Balcreuchan Port to Port Vad

[NX 100 878]–[NX 093 869]

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Introduction

Balcreuchan Port and Port Vad are both small embayments, backed by steep cliffs, on the northern flank of Bennane Head. The coastal section in this area affords magnificent exposure through part of the volcanosedimentary Balcreuchan Group in the central zone of the Ballantrae Complex ophiolite. The features preserved were fundamental in persuading Bonney (1878) that the rocks have a volcanic origin and an extensive description in those terms was provided by Peach and Horne (1899). A sequence of early Ordovician pillow lavas contains the very unusual lithology boninite, erupted only at primitive oceanic island arcs. This is the only unambiguous occurrence of boninite lava so far recorded from Britain. The island-arc lavas are faulted against a more disparate lava sequence believed to have originated at a within-plate, oceanic hot spot. Pillow structure is particularly well developed in the within-plate lavas, some of which are remarkably plagioclase-phyric. Interbedded sedimentary strata are sparsely fossiliferous, establishing an early to mid-Arenig age range and allowing structural imbrication of the sequence to be proven. Quite apart from its geological attractions Balcreuchan Port also features in Scottish legend as the lair of Sawney Bean and family, the infamous cannibal tribe finally brought to account and executed *en masse* in 1604 by personal command of King James VI.

The ophiolitic interpretation of the Ballantrae Complex (e.g. Church and Gayer, 1973) regarded the lavas as oceanic lithosphere and much subsequent work has been geochemically orientated in attempts to test this hypothesis. Wilkinson and Cann (1974) pioneered this approach, concluding that the Bennane Head section contains island-arc (at Balcreuchan Port) and ocean-island, hot-spot (south from Balcreuchan Port towards Port Vad) basalt lavas; a faulted relationship was inferred. Lewis and Bloxam (1977) also found a preponderance of island-arc lava types in the section but were also impressed by the apparent conformity of the sequence, placing it within a 4 km-thick lava pile. They considered this great thickness to be most compatible with an island-arc eruptive environment and regarded the hot-spot basalts as anomalous components within a single succession. A more sophisticated geochemical study by Thirlwall and Bluck (1984) confirmed the original conclusions of Wilkinson and Cann and re-established the fault juxtaposition of two very different lava sequences. The island-arc associations of the Balcreuchan Port rocks have also been confirmed by the discovery of characteristic boninite lavas (Smellie and Stone, 1992; Smellie *et al,* 1995).

Graptolites had been recorded from sedimentary interbeds by Peach and Horne (1899) and assigned a generally mid-Arenig age. Further discoveries and a review of old collections allowed Stone and Rushton (1983) to establish biostratigraphical control on the lava sequence, which they showed to range from the early to the mid-Arenig. Despite the apparent conformity and uniform younging sense the biostratigraphy shows repetitions, and the structural imbrication of an originally relatively thin lava sequence seems the most likely explanation.

A detailed description of the Bennane Head section is given by Stone and Smellie (1988) and a field guide is provided by Stone (1996).

Description

The steep sea cliffs surrounding Balcreuchan Port expose an extensive array of pillow lavas intercalated with sporadic more' massive lava flows. There is some autobrecciation of the pillows but intercalated sedimentary rocks are notable by their absence. The eastern margin of the bay coincides with a major N–S fault which, at sea level, juxtaposes the pillow lavas in the cliff against highly altered ultramafic rock forming the foreshore exposures. Alteration in the ultramafic rock lessens across the bay so that on the SW side serpentinized dunite and harzbur-gite are exposed in the intertidal zone. The cliff sections show no signs of ultramafic rock and a sub-horizonal structural contact is envisaged, between serpentinite below and pillow lava above, cut off by the N–S fault on the east side of the bay (Figure 2.35). An added point of interest in the foreshore exposures is a well-exposed Palaeogene dyke trending just east of north; it is about 50 to 60 cm wide with amygdales concentrated into zones parallel to the dyke margins.

