Caledonian Igneous Rocks of Great Britain

Compiled and edited by

D. Stephenson
British Geological Survey, Edinburgh

R.E. Bevins
National Museum of Wales, Cardiff

D. Millward
British Geological Survey, Edinburgh

A.J. Highton
British Geological Survey, Edinburgh

I. Parsons
University of Edinburgh, Edinburgh

P. Stone
British Geological Survey, Edinburgh

and

W.J. Wadsworth
University of Manchester, Manchester

GCR Editor: **L.P. Thomas**

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British Geological Survey

Chapter 9

Late Silurian and Devonian volcanic rocks of Scotland

INTRODUCTION

D. Stephenson

The most voluminous phase of magmatism within the Caledonian Igneous Province of Scotland took place during the later stages of orogenesis, following the collision of Eastern Avalonia with Laurentia along the line of the Iapetus Suture. The 'Newer Granites' (described in Chapter 8), were emplaced during or following the ensuing late tectonic uplift, which ultimately gave rise to the Caledonian mountain chain. Overlapping in age with pluton emplacement was a widespread development of essentially calc-alkaline volcanic rocks and swarms of minor intrusions. On mainland Scotland the products of this volcanism are restricted to the upper Silurian and Lower Devonian, but in Orkney and Shetland they occur in the Middle Devonian, and show geochemical transitions away from calc-alkaline towards both tholeiitic (Shetland) and alkaline (Orkney) compositions. Both the plutonic and the volcanic rocks contributed greatly to the construction of the Caledonian mountain chain; many of the more dramatic mountains of the Scottish Highlands are carved out of the plutons, while the volcanic rocks also form many of the more prominent hill ranges of lowland Scotland.

The locations of all significant outcrops of late Caledonian volcanic rocks in Scotland are shown on Figure 9.1. The volcanic province extends south-westwards into Antrim, Tyrone and Roscommon in Ireland and similar volcanic rocks may have been exposed formerly to the east of the Grampian Highlands, contributing material to volcaniclastic sediments in the lower part of the Lower Old Red Sandstone succession of the northern Midland Valley. They are absent from the area NW of the Great Glen Fault, apart from in Orkney and Shetland, possibly because of significant lateral and/or vertical movements on this fault. All are associated with Old Red Sandstone sedimentary sequences of continental molasse facies. Most are now preserved in fault-bound basins and their original extent may have been far more extensive prior to erosion from the intervening uplifted areas. In some cases the volcanicity was intimately associated with high-level plutons. Volcanic rocks occur in small down-faulted blocks as a result of 'cauldron subsidence' at Glen Coe and within the Ben Nevis pluton. Elsewhere plutons have risen through volcanic sequences, as at Glen Etive and Cruachan where the Etive pluton cuts earlier lavas, and also far to the south in the Cheviot Hills, where an extensive lava field is intruded by a granite pluton.

The stratigraphical age of the volcanic rocks, and consequently of the continental Old Red Sandstone successions, was originally poorly defined, being based on a few fragmental fish, arthropod and plant remains (House *et al.*, 1977; Rolfe, 1980), although many more precise determinations are now available as a result of spore data (e.g. Richardson *et al.*, 1984; Marshall, 1991; Wellman, 1994). Published radiometric ages are of variable quality in these rocks, which are in general notorious for their secondary alteration, and many conflicting and confusing interpretations have been presented. All methods of radiometric age determination require critical interpretation of their analytical precision and petrological significance (i.e. as to which crystallization or alteration event is actually being dated). Even where radiometric dates appear to be confirmed by more than one independent method, good geological and palaeontological evidence should not be ignored, and in this volume this always takes precedence, where it is available (e.g. see Figures 1.2 and 9.2). However, radiometric age determinations by several methods have been reviewed objectively by Thirlwall (1988), who has shown that the radiometric ages of the volcanic rocks and closely related intrusions vary systematically across the strike of the Scottish Caledonides (Figure 9.2). In the Grampian Highlands the volcanicity ranges from 424 to 415 Ma (early to mid Ludlow), although related plutonism extends to a minimum of 408 Ma. In the Midland Valley the range of most volcanic rocks and intrusions is 415–410 Ma (late Ludlow to early Přídolí), although Thirlwall does not rule out the possibility of unexposed older igneous rocks in this area, coeval with those of the Highlands. In the north-western Southern Uplands, intrusions range from 413 to 407 Ma (late Ludlow to early Lochkovian), but intrusions and volcanic rocks in the south-eastern Southern Uplands and the Cheviot Hills, closest to the Iapetus Suture, are notably younger at 398–391 Ma (late Lochkovian to late Pragian), contemporaneous with the youngest granites in the Lake District.

These radiometric dates are very important in reconstructing the sequence of tectonic, magmatic and stratigraphical events in the late stages of the Caledonian Orogeny and, since the vol-

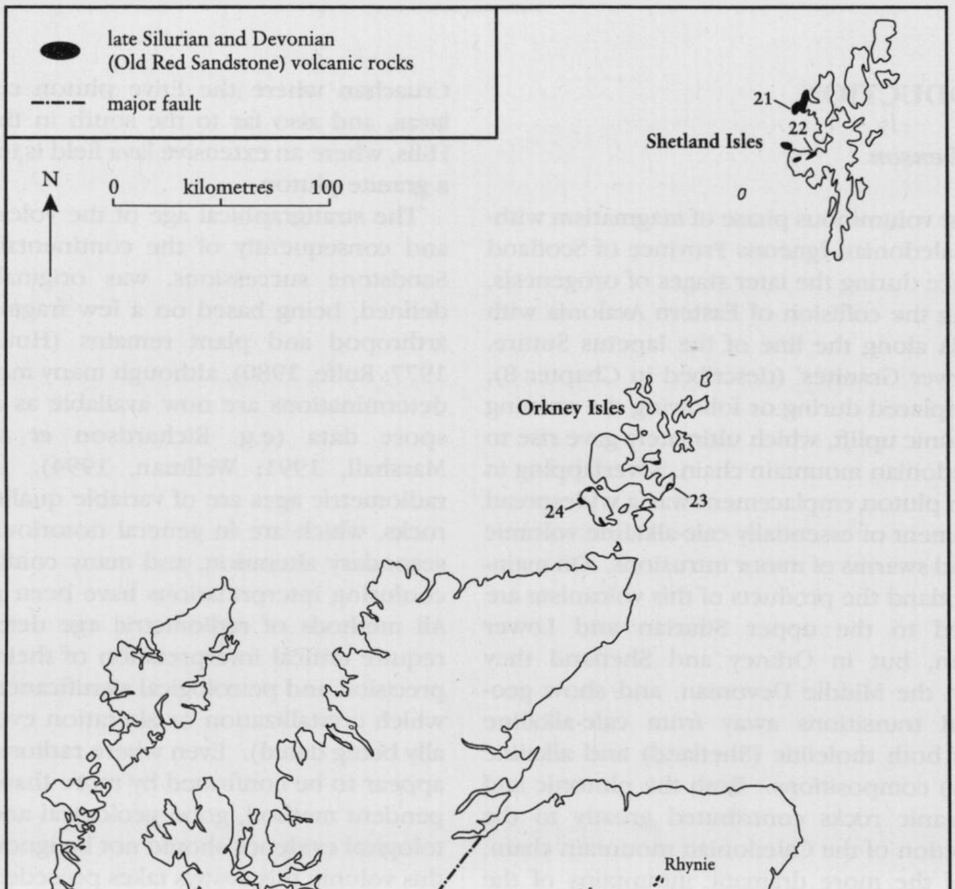

Figure 9.1 Location of late Silurian and Early- to Mid-Devonian age volcanic rocks of northern Britain. GCR sites: 1, South Kerrera; 2, Cruachan Reservoir (Chapter 8); 3, Ben Nevis and Allt a'Mhuilinn; 4, Bidean nam Bian; 5, Stob Dearg and Cam Ghleann; 6, Buachaille Etive Beag; 7, Stob Mhic Mhartuin; 8, Loch Achtriochtan; 9, Crawton Bay; 10, Scurdie Ness to Usan Harbour; 11, Black Rock to East Comb; 12, Balmerino to Wormit; 13, Sherriffmuir Road to Menstrie Burn; 14, Craig Rossie; 15, Tillicoultry; 16, Port Schuchan to Dunure Castle; 17, Culzean Harbour; 18, Turnberry Lighthouse to Port Murray; 19, Pettico Wick to St Abb's Harbour; 20, Shoulder O'Craig; 21, Eshaness Coast; 22, Ness of Clousta to The Brigs; 23, Point of Ayre; 24, Too of the Head.

canic activity spans the Silurian–Devonian boundary, they have assumed great international significance in the construction of the Geological Time Scale. The most commonly accepted date for the base of the Devonian at the time of writing is around 409 Ma (e.g. Harland *et al.*, 1990, as used in this volume), which implies that most of the volcanicity, and consequently much of the Lower Old Red Sandstone sedimentary succession is of late Silurian rather than Early Devonian age. Thirlwall himself suggested 412 Ma on the basis of his dates on Scottish lavas, and a more recent rationalization of the British dates and spore evidence (in particular from Glen Coe and the northern Midland Valley) has resulted in a considerable revision of the estimated date of the Silurian–Devonian boundary to 417 Ma (Tucker and McKerrow, 1995). If this boundary date becomes accepted, as has been proposed by Gradstein and Ogg (1996), most of the volcanicity will be regarded as Early Devonian (Figure 9.2). The only exception will be that of the Grampian Highlands (Glencoe and Lorn), which has given slightly earlier dates of 424–421 Ma, in contradiction with the presence of Lower Devonian fish and arthropods, but within the range of recent spore estimates of latest Silurian to Early Devonian (Marshall, 1991; Wellman, 1994).

The late Silurian and Devonian age volcanic rocks of Scotland and the north of Ireland have been reviewed by Stillman and Francis (1979), Elliot (1982) and Fitton *et al.* (1982) and there have been several detailed studies of the petrology and geochemistry of lava sequences in individual areas (Taylor, 1972; Gandy, 1972, 1975; Groome and Hall, 1974; Slater, 1977; French *et al.*, 1979). However, it was the comparative study of lavas from across the whole province by Thirlwall (1979, 1981a, 1982) which led to a significant advance in the understanding of the origin and evolution of the magmas and a controversial unifying theory of their tectonic setting, related to the subduction of Iapetus oceanic lithosphere beneath the Laurentian continental margin.

The volcanic rocks comprise a high-K calc-alkaline suite, with particularly high K_2O (relative to silica) in such areas as the Sidlaw Hills, the western Ochil Hills and Lorn, suggesting affinities with the 'shoshonitic' suites of active continental margins. Compositions range from basalt to rhyolite, although in most of the more widespread sequences basaltic andesites and andesites predominate. The more acid magmas were erupted from local centres, commonly as pyroclastic material, and ignimbrites are common in several centres.

Most of the lavas are quartz-normative with SiO_2 ranging from 52 to 63% and alumina is generally high. High levels of Mg, Ni, Cr and V in the more basic rocks are taken by most authors to indicate that these are derived from primitive magmas that originated by partial melting of upper mantle material. However, the generally high levels of Ba, Sr, Rb, K, light rare earth elements (LREE) and other incompatible elements are difficult to derive by fractionation of mantle material, which generally has low levels of such elements. It is therefore necessary to invoke an additional source, such as partial melting of the lower continental crust (Groome and Hall, 1974) or subducted, hydrous, oceanic lithosphere (Taylor, 1972). Thirlwall (1982, 1983b, 1986) discussed the origin of the magmas in more detail, based upon a regional study of the trace element geochemistry, together with Sr, Nd and Pb isotopes. He invoked the mixing of melts from two primary sources: primitive mantle, giving the high Ni and Cr levels; and subducted Lower Palaeozoic greywackes, giving the high content of incompatible lithophile elements. The same study concluded that contamination by continental basement material is not likely and that most of the more evolved compositions were probably derived by closed-system fractional crystallization at high crustal levels. Most other authors have also invoked varying degrees of fractional crystallization to produce the more evolved compositions. For example high-pressure melting experiments on lavas from the Sidlaw Hills by Gandy (1975) suggested a multistage model involving fractionation during the ascent of a picritic magma to give a range of high-alumina basalts, followed by further low-pressure fractionation of olivine, plagioclase and ilmenite.

In his original study, Thirlwall (1979, 1981a) concentrated on the more primitive basalts and andesites with high Mg, Ni and Cr. He found that these rocks show pronounced spatial chemical variations, with Sr, Ba, K, P, LREE and the ratio La/Y in particular showing up to a six-fold increase north-westwards from the Southern Upland Fault across the Midland Valley and Grampian Highlands, perpendicular to the main Caledonian structural trend (Figure 9.3). The more evolved rocks show similar increases, but

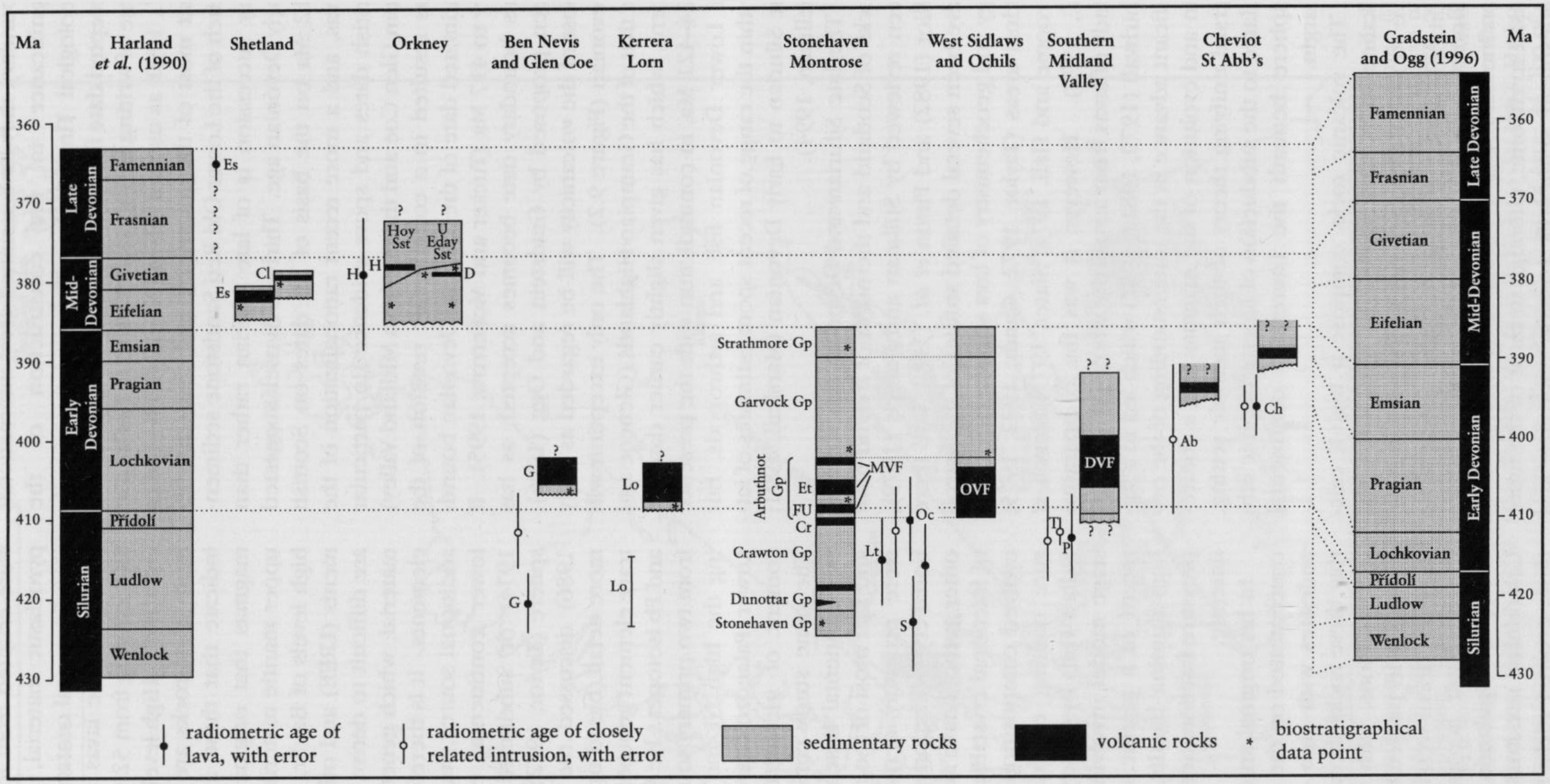

Figure 9.2 Stratigraphical relationships and ages of late-Silurian to Mid-Devonian age volcanic rocks of northern Britain. Biostratigraphical ages (where known) are given precedence and are plotted relative to the time-scale of Harland *et al.* (1990) (on the left). Note the consistent discrepencies between the biostratigraphical ages and the radiometric ages, which are not present if the time-scale of Gradstein and Ogg (1996) (on the right) is used. Where there is no biostratigraphical control (i.e. Southern Midland Valley, St Abb's and Cheviot), the volcanic sequences are projected from the radiometric dates. For example Cheviot at 396 Ma is early Emsian on the Gradstein and Ogg timescale, so it is plotted in the early Emsian position on the Harland *et al.* time scale.

