrusive mass overlying the mantle and separated from it by the petrological Moho (Figure 2.2). It corresponds to the ultramafic layered lower crustal unit (transition zone *sensu lato*) of the conventional ophiolite succession. The intrusive nature of the metadunite layer and the adjacent metagabbro layer to the south can be demonstrated in the Skeo Taing to Clugan GCR site by the presence in both layers of xenoliths and screens of banded wehrlite–clinopyroxenite. In the Qui Ness to Punds Stack GCR site the eastern boundary of the metagabbro layer is marked by a discontinuous layer of wehrlite–clinopyroxenite xenoliths and screens, beyond which is an upper metagabbro layer. The latter is characterized by fine-grained metagabbros intruded by a large number of basic, dyke-like sheets giving this layer a quasi-sheeted appearance. The Ham Ness GCR site presents the upper metagabbro layer overthrust by the Upper Nappe.

The Highland Border Complex

Within the Highland Boundary Fault Zone (Figure 2.1), a series of structurally isolated slivers contain various combinations of serpentinite, pillow lava, black shale, chert, limestone and sandstone, apparently ranging in age from Early Cambrian to late Ordovician. The igneous components of this lithological association are distinct from the Dalradian Supergroup rocks to the north and the whole assemblage contrasts with the Upper Palaeozoic strata of the Midland Valley Terrane to the south. All of the disparate elements are grouped together as the Highland Border Complex which remains largely enigmatic. The current consensus view of the regional development of the complex (see Robertson and Henderson, 1984; Curry *et al.,* 1984) envisages its formation in a small oceanic basin marginal to the Laurentian continent. However, there are aspects of the relationship between the Highland Border Complex and the Dalradian that remain poorly understood. In particular, some of the Early Cambrian sedimentary strata seem to lie in stratigraphical continuity with parts of the Dalradian succession and to have experienced a similar structural history (Tanner, 1995 and references therein). The problems are accentuated by the extreme tectonic disruption whereby the complex now exists as about ten fault-bound lenses, spread along the length of the Highland Boundary, from Stonehaven on the east coast of Scotland to Arran in the west (Figure 2.1).

Despite the tectonic disruption an overall succession has been established. The serpentinites are regarded as the oldest igneous component, of Late Cambrian or early Ordovician (Tremadoc?) age, and are overlain unconformably by conglomerates with serpentinite clasts; an associated limestone unit contains a mid-Arenig fauna. This part of the succession is well displayed at the Balmaha and Arrochymore Point GCR site and serpentinite is also present in the Garron Point to Slug Head GCR site. The relationship of the serpentinite to a slightly younger sequence dominated by basic pillow lava and black shale is uncertain but the lava-shale unit appears to range in age from the Arenig, through the Llanvirn and possibly into the Llandeilo. Associated with the lava and shale are tuff, chert and quartz-greywacke. A probable Arenig part of this unit, including an impressive array of pillow lava, is well exposed in the North Glen Sannox GCR site; the pillow lavas seen in the Garron Point to Slug Head GCR site may possibly be younger (Llanvirn–Llandeilo) in age although the evidence is meagre. The youngest part of the Highland Border Complex appears to be a Caradoc to possibly Ashgill sedimentary sequence of sandstone with ophiolitic, acid volcanic and quartz clasts, limestone and shale. Elements of this sedimentary association are seen in the Balmaha and Arrochymore Point and the North Glen Sannox GCR sites.