The pillow lavas forming the Balcreuchan Port cliffs range up to about 1.5 m across but most are relatively small (less than 1 m). They are only sparsely vesicular. Small phenocrysts of plagioclase are much in evidence, accompanied by clinopyroxene phenocrysts (probably augite) and rare pseudomorphs after olivine; the matrix is dominated by altered glass. Spilitization has caused the alteration to albite of the originally more calcic plagioclase while low-grade metamorphism has produced the secondary mineral assemblage titanite-epidote-prehnite. The lavas are tholeiitic basalts forming a continuous sequence with those farther NE along the coast at the Games Loup GCR site. There, the relative freshness of the clinopyroxene phenocrysts allowed Thirlwall and Bluck (1984) to obtain a Sm-Nd age of 476 ± 14 Ma.

One very important lithological variation occurs in the sequence adjacent to the fault on the east side of Balcreuchan Port. Around the high-water mark a thickness of 5–10 m of lava shows only poorly defined pillows and is less porphyritic than most of the sequence. In thin-section the rock proves to have more glassy matrix and the scarcity of plagioclase microphenocrysts is confirmed. Conversely, clinopyroxene and olivine phenocrysts are slightly more abundant. Geochemical data show relatively high SiO_2, MgO, Cr and Ni but relatively low Al_2O_3 when compared to the normal tholeiites. These lavas are boninites (Smellie and Stone, 1992; Smellie *et al.,* 1995), a rare lithology that has no other unambiguous occurrence in Britain.

Westwards from Balcreuchan Port the lava sequence continues, with an increasing proportion of brecciated flows, as far as a second major N–S fault (Figure 2.35). Beyond this fault there is a marked change in the nature of the volcanic succession, which becomes lithologically much more variable. Adjacent to the fault about 30 m of sedimentary strata form the base of this varied sequence. Sandstone, shale, chert and conglomerate are all present and a graptolite fauna has been recovered that gives an early Arenig age (Stone and Rushton, 1983). The beds have a N–S strike and are sub-vertical with sedimentary structures showing that they young towards the west. They are overlain conformably by exceptionally well-formed pillows of markedly porphyritic lava in which large plagioclase phenocrysts, up to 1 cm long and tabular in form, are contained in a pervasively reddened fine-grained matrix. The consistent asymmetry of the pillows (Figure 2.36), which range up to 2 m across, is consistent with the N–S strike, steep dip and westward younging deduced from the underlying sedimentary strata. The red, feldspar-phyric lavas form a unit about 150 m thick that is cut in places by thin dykes (less than 50 cm) of unreddened, aphyric basalt. These are the feeders for the overlying unit, which consists of about 150 m of dark grey-green aphyric lava in well-formed pillows generally smaller than those of the reddened lava type. Despite the presence of numerous minor faults in the section a conformable relationship can be seen between the two lava units, with aphyric pillows resting directly on reddened feldspar-phyric pillows. There is no intervening sedimentary material. Up sequence the aphyric pillows become increasingly more brecciated and interbeds of elastic rock appear. For one of these sedimentary intervals, just SW from the mouth of the Bennane Burn, a graptolite fauna indicates a mid-Arenig age (Stone and Rushton, 1983).

In the Bennane Head sector the succession described above (sedimentary beds (early Arenig)-red feldspar-phyric pillow lavas-aphyric pillow lavas-aphyric lava breccia-sedimentary interbeds (mid-Arenig)) is then terminated by faulting. However, biostratigraphical and lithostratigraphical comparisons suggest that it is repeated to the SW in a series of imbricate fault slices (Stone and Rushton, 1983). Throughout the imbricated succession the overall strike and dip and the younging direction remain constant. One repetition extends from red feldspar-phyric pillow lava just SW of Bennane Burn to brecciat-ed aphyric pillow lava NE from Port Vad. At this point faulting re-introduces the red feldspar-phyric lava and another repetition of the sequence continues thence around Bennane Head (Figure 2.35). From Port Vad this highest structural repetition continues farther up the sequence with a much greater thickness of aphyric lava breccia preserved. It is this lithology (Figure 2.37) that forms the steep cliffs of Bennane Head itself. Ultimately the stratigraphy continues southwards to the Bennane Lea GCR site where the youngest part of the succession is exposed.

