Ordovician Ballantrae Complex

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In the south-west of the Scottish Midland Valley, between and inland from Girvan and Ballantrae, a structurally dismembered assemblage, mostly comprising Early Ordovician mafic and ultramafic igneous rocks, the Ballantrae Complex, is unconformably overlain by an Ordovician to Silurian sedimentary succession of clastic rock with some limestone (P912319). These Ordovician and Silurian rocks provide a geological link between the Southern Uplands and Midland Valley terranes.

**Ordovician Ballantrae Complex**

The Ballantrae Complex is a tectonised assemblage of mainly igneous rocks that originated as the various components of the oceanic crust and mantle. When tectonically removed from their oceanic origins and accreted at a continental margin, such associations are commonly referred to as ophiolite complexes. In an ideal state they preserve the quasi-stratigraphical succession of the ocean crust and mantle (P912320): a basal ultramafic component passing upwards through gabbros and sheeted dykes into a volcanic and volcanosedimentary succession dominated by submarine pillow lavas, all capped by marine sedimentary rock. In common with most ophiolites, only disaggregated parts of this succession are present in the Ballantrae Complex, which crops out over about 75 km² between Girvan and Ballantrae, immediately to the north of the Stinchar Valley Fault, the local expression of the Southern Upland Fault and the southern boundary of the complex (P912319). Geophysical evidence suggests an eastwards extension beneath the unconformable cover of younger sedimentary rocks.

Within its relatively small outcrop area, the ophiolitic Ballantrae Complex demonstrates a bewildering variety of rock types. Different lithologies that are now in structural contact originated at contrasting levels in the oceanic crust and mantle, spanning a considerable depth range (P912320). Moreover, several entirely different oceanic regimes are represented, spanning island-arc and within-plate volcanoes, and it is clear that only tiny fragments derived from each have been
preserved and juxtaposed. The environment of volcanism can be established by the trace element content of the basaltic lavas produced. Elements such as titanium, zirconium and yttrium are particularly useful in this respect and their ratios can be used to indicate island-arc, ocean-island (also known as within-plate or Hawaiian-type) or mid-ocean-ridge (MORB — where the B stands for basalt) eruption. A series of analytical studies has established that the Ballantrae Complex lavas are polygenetic, with all three of the main environment types represented (although MORB-type are relatively rare) and the island-arc varieties showing clear subdivisions; an indication of the distribution of the different lava types is shown in the inset map in P912319.

Compressive, subduction-related movement might produce the assemblage of rock types present in the Ballantrae Complex, but it could probably be achieved more readily with additional components of backarc extension and strike-slip tectonics. P912321 gives one idea of the possible original relationships between the different elements now present, but there are other, equally valid possibilities. Although the area has been the focus of considerable research, and an extensive geological literature is available, there is still much to be discovered about the Ballantrae Complex and it remains one of the more enigmatic geological features of southern Scotland.

The ophiolitic lithologies have structurally complicated relationships within the complex but two main elements dominate, interleaved by faulting: serpentinised ultramafic rocks derived from the oceanic mantle, and volcanic sequences representing the remains of island-arc and oceanic crust (P912320). The principal structures are north-east to south-west faults that split the complex into discrete lithological zones such that northern and southern serpentinite belts separate three areas of mainly volcanic rock (P912319). A late Cambrian to Early Ordovician age has been established for eruption of the island-arc volcanoes from radiometric (Sm-Nd) dating of their basalts at 501 ± 12 and 476 ± 14 Ma. The age of the within-plate components also fall into this range since the interbedded sedimentary strata contain early Arenig (ca 478 Ma) graptolite faunas (P912316g). Minor components of the complex include gabbro and leucotonalite (traditionally described as trondhjemite or plagiogranite) intrusions, a fragment of a sheeted dyke assemblage, and sheared sedimentary mélangé deposits. Zircons from the leucotonalite have been dated (U-Pb) at 483 ± 4 Ma. These minor components take on a disproportionate significance in the interpretation of the complex as an ophiolite.