The closure of the Highland Border Complex basin (or basins) seems likely to have been a polyphase and protracted event involving oblique terrane amalgamation. A complicated and possibly protracted metamorphic history is suggested by stable isotope and petrographical evidence presented by Ikin and Harmon (1984). Indications of Cambrian tectonism come from the radiometric ages of around 540 Ma reported by Dempster and Bluck (1991) for an amphibolite associated with serpentinite on the island of Bute. This was taken as evidence for Cambrian initiation of ophiolite obduction but, elsewhere, Ordovician sedimentation clearly occurred at least during the Arenig–Llanvirn and Llandeilo–Caradoc intervals (Curry *et al.,* 1984). Structural evidence is similarly ambiguous. Henderson and Robertson (1982) thought that tectonic features suggest a similar deformation history for the Highland Border Complex and the Dalradian succession to the NW; they envisaged thrust emplacement of the complex towards the SE. Conversely, Curry *et al.* (1984) proposed that remnants of a marginal basin floor were obduct-ed towards the NW onto the already deformed Dalradian. As a further complication, Harte *et al.* (1984) concluded that the later transcurrent faulting was largely responsible for the present lenticular disposition of the complex along the Highland Boundary Fault.

The Ballantrae Complex

Between Girvan and Ballantrae, on the west coast of southern Scotland, a structurally complicated assemblage consisting mainly of serpentinized ultramafic rocks and tholeiitic lavas crops out over an area of about 75 km^2. This is the Ballantrae Complex, which has been widely interpreted as an obducted ophiolite (Church and Gayer, 1973; Bluck, 1978a) although there is little evidence of sheeted dykes and only fragmentary occurrences of layered gabbro. The outline geology and location of the GCR sites is shown in (Figure 2.5). The internal structural relationships are complicated and all of the major lithological boundaries are faulted. The volcanic rocks form three fault-defined blocks trending NE–SW and separated by two blocks of ultramafic rock, the Northern and Southern serpentinite belts.

The lavas, together with abundant volcaniclastic breccia and sandstone, have been lithostratigraphically defined as the Balcreuchan Group (Stone and Smellie, 1988) aspects of which may be seen within the Slockenray Coast, Games Loup, Balcreuchan Port to Port Vad and Bennane Lea GCR sites, The lavas were erupted in a submarine environment with pillow structure widely developed. At a few localities, graptolites of Arenig (early Ordovician) age have been recovered from sedimentary interbeds (Stone and Rushton, 1983; Rushton *et al.,* 1986) while the tholeiitic basalt lavas have themselves given Sm-Nd radiometric ages of 501 ± 12 Ma and 476 ± 14 Ma (Thirlwall and Bluck, 1984). Eruption would therefore seem to have commenced during the Tremadoc and probably reached its peak during the Arenig. However, a number of studies of the lava geochemistry have concluded that eruption took place in disparate geotectonic environments with the Balcreuchan Group therefore containing a polygenetic structural assemblage (Wilkinson and Cann, 1974; Thirlwall and Bluck, 1984). The basis for this conclusion lies in the different trace element ratios and abundances characteristic of basalts erupted in either mid-ocean ridge, or within-plate, or island arc settings. A clear consensus has emerged that island-arc and within-plate lavas are both present but that there is very little evidence for a mid-ocean ridge volcanic component (Wilkinson and Cann, 1974; Lewis and Bloxam, 1977; Thirlwall and Bluck, 1984; Stone and Smellie, 1990). Further support for an island-arc involvement has come from the discovery of boninite lavas and breccias at the Balcreuchan Port to Port Vad GCR site (Smellie and Stone, 1992; Smellie *et al.,* 1995); these are unusual lithologies with modern examples known only from primitive, oceanic island arcs.