Ab, St Abb's; Ch, Cheviot; Cl, Clousta; Cr, Crawton; D, Deerness; DVF, Duneaton Volcanic Formation; Es, Eshaness, Papa Stour and Melby; Et, Ethie; FU, Ferryden and Usan; G, Glen Coe; H, Hoy; Lo, Lorn; Lt, Lintrathen; MVF, Montrose Volcanic Formation; Oc, Ochil Hills; OVF, Ochil Volcanic Formation; P, Pentland Hills; S, Sidlaw Hills; T, Tinto.

their regional pattern is complicated by the effects of fractional crystallization. Broadly similar spatial chemical changes are shown by the late Caledonian plutonic suites (Stephens and Halliday, 1984; see Chapter 8). These spatial variations, coupled with the overall geochemical and petrographical features of the volcanic rocks, are typical of calc-alkaline suites associated with subduction at continental margins. Hence Thirlwall postulated the former presence of a WNW-dipping subduction zone beneath present-day Scotland that originated on the SE margin of the Laurentian continent during closure of the Iapetus Ocean. Compositional stratification in the mantle source, with depleted overlying enriched mantle, is considered to be the cause of the observed spatial variation, which reflects the depth of melting of the primitive source above the subduction zone (Thirlwall, 1982).

Although the subduction model is attractive in that it explains and unites many of the observed features of the late Caledonian igneous activity, it is beset by serious problems related to the overall timing of tectonic events and the distribution of some of the magmatism. For instance, it is now generally accepted from a wide range of evidence that the Iapetus Ocean had closed by the end of Wenlock time, and hence that active subduction had all but ceased, before the onset of volcanicity in the early Ludlow, and prior to the emplacement of most late Caledonian granitic plutons. A further problem is that the volcanic and plutonic rocks of the south-eastern Midland Valley and Southern Uplands are very close to the projected line of the Iapetus Suture relative to rocks of comparable composition in modern subduction settings.

The relationships of the later, Mid-Devonian volcanism in Orkney and Shetland to the main part of the volcanic province have been the subject of some debate. Thirlwall (1981a) and Fitton *et al.* (1982) argued that the trace elements and general transitional calc-alkaline to tholeiitic characteristics of the Shetland and some Orkney lavas suggest a relatively close proximity to the surface trace of the proposed subduction zone. Hence they proposed a curved suture, convex to the SE, which follows the regional Caledonian strike and passes close

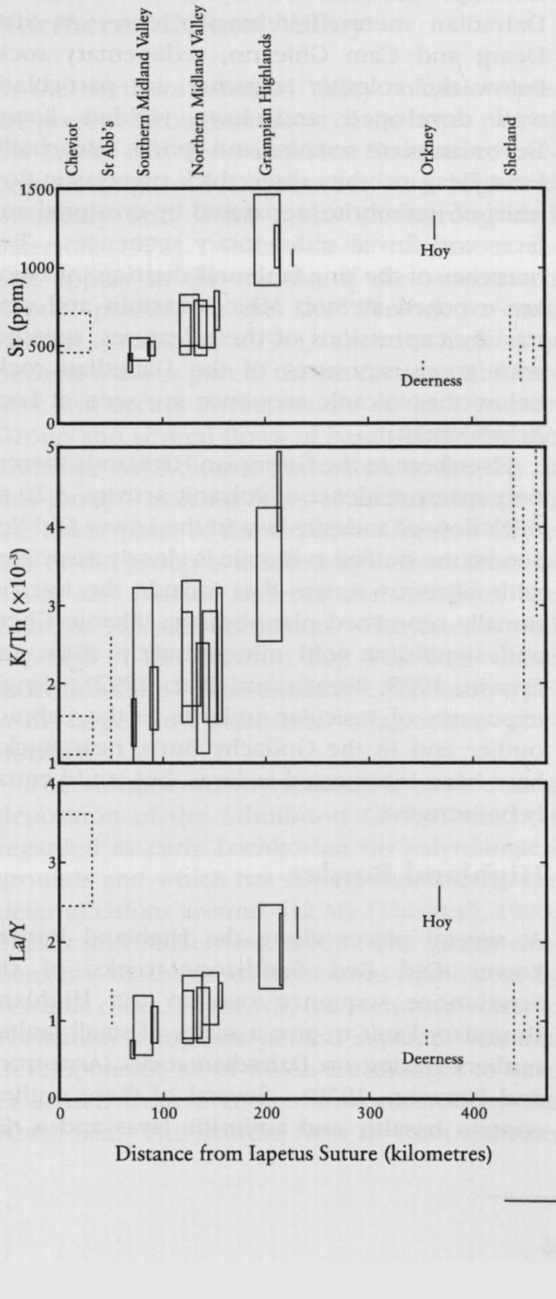

Figure 9.3 Ranges of whole-rock Sr, K/Th and La/Y from late Silurian and Devonian volcanic rocks of northern Britain, plotted against projected distance from the Iapetus Suture of Phillips *et al.* (1976). Adapted from Fitton *et al.* (1982, fig. 9). The heights of rectangles and bars represent the range of values within geographically related outcrops; the width of the rectangles represents each outcrop width.
Southern Midland Valley: Pentland Hills and Lanarkshire, Ayrshire Coast, Straiton;
Northern Midland Valley: Ochil Hills, north Fife hills, Sidlaw Hills, Montrose, Highland Border;
Grampian Highlands: Ben Nevis, Glen Coe, Lorn Plateau;
Orkney: Deerness, Hoy;
Shetland: Eshaness, Papa Stour, Clousta;
Note the anomalous values (dotted lines) from the Cheviot and St Abbs outcrops, close to the proposed line of suture, and from the Deerness outcrops of Orkney and all of the Shetland outcrops (see text for discussion).

to the east of Shetland. However, Astin (1983) advocated caution in interpreting the Orkney and Shetland data in terms of subduction, and it has subsequently become accepted that the Middle Devonian sediments and volcanic rocks of this area developed in an extensional basin (McClay *et al.*, 1986; Enfield and Coward, 1987; Astin, 1990). The Shetland lavas and the Deerness lavas of Orkney do have geochemical characteristics that may be a relict of earlier subduction, but 'it cannot be stated with certainty that they are closely related to the rest of the province' (Thirlwall, 1981a); furthermore, the alkaline nature of the Hoy lavas could be seen as marking the start of the Carboniferous intraplate alkaline volcanism (Francis, 1988).

Since the subduction model depends upon the evidence of several suites of Caledonian igneous rocks, it has been discussed, with alternative interpretations, in Chapter 1 in the context of the tectonomagmatic setting of late Caledonian magmatism in general.

Grampian Highlands

The most extensive development of volcanic rocks in the Grampian Highlands is the Lorn Plateau sequence, which extends over some 300 km^2 and is up to 800 m thick, comprising mainly flows of basalt and andesite, with rare acid lavas and ignimbrites. The whole Lorn sequence is 'shoshonitic' (enriched in potassium and other incompatible elements) and the flows on the island of Kerrera are the most shoshonitic in the whole province. The South Kerrera GCR site illustrates a range of features in these lavas, which rest upon fluvial sedimentary rocks containing macro- and microfossils of latest Silurian to earliest Devonian age. Lavas of the Lorn sequence are also seen in the Cruachan Reservoir GCR site (Chapter 8), where they are preserved in a down-faulted screen within the margin of the Etive pluton.

Volcanic rocks are also preserved in cylindrical down-faulted blocks in the classic settings of Ben Nevis and Glen Coe, which illustrate the relationships between surface volcanicity, subvolcanic complexes and underlying granitic plutons. It was in these areas that the concept of 'cauldron subsidence' was first developed by E. B. Bailey and others of the Geological Survey almost a century ago. The model has subsequently been applied worldwide but these original sites, which provide spectacular three-dimensional exposures of the roots of central volcanos, have continued to stimulate teaching and research to the present day. The Ben Nevis and Allt a'Mhuilinn GCR site represents the Ben Nevis pluton (cf. Chapter 8), within which is a subsided block of sedimentary rocks and, largely volcaniclastic, andesitic volcanic rocks, some 650 m thick. The Glencoe volcanic sequence comprises over 1500 m aggregate thickness of fluvial, graben-controlled sedimentary rocks, andesitic lavas and high-level sills, rhyolitic lavas and ignimbrites, and a variety of other volcaniclastic rocks, all enclosed by a later ring fracture and granitic ring intrusion. The complex is represented by five GCR sites. The Bidean nam Bian site gives the most complete section through the volcanic sequence and exposes relationships with the underlying land surface of Dalradian metasedimentary rocks. At Stob Dearg and Cam Ghleann, sedimentary rocks below the volcanic sequence are particularly well developed and have yielded Lower Devonian plant remains and spores. Buachaille Etive Beag exhibits three thick pyroclastic flow units of ignimbrite, separated by erosional surfaces and fluvial sedimentary sequences. Two branches of the ring fault and the ring intrusion are exposed at Stob Mhic Mhartuin and contrasting expressions of these features, together with good exposures of the Dalradian rocks below the volcanic sequence are seen at Loch Achtriochtan.

Elsewhere in the Grampian Highlands there is only sparse evidence of volcanic activity. A 20 m-thick flow of andesite lava in the Lower Old Red Sandstone outlier at Rhynie is closely associated with siliceous sinters that include the internationally renowned plant-bearing 'Rhynie Chert' and significant gold mineralization (Rice and Trewin, 1988; Trewin and Rice, 1992). Single exposures of vesicular andesite in the Cabrach outlier and in the Gollachy Burn, near Buckie have been interpreted as lavas, but could equally be intrusive.

Highland Border

At several places along the Highland Border, Lower Old Red Sandstone rocks of the Strathmore sequence overlap the Highland Boundary Fault to give a series of small faulted outliers resting on Dalradian rocks (Armstrong and Paterson, 1970). Several of these outliers contain basaltic and andesitic lavas and a distinctive dacitic ignimbrite, the 'Lintrathen Porphyry', forms a stratigraphical marker at the top of the Crawton Group on both sides of the fault (Paterson and Harris, 1969). This ignimbrite has been dated at around 416 Ma (Thirlwall, 1988) and is potentially a significant marker close to the Silurian–Devonian boundary. In Kintyre, Lower Old Red Sandstone conglomerates contain boulders of 'lava', possibly derived from the north, thin acid tuffs occur locally and three vents at Southend are very close to the projected position of the Highland Boundary Fault (Friend and Macdonald, 1968). An andesite lava, overlain by conglomerates containing lava pebbles, also occurs in the Lower Old Red Sandstone just south of the fault on Arran.

Northern Midland Valley

In the northern Midland Valley volcanic rocks are present throughout most of the lower part of the Lower Old Red Sandstone Strathmore succession (Figure 9.2), between the Highland Boundary and Ochil faults (Armstrong and Paterson, 1970). Volcaniclastic conglomerates first appear in the middle of the Stonehaven Group, possibly in the late Wenlock to early Ludlow (Marshall, 1991), above which they become a major part of the succession. The earliest lava occurs in the middle of the Dunottar Group and several flows of basalt comprise the Tremuda Bay Volcanic Formation at the top of this group. Isolated flows of andesite occur in the lower parts of the Crawton Group and the top of the group is marked by several flows of basalt and basaltic andesite that comprise the Crawton Volcanic Formation. The latter is well exposed in the Crawton Bay GCR site, where most flows are of the distinctive 'Crawton type' with large flow-orientated plagioclase phenocrysts.

The volcanic activity reached a peak during deposition of the Arbuthnott Group, which is regarded as early Lochkovian on palynological grounds and which has several radiometric age determinations around 412 Ma (Thirlwall, 1988; Tucker and McKerrow, 1995). The group contains two diachronous formations dominated by volcanic rocks. In the NE, the Montrose Volcanic Formation comprises several separate volcanic developments, all of which are thought to have emanated from a centre now covered by the North Sea. The Scurdie Ness to Usan Harbour GCR site represents the lower part of the formation, which comprises two sequences, informally termed the 'Ferryden lavas' (predominantly basaltic andesites) and the 'Usan lavas' (predominantly basalts). The Black Rock to East Comb GCR site exposes the basaltic andesites of the 'Ethie lavas' in the upper part of the formation. The Ochil Volcanic Formation forms the Ochil Hills (Francis *et al.*, 1970) and the Sidlaw Hills (Harry, 1956, 1958) and has a maximum thickness of over 2400 m. Olivine basalts and pyroxene andesites predominate throughout the formation, but minor trachyandesites, dacites and rhyodacites also occur. Pyroclastic rocks are thickest, coarsest and most common close to the Ochil Fault suggesting that the main centre of eruption lay to the south of the fault and is now concealed beneath younger strata. Two GCR sites provide sections through typical sequences of basaltic to andesitic lavas and intercalated volcaniclastic sedimentary rocks; Balmerino to Wormit in the eastern Ochils is a coastal section through a 350 m-thick sequence that has also provided radiometric and palaeontological age dating evidence, and Sheriffmuir Road to Menstrie Burn in the western Ochils exposes a 600 m-thick sequence in the dramatic Ochil Fault scarp. Rare acidic lavas are represented by the rhyodacite of the Craig Rossie GCR site and a suite of diorite stocks that cut the volcanic sequence within a wide thermal aureole show a variety of interesting contact relationships in the Tillicoultry GCR site.

The youngest volcanic activity in the northern Midland Valley is recorded by a few local flows of basalt and andesite in the upper part of the Garvock Group, south of Laurencekirk. The succeeding Emsian, Strathmore Group contains no primary volcanic rocks.

Southern Midland Valley

On the SE side of the Midland Valley volcanic rocks occur in a series of generally poorly exposed Lower Old Red Sandstone outcrops, separated by major NE–SW faults, in a 10 km-wide zone parallel to the Southern Upland Fault. At the NE end of this zone, the Braid Hills and Pentland Hills expose up to 1800 m of lavas and pyroclastic rocks with compositions ranging from olivine basalt to rhyolite (Mykura, 1960), that have been dated at *c.* 412 Ma by Thirlwall (1988). Farther to the SW major outcrops occur between West Linton and Douglas (the 'Biggar

Centre' of Geikie, 1897), SE of Muirkirk (the Duneaton Volcanic Formation; Phillips, 1994; Smith, 1995), and in the Straiton–Dalmellington area (Eyles *et al.*, 1949). Sequences in the SW are almost entirely of olivine basalt and basaltic andesite, although acid rocks are present in several large sills and laccoliths, such as that of Tinto hill (Read, 1927) which has yielded precise isotope dates of *c.* 412 Ma by both Sm-Nd and ^{39}Ar-^{40}Ar methods (Thirlwall, 1988). Intercalated volcaniclastic sedimentary rocks are common in the south-western outcrops but pyroclastic rocks and recognizable vents are rare.

Other outcrops of volcanic rocks in the Lower Old Red Sandstone occur to the NW of this zone near Galston and in the Carrick Hills. In the latter area a sequence of 300–450 m, consisting almost entirely of olivine basalts and andesites with intercalated fluvial and lacustrine sedimentary rocks, is particularly well exposed on the coast. Three GCR sites at Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray exhibit a variety of sedimentary inclusions, infillings and intercalations within the igneous rocks, which suggest that the magmas were emplaced as shallow subvolcanic sills within unconsolidated wet sediment (Kokelaar, 1982). Such features have subsequently been recognized in many other parts of the Old Red Sandstone province, and also within Ordovician sequences (Chapters 4 and 6) where many parts of the lava sequences have now been re-interpreted as high-level sill complexes.

Southern Uplands

South-east of the Southern Upland Fault an extensive lava field in the Cheviot Hills is the most south-easterly expression of the Siluro-Devonian volcanicity (Carruthers *et al.*, 1932; Thirlwall, 1979, 1981a). A poorly exposed sequence of over 500 m, consisting almost entirely of acid andesites and dacites with only local pyroclastic interbeds, is located over the projected line of the Iapetus Suture. Some 25 km to the north, the somewhat smaller outcrop around St Abb's and Eyemouth is magnificently exposed on the coast at the Pettico Wick to St Abb's Harbour GCR site. Here, a 600 m-thick sequence of basalt and basaltic andesite lavas, with interbedded volcaniclastic sedimentary rocks, exhibits a variety of flow features, preserved by rapid burial in a high-energy volcano-sedimentary environment. Volcanic activity farther to the SW in the Southern Uplands is suggested by the presence of a number of subvolcanic vents in Kirkcudbrightshire that are represented by the Shoulder O'Craig GCR site. This coastal locality exposes an intrusion breccia, a basalt intrusion and a series of slightly younger lamprophyre dykes that are part of an important regional swarm (Rock *et al.*, 1986b; see Chapter 8, Introduction).

Shetland and Orkney

In Shetland and Orkney volcanic activity occurred during late Mid-Devonian time, significantly later than in mainland Scotland, and it is not certain whether it originated in the same tectonomagmatic setting. The most extensive outcrops are in west Shetland at Melby, Papa Stour and Eshaness, all of which are thought to be of similar late Eifelian age, as are thin tuffs in the Upper Stromness Flags of Hoy, Orkney. The Eshaness GCR site illustrates a sequence of lavas, shallow sills and pyroclastic rocks of olivine basalt to andesitic composition, and a rhyolitic ignimbrite, all exposed by spectacular coastal erosion. Volcanic rocks of Givetian age occur on the Walls Peninsula of Shetland (the Clousta volcanic rocks), and on Orkney at Hoy (the Hoy Volcanic Member) and at Deerness, Shapinsay and Copinsay (the Deerness Volcanic Member). The Clousta volcanic rocks are represented by the Ness of Clousta to the Brigs GCR site, which is notable for its well-bedded pyroclastic rocks, intercalated with alluvial deposits and well preserved beneath a penecontemporaneous basaltic shallow sill. The pyroclastic rocks have been interpreted as the products of phreatic and phreatomagmatic eruptions that emanated from maars and tuff-rings. The Hoy Volcanic Member comprises basaltic breccias, tuffs and lavas of nepheline-normative alkali olivine basalt and hawaiite; they are represented by the Too of the Head GCR site. Although some of the lavas of the Deerness Volcanic Member also show alkaline characteristics, this is regarded as a secondary effect. The member is represented by the Point of Ayre GCR site, where the margin of a basalt lava flow is exposed, together with an underlying air-fall tuff and lacustrine sediments that show synsedimentary deformation associated with the volcanicity.