Interpretation

The lava sequence in the Balcreuchan Port to Port Vad area can be divided into two parts on lithostratigraphical grounds. The north-eastern sector consists exclusively of pillow lava and lava breccia with little obvious lithological variation and a complete absence of sedimentary inter-beds. In contrast, the south-western sector contains an alternation of aphyric and reddened feldspar-phyric pillow lavas with abundant sedimentary intercalations. From the available evidence their ages are indistinguishable: the north-eastern lavas have a Sm-Nd radiometric age of 476 ± 14 Ma, the south-western lavas are early to mid-Arenig on biostratigraphical grounds. They are divided by a major N-S fault.

In a series of geochemical studies the Balcreuchan Port to Games Loup (north-eastern) lavas have consistently been interpreted as the products of eruption at an oceanic island arc (Wilkinson and Cann, 1974; Lewis and Bloxam, 1977; Thirlwall and Bluck, 1984). Most of the analyses published by these authors were derived from the Games Loup end of the section, now designated as a separate GCR site. More recent results from the Balcreuchan Port area (Stone and Smellie, 1990; Smellie and Stone, 1992; Smellie *et al.,* 1995) have confirmed the bulk of the lava sequence as of low-Ti tholeiitic character, and have also established the presence of the boninitic lavas. Examples of the geochemical discriminations used, based on abundances and ratios of trace elements such as Ti, Y and Zr, are shown in (Figure 2.38)a.

Despite their relative scarcity the boninites are of great importance in interpretation of the Ballantrae Complex because of the unique combination of circumstances involved in their petrogenesis. Important factors include: they are found exclusively in the intra-oceanic realm; their major element contents resemble those of primary magmas derived by partial melting of strongly depleted sources; the partial melting may occur at abnormally high geothermal gradients at relatively shallow levels. In most modern examples a general association with supra-subduction zone extension is apparent and in this respect the interbedding of the boninites with 'normal' island-arc tholeiites is important. Hence, arc-splitting during the initiation of a back-arc basin was invoked by Smellie and Stone (1992). After more detailed analytical work Smellie *et al.* (1995) noted that the low-Ti tholeiitic rocks, an unusual suite in their own right, shared some of the boninitic characteristics, such as the high Cr content ((Figure 2.38)b) and could not be definitively distinguished from basalts erupted in back-arc basins. A solution was proposed whereby the distinctive features of the combined sequence arose from mantle source heterogeneity caused by metasomatism above a subducting slab. Whatever the detailed mechanism the association with an intra-oceanic island arc seems unequivocal.