The Ballantrae Complex ophiolite was finally emplaced (obducted) onto the Midland Valley continental basement, at that time the leading edge of Laurentia, during the mid to late Arenig. High-grade metamorphic rocks were formed at this stage as hot mantle material was thrust up and across the basalt lavas of the oceanic crust. These are now seen as a metamorphic ‘sole’ at the base (the south-east margin) of the northern serpentinite belt and have been radiometrically dated (K-Ar) at 478 ± 8 Ma, whilst upper Arenig sedimentary rocks that were probably deposited during the obduction process are now structurally included within the complex. The oldest strata within the unconformably overlying cover sequence (comprising the Barr Group) are of Llanvirn age. In a regional context, the obduction of the Ballantrae Complex would seem to be part of the large-scale, arc-continent collision at about 470 Ma that drove the Grampian phase of the Caledonian Orogeny.

**Ultramafic rocks**

Within the Ballantrae Complex, the ultramafic rocks have been pervasively altered, with serpentine replacing the original olivine to produce a dark green to black, generally fine-grained rock, locally containing yellowish green, bastite pseudomorphs of altered orthopyroxene. Complex veining by quartz and carbonate is a general feature of the faulted margins to the ultramafic bodies. Olivine was the dominant original mineral but since it has been largely altered to serpentine the resulting ultramafic rock is referred to generally as serpentinite. This lithology is relatively soft and readily eroded, so that exposure of the serpentinite is very limited. A small proportion of the ultramafic rock
is composed mainly of varieties of pyroxene, so is appropriately referred to as pyroxenite.

Some of the olivine-rich ultramafic rocks originally crystallised within oceanic mantle at depths of up to 60 km. Their composition indicates that they are residues after the extraction of a basaltic melt. However, the detailed chemistry of rocks from both ultramafic belts, and also of the chrome spinel grains that they contain, is anomalous for normal ocean lithosphere and suggests that they formed in metasomatised mantle above a subduction zone. Subtle but significant differences in composition between the two main outcrops, the northern and southern serpentinite belts, show that they do not share the same history of formation. The northern serpentinite is the more metasomatised of the two and most probably originated in a sub-arc environment. The southern serpentinite, though still metasomatised, has more of the characteristics of mid-ocean mantle. To accentuate these differences, the following account will utilise rock names reflecting the original composition of the rocks, prior to serpentinisation.

The northern serpentinite belt (P912319) is composed mainly of harzburgite (olivine with accessory orthopyroxene) with some lherzolite (olivine with both accessory orthopyroxene and clinopyroxene) and a variety of pyroxenites; concentrations of finely disseminated chromite are present locally. There is a widespread tectonic fabric that is strongly developed in places. In contrast, the southern serpentinite belt has either no tectonic fabric or one that is only weak and localised, and also has a slightly different lithological assemblage to that seen in the north. In the southern belt, although harzburgite is again dominant, it is generally coarser grained than in the north and is accompanied by dunite (>90 per cent olivine), wherlite (olivine with accessory clinopyroxene) and troctolite (olivine-rich gabbro). At one locality, Poundland Burn (NX 167 882), a local concentration of chrome spinel grains forms a distinctive nodular lithology. The overall implication is that, quite apart from their different geotectonic environments, the ultramafic protolith of the southern serpentinite belt formed at a substantially shallower depth than its northern counterpart.

**Volcanic rocks**

The volcanogenic sequences within the complex are dominated by pillow lavas produced during submarine eruptions (P005992) and the breccias derived from them. A number of formations have been defined locally, but all of the volcanic rocks are included within the Balcreuchan Group, named after Balcreuchan Port (NX 098 876), the putative home in the early 17th century of the legendary Sawney Bean and his cannibal tribe. Some parts of the group comprise uniform accumulations of dark greenish grey, mainly aphyric, basalt pillows, whereas other sections show alternations of aphyric and coarsely feldsparphyric lavas (P220326), reddened in places, interbedded with sedimentary layers of chert and shale and merging vertically and laterally with thick breccia units. The lavas are tough and resistant to erosion so that they form most of the high ground within the complex and create some spectacularly rugged coastal sections.