SOUTH KERRERA (NS 794 279–803 256)

G. Durant

Introduction

Volcanic and volcaniclastic rocks form part of a Lower Old Red Sandstone sequence that unconformably overlies Dalradian metasedimentary rocks on the island of Kerrera. The Kerrera volcanic rocks represent part of the extensive Lorn plateau lavas, which crop out over an area of 300 km² between Glencoe and the Oban district. The Lorn lava sequence is up to 800 m thick and comprises flows of basalt, pyroxene-, hornblende-, and biotite andesite with rare acid lavas and ignimbrites (Groome and Hall, 1974). Individual flows are 5 to 30 m thick but they cannot be traced for any distance inland because of poor exposure; only on the north side of Loch Etive can individual flows be traced for several kilometres. The Kerrera lavas are geochemically distinct in being the most shoshonitic (i.e. enriched in potassium and other incompatible elements), in the Old Red Sandstone volcanic suite (Groome and Hall, 1974; Thirlwall, 1979, 1981a). The volcanic rocks typically rest directly on Dalradian rocks although locally, as on Kerrera, there are sedimentary rocks at the base of the volcanic sequence.

The Lower Old Red Sandstone volcanic rocks crop out in two principal areas on Kerrera (Figure 9.4). The main outcrop is in the SW of the island, where it is well exposed around the coast immediately south of Port Phadruig (794 280) and just west of Port Dubh (793 263). Part of the sequence is also preserved as a narrow downfaulted outcrop which extends the length of the island, but which is particularly well exposed along the coast to the north of Rubha Seanach (8062 2620–8030 2563).

The sedimentary rocks underlying the lavas on Kerrera have yielded Early Devonian fish and arthropods (Kynaston and Hill, 1908; Lee and Bailey, 1925; Morton, 1979; Rolfe, 1980), but more precise spore data indicate a latest Silurian to earliest Devonian age (Marshall, 1991). Therefore the Lorn volcanic rocks have international significance as a time marker for the Silurian–Devonian boundary, with radiometric ages currently estimated in the range 424 to 415 Ma (Thirlwall, 1988).

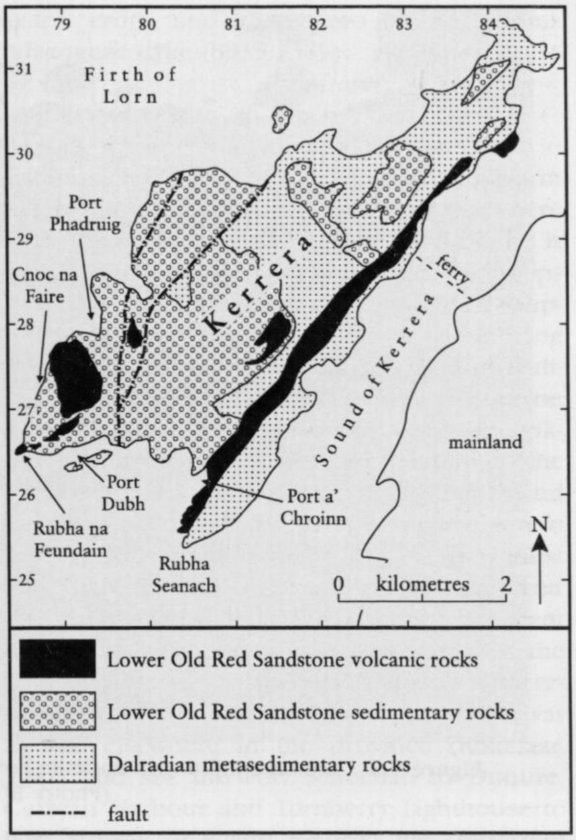

Figure 9.4 Map of Kerrera.

Description

The most complete section is that exposed along the western coast, where the volcanic rocks overlie a sequence of green conglomerates, green coarse-grained sandstones and well-laminated red fine-grained sandstones.

The base of the lava sequence is well exposed on the south side of Port Phădruig, where a 10 m-long lens of deep red jasper forms a conspicuous marker; large pillowed lobes of vesicular lava protrude into the jasper and selvages of jasper can be traced around one lobe. These relationships suggest that the jasper is silicified sediment, which was unconsolidated at the time of eruption of the basalt. A short way to the SW (7914 2788) the base is marked by a breccia characterized by blocks of vesicular basalt in a pale-pink matrix of fine-grained sandstone. The basalt fragments vary from being subrounded to angular and are up to 1 m across. Some show well-developed flow alignment of the vesicles which are now filled by calcite and quartz. The

Figure 9.5 Columnar jointing in andesite flow, south of Port Phadruig, Kerrera (NS 7888 2767). (Photo: BGS no. C 2647.)

blocks are monolithological, and some have been broken *in situ*, with little movement following disaggregation of the magma. Lobes of the succeeding lava protrude into this breccia.

The base of the lava sequence is also exposed in a raised sea stack beneath the main cliff NW of Cnoc na Faire (7884 2743). Here, the northerly dipping top surface of the underlying conglomerates and sandstones forms the wave-cut platform at the south end of the bay. In the sea stack, the lobate base of the lowest lava cuts down through a pale-green coarse-grained sandstone and a conglomerate into well-laminated red sandstone. Well-rounded pebbles from what was clearly an unconsolidated gravel have been caught up and are now included within the lava. The green sandstone includes fragments of vesicular basalt, the largest being 50 cm, and rip-up clasts of laminated red sandstone. The conglomerate contains well-rounded pebbles of volcanic rock and quartzite.

A breccia with angular to subrounded fragments of vesicular basalt in a limestone matrix forms a striking rock, particularly in the wave-polished boulders beneath the main cliff and on the beach. The basalt fragments, generally up to 10 cm but larger in some of the beach boulders, are supported within, and fairly evenly distributed through, the calcareous matrix. A second type of breccia has highly angular fragments of basalt in a white calcite matrix. The basalt fragments show little displacement during fragmentation and can easily be matched up to adjacent fragments. This type of breccia crops out on the wave-cut rock platform and is visible beneath and between the huge boulders. Basalt boulders on the beach contain amygdales and irregular cavities filled by quartz, calcite and agate.

In the main cliff itself (7892 2745), both columnar-jointed and more massive flows are present. Well-developed 20–30 cm-wide columns can be examined close to sea level in a down-faulted block of pale-grey compact basalt, which forms a marked 'whale-backed' outcrop, and also a short distance to the south (Figure 9.5). This flow is overlain by a massive extremely vesicular basalt, which is patchily autobrecciated and cut through by irregular curving joints, well seen close to a conspicuous gully formed by erosion of a Palaeogene dyke (7890 2772). Elsewhere, hexagonal columns up to 1 m across occur with selvages of sediment preserved locally within the joints.

In the extreme SW of the island the base of the lava sequence is exposed in the low cliffs to the west of Port Dubh (7875 2668). Here the pillowed base of a vesicular basalt flow overlies sandstone and a coarse conglomerate. Enclaves of laminated sandstone occur between pillowed masses of basalt, which cut down through the bedding laminations of a pinkish-red sandstone to rest directly on top of the conglomerate. Individual pillowed lobes are flattened and are up to 2 m across. A short distance from Rubha na Feundain, just to the east of a conspicuous gully formed by the erosion of a Palaeogene dyke (7866 2671), the surface of a thin basalt flow shows distinctive pahoehoe texture, which indicates that this subaerial lava was locally flowing in what is now a south-westerly direction.

The hill forming Rubha na Feundain is made up of columnar-jointed orange-weathering biotite andesite. A steeply dipping contact can be traced around the base of the outcrop, defining an oval vent-like feature. The age of this plug is uncertain. It may be coeval with the Lower Old Red Sandstone lavas but it could be younger. A biotite-augite andesite cropping out on the nearby Bach Island (7780 2690) has been assigned to the Lower Old Red Sandstone volcanic sequence (Lee and Bailey, 1925).

In the down-faulted south-eastern inlier, the lavas vary from compact to rubbly and are much fractured due to the proximity of the faults. The tops and bases of individual flows are commonly brecciated, as is well seen in wave-polished exposures in the small bays at the NE and E sides of Port a'Chroinn.

The bay immediately north of Rubha Seanach has formed along the line of the NE–SW fault that separates Dalradian pelites and limestones from the down-faulted lavas. The lowest exposed part of the lava sequence, a breccia of volcanic rock fragments in a red sandstone matrix, is seen on the north side of the bay. This breccia is overlain by a sliver of red laminated sandstone and a lens of purplish coarse-grained sandstone which dip steeply to the west. The purplish sandstone is cut out by the lobate base of the overlying blocky lava which has a reddened top. The succeeding flow, a pale-grey weathering compact basalt, permeates the rubbly top of the underlying flow, forming irregular enclaves (8027 2566). A much reddened rubbly lava forms the small headland north of Rubha Seanach (8028 2577) and a short distance NE of this, a breccia composed of volcanic rock fragments in a green coarse-grained sandstone matrix crops out adjacent to a conspicuous Palaeogene dyke (8035 2589).

Interpretation

The basalt lavas of Kerrera are of a more uniform composition than those of similar age elsewhere in the Lorn Plateau where a greater thickness is preserved. The lavas commonly have slaggy tops and bases that are much brecciated due to eruption onto or into wet sediment. In considering the general inter-relationship of lava and sediment within the Lower Old Red Sandstone province, Geikie (1897) noted that 'a more striking proof of the subaqueous character of the eruptions could hardly be conceived'. Lee and Bailey (1925) noted that 'there is good reason to believe that the lavas from time to time, must have encountered expanses of water in their path' and that there must have been 'frequent recurrence of aqueous conditions during the accumulation of the volcanic rocks'. The re-interpretation of Lower Old Red Sandstone lavas as sills elsewhere in the province (Kokelaar, 1982; and see the Port Schuchan to Dunure, Culzean Harbour and Turnberry Lighthouse to Port Murray GCR site reports) has important bearing on the nature of the Kerrera lavas and some at least could be sills intruded in to wet sediment. However, the pahoehoe flow near Rubha na Feundain and the reddened tops of flows near Rubha Seanach argue for a subaerial origin for others. There can be no doubt that the lavas or sills encountered wet sediment in their path producing the breccias and that some of the sediment has been removed in the process. Rare veins of sandstone within columnar-jointed lavas could have originated in the manner suggested by Kokelaar for similar features in the Ayrshire coast Lower Old Red Sandstone sequence. The erosion of sediment at the base of lavas is demonstrated at a number of localities, particularly the raised sea stack below the cliffs NNW of Cnoc na Faire. However it is doubtful whether a flow could remove 20 m of sediment and hence the suggestion of Lee and Bailey (1925) that the lavas were erupted onto an eroded surface of sandstone and conglomerate with at least 20 m of relief requires further examination. It is clear that an adjacent volcanic area was being eroded prior to eruption of the main Kerrera lava sequence to provide the source of andesite, olivine basalt and highly vesicular basalt for the conglomerates that underly the main volcanic sequence on the island.

Conclusions

The Kerrera GCR site is of regional and national importance as a representative of the extensive Lorn Plateau volcanic sequence. These rocks are some of the most enriched in potassium and other 'incompatible' elements in the whole late Caledonian calc-alkaline volcanic suite and hence are believed to have originated in the deepest levels of a postulated subduction zone beneath the Laurentian continental margin (Thirlwall, 1981a).

Coarse conglomerates rich in volcanic debris are a significant component of the lower part of the sequence demonstrating that an adjacent volcanic landscape was being eroded before the eruptions of basalt that form the upper part of the sequence. Some of these lavas are characterized by columnar jointing and autobrecciation and some have pillowed bases demonstrating that they were erupted onto or into wet sediment. Other flows have reddened surfaces and one shows a pahoehoe-textured surface indicating subaerial eruption.

When taken in conjunction with the other geological features on Kerrera, particularly the spectacular unconformity at the base of the Lower Old Red Sandstone sequence, a visit to the south and west of Kerrera must rank as one of the finest excursions in Scottish geology.

BEN NEVIS AND ALLT A'MHUILINN (NN 140 757–167 713)

D. W. McGarvie

Introduction

The international importance of this GCR site is that it is a well-exposed Caledonian post-tectonic granitic intrusion, around 425 Ma old, within which is preserved a sequence of volcanic rocks. The presence of the volcanic rocks warrants inclusion of the site in this chapter, but the plutonic rocks are important representatives of the Argyll and Northern Highlands Suite described in Chapter 8.

Ben Nevis is Britain's highest mountain; its summit and spectacular north-facing cliffs (Figure 9.7) are part of a down-faulted block (*c.* 2.5 km in diameter) of volcanic and sedimentary rocks that subsided along an encircling ring fracture during a caldera-forming eruption. All traces of the surface caldera and the accompanying volcanic rocks have been removed by erosion, but the deeper structural feature (i.e. the cauldron subsidence) remains. The down-faulted block is completely surrounded by a granitic intrusion (the Inner Granite), which is in turn

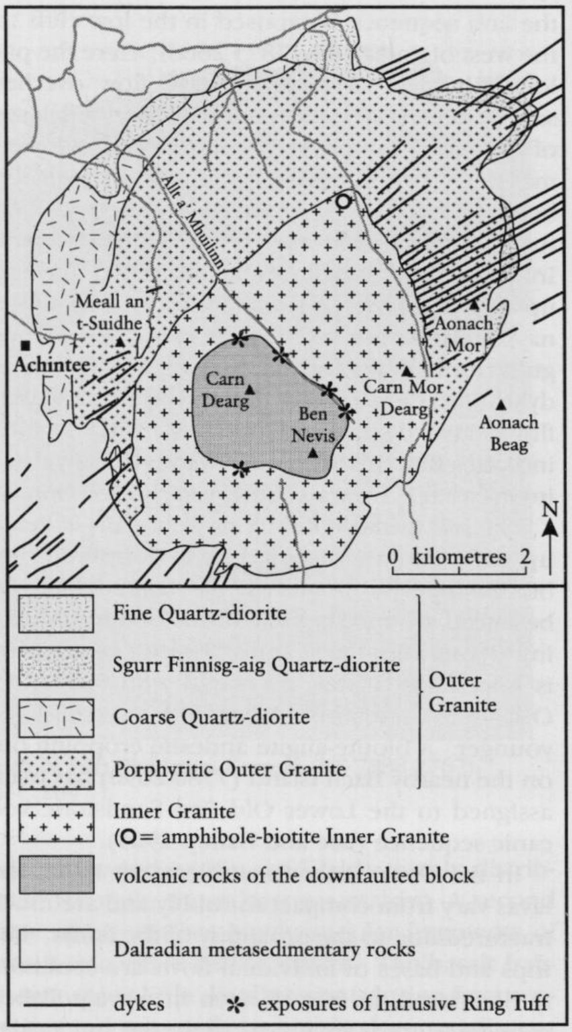

Figure 9.6 Map showing units comprising the Ben Nevis igneous complex. Note the Inner Granite (essentially a ring intrusion) completely surrounding the down-faulted block. The contact between the two is where the rhyolite and 'flinty crush-rock' (i.e. an ancient vent) is found. The Outer Granite consists of four distinct (and mappable) subunits, emplaced in a margin-to-core sequence. Note also that the dyke-swarm cuts through all subunits of the Outer Granite that lie in its path, but does not penetrate the Inner Granite or the downfaulted block. After Bailey (1960), Burt (1994) and Burt and Brown (1997).

Figure 9.7 View up the Allt a'Mhuilinn towards Coire Leis, showing the volcanic rocks of the downfaulted block (cliffs of Ben Nevis on the right), and the Inner Granite (low-lying ground on the left and the backwall of the coire in the distance. (Photomosaic: BGS nos. C 1794 and 1795.)

partly surrounded by an earlier granitic intrusion (the Outer Granite).

Geochemical relationships reveal a complex story of magma evolution involving interactions between different batches of magma and various petrogenetic processes (i.e. mantle melting, fractional crystallization, and crustal melting).

The GCR site includes terrain within 2 km of the summit of Ben Nevis, plus a narrow strip along the Allt a'Mhuilinn, which flows NW from the northern corrie, Coire Leis, giving a section across the plutonic units.

Description

The Ben Nevis igneous complex (*c.* 42 km^2) is dominated by granitic rocks, with volcanic rocks restricted to an elliptical outcrop in the south (*c.* 3.5 km^2). Early workers (Maufe, 1910; Bailey and Maufe, 1916) recognized three principal lithologies: (1) Outer Granite, (2) Inner Granite, and (3) a down-faulted block dominated by volcanic rocks. They noted that the Inner Granite is a homogeneous intrusion, whereas the Outer Granite consists of four distinct intrusive sub-units. Later workers (Anderson, 1935b; Haslam, 1965; Burt, 1994) remapped the contacts between the four Outer Granite sub-units. This description follows the work of Burt (1994), which is encapsulated in Figure 9.6.

The Ben Nevis granitic rocks are intruded into various garnet-grade Dalradian metasedimentary rocks, which generally strike NE–SW:

(youngest)	Ballachulish Slate (Ballachulish Subgroup)
	Ballachulish Limestone (Ballachulish Subgroup)
	Leven Schist (Lochaber Subgroup)
(oldest)	undifferentiated rocks of the Grampian Group

To the SE the granitic rocks cut the Fort William Slide which generally forms the junction between Grampian Group rocks and younger lithologies. This 'coincidental' association between a Siluro-Devonian volcano-plutonic complex and a major ductile slide is also evident at Glen Coe.