The ultramafic components of the Ballantrae Complex are now largely serpentinized; the pro-toliths were principally dunite and harzburgite with a small proportion of wehrlite and various pyroxenites. Ultramafic rocks are a particular feature of the Knockormal, Knocklaugh and Games Loup GCR sites. An origin within 'normal' (mid-ocean ridge) oceanic mantle was initially assumed in the ophiolite interpretation, and a geochemical study of a limited area of the Northern Serpentinite Belt by Jelínek *et al.* (1980) has supported this assumption. However, Stone and Smellie, (1990) considered that a range of features are atypical of ultramafic rock from mid-ocean ridge ophiolites but instead match those considered characteristic of supra-subduction zone (i.e. volcanic arc) environments by Pearce *et al.* (1984). Important aspects encouraging this conclusion are the overall lithological dominance of titanium-depleted harzburgite, the dominance of wehrlite over troctolite in the layered sequences, and the relative chromium enrichment of the accessory spinels over those found in a mid-oceanic setting. Thus the ultramafic rocks of the Ballantrae Complex are also indicative of an origin, for at least part of the complex, at an island arc above an oceanic subduction zone. The involvement of older oceanic mantle, perhaps forming the foundation to the arc development, is suggested by a Sm-Nd radiometric age of 576 ± 32 Ma reported by Hamilton *et al*. (1984) from a garnet clinopyroxenite body within the Knockormal GCR site, that was interpreted as a segregation in mantle harzburgite by Smellie and Stone (1984). A minimum age is provided by a U-Pb on zircon radiometric date of 483 ± 3 Ma reported by Bluck *et al.* (1980) from a leucotonalite, intruded into and chilled against the Northern Serpentinite Belt, within the Byne Hill GCR site.

The Byne Hill leucotonalite is gradational from gabbro but the gabbroic and sheeted dyke components of the ideal ophiolite assemblage are sparse and fragmentary within the Ballantrae Complex. Foliated gabbros cut by numerous dykes within the Millenderdale GCR site have been likened to a sheeted dyke association but with reservations (Bluck, 1978a). An exceptionally coarse pegmatitic gabbro segregation within harzburgite occurs within the Slockenray Coast GCR site.

The most likely setting for generation of the Ballantrae Complex would seem to be within a Tremadoc to Arenig oceanic island arc and associated marginal, back-arc basin. The youngest graptolite fauna recovered from the complex is of late Arenig age (about 480 Ma) (Stone and Rushton, 1983) while a number of radiometric dates overlap around an upper range of 475–485 Ma. Obduction of the ophiolite, perhaps caused by collision of the volcanic arc with the continental margin of Laurentia, could have followed soon after. Its initiation may well be dated by the K-Ar age of 478 ± 8 Ma reported by Bluck *et al.* (1980) from an amphibolite within the Knocklaugh GCR site. This amphibolite is part of a metamorphic assemblage thought to have formed in a dynamothermal aureole adjacent to the base of the Northern Serpentinite Belt when, as a slab of hot mantle material, it was thrust up through the crustal carapace of volcanic-arc lavas. A minimum age for obduction of the Ballantrae Complex is provided by the unconformably overlying, Llanvirn shallow-marine strata.