The tectonic slicing of the complex into numerous fault-defined structural blocks prevents the establishment of a comprehensive stratigraphy, but similarities are apparent between some of the blocks: for example, the mixed volcanic–sedimentary sequences at Pinbain, Bennane Head and Knockdolian (P912319). These mixed lava (aphyric and feldsparphyric) and sedimentary rock associations prove to be of exclusively ocean island (within-plate) origin. At Bennane Head, graptolites from the shale and chert layers that are interbedded with the lavas establish an early Arenig age (P912316q) and imply fairly deep-water conditions. Conversely, some sedimentary features of these ocean island sequences (such as rounded clasts in breccias, reddened tops to some lava flows, and rare volcanic lapilli tuff beds) indicate relatively shallow water conditions or even sporadic and temporary emergence of the lava pile. A variable and unstable depositional environment seems certain, whilst one feature of the Pinbain assemblage suggests that different depositional regimes were in relatively close proximity. At the base of the Pinbain succession of
within-plate lavas is a unit of volcaniclastic sandstone (the Kilranny Hill Formation) with the geochemical characteristics of a mature island arc, characteristics that are shared with the Mains Hill lavas farther to the south. The Kilranny Hill Formation also contains early Arenig graptolites.

The pillow lava accumulations of island-arc origin contain very little interbedded sedimentary rock. Most of the lavas are aphyric but some contain pyroxene phenocrysts, in particular those at Mains Hill and to a lesser extent those at Games Loup (NX 104 880). The radiometric (Sm-Nd) dates of $501 \pm 12$ and $476 \pm 14$ Ma that have been obtained, respectively, from these two localities span the late Cambrian and Early Ordovician. Of particular interest in the Games Loup section is the presence of lavas with an unusual composition: relatively high silica content accompanied by high levels of MgO, Cr and Ni. Such lavas, known as boninites, are characteristic of eruption in an oceanic, but supra-subduction setting and modern examples are typically found in the forearc region of volcanic island arcs or as the earliest products of backarc spreading. If the Games Loup boninites are taken to indicate crustal extension in a backarc basin, the likely age difference between these relatively primitive arc rocks and the more evolved, mature arc basalts (e.g. those at Mains Hill and Bargain Hill), permits the latter to be interpreted as part of an early-formed volcanic arc that was split by supra-subduction zone extension. Subsequent, within-plate eruptions and gabbroic intrusion then took place in the ensuing backarc basin. This is the tectonic model illustrated in P912321.

Lavas with the geochemical characteristics of eruption in an extensional environment at a mid-ocean ridge (MORB-type) are relatively uncommon in the Balcreuchan Group. The closest association is shown by basalts in the central part of the Ballantrae Complex that lie in a zone along the northern margin of the southern serpentinite belt. Though the composition of these basalts differs in several subtle respects from the normal MORB type, it compares closely with that of basalts generated at some backarc spreading centres.

**Intrusive gabbro and granite**

Coarse-grained intrusive rocks are a widespread, minor component of the Ballantrae Complex and form substantial, composite bodies at three localities: between Byne Hill and Grey Hill, around Millenderdale and north-east of Mains Hill. At Byne Hill (NX 179 947), an intrusive body ranges in composition from a leucotonalite core, through dioritic lithologies, to gabbro at the margins that is chilled against the host northern serpentinite belt. Zircons from the leucotonalite have provided a U-Pb cooling age of about 483 Ma, but despite the similarity in age, the relationship of the Byne Hill–Grey Hill intrusion to the rest of the Ballantrae Complex is uncertain. The geochemistry of the gabbro and leucotonalite suggests an origin in association with magmatism in an extensional, mid-ocean-ridge setting but with an additional supra-subduction influence, whilst the field relationships are more indicative of post-obduction intrusion. A smaller gabbro intrusion into the northern serpentinite belt, known as Bonney’s Dyke (NX 135 911) is markedly pegmatitic. Near Millenderdale (NX 172 906), intrusive gabbro bodies are banded and foliated and are cut by several generations of doleritic dykes, the earlier of which are themselves foliated. Most of the dykes and parts of the gabbro bodies have been subjected to high-temperature metamorphic recrystallisation and are now granular-textured metamorphic rocks. The relationship of the Millenderdale rocks to the rest of the Ballantrae Complex remains conjectural, although their geochemistry suggests an origin in association with ocean island (within-plate) magmatism. Within the southern serpentinite belt, foliated and metamorphosed doleritic rock forms a large number of small tectonic inclusions.