The Outer Granite

The Outer Granite has steep external contacts with the surrounding metasedimentary rocks (Maufe, 1910; Anderson, 1935b). The contact is usually sharp, but in the east there are zones showing considerable brecciation and veining. Veins from a few millimetres to several metres in width penetrate the metasedimentary rocks up to 100 m from the contact, while brecciation is confined to discrete zones within 20 m of the contact. The breccia matrix is granitic, and metasedimentary blocks within the breccia have moved only a few metres (Burt, 1994).

Burt (1994) noted that each of the four units of the Outer Granite (see Table 9.1) are themselves composed of multiple pulses of magma. This is more evident in the earlier units, where more rapid cooling has preserved boundaries between pulses. Later units that cooled more slowly (e.g. the Porphyritic Outer Granite) show considerable mingling between the pulses of magma.

All four units of the Outer Granite are cut by a prominent NE–SW dyke-swarm, which is particularly intense in the east. The average width of the dykes is 3 m (Anderson, 1935b), and Bailey (1960) reported that they vary in composition from *c.* 58 to 75% SiO_2. In complete contrast, the dyke-swarm does not cut the Inner Granite, yet the Inner Granite can be observed cutting five dykes that intrude the adjacent Outer Granite (Maufe, 1910; Bailey, 1960).

The Inner Granite

The Inner Granite is a notably fine-grained granitic rock that is unusually rich in plagioclase, and this led Bailey (1960) to classify it as a 'trondhjemite' (= leucotonalite). The ring of Inner Granite has contacts with three different lithologies – outer contacts (steep and inclined outwards) with Dalradian rocks and the Outer Granite, and an inner contact (also steep and inclined outwards) encircling the down-faulted block (Maufe, 1910; Bailey, 1960; Burt, 1994).

In places, at the contact between the Inner Granite and the down-faulted block, there is an unusual fine-grained, pinkish to dark-grey rhyolite with contact-parallel flow-banding. Within this rhyolite is a 'flinty crush-rock' very similar to that at Glen Coe (see the Stob Mhic Mhartuin GCR site report). Burt and Brown (1997) described this rhyolite in detail, noting that the best exposure is along the Allt a' Mhuilinn *c.* 250 m upstream of the climbing hut. The rhyolite contains abundant euhedral phenocrysts of plagioclase (up to 2 mm), plus some biotite, amphibole, and rare quartz. Rare xenoliths (rounded and less than 1 cm) include examples of Dalradian rocks, dacitic lava, and unmetamorphosed sedimentary rocks, all of which can be correlated with lithologies that occur within the down-faulted block. Rhyolite veins (from 1 to 40 cm in width) penetrate the down-faulted block for up to 500 m from the contact.

The down-faulted block

The down-faulted block is approximately 2.5 km in diameter and is surrounded on all sides by the Inner Granite. It has a basin-like structure, with the margins markedly buckled upwards (Maufe, 1910; Bailey, 1960). Burt (1994) has divided the down-faulted block into four distinct volcaniclastic formations (Table 9.2), which rest on Dalradian metasedimentary 'basement'. The exposed thickness is approximately 650 m.

Table 9.1 Nomenclature of the Outer and Inner granites of Ben Nevis by various workers. SiO_2 contents from Burt (1994).

Maufe (1910)	Anderson (1935)	Burt (1994)	SiO_2 (wt.%)
Outer Granite	Outer Quartz–diorite	Fine Quartz–diorite	58.0–62.2
Outer Granite		Sgurr Finnisg-aig Quartz-diorite	63.1
Outer Granite	Inner Quartz–diorite	Coarse Quartz–diorite	53.0–61.7
Outer Granite	Porphyritic Quartz–diorite	Porphyritic Outer Granite	63.7–70.9
Inner Granite	Inner Granite	Inner Granite	67.9–71.9

Three broad trends are evident: (1) the persistence of subaqueous conditions throughout the sequence; (2) the absence of volcaniclastic material in the early deposits, which contrasts with the dominance of such material in later deposits; (3) lateral thickness variations in all four formations.

Interpretation

Field relationships indicate an age sequence from Outer Granite to down-faulted block (i.e. volcanic activity) to Inner Granite. The prominent NE–SW dyke-swarm (which only cuts the Outer Granite) provides two important pieces of information: (1) that the regional stress field involved local dilation along a NW–SE axis; and (2) that the dykes were injected before intrusion of the Inner Granite. Although the dykes do not cut the down-faulted block, this may simply be a consequence of the down-faulted block descending from a level in the crust that did not favour dyke injection. However, it does indicate that dyke injection took place *before* subsidence of the down-faulted block, and it is conceivable that dyke injection was contemporaneous with the development of volcanism at Ben Nevis.

The variable nature of the Outer Granite has been commented upon by all workers (Maufe, 1910; Anderson, 1935b; Bailey, 1960; Haslam, 1968; Burt, 1994), who all recognized four mappable units within the discontinuous ring (although each drew slightly different boundaries between the units). Burt (1994) argued that the Outer Granite units were emplaced into the crust in a 'forceful ballooning style of intrusion' and that in places intrusion was accompanied by explosive release of volatiles, with the development of intrusion breccias. The preservation of internal contacts within each unit suggests that each consists of a number of separate pulses. These contacts are better preserved in the earlier units (e.g. the Fine Quartz-diorite) suggesting more rapid cooling in early units relative to later units. The margin-to-core sequence of intrusion partly explains this, with

Table 9.2 Succession in the down faulted block of Ben Nevis (after Burt, 1994).

Formation	Description	Interpretation
Summit Formation	Autobrecciated andesite-dominated; pervasive brecciation throughout andesite sheet; vesicle-poor; sills present; monolithological volcanic breccia beds are subordinate; lateral variations evident.	Proximal flows of largely degassed andesite lava, plus block-and-ash flows; probably erupted and deposited subaqueously (at least in part).
Ledge Route Formation	Moderately well-sorted volcanic (andesite-dominated) breccias; all strongly clast-supported; have deformed underlying fine-grained beds; lateral variations evident.	Proximal ash-fall deposit reworked by mass flow processes; fine-grained beds indicate quiescence and lacustrine conditions.
Coire na Ciste Formation	Massive unsorted volcanic breccias and block-and-ash flows; exotic clasts of welded ignimbrite and rhyolite lava; vesicle-poor andesite clasts; baked mudstone clasts; andesite lavas and sills; some quartzite-dominated breccias; lateral variations evident.	Volcaniclastic lahars and debris flows, andesite lavas and sills, and pyroclastic flow deposits; all deposited in subaqueous environment (i.e. lacustrine); fine-grained and laminated mudstones indicate periods of quiescence.
Allt a'Mhuilinn Formation	Unconformably overlies Dalradian lithologies; largely mudstone and siltstone (laminated, with rhythmic small-scale fining-up beds), with intercalations of non-volcaniclastic conglomerates (quartzite-dominated); lateral variations evident; no igneous materials present.	Freshwater lacustrine environment; mudstones and siltstones are low-volume fine-grained turbidites developed from bank collapse; conglomerates are subaqueous debris flows and lahars.
Dalradian rocks (Leven Schist?)	Pelites and semipelites; older ductile folding plus later brittle fracturing.	Part of the original land surface (bottom of lake bed).

early pulses encountering 'cold' Dalradian crust and later pulses encountering either pre-warmed crust or still hot earlier granitic magma. Anderson's (1935b) observations that the Outer Granite becomes more silicic with height (*c.* 1200 m of vertical exposure) is interesting, as this might be a relict of an original magma chamber stratification that existed prior to final cooling and solidification. This point has not been fully addressed by later workers and requires re-assessment.

The Inner Granite has steep, outward-dipping inner and outer contacts (Maufe, 1910; Burt, 1994), and appears to have been intruded in a passive (permitted) manner (Burt, 1994). It varies in composition from 67.9 to 71.9% SiO_2 which suggests that it might be the remnants of a zoned magma body.

The sedimentary rocks preserved in the down-faulted block appear to be similar to modern-day playa lake deposits and indicate that a freshwater lake existed (and persisted) at Ben Nevis. It is likely that a small sedimentary basin existed (or that the Ben Nevis basin was part of a larger structure), in which flash floods were a persistent feature in the warm and arid climate of the time (Burt, 1994). Early non-volcaniclastic sediments gradually became replaced by volcaniclastic sediments and by proximal volcanic rocks. The presence of Dalradian clasts in debris flows suggests that there was considerable relief in the area (Burt, 1994 estimates at least 300 m of relief), and there is good evidence of active erosion after emplacement of the various volcanic and sedimentary formations. It is notable that no volcanic rocks more evolved than andesites are found *in situ* – although 'exotic' clasts of dacite and rhyolite do occur, which may have come from neighbouring volcanic centres.

The down-faulted block indicates that substantial subsidence occurred (well over 650 m), and the upturned margins of the block suggest that there was frictional dragging as the block subsided (Maufe, 1910; Bailey, 1960). This conflicts with observations (and published cross sections) showing that the contact is outward-dipping, and further work is needed to resolve this paradox. (It is possible that inward-dipping ring faults are characteristic of near-surface environments, and that these become vertical and then outward-dipping at depth.) Subsidence was probably accompanied by venting of magma to the surface, and the fine-grained rhyolite at the junction of the down-faulted block and Inner Granite is interpreted by Burt and Brown (1997) as the remains of an ignimbrite conduit formed during caldera collapse. As such it is comparable to features developed in the Glencoe ring intrusion (see the Stob Mhic Mhartuin GCR site report) and it has been named the 'Ben Nevis Intrusive Ring Tuff' by Burt and Brown.

Large-scale subsidence along encircling ring fractures at evolved silicic centres is generally accompanied by pyroclastic eruptions at the surface (cf. Druitt and Sparks, 1984), and it appears that Ben Nevis supported an evolved magma system that vented to the surface during a cataclysmic eruption (Burt, 1994; Burt and Brown, 1997). It should be stressed that only the early products of the Ben Nevis volcano are preserved in the down-faulted block; later volcanic rocks (which may have included syncaldera dacites and rhyolites) have all been removed by erosion.

One of Burt's (1994) major contributions is a comprehensive geochemical survey of the igneous complex. The following points summarize his main findings.

1. Ben Nevis is a typical Argyll and Northern Highlands Suite calc-alkaline igneous complex.
2. High-K, calc-alkaline compositions of all igneous rocks (with some volcanic rocks being mildly alkaline).
3. Inner Granite and Outer Granite lie on separate geochemical trends, suggesting two distinct phases of intrusive activity; the Ben Nevis Intrusive Ring Tuff has geochemical similarities to a locally preserved amphibole-biotite granite marginal phase of the Inner Granite (Burt and Brown, 1997).
4. Volcanic rocks (andesite, dacite and rhyolite) spent little time in subsurface magma chamber(s) prior to their eruption.
5. Andesite compositions cluster between 63 and 67% SiO_2.
6. Early andesites show the largest amount of contamination with crustal rocks; later andesites are relatively uncontaminated (inferred from Nd and Sr isotope systematics).
7. Plutonic rocks reached the upper crust (*c.* 1 kb depth).
8. Trace element geochemistry indicates a major role for amphibole fractionation at depth (for all magmas).
9. Plagioclase fractionation largely controlled the geochemical evolution of magmas once

they were emplaced in the upper crust.

10. Strong temporal trend of magma system, generating variable early compositions and more homogeneous later compositions.
11. Appinite intrusion may be intimately related to the development of the igneous complex (i.e. appinites pre-, syn- and post-date the Coarse Quartz-diorite).

Incorporating these findings with the field evidence, Burt (1994) provided a synthesis of the magmatic evolution of Ben Nevis as follows.

1. Initiation of melting in SW Highland light rare-earth element (LREE)-enriched mantle.
2. Early magmas contaminated by interaction with lower crust and influenced by processes of assimilation and fractional crystallization; periodic intrusion of magmas to mid-crustal magma chamber(s); some early andesites and granitic rocks probably reached upper crust direct from lower crust without residing in mid-crustal magma chamber.
3. Fractional crystallization in developing mid-crustal magma chamber(s), with assimilation of Dalradian metasedimentary rocks.
4. Establishment of upper crustal magma chamber(s) where fractional crystallization became dominant, accompanied by localized contamination (by upper crustal Dalradian metasedimentary rocks) of chamber magmas and the magmatic conduits leading to the surface; these upper crustal magmas later solidified to form the various granitic rocks (which are believed to be the source rocks for much of the indigenous volcanic rocks within the down-faulted block).

Conclusions

At Ben Nevis the highest ground is occupied by volcanic rocks that sunk hundreds of metres into an underlying body of still-molten magma. This subsidence was accompanied by the eruption of magma to the surface through an encircling ring fracture. Erosion has removed all trace of the volcanic depression (caldera) that would have been created during this major subsidence event (cauldron subsidence), and the deposits of the accompanying eruption (pyroclastic flows). The volcanic rocks are preserved only because of large-scale subsidence of a down-faulted block, and provide compelling evidence that some of the igneous complexes associated with the Caledonian Orogeny reached high levels in the crust and supported flourishing volcanic superstructures. The international scientific importance of Ben Nevis is that it provides access to levels within an ancient igneous complex where relationships between volcanic rocks (erupted on the land surface), subvolcanic rocks (emplaced just beneath the surface), and plutonic rocks (emplaced deeper beneath the surface), can be investigated and interpreted.

THE GLENCOE VOLCANO – AN INTRODUCTION TO THE GCR SITES

D. W. McGarvie

Introduction

Glen Coe is famous worldwide as a classic example of cauldron subsidence – where a roughly cylindrical block of volcanic and basement rocks subsided into an underlying magma body. As this down-faulted inner block subsided, magma rose up around the margins and intruded the rocks outside in the form of a ring intrusion. A full wine bottle is a useful analogy: push down the cork (the down-faulted inner block) into the wine (underlying magma body), and as the cork is pushed in, wine will rise up (the ring intrusion) around the edges of the cork. One fortuitous outcome of cauldron subsidence is that the down-faulted rocks are preserved long after the surrounding volcanic products and features have been eroded away. In this part of Scotland, two spectacular and important examples of cauldron subsidence exist, at Glen Coe (five GCR sites) and Ben Nevis (one GCR site). Of these, Glen Coe contains the greater diversity of rock types and the greater structural complexity; spectacular erosion has revealed the original land surface of Dalradian metasedimentary rocks upon which the volcanic rocks were deposited, plus the three-dimensional shapes of many volcanic and intrusive units. These attributes have challenged geologists for over a century, and will continue to challenge the geologists of the future.

Cauldron subsidences are the subvolcanic expressions of volcanic calderas, where deeper erosion has revealed the rock types and structural features that accompanied surface caldera collapse and volcanism. The Glencoe volcanic rocks currently occupy an elliptical area approx-

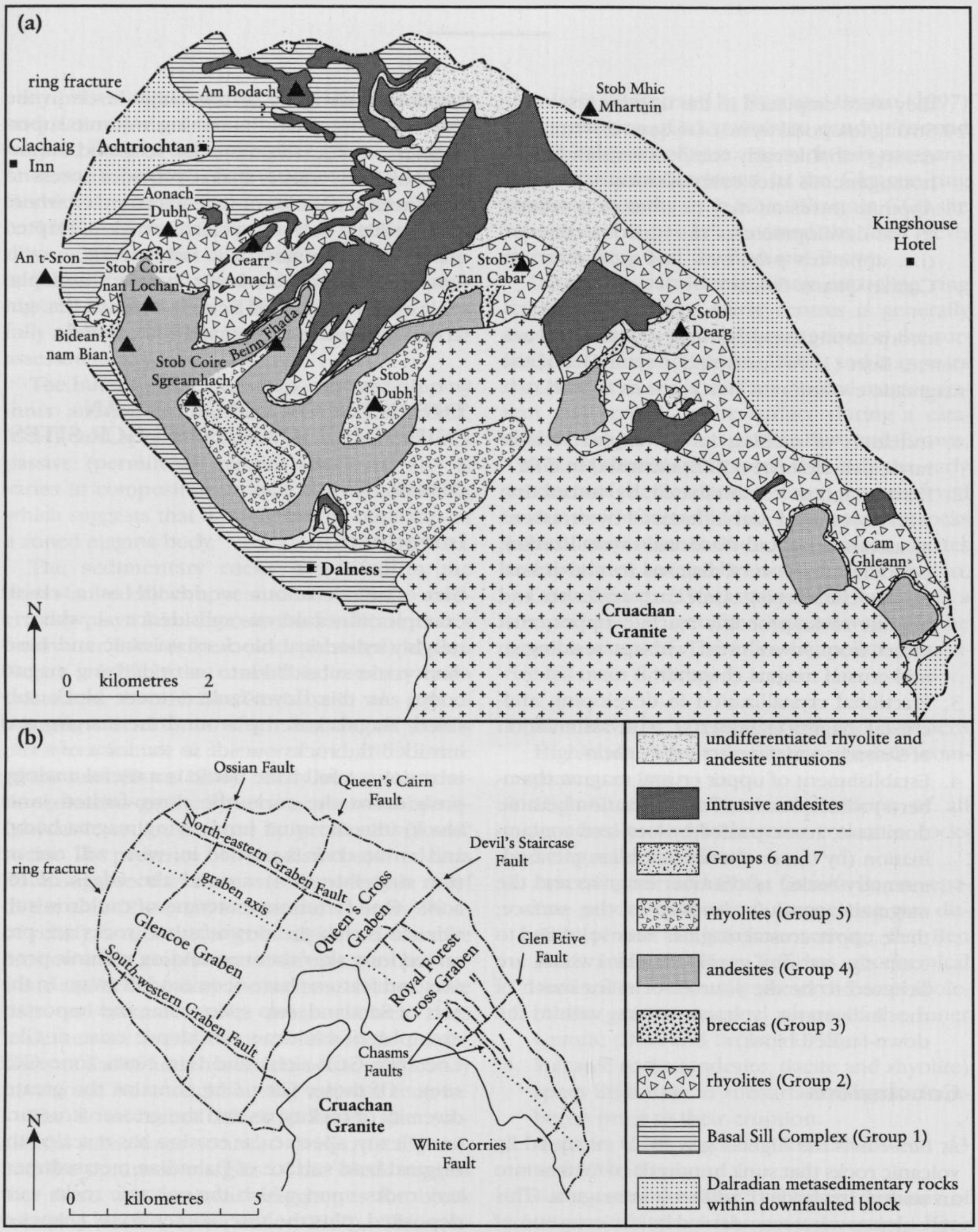

Figure 9.8 (a) Map of Glen Coe showing rocks enclosed by the ring fracture (i.e. within the down-faulted block); Dalradian metasedimentary 'basement'; groups 1 to 7 (with groups 6 and 7 shown together); and undifferentiated intrusive rocks (rhyolite and andesite). Group 3 rocks are sandwiched between groups 2 and 4 rocks throughout most of the area, and only substantial group 3 outcrops are shown. The Etive Dyke-Swarm, minor intrusions, and small outcrops are omitted. The ring intrusion is not shown (see the Stob Mhic Mhartuin GCR site report). Note the incursion of the younger Cruachan granite into the cauldron block from the south. Redrawn after Clough *et al.* (1909), Roberts (1966a), Roberts (1974), and Moore (1995).
(b) Map of the Glencoe cross-graben fault system preserved within the ring fracture (after Moore and Kokelaar, 1997).