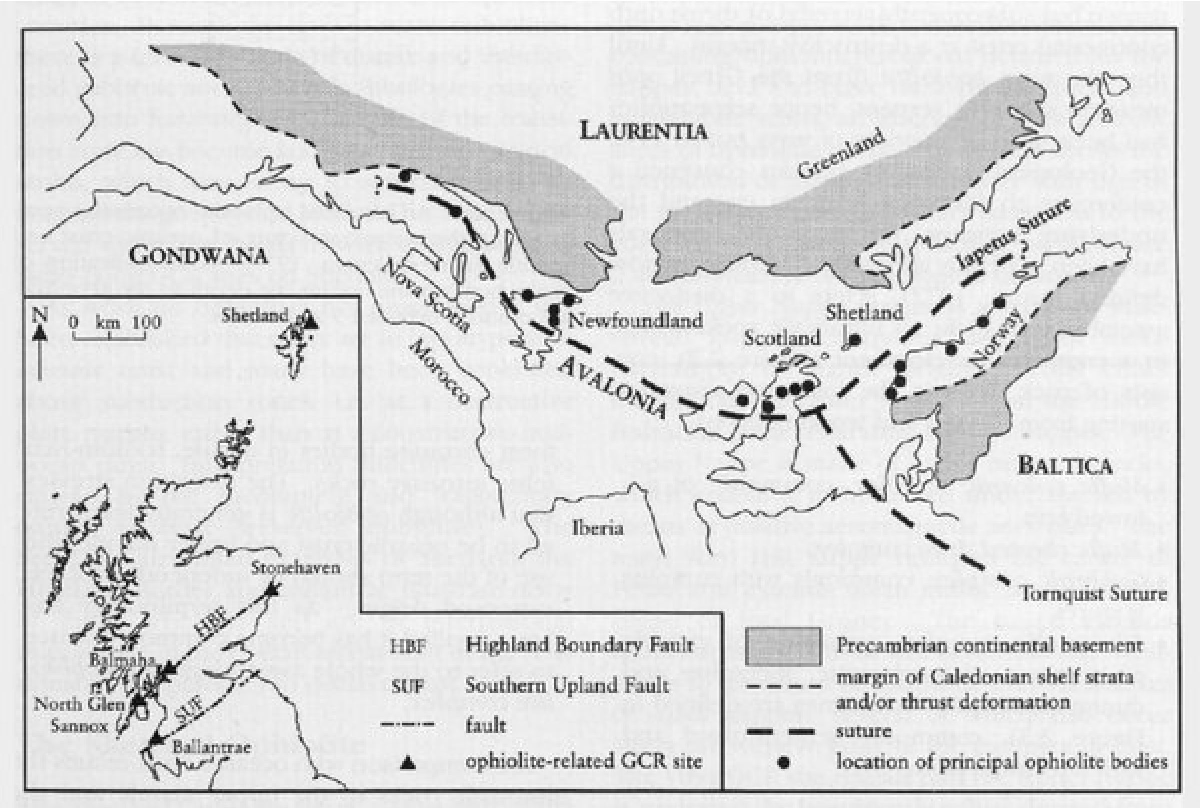
The Southern Uplands

The Southern Uplands Terrane formed as an accretionary thrust complex at the Laurentian continental margin during Ordovician and Silurian subduction of the Iapetus Ocean. The terrane has been widely interpreted as a fore-arc prism, formed above the active subduction zone (Leggett *et al.,* 1979; Leggett, 1987). Alternatively, it may have developed from an Ordovician back-arc setting into a mid-Silurian foreland basin, the latter generated as the thrust front migrated onto the Avalonian continent following closure of the Iapetus Ocean (Stone *et al.,* 1987). In either model the resulting structural configuration is the same: a sequence of southward propagating imbricate thrusts separating lithostratigraphical tracts of steeply inclined strata that strike NE–SW Internally the tracts have an overall sense of younging towards the north, whereas the minimum age of each tract decreases southwards. This phenomenon has been recently illustrated and discussed by Rushton *et al.* (1996 and references therein) while a full stratigraphy is given by Floyd (1996). The dominant lithology within each tract is turbidite-facies greywacke but this overlies a thin basal assemblage of black mudstone, chert and sporadic basic lava and hyaloclastite. The lava and hyaloclastite are found in the northern part of the terrane and appear to range in age from Arenig to Caradoc; recent reviews are provided by Phillips *et al.* (1995b) and Armstrong *et al*. (1996). The mudstone and chert range in age from the Caradoc well up into the mid-Silurian and throughout the succession are interbedded with subalkaline and mildly peralkaline metabentonite layers (Merriman and Roberts, 1990).