Several small gabbro bodies are intruded into the southern serpentinite belt in the vicinity of Mains Hill (NX 093 829), and are chilled against the host ultramafic rock, but the largest gabbroic mass in this part of the complex appears to have entirely faulted margins. These may be post-obduction in age, as are numerous small intrusions of dolerite and gabbro in the central part of the Ballantrae...
Complex, between Knockdaw and Balsalloch. There, both serpentinite and Balcreuchan Group lavas have been intruded and on the north side of Carleton Hill (NX 127 894) intrusive dolerite cuts across the metamorphic zone at the base of the northern serpentinite belt. None of the post-obduction intrusions cut the Llanvirn and younger sedimentary succession that overlies the Ballantrae Complex.

**Origins and emplacement of the Complex**

There is general agreement that the Ballantrae Complex is an assemblage of polygenetic, oceanic rocks, most of which originated in one or more island arcs and adjacent, actively spreading backarc zones. There is less of a consensus as to how and when the various components were brought together and what tectonic processes were responsible. It is possible to derive an idealised, island-arc and backarc basin model in which most of the components can be accommodated (P912321). In this interpretation, horizontal compression is largely driven by subduction, but tectonic juxtaposition of the various different parts is then eased if significant strike-slip movement is invoked during closure of the marginal basin and collision of the arc with the Laurentian continental margin. Even so, major problems of timing remain. Not least of these is the requirement to uplift mantle ultramafic rocks so that they might cool prior to the intrusion of the gabbro bodies at Byne Hill and Mains Hill.

The thrusting of hot, mantle ultramafic rock through and across the crustal sequences is recorded by the dynamothermal metamorphic aureole seen at the southern margin of the northern serpentinite belt. Radiometric dates from these metamorphic rocks, 505 ± 11 Ma (Sm-Nd) and 478 ± 8 Ma (K-Ar), suggest that this process was either protracted or polyphase. It was also contemporaneous with the continuing igneous development of the complex since ultramafic rock has been intruded by gabbro and leucotonalite, at Byne Hill for example. There, the igneous bodies have chilled margins, demonstrating that the host serpentinite had cooled by the time of intrusion, 483 ± 4 Ma (U-Pb) in the case of the leucotonalite. Elsewhere, at Carleton Hill, the dynamothermal metamorphic aureole is cut by dolerite dykes that do not penetrate the Llanvirn and younger sedimentary cover, so constraining magmatism to the late Arenig.

Note the overlap between the production of the metamorphic aureole by the emplacement of hot ultramafic rock at 478 ± 8 Ma but the intrusion of leucotonalite and gabbro into cool ultramafic rock at 483 ± 4 Ma. The two sets of data come from adjacent areas of the northern serpentinite belt and suggest that the later stages of the complex’s development were of short duration. That message is reinforced by the appearance in sedimentary mélange deposits, themselves intimately associated with the Balcreuchan Group, of amphibolite schist clasts probably derived from the dynamothermal aureole. The mélange deposits also contain a range of volcanic and intrusive rock types, probably sourced locally during the final stages of tectonic assembly of the complex, as well as more exotic lithologies including blue-amphibole schists. The latter were formed at considerable depth and were most likely derived from a pre-existing subduction complex.

The youngest strata known to be associated with the Ballantrae Complex form a clastic sequence at North Ballaird (NX 121 878) that contains a late Arenig graptolite fauna. All of its margins are faulted against parts of the Balcreuchan Group. Granules of altered serpentinite in one of the upper Arenig beds have algal rims, demonstrating that mantle-derived, ultramafic rock was available for erosion into shallow water by the late Arenig. This presumably marks the final stage of obduction and tectonic assembly, processes that were essentially complete by the early Llanvirn when the lowest beds of the unconformable sedimentary cover sequence were deposited. The detail of the obduction-related structure is difficult to decipher and has most probably been further complicated by subsequent tectonic events. Some indication of that complexity is shown by the tectonic repetition, probably a syn-obduction effect, of a graptolitic mudstone–chert–lava succession between
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