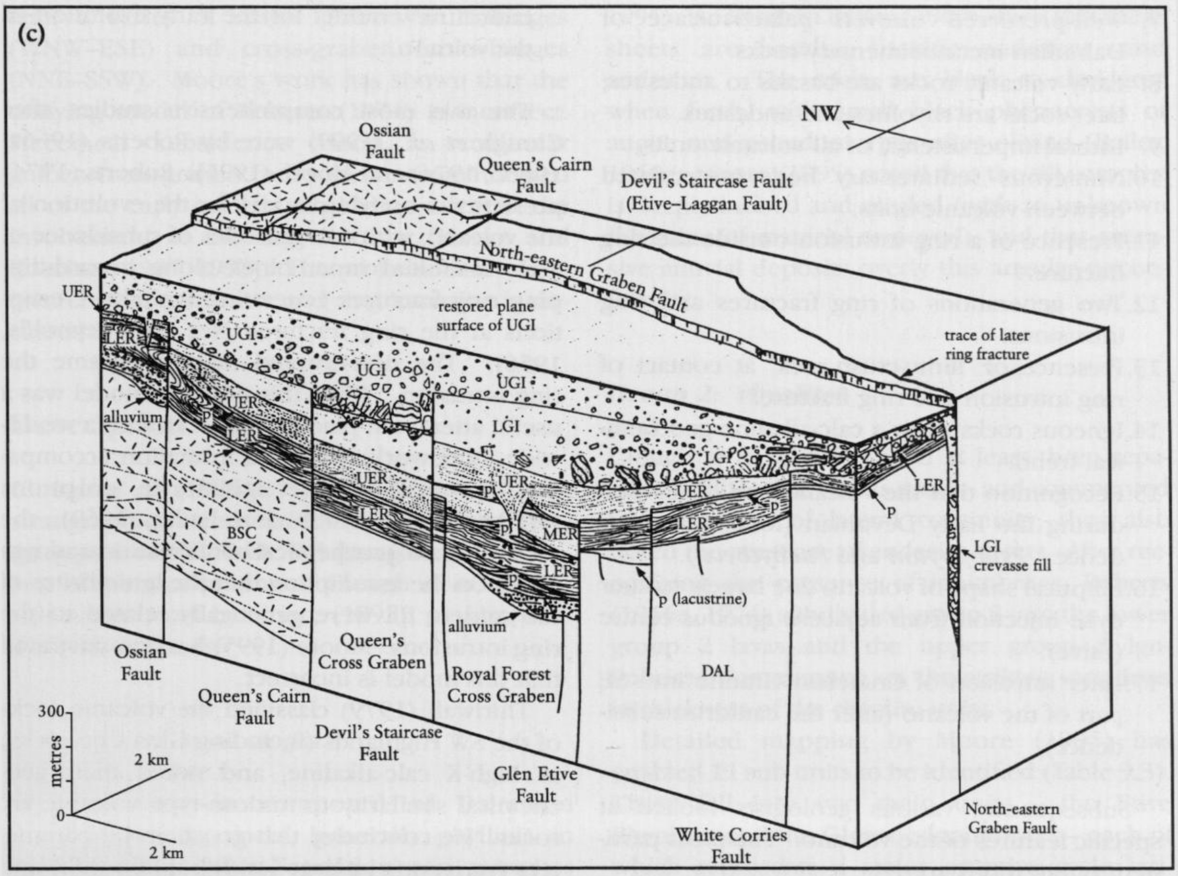

Figure 9.8 *–contd*. (c) Block diagram showing the 3D structure of the Glencoe caldera as interpreted by Moore and Kokelaar (1997). The sections have been restored to a horizontal plane surface presumed to have been formed by the eruption of the 'Upper Glencoe Ignimbrite' (top of Group 2). Thin deposits from this eruption extended north of the North-eastern Graben Fault, but are not shown. The long axis of the block diagram lies along the axis of the Glencoe Graben. DAL, Dalradian metasedimentary rocks; BSC, Basal Sill Complex; LER, MER and UER, Lower, Middle and Upper Etive rhyolites (lower Group 2); LGI and UGI, Lower and Upper Glencoe ignimbrites (upper Group 2); p, phreatomagmatic tuff.

imately 16 × 8 km, with the long axis orientated WNW–ESE (Figure 9.8). This is certainly not the original shape of the volcano; the injection of innumerable NE–SW dykes from the Etive Dyke-Swarm, well after cauldron subsidence, resulted in major dilation along the WNW–ESE axis. However, even with a generous allowance for this dilation, the original shape of the volcano was probably slightly elliptical.

The first major investigations at Glen Coe were undertaken by C. T. Clough and his co-workers when they mapped the area for the Geological Survey. Many subsequent investigators have commented on both the detail and the accuracy of their mapping, and on their perceptive and precise observations. The paper summarizing this work (Clough *et al*., 1909) and the minor modifications in later summaries (Bailey and Maufe, 1916; Bailey, 1960) are revered as classics. Here is a brief summary of their main findings.

1. All the volcanic and related rocks are contained within a ring fracture.
2. Marginal steepening of rocks within the inner block at the ring fracture.
3. Metasedimentary rocks within the ring fracture are of a lower grade than those outside.
4. Large-scale subsidence of a down-faulted inner block (cauldron subsidence).
5. Subdivision of volcanic (and related) rocks into seven groups.
6. General (regional) dip of rock units in a southerly direction (approximately 10–20°).

7. Well-preserved uneven palaeosurface of Dalradian metasedimentary rocks.
8. Early volcanic rocks are basalts to andesites; later rocks are rhyolites and andesites.
9. Lateral impersistence of all volcanic units.
10. Numerous sedimentary beds intercalated between volcanic units.
11. Presence of a ring intrusion outside the ring fracture.
12. Two generations of ring fractures and ring intrusions.
13. Presence of 'flinty-crush-rock' at contact of ring intrusion and ring fracture.
14. Igneous rocks show a calc-alkaline geochemical trend.
15. Recognition that the volcano had developed during the Early Devonian (fossil plant evidence – *Psilophyton* and *Pachytheca*).
16. Elliptical shape of volcano due largely to later dyke injection from adjacent igneous centre (Etive).
17. Later intrusion of Cruachan Granite into SE part of the volcano (after the cauldron subsidence).

Subsequently, various geologists looked at specific features of the volcano. The most pertinent publications are:

- Reynolds (1956): examined features of the ring fractures.
- Hardie (1963, 1968): investigated various breccia units.
- Roberts (1963, 1966a, 1966b, 1974): examined ring fracture and ring intrusion; recognized the presence of ignimbrites; recognized sub-groups within the major groups of Clough *et al*. (1909); developed a unifying model for the evolution of the volcano.
- Ferguson (1966): examined rhyolite flow structures.
- Taubeneck (1967): demonstrated overall inward-dip of ring fracture; recognized a major palaeoslope down to the west; and that abundant sedimentary rocks testified to incremental caldera collapse.
- Thirlwall (1979): analysed some Glen Coe volcanic rocks as part of a regional geochemical survey.
- Garnham (1988): research on ring fractures and associated intrusions.
- Moore (1995), Moore and Kokelaar (1997, 1998): re-mapping of the volcano; detailed investigation of early volcanism; developed radical new model for the early evolution of the volcano.

The two most comprehensive studies after Clough *et al*., (1909) were by Roberts (1966a, 1966b, 1974) and Moore (1995). Roberts (1974) presented a unifying model for the evolution of the volcano, with two episodes of subsidence of a down-faulted inner block along inward-dipping ring fractures generating ignimbrite eruptions at the ring fractures (see also Reynolds, 1956). The non-erupted magma became the ring intrusion. While this unifying model was a useful attempt at placing Glen Coe into a worldwide framework of caldera formation accompanied by ring-fracture ignimbrite eruptions (established by Smith and Bailey, 1968), the model lacked geochemical confirmation and was based on the assumption that the ignimbrites of the caldera fill were genetically related to the ring intrusions. Moore (1995) has demonstrated that this model is incorrect.

Thirlwall (1979) classified the volcanic rocks of the SW Highlands (including Glen Coe rocks) as high-K calc-alkaline, and noted their geochemical similarity to Andean-type volcanic arc rocks. He concluded that geochemical parameters (variations in large ion lithophile (LIL) and high field strength (HFS) elements, and concentrations of Ni, Sr, and Cr) do not support fractional crystallization as a key process linking together the different magma types. Instead, production of magmas in the mantle (via partial melting, mixing, and contamination) was considered more likely. While Thirlwall's study enabled some generalizations to be made about magmatism in the SW Highlands and provided some analyses of Glen Coe volcanic rocks, the likelihood of magma mixing in many Glen Coe eruptions (discussed later) requires caution in interpreting the geochemical data. Analyses of a comprehensive and well-characterized suite of samples are not available at present, and consequently any comments on magma sources and evolution at Glen Coe would be highly speculative at best.

The recent work of Moore (1995) has brought a modern volcanological perspective to Glen Coe. This work focused on the early evolution of the volcano (groups 1 to 3 of Clough *et al*., 1909). He further subdivided these three groups, and convincingly demonstrated that the early volcanic and structural evolution of the volcano was controlled by a rectilinear fault system; a series of major graben faults/hinges (WNW–ESE) and cross-graben faults/hinges (NNE–SSW). Moore's work has shown that the unifying model of Roberts (1974) is incorrect. Piecemeal subsidence along a rectilinear graben/cross-graben fault system accommodated all of the early caldera subsidence, without the involvement of the ring fracture (Moore and Kokelaar, 1997, 1998). The probable role of the encircling ring fracture and ring intrusion is discussed later.

Description

Clough *et al.* (1909) established seven volcanostratigraphical units in the Glencoe volcano (groups 1 to 7). Table 9.3 provides a comparison of the stratigraphy of Clough *et al.* (1909) and recent work by Moore (1995), plus approximate thicknesses.

The original land surface

The basement is composed of Dalradian metasedimentary rocks, generally phyllites in the west (Leven Schist Formation) and quartzites and semipelites in the east. The land surface developed on these rocks was heavily eroded and uneven. Clough *et al.* (1909) recorded lenticular masses of conglomerates that they considered to be deposits from flash floods, and also noted that the terrain in the east of the volcano was much steeper than that in the west. Taubeneck (1967) recorded an input of clastic sediment from the east, and noted a 'marked downward slope to the west' which he considered to be 'as much as 2000 feet'. Moore (1995) developed these findings further and described canyons and other fluvial channels etched into the basement.

Group 1: Basal Sill Complex

The lowest 'volcanic rocks' consist of approximately 17 separate sheets with an aggregate thickness of 450 m (Clough *et al.*, 1909; Bailey, 1960). Although Clough *et al.* (1909) described extensive brecciation of the sheet margins and the presence of red sandstones and shales in the matrix, it is only recently that these features have been recognized as peperites, which formed when magmas intruded wet sediments (Moore, 1995). Analyses in Bailey (1960) show that these sheets are basalts, basaltic andesites, and andesites. The rocks are black to dark-grey when fresh, with small black phenocrysts of augite and pseudomorphs after olivine (Bailey, 1960). Moore (1995) noted that the sill complex is deeply incised and eroded (with an unknown thickness of material removed), and that extensive alluvial deposits overly this angular unconformity.

Group 2: rhyolites

Clough *et al.* (1909) noted at least three separate rhyolite units in this group, and commented on their lack of lateral continuity; they also noted the presence of andesite sheets. After recognizing the presence of ignimbrites, Roberts (1966a, 1974) subdivided group 2 into the lower group 2 lavas and the upper group 2 ignimbrites, commenting on the striking variations in thickness of the rhyolite units.

Detailed mapping by Moore (1995) has enabled 11 sub-units to be identified (Table 9.3). These fall into two main units – the Etive Rhyolites and the Glencoe Ignimbrites – each of which represents a major eruptive cycle intimately related to graben-controlled caldera formation.

The first major eruptive cycle involved the eruption of three rhyolite lavas (producing the Lower, Middle, and Upper Etive rhyolites). Each began with a phreatomagmatic phase, which was followed by a flow-laminated rhyolite. A period of quiescence was marked by fluvial incision and sedimentation, and this sequence was repeated two further times. Each eruption was accompanied by subsidence (caldera collapse) of sufficient magnitude to enable fluvial systems to become re-established. Towards the end of this major eruptive cycle, andesite sheets (sills and possibly some lavas) were emplaced, which appear to be mixed magmas (with andesite dominant over rhyolite). Fluvial incision and sedimentation record further subsidence after andesite emplacement.

The second major eruptive cycle produced three ignimbrites (the Lower, Middle, and Upper Glencoe ignimbrites). Of these, the middle ignimbrite is the smallest and has a very limited outcrop, whereas the other two are larger in volume and are more widespread. The first two eruptions were accompanied by irregular

Table 9.3 Stratigraphy of the volcanic and associated sedimentary rocks preserved in the Glencoe cauldron subsidence.

	Group names of Clough *et al.* (1909)	Group names used in this account	Main units of Moore (1995)	Sub-units of Moore (1995)
Group 7 *c*.100 m thick	Andesites and rhyolites	Andesites and rhyolites	–	–
Group 6 *c*.20 m thick	Shales and sandstones	Shales and sandstones	–	–
Group 5 *c*.80 m thick	Rhyolites	Rhyolites	–	–
Group 4 *c*.280 m thick	Andesites	Andesites	–	–
Group 3 *c*.80 m thick	Agglomerates	Collapse breccias and alluvium	Collapse breccias and alluvial deposits	Glas Coire Alluvium Church Door Buttress Breccias Upper Queen's Cairn Breccias
Group 2 *c*.600 m thick	Rhyolites	Rhyolites	Glen Coe Ignimbrites	Upper Glen Coe Ignimbrite Lower Queen's Cairn Breccias Queen's Cairn Fan Middle Glen Coe Ignimbrite Lower Glen Coe Ignimbrite
			Etive Rhyolites	Upper Etive Rhyolite Crowberry Ridge Tuff Middle Etive Rhyolite Raven's Gully Tuff Lower Etive Rhyolite Kingshouse Tuff
Group 1 *c*.500 m thick	Augite andesites and basalts	Basal Sill Complex	**Pre-caldera Basal Andesite Sill Complex	

**Analyses in Bailey (1960) show that some of the sheets are in fact basalts and basaltic andesites.

caldera collapse. More substantial caldera collapse accompanied the eruption of the third ignimbrite, and two syncaldera breccia deposits were produced – the Lower Queen's Cairn Breccias and Upper Queen's Cairn Breccias. After this second major eruptive cycle a further series of andesite sheets was emplaced.

Group 3: collapse breccias and alluvium

Clough *et al.* (1909) noted that this group consists of a complex sequence of 'agglomerates', intercalated with various locally developed sedimentary units, all showing considerable thickness variations. They suggested that these 'agglomerates' might be detrital, and this view was shared by Roberts (1966a, 1974) and Taubeneck (1967), who considered them to be collapse breccias, fluvial deposits and lacustrine sediments. Moore (1995) concluded that there was widespread collapse of the caldera floor after eruption of the Upper Glencoe Ignimbrite, and that this subsidence is reflected in two contrasting types of deposit: fault-scarp collapse – the Church Door Buttress Breccias; and re-establishment of a fluvial system through the caldera, depositing alluvial and caldera lake sediments – the Glas Coire Alluvium.

Group 4: andesites

These are described by Clough *et al.* (1909) and Bailey (1960) as greenish-grey to black andesites typically containing small hornblende and feldspar microphenocrysts set in a flow-banded matrix. A number of sheets are present, attaining an aggregate thickness approaching 300 m; they crop out across much of the volcano. Thin rhyolite units, which may be ignimbrites, and sandstone and shale beds (up to 10 m thick) are intercalated within the andesites (Roberts, 1974).