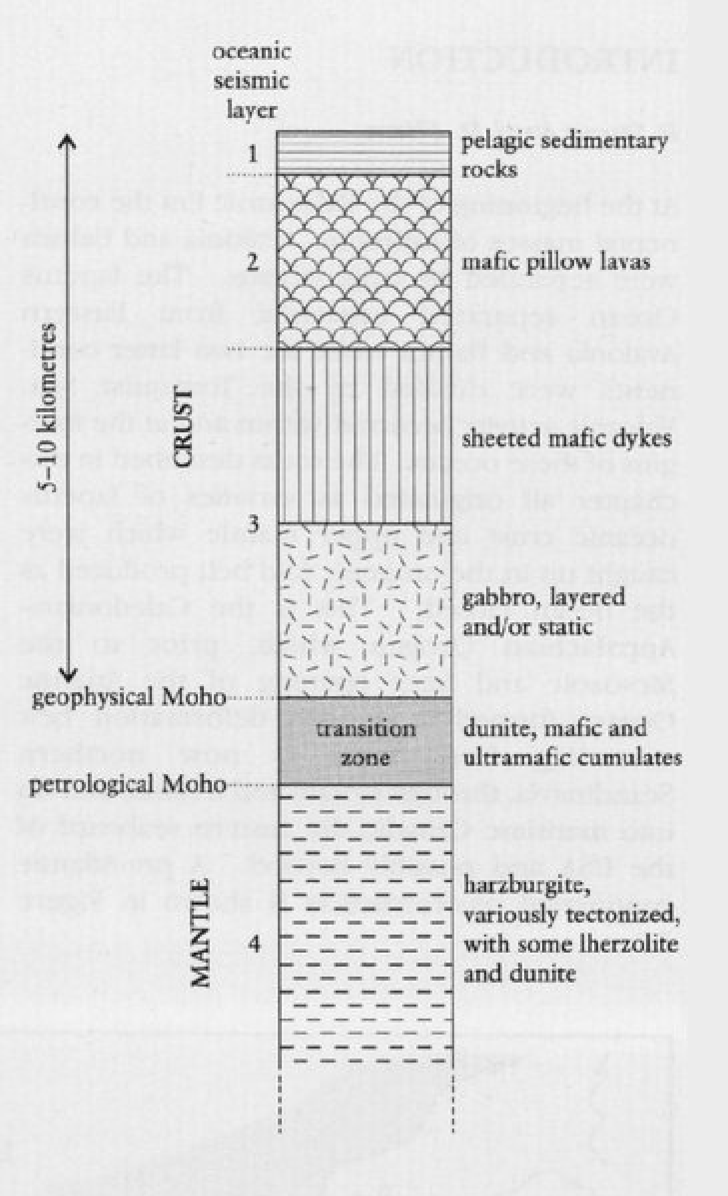
Phillips *et al*. (1995b, 1999) show that the oldest (Arenig) lavas include both alkaline within-plate basalts and tholeiitic varieties with probable mid-ocean ridge basalt characteristics. Other lavas of uncertain age within the Arenig–Caradoc range have compositions more suggestive of an island-arc source, while definite Caradoc lavas are of within-plate, ocean island affinity. Some of the latter are interbedded with the greywacke sequence rather than forming a base to the mudstone. Apart from these lava occurrences, three other examples of Ordovician volcanic rocks are worthy of note.

1. Peralkaline rhyolite and tuff (the Wrae or Tweeddale lavas), interbedded with greywacke of late Caradoc or early Ashgill age, may have been emplaced as a debris flow from a sea-mount volcano (Thirlwall, 1981b).
2. The Bail Hill Complex is a 1.8 km thickness of pyroclastic rock and lava, the latter comprising mugearite and hawaiite, thought to represent a sea-mount volcano enclosed by transgressive early Caradoc greywackes (Hepworth *et al.,* 1982; Phillips *et al.,* 1999).
3. The Downan Point Lava Formation (Stone and Smellie, 1988 and references therein) occupies a faulted wedge sandwiched between the northern margin of the Southern Uplands Terrane and the Ballantrae Complex. Tholeiitic basalts predominate and have within-plate, ocean island geochemical affinities. The formation has been associated historically with the Ballantrae Complex of Arenig age but a current consensus favours a younger, early Caradoc age and considers it to form the northernmost tract of the Southern Uplands. The coastal exposures present an extraordinary array of pillow structures, as seen at the Sgavoch Rock GCR site.
4. The full assemblage of Ordovician volcanic rocks in the northern part of the Southern Uplands Terrane is difficult to readily reconcile with either of the geotectonic models proposed for its development; fore-arc accretionary prism or back-arc (to Silurian foreland basin) thrust belt.