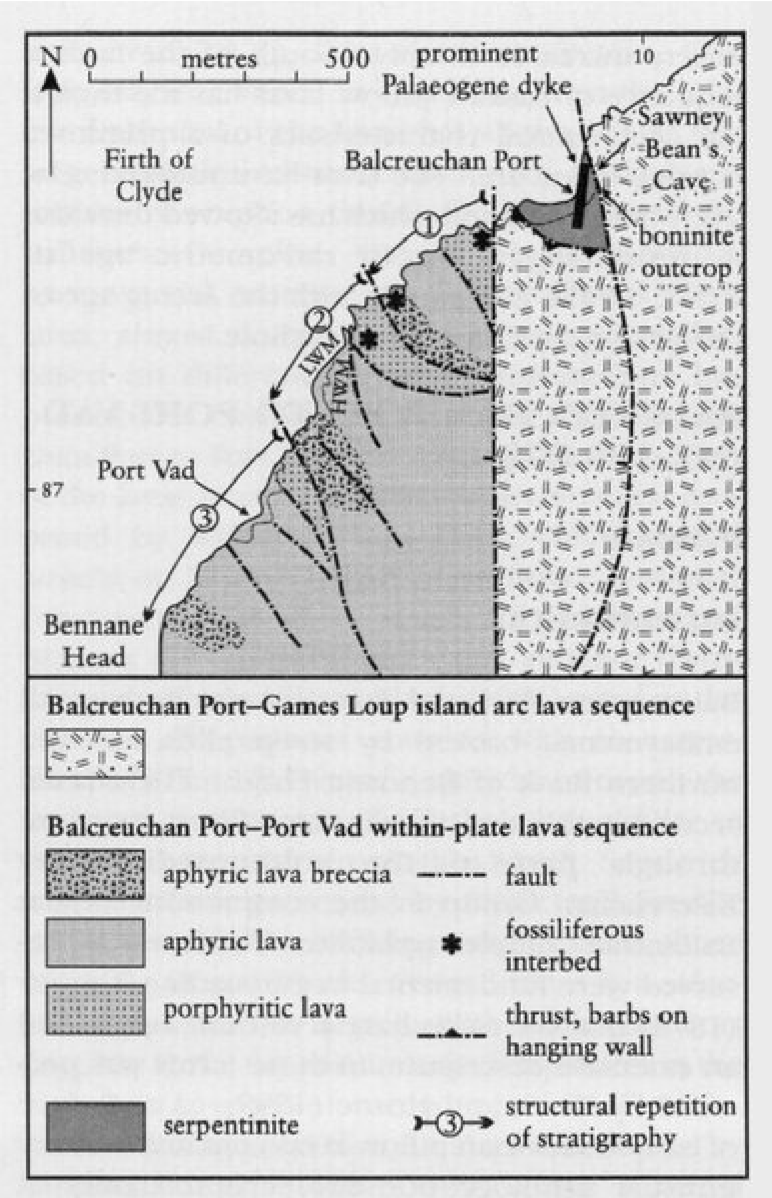
The more varied volcanosedimentary succession extending SW from Balcreuchan Port towards Port Vad has also been included in a number of geochemical studies (Wilkinson and Cann, 1974; Lewis and Bloxam, 1977; Thirlwall and Bluck, 1984; Stone and Smellie, 1990). The geochemical results have been consistently indicative of eruption in a within-plate environment above a mantle hot spot with the lavas forming a Hawaiian-type ocean island ((Figure 2.38)a). Controversy was introduced into the interpretation by Lewis and Bloxam who regarded the whole Ballantrae Complex succession as essentially conformable and abnormally thick, over 4 km and dominated by island-arc lavas. This apparently great thickness could be best accommodated in an island arc environment and so the Balcreuchan Port to Port Vad results were taken to be anomalous. The dilemma was resolved by recognition of structural imbrication of the within-plate sequence (Stone and Rushton, 1983). The nature of both the intercalated sedimentary rocks and those farther south at the top of the sequence (within the Bennane Lea GCR site) suggests deposition in fairly deep water and the reddening of the porphyritic lavas may have been caused by lengthy sea-floor weathering. This contrasts with the shallow-water environment deduced for the volcano-sedimentary succession forming the Slockenray Coast GCR site, which contains geochemically indistinguishable (but largely unreddened) lavas of the same early Arenig age. It would seem reasonable to regard these two successions as facies variants formed coevally at the same ocean island.

Between Balcreuchan Port and Port Vad the N–S fault zone separating the two lithologically and geochemically distinct lava sequences (Figure 2.35) and (Figure 2.38) intersects the coast at [NX 0971 8751], about 100 m west of the SW corner of Balcreuchan Port. It has had a polyphase history of movement but is unlikely to be the original structure formed during the imbrication of the lava sequence, which was probably a low-angle thrust. Some trace of this may be preserved to the immediate east of the main fault in a small and complex subsidiary fault-block. On the west side of the main fault a pronounced swing of strike suggests a sinistral movement laterally. However, in regional terms the fault is part of a plexus forming the eastern margin of a largely offshore Permo-Triassic basin and so has a significant downthrow to the west. Taking this latter movement alone, the island-arc sequence at Balcreuchan Port may have originally been at a greater structural depth within the obducted ophiolite thrust stack than the juxtaposed within-plate sequence forming Bennane Head.