Group 5: rhyolites

Clough *et al.* (1909) described this group as a black, vitreous, feldspar-phyric, flow-banded rhyolite up to 80 m thick, containing an abundance of lithic clasts (rhyolite, minor andesite, and infrequent quartzose schist) at its base. Both Roberts (1966a, 1974) and Taubeneck (1967) reinterpreted this sheet as an ignimbrite of rhyodacitic composition, and their descriptions hint at the presence of more than one eruptive unit. This rock may be a product of magma mixing, as Roberts (1966a) described flattened (i.e. once molten) inclusions (up to 25 cm) of a dark, porphyritic rock within the rhyolite.

Group 6: shales and sandstones

This group consists of a sequence of well-stratified greenish-grey shales and sandstones, of variable thickness up to a maximum of 20 m, which is exposed only around the southern shoulder of Beinn Fhada (Clough *et al.*, 1909). Taubeneck (1967) concluded that marked subsidence must have followed the eruption of the Group 5 ignimbrite(s) and attributed delicate lamination in the sediments to formation in a caldera lake.

Group 7: andesites and rhyolites

These are the youngest volcanic units preserved within the volcano. They consist of rhyolites and hornblende andesites (and possibly a basaltic andesite) that have accumulated in an irregular fashion, to a maximum thickness of 100 m (Clough *et al.*, 1909). They are exposed only in impersistent outcrops around the southern shoulder of Beinn Fhada. Taubeneck (1967) reported the presence of a thin dacitic to rhyodacitic ignimbrite, containing numerous fragments of volcanic rocks and quartzose basement.

Interpretation

The evolution of the Glencoe volcano can conveniently be divided into three phases: pre-caldera; graben-controlled caldera; and cauldron subsidence (ring-fracture-controlled caldera). Only the first two are represented in the preserved volcanic stratigraphy (Moore, 1995; Moore and Kokelaar, 1997, 1998).

Pre-caldera phase

1. Uneven palaeosurface developed on Dalradian metasedimentary rocks, sloping down to the west.
2. Input of fluvial material from the east, with fluvial system traversing the putative Glencoe caldera, exiting to the west.
3. Localized subsidence in the west, leading to development of a small sedimentary basin (containing red sandstones and shales).
4. Group 1. Sills of basalt to andesite composition injected into the wet sediments (the Basal Sill Complex).
5. Major erosion of the Basal Sill Complex, and deposition of alluvial deposits.

Graben-controlled caldera phase

6. Group 2. First cycle of rhyolitic volcanism (the Etive Rhyolites), with three subcycles of activity: each involving initial phreatomagmatic eruption, then rhyolite eruption, then caldera collapse, then re-established fluvial activity. First cycle culminated in eruption of andesite (mixed magma) sills and lavas.

7. Group 2. Second cycle of rhyolitic volcanism (the Glencoe Ignimbrites), similar in pattern to the first cycle, but explosive eruptions generated ignimbrites instead of lavas, and major collapse accompanied eruption of the last ignimbrite. Second cycle also culminated in eruption of andesite (mixed magma) sills and lavas.
8. Group 3. Major fault-scarp collapse generating breccias, alluvial deposits and lake sediments. Re-establishment of the fluvial system.
9. Group 4. Eruption of andesite sheets across the entire caldera. Presence of sedimentary beds and thin rhyolite units suggests periods of quiescence and collapse between eruptions. Thin rhyolite units may be ignimbrites.
10. Group 5. Ignimbrite eruption(s). Original lateral extent unknown. Caldera collapse. Erosion of upper parts of ignimbrite sheet.
11. Group 6. Establishment of caldera lake (and fluvial system?).
12. Group 7. Eruption of rhyolite and andesite, with at least one explosive rhyolite eruption producing an ignimbrite. Later eruptions of unknown volume and composition were subsequently removed by erosion (see 14 below).

Cauldron subsidence phase (ring-fracture-controlled caldera)

13. Cauldron subsidence (i.e. cataclysmic caldera collapse along ring fractures), probably accompanied by major ignimbrite eruption(s). Emplacement of the ring intrusion – which chilled against the ring fractures. Fine-grained facies (flinty crush-rock) found at the margins of the ring intrusion is possibly an intrusive tuff emplaced during surface venting that generated syncaldera ignimbrites.
14. Removal of an unknown thickness of volcanic and sedimentary rocks from above the preserved Group 7 rocks.

This late-stage, large-scale down-faulting of a cauldron block along encircling ring fractures (i.e. major caldera collapse) contrasts strongly with the piecemeal, incremental graben-controlled caldera subsidence described by Moore (1995) during Group 2 to Group 3 time. It follows that a substantial volume of magma was vented some time after Group 7 time, when the major (sub-circular) caldera was formed. The syncaldera volcanic rocks, which would have filled the large (*c.* 8 km diameter) caldera during this event, have been completely removed by erosion and consequently the volcanic rocks that remain (i.e. groups 1 to 7) represent only the early (non-cataclysmic) magmatic and structural evolution of the Glencoe volcano.

It is instructive to compare the Glencoe and the Ben Nevis igneous centres (see the Ben Nevis and Allt a'Mhuilinn GCR site report), as these are the only two centres in the region where caldera-forming eruptions are known to have taken place and where down-faulted blocks have preserved the products of central volcanoes. The following similarities are apparent.

- both volcanic centres developed on Dalradian 'basement',
- early pre-caldera volcanic sequences at both volcanic centres are dominated by basalts and andesites,
- there was substantial subsidence, deposition of fine-grained sediments, and lacustrine conditions at both centres,
- both centres display a sharp contact between the down-faulted blocks and the encircling ring intrusions,
- a fine-grained variant of the ring intrusion (rhyolite plus flinty crush-rock) is found at the contact with both down-faulted blocks,
- late-stage volcanic products (including possible syncaldera ignimbrites) have been removed by erosion.

However, the downfaulted block at Ben Nevis is only *c.* 2.5 km in diameter whereas at Glen Coe it is *c.* 8 km. The sizes of blocks that subside during caldera-forming ignimbrite eruptions are intimately related to magma chamber diameter (Smith and Bailey, 1968; Smith, 1979), and from this it can be concluded that the Glencoe upper crustal magma chamber was probably the larger of the two. There is thus a greater likelihood that larger volumes of more evolved (silicic) magma were produced at Glen Coe than at Ben Nevis. Furthermore, it is apparent that intrusive rocks are dominant at Ben Nevis (*c.* 90% of the complex) whereas at Glen Coe they are subordinate and are concentrated at the discontinuous ring intrusion. It is likely that Glen Coe and Ben

Nevis represent different erosion levels of broadly similar igneous centres, with Ben Nevis being more deeply eroded. The presence of major granite intrusions adjacent to Glen Coe (e.g. Starav, Etive, Cruachan, Moor of Rannoch) suggests that the Glencoe ring intrusion may be more extensive at depth, where it may look more like the Ben Nevis Inner Granite.

Two tectonic features may have an intimate association with the magmatism: (1) the major slides (Ballachulish and Sgurr a' Choise) that are cut by the volcanoes; and (2) the proximity of the Great Glen Fault. Jacques and Reavy (1994) commented on the possible influence of the Great Glen Fault on igneous centres that lie within 20 km of the fault. Moore (1995) recognized a system of main graben faults (and orthogonal cross-graben faults) at Glen Coe, with the cross-graben faults aligned parallel to the Great Glen Fault. Strike-slip movements on the Great Glen Fault could have developed localized transtension in the Glen Coe area (main graben faults), especially if a pre-existing crustal weakness or lineament was present. Evolved calc-alkaline magmatism in compressional regimes requires localized extension (see Pitcher, 1993), and localized transtension associated with movements of the Great Glen Fault is one possible mechanism for focusing and stimulating magmatism at Glen Coe.

It is apparent that, despite being a classic area of the geology of Great Britain, there are still numerous gaps in our understanding of the Glen Coe magmatism. At the time of writing no modern study has been made of groups 4 to 7, and it is not known how much material has been removed by erosion from above Group 7. Furthermore, it is possible that neighbouring igneous centres (e.g. Etive, Cruachan) supported flourishing volcanic systems (now removed by erosion), that could have contributed caldera fill material to Glen Coe, and that some of the rocks preserved could be from these sources. Other aspects needing further investigation include: how the volcano evolved geochemically; the role of magma mixing; eruption mechanisms of the rhyolites; why there is such extensive sill emplacement; relationships between local and regional magmatism; relationships between local and regional tectonics (especially the nearby Great Glen Fault system); the precise mechanism of cauldron subsidence; and emplacement of the ring intrusion.

BIDEAN NAM BIAN (NN 150 546)

D. W. McGarvie

Introduction

This GCR site is internationally important because it reveals a detailed section through the Glencoe volcano (see 'The Glencoe volcano – an introduction to the GCR sites', above). Spectacular erosion has fortuitously exposed the contact between the original land surface and the lower volcanic units, and has provided an easily accessible section through the volcanic pile preserved in the down-faulted inner block.

The site lies to the south of the River Coe and encloses the highest terrain in the area, including the mountains Bidean nam Bian (1150 m), Stob Coire Sgreamhach (1070 m) and Stob Coire nan Lochan (1115 m). It also includes parts of the 'three sisters' of Glen Coe – Aonach Dubh, Gearr Aonach, and Beinn Fhada.

Description

Figure 9.8a shows the surface outcrop of groups 1 to 7, within the whole of the Glen Coe down-faulted block. A general view of the Bidean nam Bian GCR site, looking south, is given in Figure 9.9, which shows the terrain from the River Coe up to Bidean nam Bian (part of the Loch Achtriochtan GCR site is seen to the right of the photograph). Figure 9.10 illustrates the outcrop of groups 1 to 4 on this photograph (after Bailey, 1960). The lower slopes consist of the Leven Schist Formation (Clough *et al.*, 1909) which is overlain by the Basal Sill Complex (Group 1). This in turn is overlain by the rhyolites of Group 2, which here consist of three thick units. These are the Lower Etive Rhyolite, the Upper Etive Rhyolite, and the Upper Glen Coe Ignimbrite (Moore, 1995). The Group 3 collapse breccias and alluvium deposits crop out on the shoulder of Aonach Dubh and beyond Stob Coire nam Beith, and then the Group 4 andesites crop out towards Bidean nam Bian. These are the youngest rocks seen on Figure 9.9 (Bailey, 1960). Outcrops of groups 1 and 2 on the west face of Aonach Dubh are shown in Figure 9.11.

Exposures revealing the unconformable contact between the Leven Schist Formation and the overlying Basal Sill Complex show an irregular

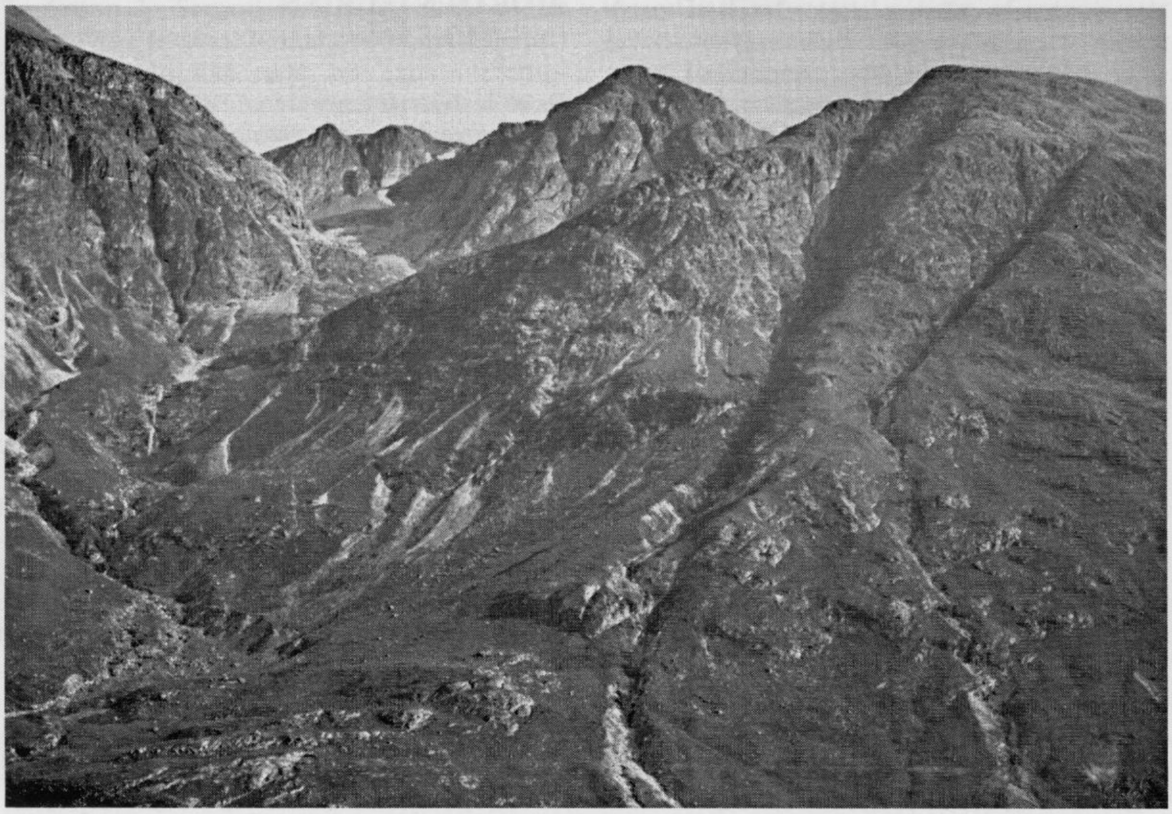

Figure 9.9 View up Coire nam Beitheach towards Bidean nam Bian, Glen Coe, showing the outcrop of groups 1 to 4, plus the ring fracture and ring intrusion. See Figure 9.10 and the text for details. (Photo: BGS no. B619.)

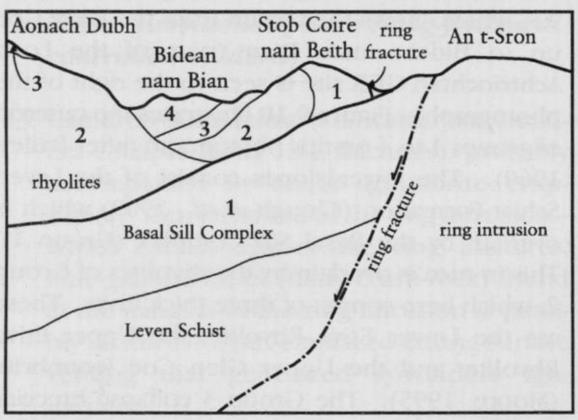

Figure 9.10 Interpretative sketch of Figure 9.9 showing the relationships between topography and lithologies at the Bidean nam Bian GCR site, after Clough *et al.* (1909). See text for details.

original land surface, with impersistent beds of conglomerate, sandstone, and shale above (Moore, 1995). Conglomerates are localized and appear to infill fluvial channels. In the stream draining Coire nam Beith, Clough *et al.*, (1909) recorded a *c.* 1 m-thick bed of purple sandy shale containing fragments of rock from the Leven Schist Formation.

Clough *et al.* (1909) and Bailey (1960) noted that the *c.* 17 sheets of igneous rock in Group 1 range from basalt through to andesite (the dominant lithology). The sheets exhibit flow-banding, and are largely non-vesicular. Brecciation of the upper and lower surfaces of sheets was noted by Clough *et al.* (1909), with sandy shale in the interstices (often retaining bedding). Recent investigations of these sheets (Moore, 1995) have shown that the entire sequence consists of sills with peperitic upper and lower surfaces (Figure 9.12); some sills pinch-out and bifurcate.

Clough *et al.*, (1909) commented on the uneven upper surface of the Group 1 rocks, and Moore (1995) has shown that this is a major erosional unconformity. Above this unconformity is a thin (less than 10 m thick) and irregular sequence of conglomerates and bedded sandstones infilling hollows and channels in the erosional surface.