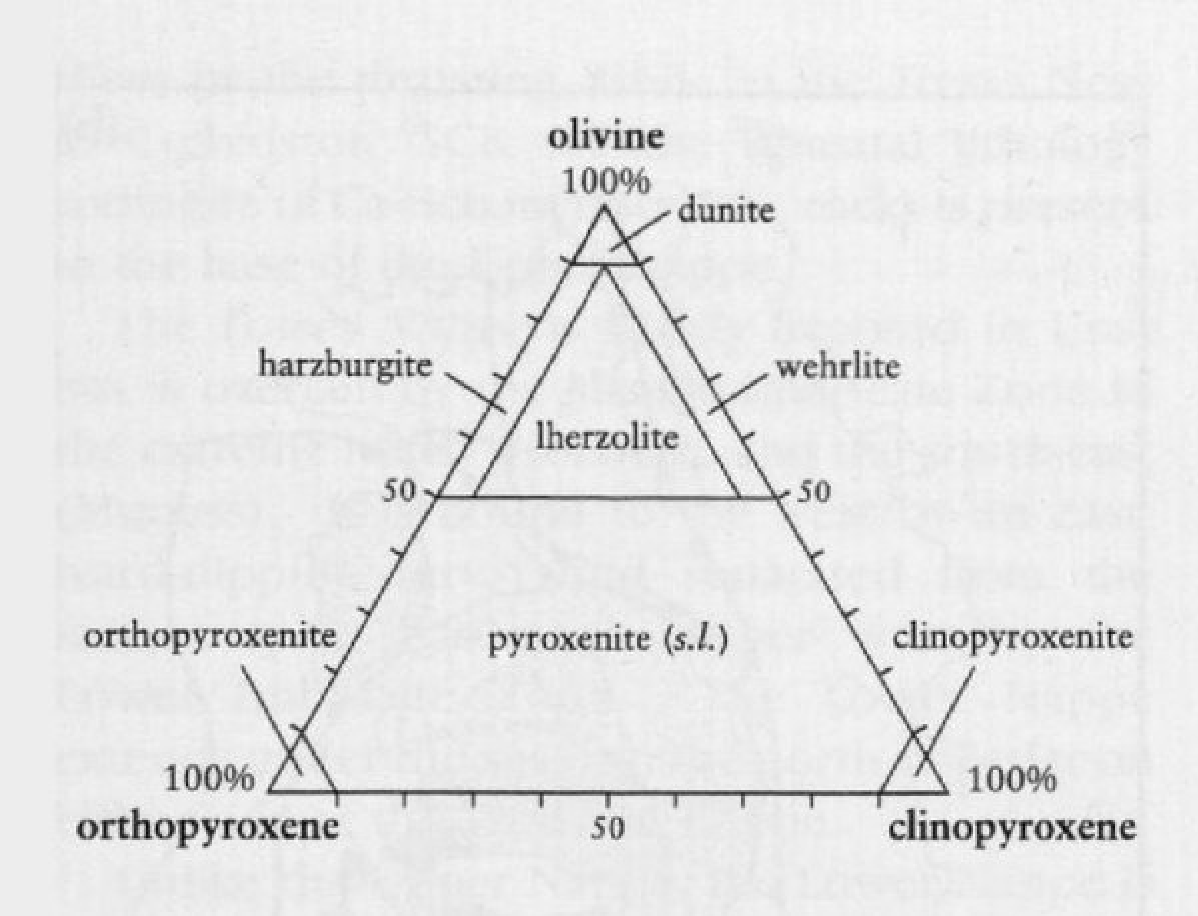
[References](#)