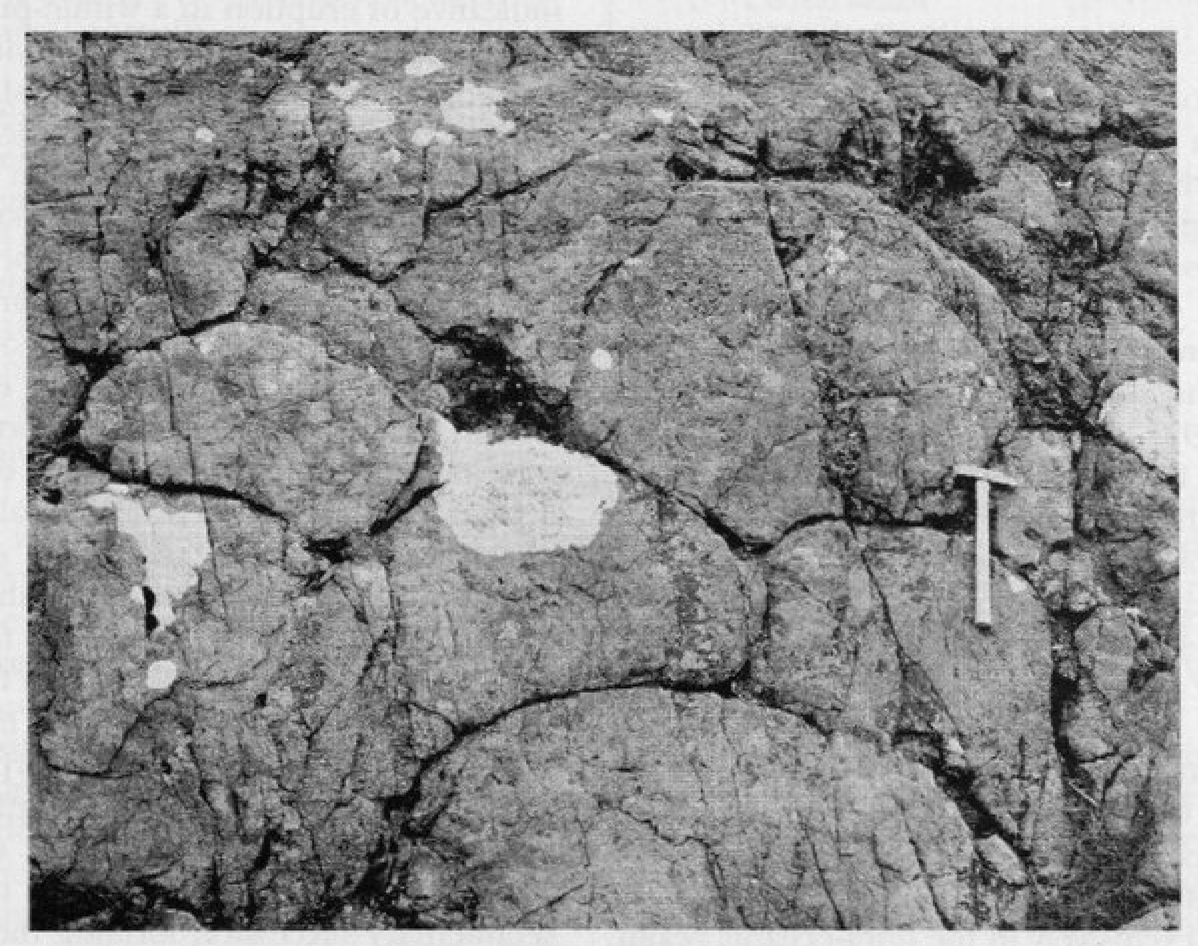
Conclusions

The Balcreuchan Port to Port Vad sector of the Ballantrae Complex provides crucial data for its interpretation and is important internationally for the more general assessment of ophiolite generation and obduction models. Within the site, two dissimilar lava sequences are separated by a major N–S fault. To the east of the fault, at Balcreuchan Port, pillow lavas and lava breccias of uniform tholeiitic basalt were generated in an oceanic island arc. Rare intercalated boninite lavas are definitive of island-arc eruptions; they are a rare but petrogenetically important lithology and no other unambiguous examples are currently known from Britain. To the west of the fault, towards Port Vad, a varied assemblage of basalts were erupted in a within-plate, ocean-island environment; pillow-forms are well developed and sedimentary interbeds of deep-water facies contain graptolites of early to mid-Arenig age. The rare combination of biostratigraphy and distinctive lithostratigraphy proves the structural repetition of the within-plate sequence.