Above the erosional unconformity are the

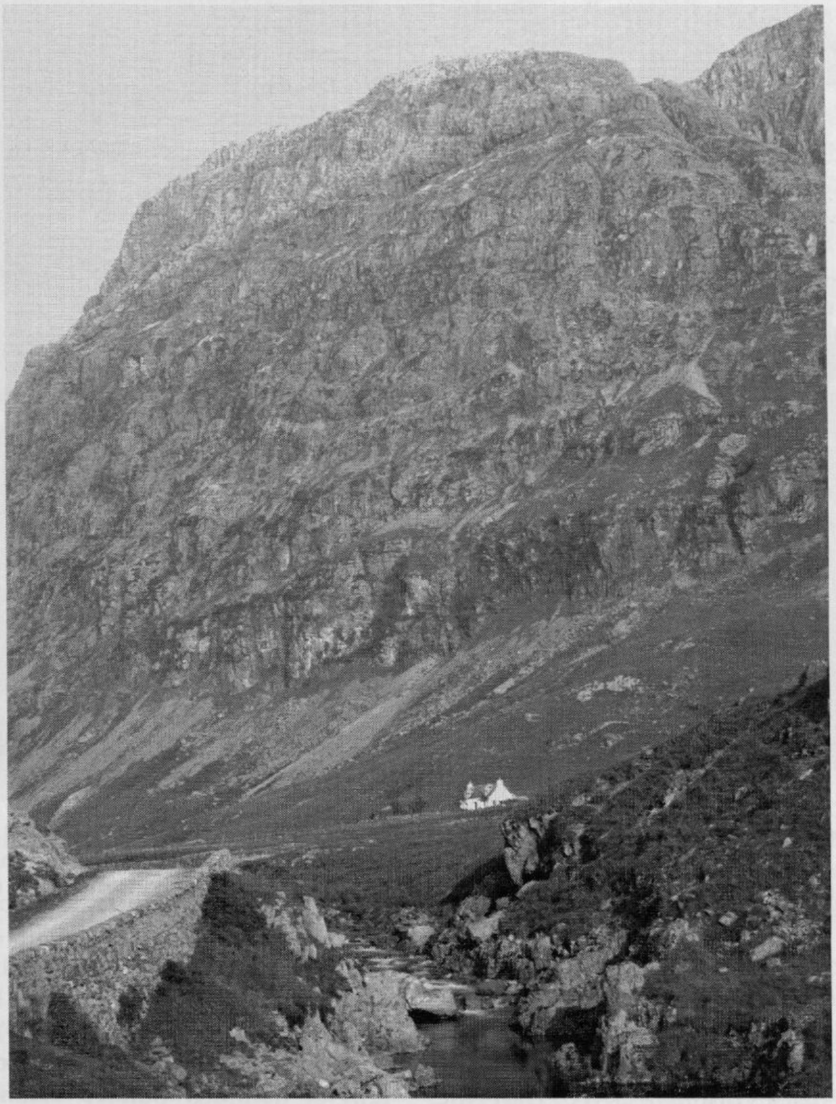

Figure 9.11 The west face of Aonach Dubh, Glen Coe. Scree-covered lower slopes are Leven Schist, which is overlain by intrusive sheets (up to 17) and sedimentary rocks of the Basal Sill Complex (Group 1). The summit region is capped by the thicker rhyolites of Group 2. (Photo: BGS no. B616.)

Group 2 rhyolites, which are described in detail by Moore (1995). A thin phreatomagmatic tuff layer up to 2 m thick and consisting of planar and cross-stratified tuffs with accretionary lapilli is overlain by the Lower Etive Rhyolite, a *c.* 100 m-thick flow-laminated rhyolite with a low aspect ratio (*c.* 1:140). A stratified tuff layer represents the first phase of the eruption, but the bulk of the flow consists of flow-laminated rhyolite, accompanied by a persistent upper autobreccia and a less well-developed lower autobreccia. Overlying this is the Upper Etive Rhyolite (20–30 m thick), a flow-laminated rhyolite with upper and lower autobreccias. This rhyolite also has a low aspect ratio (1:100). The third Group 2 rhyolite is the Upper Glen Coe Ignimbrite which is *c.* 80 m thick here. Roberts (1966a, 1974) called this ignimbrite the upper Group 2 ignimbrite horizon.

Group 3 rocks (collapse breccias and alluvium) overlie the Group 2 rhyolites. Clough *et al.*, (1909) described these as 'agglomerates', but with a perceptive caveat, 'it is possible, indeed, that the deposit is mainly detrital in nature, and not, strictly speaking, a volcanic agglomerate at all'. Later workers (Roberts, 1966a; Taubeneck,

Figure 9.12 Peperite, clearly showing the brecciation of andesitic magma with fine-grained sandstones and shales forming the matrix between the andesite blocks. Beside the 'old road' near Achtriochtan farm, Glen Coe. This particular exposure is no longer visible; it was probably destroyed during construction of the new road, or has been covered by scree. (Photo: BGS no. C1154.)

1967) considered them to be breccias, a conclusion also reached by Moore (1995), who recorded various lithofacies distinguished by clast type; breccias dominated by either Group 1 or Group 2 clasts.

Group 4 rocks crop out around the summits of Stob Coire nan Lochan and Bidean nam Bian, and consist of a number of sheets (flows or sills?) of hornblende andesites approaching 280 m in total thickness (Clough *et al.*, 1909; Bailey, 1960). These rocks contain small phenocrysts of plagioclase and hornblende set within a matrix that is frequently flow-banded. Outcrops of the next group (Group 5 rhyolites) occur far to the SE on the shoulder of Beinn Fhada. According to Roberts (1966a), this is a rhyodacite ignimbrite sheet *c.* 80 m thick, which is notable for its abundance of plagioclase phenocrysts (Clough *et al.*, 1909). The sheet comprises a thin basal zone that contains abundant lithic clasts (rhyolite lava, hornblende andesite, quartzose schist – Clough *et al.*, 1909) succeeded by a welded ignimbrite within which the proportion of flattened pumice fragments increases markedly towards the top of the sheet, which is brecciated (Roberts, 1966a).

The group 6 and 7 rocks are restricted to outcrops on the southern shoulder of Beinn Fhada (Clough *et al.*, 1909). Surprisingly, no detailed account of these rocks has been published since this paper. The Group 6 rocks are well-bedded greenish-grey shales and sandstones that lie upon the eroded upper surface of the Group 5 rhyolites. Clough *et al.* (1909), and Bailey (1960) stated that there is much variation in thickness. The Group 7 rocks are andesites and rhyolites, and Clough *et al.* (1909) recorded rhyolites, hornblende andesites and one 'basic andesite' (basaltic andesite?), and made specific mention of their irregular accumulation. The oldest units crop out to the SE, while the youngest unit (a hornblende andesite containing large plagioclase phenocrysts) caps the southern summit of Beinn Fhada (Clough *et al.*, 1909). Taubeneck (1967) briefly mentioned the presence of an ignimbrite within Group 7, containing abundant 'inclusions of volcanic rocks and of quartzose basement rocks as much as an inch across'.

Interpretation

The palaeosurface developed on rocks of the Leven Schist Formation was heavily eroded prior to the inception of Lower Old Red Sandstone volcanism, and the evidence from sedimentary rocks lying within hollows and channels suggests that there was an active, E–W-running fluvial system. The presence of sandstones and shales suggests that a small sedimentary basin developed, which acted as a trap for finer-grained sediments. The localized development of this basin, and its later (but close) association with the Basal Sill Complex, possibly signifies localized subsidence, which was a precursor to magmatism in the area. (It is relevant to note that similar features are preserved in the neighbouring Ben Nevis cauldron subsidence – see the Ben Nevis and Allt a'Mhuilinn GCR site report.)

The emplacement of the Group 1 basaltic to andesitic sills into wet sediments within the basin resulted in explosive magma-water interactions at sill margins, with peperite development (Moore, 1995). If these sills were fed from a dyke-like body (cf. Francis, 1982), the magma source would have been beneath the area. In addition, most of the sheets are andesitic, and the higher viscosities of andesitic magmas (relative to basalt) would reinforce the argument for a local source. Accordingly, they are probably indigenous to Glen Coe, whereas Clough *et al.* (1909), Bailey (1960), and Roberts (1974) believed them to be outlying members of the Lorn lavas.

The erosional unconformity above the sill complex indicates that there was a substantial period of quiescence after the Group 1 magmatism, and Moore (1995) concluded that an unknown thickness of rocks had been removed. The Group 2 rhyolites mark the onset of the graben-controlled caldera phase of Glencoe volcanism, and they are therefore syncaldera eruptive rocks. Taubeneck (1967) speculated that incremental caldera collapse was intimately associated with Group 2 eruptions – a conclusion confirmed by the detailed mapping of Moore. The first Group 2 volcanic rock, a phreatomagmatic rhyolitic tuff, indicates that this volatile-rich early magma was fragmented even further by interactions with ground, surface or hydrothermal water at the vent. The two rhyolite lavas (Lower and Upper Etive rhyolites) are not typical of rhyolite lava flows. Moore commented on features that suggest surprisingly low viscosities for such high-silica magmas, concluding that (Hawaiian) fountaining at the vent produced a 'lava-like' deposit from a pyroclastic eruption column with a very high effusion rate (possibly with an initial high volatile content lost during degassing at the vent). Hausback (1987) reported similar features from a rhyodacite flow in Mexico, where he concluded that high volatile contents plus high eruption temperatures produced a lava flow varying in thickness from 120 m to 20 m, and of unusually low-viscosity *c.* 10^5 poise (note that 10^9 to 10^{11} poise is normal for rhyodacite magma). Clearly, further work is needed on the eruptive mechanisms of the Etive rhyolites. The pyroclastic origin of the third prominent rhyolite unit – the Upper Glen Coe Ignimbrite – was previously noted by Roberts (1966a, 1974) and Taubeneck (1967).

Graben-controlled caldera collapse was associated with all of the Group 2 rhyolite eruptions, and the presence of sedimentary rocks in eroded upper surfaces of each eruptive unit indicates two important features: that caldera collapse cancelled out any constructional features created by the Group 2 eruptions; and that periods of quiescence between eruptive episodes allowed re-establishment of fluvial systems (Taubeneck, 1967; Moore, 1995; Moore and Kokelaar, 1997, 1998).

The Group 3 clastic deposits record a major phase of fault-scarp collapse and re-establishment of fluvial/lacustrine conditions (Taubeneck, 1967; Roberts, 1974; Moore, 1995; Moore and Kokelaar, 1997, 1998). The origins of the Group 4 andesites overlying the Group 3 rocks are unknown, but their aggregate thickness (*c.* 280 m) indicates a major phase of andesitic magmatism after the two major cycles of syncaldera rhyolitic volcanism (Group 2). These andesites are probably indigenous to Glen Coe, and consequently they record a significant change in the underlying magma system, with less evolved compositions predominating and available for eruption; they could represent the 'dominant volume' magma of Smith (1979). These Group 4 andesites suggest that there was insufficient repose time for the magma system to produce new quantities of silicic magma. The Group 5 crystal-rich rhyodacite ignimbrite marks a return to the explosive eruption of evolved magma. The crystal-rich nature of the rhyodacite is unusual, as the Group 2 rhyolites are markedly crystal-poor. The presence of dark inclusions of more basic magma suggests a role for magma mixing, possibly as a trigger for the rhyodacite eruption. A thorough geochemical study of the rhyolites and andesites from groups 2 to 5 would clarify possible genetic relationships.

Little is known of the rocks of groups 6 and 7, although Taubeneck (1967) concluded that Group 6 rocks record a period of post-subsidence sediment accumulation in a caldera lake. The rhyolites and andesites of Group 7, including an ignimbrite, mark a phase of renewed volcanism in the caldera, with evolved compositions again being available for eruption. Post-Group 7 volcanic and sedimentary rocks, including any syncaldera ignimbrites erupted during the late-stage, cataclysmic caldera-forming (cauldron subsidence) event, have all been removed by erosion.

Conclusions

This extensive GCR site provides superb three-dimensional sections through the calc-alkaline Glencoe volcano, a well-preserved example of cauldron subsidence. Rocks preserved include those forming the ancient land surface (Dalradian metasedimentary rocks), and a graben-controlled caldera fill of volcanic and sedimentary rocks. An unknown thickness of material has been removed by erosion.

After an initial pre-caldera andesite-dominated phase (Group 1), there were two major cycles of syncaldera rhyolitic volcanism and caldera collapse (Group 2), which were followed by major fault-scarp collapse and a lengthy period of quiescence (Group 3). Renewed magmatism (Group 4) resulted in a substantial thickness of andesite sheets being emplaced, before a return to the explosive eruption of rhyodacite magma (Group 5). Sedimentary caldera-lake deposits (Group 6) indicate substantial graben-controlled caldera collapse after the volcanism of groups 4 and 5, while the rhyolites and andesites of Group 7 (the youngest rocks preserved) record further eruptions of evolved magma.

One final point is worthy of emphasis: the rocks preserved here record a consistent pattern of eruptive activity accompanied by incremental, graben-controlled caldera collapse. Subsidence kept pace with intracaldera volcanic and sedimentary fill during the early development of the Glencoe volcano. Late-stage, ring-fracture-controlled caldera collapse (cauldron subsidence) certainly took place, and this was directly responsible for preserving the rocks of groups 1 to 7, but unfortunately, the volcanic products of this late-stage, cataclysmic event have been removed by erosion.

STOB DEARG AND CAM GHLEANN (NN 224 547 AND 246 521)

D. W. McGarvie

Introduction

This site is the most easterly of the five GCR sites representing the Glencoe volcano. Relationships here between the volcanic rocks and the original land surface of Dalradian metasedimentary rocks contrast strongly with those in the west of the volcano, indicating important spatial differences in the early volcanic activity. Sedimentary rocks underlying the volcanic sequence at this site yielded the remains of Early Devonian plants during the initial survey, and spores obtained more recently have suggested a more precise biostratigraphical age.

The site comprises two areas: one NW of the River Etive consisting of the 1022 m-high peak of Stob Dearg (at the NE end of the Buachaille Etive Mor ridge) (Figure 9.13); and another SE of the River Etive, around Cam Ghleann.

Description

This GCR site is dominated by Group 2 rocks (see 'The Glencoe volcano – an introduction to the GCR sites', above), which lie directly on top of Dalradian metasedimentary rocks. The marked absence of Group 1 rocks at this site was commented on by Clough *et al.* (1909), Bailey (1960) and Moore (1995).

The Dalradian metasedimentary rocks are quartzites, quartzo-feldspathic psammites and semipelites, comprising the Eilde Flags and the Eilde Quartzite (Clough *et al.*, 1909). These are commonly brecciated and fragmented.

Clough *et al.* (1909) and Bailey (1960) provided a detailed description of a complex sequence of psammite breccias, conglomerates and well-bedded quartzose sandstones, red laminated sandstones, and shales sandwiched between the metasedimentary rocks and the overlying Group 2 rhyolites near the foot of Stob Dearg (Table 9.4). From a dark shale bed beneath a well-known landmark (the Waterslide slab), remains of plants were collected in 1902 by Peach, Kynaston, and Tait of the Geological Survey, which were subsequently identified by Kidston and Lang (1924) as *Psilophyton* and *Pachytheca*. This provided an Early Devonian age for the sedimentary rocks beneath the volcanic succession. Spore assemblages collected more recently suggest a late early to early late Lochkovian age (Wellman, 1994). Although Hardie (1968) and Roberts (1974) believed that the outcrop from which these plant remains were taken is a detached block disturbed during explosive volcanic activity, they concluded that the block has moved only a short distance from its original location.

Group 2 is especially well developed at this site (Clough *et al.*, 1909; Roberts, 1974; Moore,

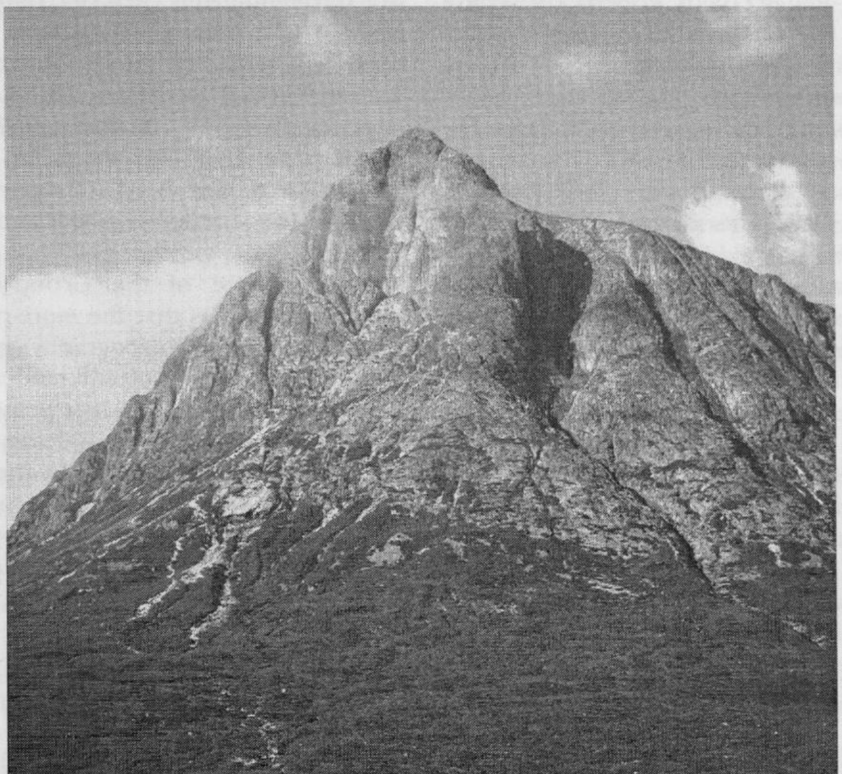

Figure 9.13 The NE face of Stob Dearg, Buachaille Etive Mor, Glen Coe. The lower, scree-covered slopes are of Dalradian metasedimentary 'basement'. The bulk of the mountain consists of rhyolite units (Group 2), with the summit area composed of a mass of intrusive rhyolite. The prominent slab in the lower left centre is the 'Waterslide slab' where fossil plant remains were collected. (Photo: D. Stephenson.)

1995). Using the more detailed subdivisions of Moore (1995), the following Group 2 units are recognized.

Stob Dearg area	*Cam Ghleann area*
Upper Glencoe Ignimbrite (top)	Upper Glencoe Ignimbrite (top)
Lower Glencoe Ignimbrite	Lower Glencoe Ignimbrite
Upper Etive Rhyolite	Upper Etive Rhyolite
Middle Etive Rhyolite	(missing)
Lower Etive Rhyolite	Lower Etive Rhyolite

In addition, Bailey (1960), Roberts (1974) and Moore (1995) report a mass of intrusive rhyolite which forms the summit region of Stob Dearg (Figures 9.13 and 9.14).

Other important lithologies present in the site are as follows (oldest first).