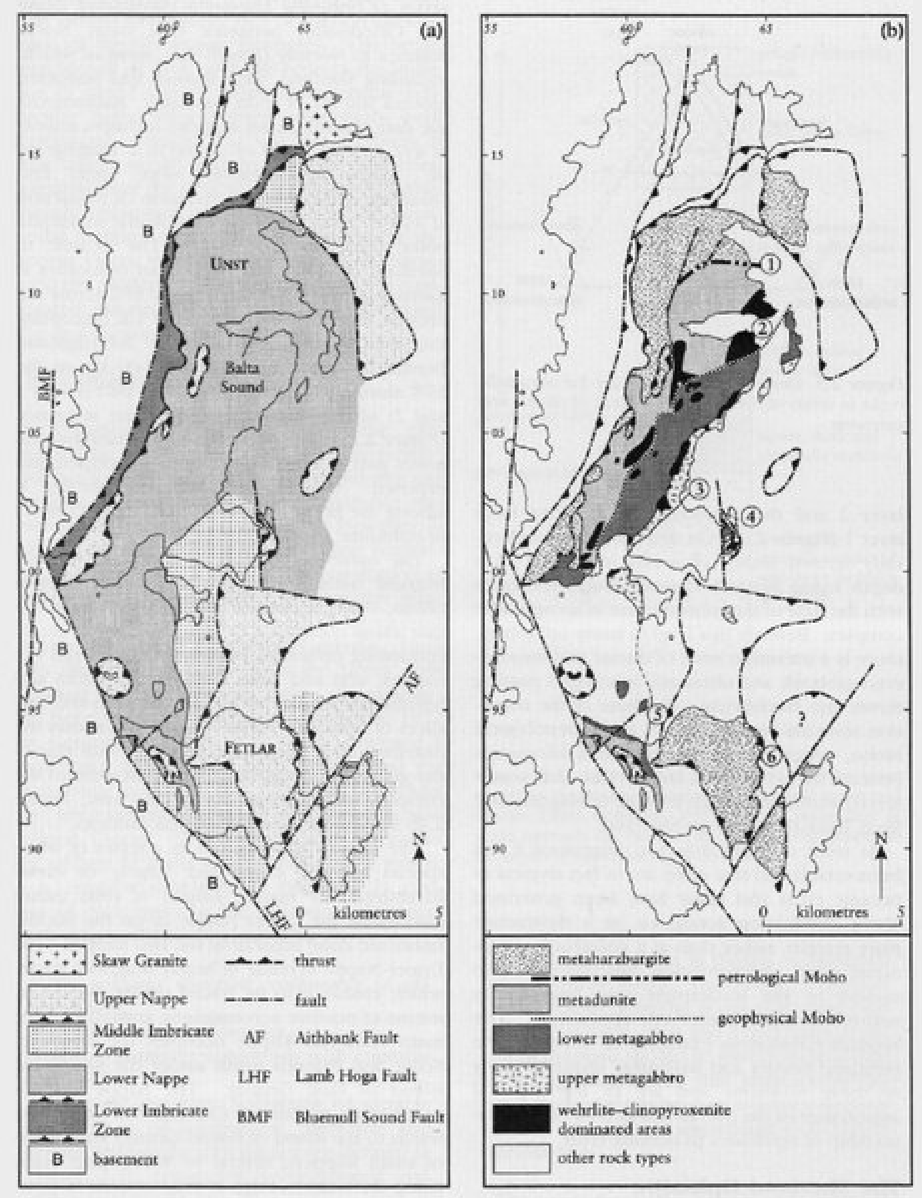
(Figure 2.1) A pre-Atlantic reconstruction of the Caledonian Orogen showing the positions of the principal ophi-olite complexes. A location map for the Scottish examples is shown inset.