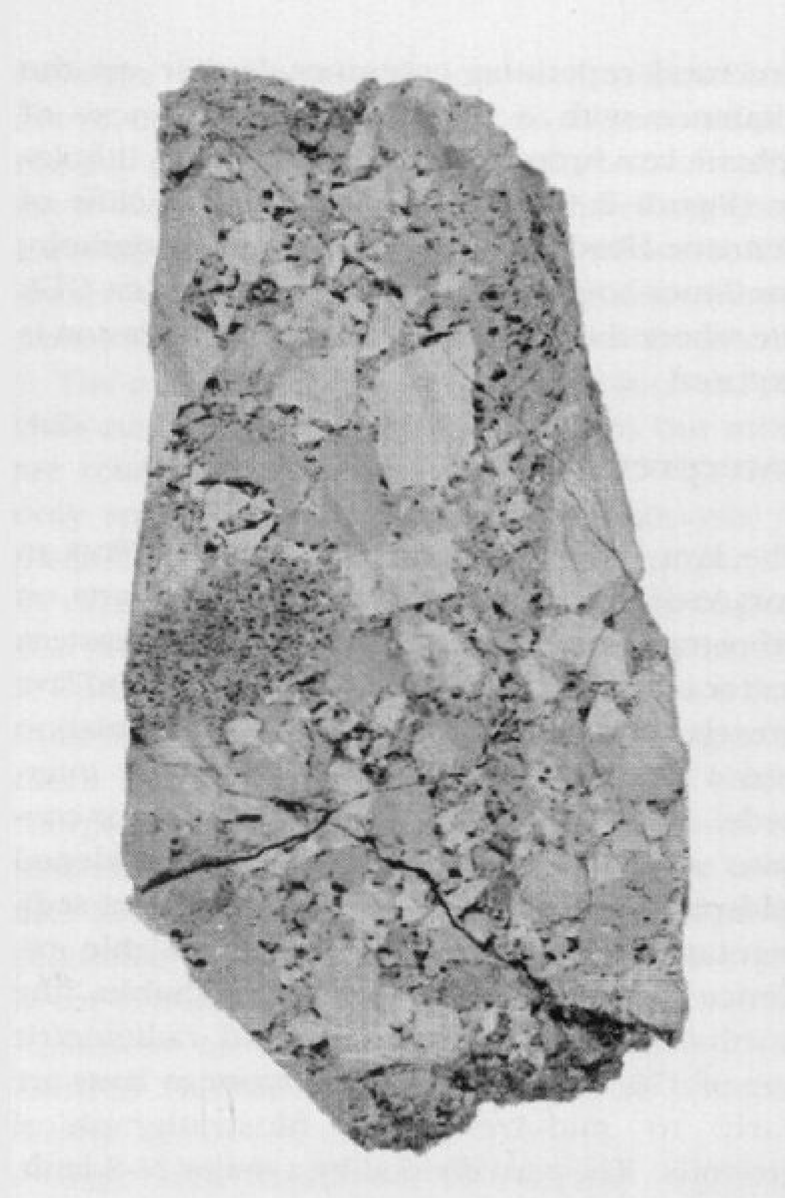
References



(Figure 2.35) Map of the Balcreuchan Port to Port Vad area, after BGS 1:25 000 special sheet, Ballantrae (1988) and Stone and Smellie (1988).



(Figure 2.36) Large, well-formed pillows of reddened, plagioclase-phyric basalt exposed SW of Balcreuchan Port. (Photo: BGS no. D3585.)



(Figure 2.37) Volcaniclastic breccia of aphyric and vesicular lava clasts from Bennane Head. The long axis of the sample is 165 mm. (Photo: BGS no. MNS3838.)