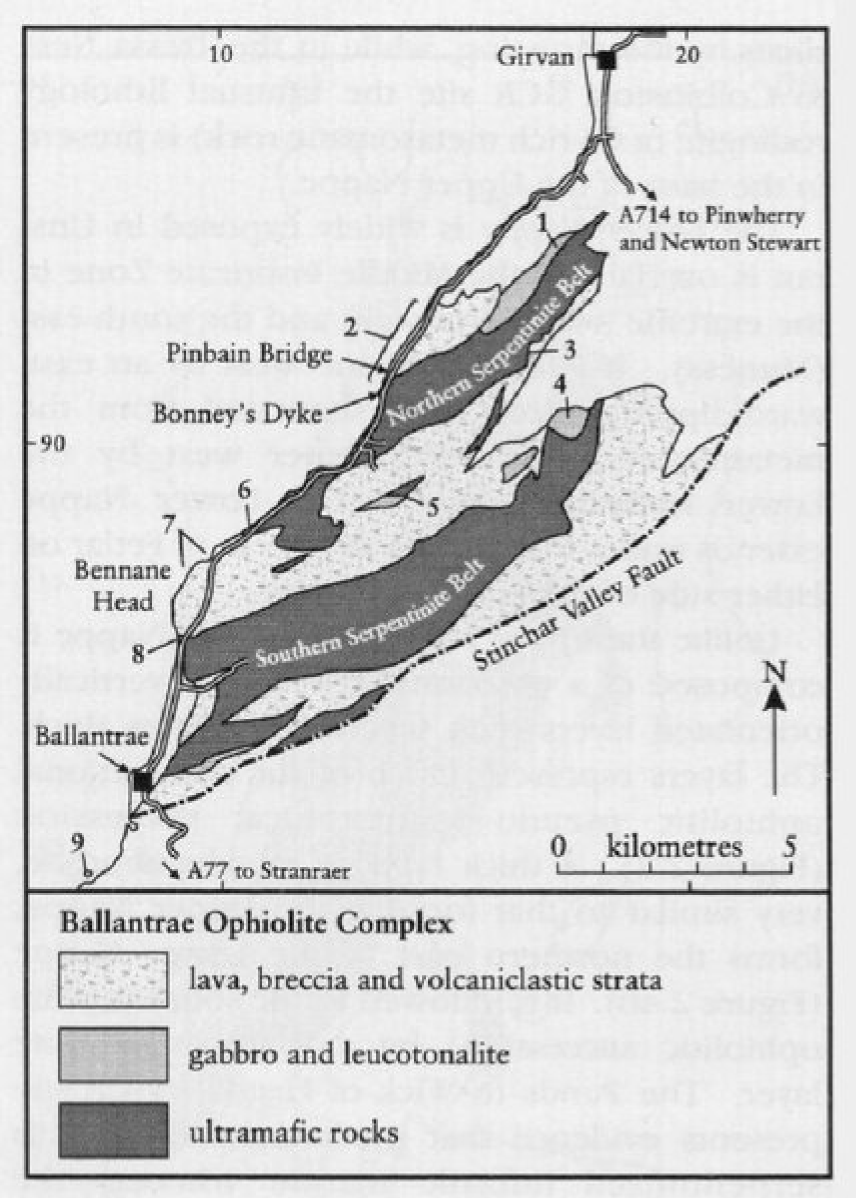
(Figure 2.2) An idealized ophiolite succession compared to the seismic structure of oceanic crust and mantle (after Coleman, 1977). As an indication of scale, beneath the oceans the depth to the geophysical moho is between 5 and 10 km.



(Figure 2.3) Descriptive nomenclature for ultramafic rocks in terms of their relative content of olivine and pyroxene.



(Figure 2.4) Maps of the Shetland Ophiolite (after Flinn, 1996): (a) principal tectonic units, (b) lithological outcrops. GCR sites: 1, The Punds to Wick of Hagdale; 2, Skeo Taing to Clugan; 3, Qui Ness to Pund Stacks; 4, Ham Ness; 5, Tressa Ness to Colbinstoft; 6, Virva.



(Figure 2.5) Outline geology of the Ballantrae Complex (after Stone and Smellie, 1988) showing the location of the GCR sites. 1, Byne Hill; 2, Slockenray coast; 3, Knocklaugh; 4, Millenderdale; 5, Knockormal; 6, Games Loup; 7, Balcreuchan Port to Port Vad; 8, Bennane Lea; 9, Sgavoch Rock.