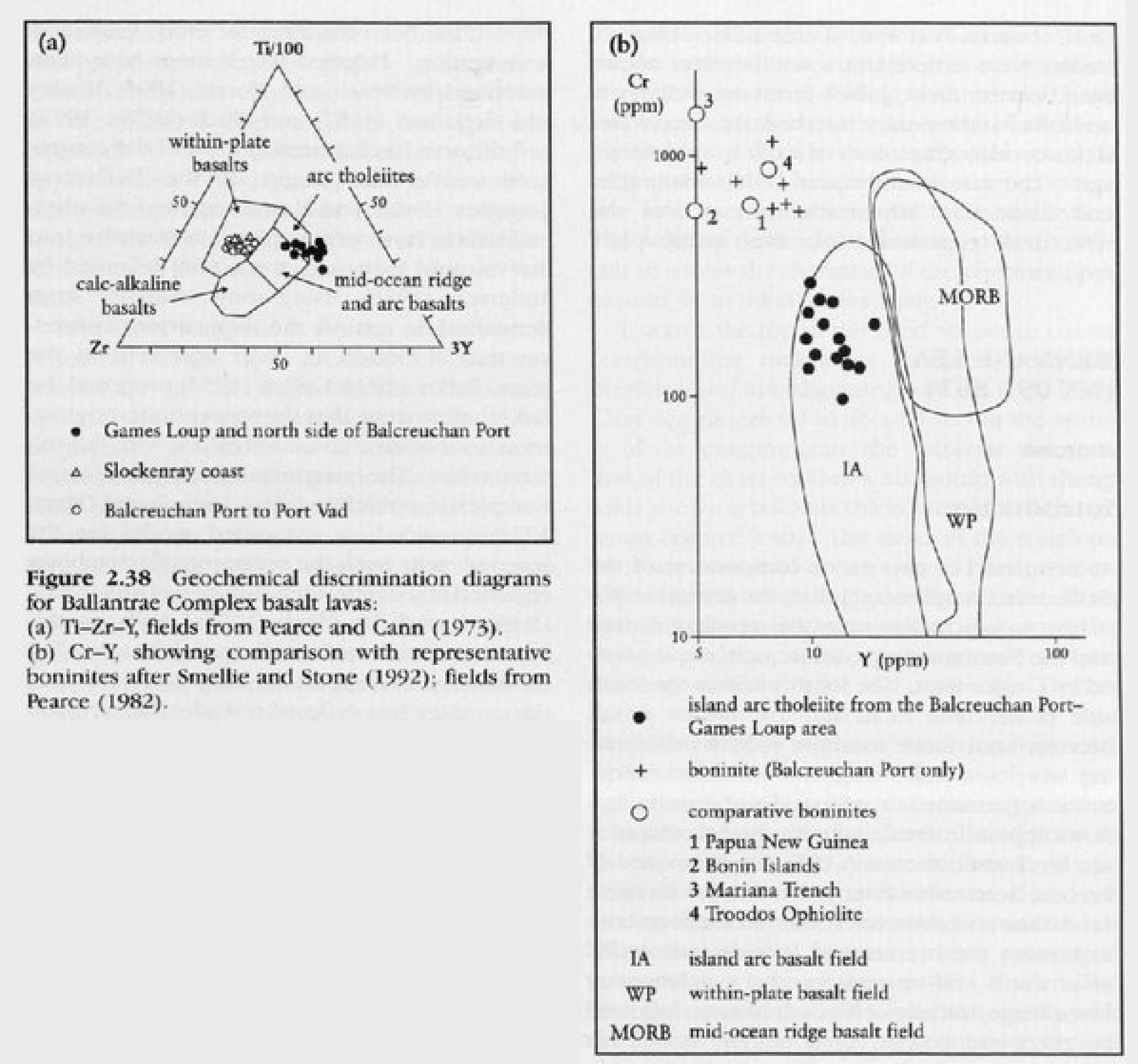


Figure 2.38 Geochemical discrimination diagrams for Ballantrae Complex basalt lavas:
(a) Ti–Zr–Y, fields from Pearce and Cann (1973).
(b) Cr–Y, showing comparison with representative boninites after Smellie and Stone (1992); fields from Pearce (1982).

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