- Phreatomagmatic tuffs that constitute the first eruptive phase of each of the Etive rhyolite eruptions are particularly well developed at this site (note the absence of the Middle Etive Rhyolite and its underlying phreatomagmatic tuff at Cam Ghleann).
- Andesitic (mixed magma) flows and sills that intrude the Glencoe ignimbrites.
- A localized breccia wedge (psammite, quartzite, and semipelite clasts) at Cam Ghleann, which overlies the Lower Glencoe Ignimbrite.
- Group 3 sedimentary rocks (alluvium deposits only at this site).
- Group 4 andesites (Cam Ghleann only).

Interpretation

The quartzites, psammites, and semipelites exposed at this site are from a lower part of the Dalradian succession than the less resistant phyllitic lithologies (Leven Schist) dominant in the west of the volcano (Clough *et al.*, 1909). The overlying sedimentary rocks have been interpreted by Moore (1995) as a locally developed alluvial fan (the Kingshouse Fan), which crops out throughout this GCR site, but is best developed at Stob Dearg. Clasts have been derived from both talus and fluvial sources and the evidence of both clasts and sedimentary structures suggests an input into the area from the east (Taubeneck, 1967; Moore, 1995). Taubeneck also believed that the eastern parts of the pre-caldera land surface were elevated some 600 m higher than the western parts.

The absence of the Group 1 Basal Sill Complex suggests that the more-resistant rocks (plus more rugged topography) of the eastern parts of the putative volcano hindered formation of a sedimentary basin. It is possible that lavas similar to the basalt and andesite sheets of the sill complex were erupted in the east but, as Moore (1995) pointed out, the erosional unconformity seen in the west indicates removal of an unknown thickness of sheets, and the more rugged topography in the eastern part of the vol-

Table 9.4 Sequence of sedimentary rocks sandwiched between the Dalradian metasedimentary rocks and overlying volcanic rocks (from Bailey, 1960). Bed thicknesses are approximate.

Top of sequence

8. Bedded breccia often resembling conglomerate, with fragments of quartzite, micaceous schist, and some felsite – all in a matrix of gritty sandstone.
7. Red shales with cornstones. (3.5 m)
6. Purple shales. (1 m)
5. Greenish and black shales, showing alternations of coarser and more sandy layers with finer graded beds. (3 m)
4. Conglomerate, with angular and subangular boulders of quartzite (Eilde Quartzite?) and quartzose schists (Eilde Flags) in a green sandy matrix. (6 m)
3. Green shales, some red, and irregular beds of conglomerate. (5 m)
2. Fine greenish breccia containing quartzite fragments. (< 0.5 m)
1. Dalradian quartzite, much shattered at the surface.

Bottom of sequence

cano would have hastened their erosion. However, it is equally possible that no early basaltic to andesitic volcanism took place in the east of the volcano.

The dominance of Group 2 rocks, and their extreme development at this site (i.e. substantial thicknesses of individual units and well-developed tuff layers), strongly suggests that they are proximal deposits. Roberts (1974) noted the great thickness of Group 2 rhyolites here, and Moore (1995) suggested that many of the vents for the Group 2 eruptions were located in the central and eastern parts of the volcano, and that they were controlled by the rectilinear system of graben and cross-graben faults (Moore and Kokelaar, 1997, 1998). This was a significant departure from the model of Roberts (1974), who argued that the major rhyolite (ignimbrite) eruptions at Glen Coe were generated at ring fractures. Moore's evidence is convincing, and highlights the need for a re-evaluation of the role and importance of both the ring fracture and the ring intrusion.

Conclusions

The 'basement' of the down-faulted inner block in the east of the Glencoe volcano is a lower part of the Dalradian succession than in the west and comprises more resistant lithologies. Overlying this is an irregular succession of sedimentary rocks varying from shales to coarse conglomerates deposited in an alluvial fan. Fossil remains found in the shales indicate an Early Devonian (Lochkovian) age. A marked downslope to the west seems probable, as is indicated by sedimentary structures and by the provenance of boulders in the conglomerates. The absence of a sill complex within the basal sedimentary succession in the eastern part of the volcano reflects either complete removal by erosion, or a restriction of this early (Group 1) volcanism to the west of the volcano.

Rhyolites that represent the first major eruptive events of the Glencoe volcano (collectively termed Group 2) are extremely well developed at this site, and thickness variations indicate that feeder vents are nearby. Two eruptive cycles are recognized; all eruptive units comprising the largely effusive first cycle (the Etive Rhyolites) are exposed on Stob Dearg, while the two major units of the pyroclastic second cycle (the Glencoe Ignimbrites) crop out throughout the site. In addition, an intrusive mass of rhyolite occupies the upper third of Stob Dearg, while andesitic sills locally intrude the rhyolitic rocks. Overlying alluvial breccias (Group 3), indicate a re-establishment of a river system following the major eruptions, and at Cam Ghleann the succeeding andesites of Group 4 occur.

BUACHAILLE ETIVE BEAG (NN 201 554)

D. W. McGarvie

Introduction

Ignimbrites form distinctive deposits, and record episodes of explosive volcanism and pyroclastic flow generation. They are especially abundant at Glen Coe, and one of the best exposed and most accessible localities is this GCR site. The site consists of the north-eastern summit (Stob nan Cabar – *c.* 800 m) of the NE–SW mountain ridge of Buachaille Etive Beag (Figure 9.14). Here all three of the Glencoe ignimbrites (Group 2) occur together, and consequently the site preserves the complete sequence of events during this cycle of explosive volcanism.

Clough *et al.* (1909) and Bailey (1960) commented on the abundance of fragmental and welded rhyolite units at Stob nan Cabar, and classified them as the uppermost rhyolite members of Group 2. Roberts (1966a) re-examined the Group 2 rhyolites and identified ignimbrites at Stob nan Cabar with an aggregate thickness exceeding 300 m, the maximum thickness achieved by ignimbrites in Glen Coe. He called them the Upper Group 2 ignimbrite horizon, recognized various subdivisions and provided a description of the sequence (Roberts, 1966a, 1974). Following Moore (1995), the ignimbrites at Stob nan Cabar are now termed the Lower, Middle, and Upper Glencoe ignimbrites, and these are overlain by breccias of Group 3 (the Upper Queen's Cairn Breccias).

Description

The lower exposures at the base of Stob nan Cabar are undifferentiated rhyolite and andesite intrusive rocks that underlie the ignimbrites (Roberts, 1974). There are several NE- to NNE-trending dykes (3 cm to 2 m thick) in these lower exposures that show pyroclastic textures, pervasive lamination, and prominent flow structures. As some are very thin (*c.* 3 cm) and others pinch-out, they are probably indigenous to Glen Coe. Although Roberts (1966a) provided a description of the Stob nan Cabar ignimbrite sequence, Moore (1995) has added considerable detail that forms the basis for the following brief description.

1. Lower Glencoe Ignimbrite (*c.* 140 m thick). Oldest unit. Lower *c.* 40 m is a poorly welded, lithic coarse tuff that contains breccia lenses with clasts derived from the Etive rhyolites and quartzites (10–40% of the deposit). Upper *c.* 100 m is a poorly welded lithic coarse tuff grading upwards into a massive strongly welded tuff, with some inclusions of porphyritic andesite displaying ragged margins.
2. Middle Glencoe Ignimbrite (*c.* 20 m thick). Sharp contact with underlying strongly welded tuff. Bulk of deposit is poorly welded lithic coarse tuff containing abundant small fragments derived from the Etive rhyolites.
3. Queen's Cairn Fan (*c.* 10 m thick). Variable sequence of alluvial conglomerates, sandstones and tuffaceous siltstones that infill erosional features cut into the underlying ignimbrites.
4. Lower Queen's Cairn Breccias (*c.* 40 m thick). Angular clasts and blocks of Dalradian metasedimentary rocks (with subordinate andesite).
5. Upper Glencoe Ignimbrite (*c.* 180 m thick). The lower *c.* 80 m is a breccia deposit with a tuffaceous matrix, containing clasts derived mainly from Dalradian metasedimentary rocks. The next *c.* 30 m is a poorly welded lithic tuff, with clasts (Dalradian metasedimentary rocks plus andesite and rhyolite) up to 40 cm diameter, and pumice lapilli (around 10% of the deposit). The next *c.* 60 m is strongly welded lithic-rich tuff (10–20% lithic fragments). Pumice lapilli increase upwards to a maximum of 25%. The final *c.* 10 m comprises poorly welded stratified lithic tuff, with upper beds notably fine grained and well laminated.
6. Upper Queen's Cairn Breccias (*c.* 60 m thick). These are Group 3 rocks, and consist of a sequence of tuffaceous breccias, with clasts derived mainly from Dalradian metasedimentary lithologies (with minor quantities of volcanic clasts).

Interpretation

The *c.* 350 m thickness of ignimbrites at Stob nan Cabar represents the extreme development of the Group 2 Glencoe ignimbrites. Clough *et al.* (1909) mapped the Group 2 rhyolites, and their cross sections (op. cit., plate XXXIII) indicate that they were fully aware of their thickness variations across the volcano. Roberts (1966a, 1974) considered that differential subsidence of the caldera floor in this area had allowed the ignimbrites to pond. Moore (1995) developed this further and demonstrated that collapse had taken place along graben and cross-graben faults, and at the same time showed that caldera subsidence in this area accompanied the eruption of the Upper Glencoe Ignimbrite.

The Glencoe ignimbrites represent the second major cycle of syncaldera rhyolitic volcanism, and the widespread development of pyroclastic flows indicates that activity was generally more explosive than the first cycle (the Etive rhyolites). The following sequence of events was proposed by Moore (1995) and Moore and Kokelaar (1997, 1998). The Lower Glencoe Ignimbrite was produced by a single pyroclastic flow, which was followed by the much smaller Middle Glencoe Ignimbrite (also produced by a single pyroclastic flow). Post-eruption subsidence, a period of quiescence, alluvial fan development, and fluvial activity generated the sedimentary deposits of the Queen's Cairn Fan. The eruption of the Upper Glencoe Ignimbrite was preceded by large-scale foundering of the caldera floor and fault-scarp collapse, producing the Lower Queen's Cairn Breccias. The Upper Glencoe Ignimbrite was produced from a single pyroclastic flow, and grades upwards from a breccia-dominated lower zone through to a poorly welded lithic coarse tuff, which is strongly welded in its upper parts. The upper *c.* 10 m of fine-grained and laminated tuff may represent ash-fall tephra deposited after pyroclastic flow activity had ceased.

Based on relationships at this GCR site, Moore was able to discern a pattern in the lateral thickness variations of the three ignimbrites, and to demonstrate that topographical control on their spatial distribution was exerted by a long-standing, re-activated graben and cross-graben fault system. He also noted that the vents for these ignimbrites must have been nearby. Consequently, the unifying model of Roberts (1974), which invoked the Group 2 ignimbrites having

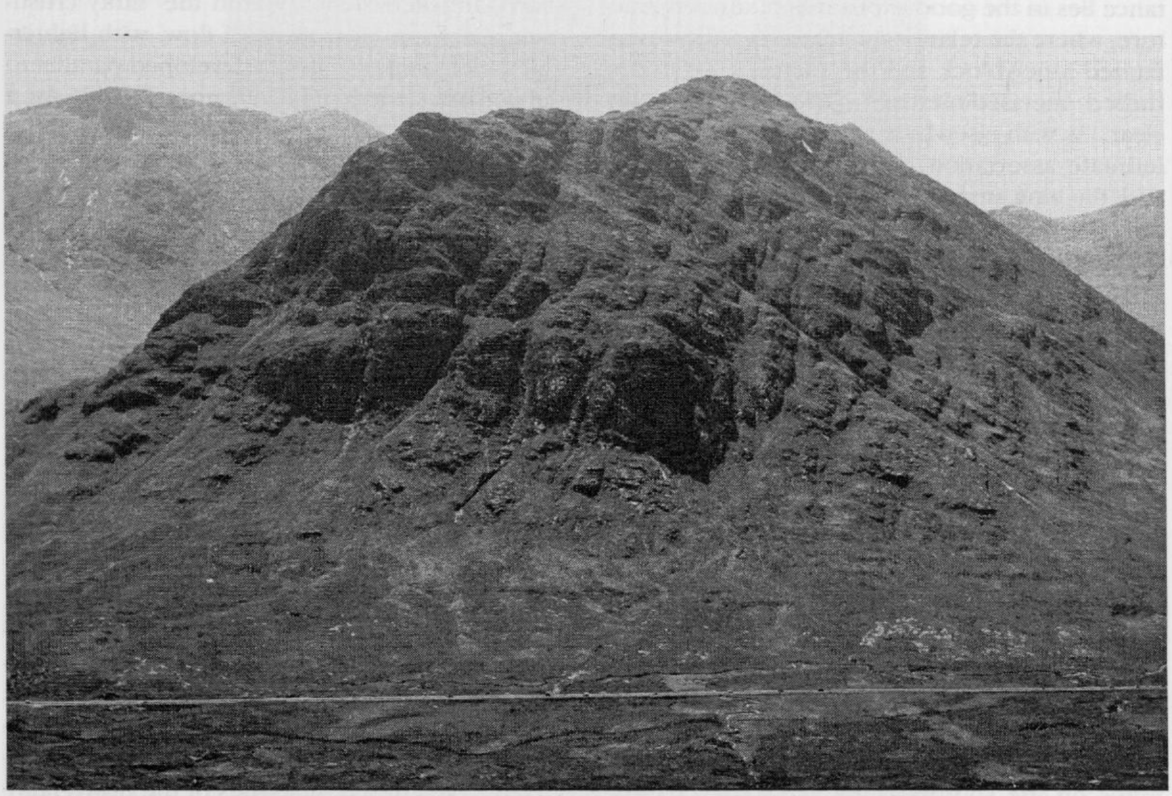

Figure 9.14 Buachaille Etive Beag, Glen Coe from the NE, looking towards Stob nan Cabar from Stob Mhic Mhartuin. (Photo: D.W. McGarvie.)

been vented at the ring fracture, must now be discarded.

Conclusions

At Stob nan Cabar there is an unusual thickness of rhyolitic ignimbrite, a rock type formed during the eruption of evolved magma when pyroclastic (hot, fragmental) flows are generated during explosive volcanic activity. The ignimbrites exposed here reach nearly 350 m in thickness, and within this total thickness three separate units are present, representing three separate phases of pyroclastic flow generation during one major eruptive cycle (the second cycle of rhyolitic eruptions responsible for Group 2 of the Glencoe volcanic succession). Ignimbrites infill depressions and hollows, and their extreme thickness in this area indicates substantial localized graben-controlled subsidence of the caldera floor accompanying the eruptions. The presence of sedimentary rocks intercalated between the second and third ignimbrites indicates a period of quiescence between eruptions.

STOB MHIC MHARTUIN (NN 208 576)

D. W. McGarvie

Introduction

The Glencoe volcano is of international importance because of the cauldron subsidence, which has preserved a sequence of Old Red Sandstone volcanic rocks within a downfaulted block, encircled by a ring fracture system and an irregular ring intrusion (see 'The Glencoe volcano – an introduction to the GCR sites', above). The ring fracture is the subject of this GCR site, which occupies the summit and surrounding area of Stob Mhic Mhartuin (706 m). Its importance lies in the good exposures of the ring fracture, where the relationships between the down-faulted inner block and the surrounding undisturbed metasedimentary rocks are especially clear. As with elsewhere at Glen Coe, there is an intimate association between the ring fracture and the ring intrusion. An unusual feature of this site is that there are two ring fractures, of different ages.

Description

Stob Mhic Mhartuin is regarded as the type locality for the ring fracture (Bailey, 1960), although it is in fact quite atypical in some aspects (Taubeneck, 1967). Clough *et al.* (1909), Bailey (1960), and Roberts (1966b) all provided detailed descriptions of the ring fracture and some of the key relationships are illustrated in Figure 9.16 (after Roberts, 1966b). Here it appears in two branches and contact metamorphic relationships led Clough *et al.* (1909) and Roberts (1966b) to conclude that the southern branch is the younger. This description concentrates on the southern (younger) ring fracture (Figure 9.15).

Immediately north of the ring fracture lies the ring intrusion, here a porphyritic microdiorite, which forms a near-continuous (but irregular) ring around the down-faulted inner block (Figure 9.17). The ring intrusion typically has a smooth and chilled inner contact against the ring fracture, which contrasts strongly with its irregular and variably chilled contact against the outlying metasedimentary rocks (Roberts, 1966b). Clough *et al.* (1909) placed great emphasis on a fine-grained lithology called 'flinty crush-rock' (described later), which lies at the smooth inner contact between the ring intrusion and the ring fracture (Figures 9.15 and 9.16). However, Roberts (1966b) reported that 'flinty crush-rock' also occurs at the outer, irregular contact, and argued that it is just a finer-grained facies of the ring intrusion.

The ring fracture strikes approximately NW–SE at this locality and dips outwards at 60° to the NE. The ring intrusion chills against the ring fracture, and there is a 2 cm-wide zone of dark, vitreous rock ('flinty crush-rock') between the chilled ring intrusion and the crushed metasedimentary rocks of the down-faulted inner block. The contact is surprisingly straight, sharp, and persistent. Within the 'flinty crush-rock' there are clear signs of flow, with lighter- and darker-coloured layers developed parallel to the contact (individual layers are traceable for a few metres), plus there are oval structures (long axes parallel to the contact) suggesting flow either down-dip or up-dip. There is a fairly sharp contact between the 'flinty crush-rock' and the adjacent lithology to the SW, which is a strongly flow-banded microbreccia with elongate and rounded fragments (smaller than 1 cm) set in a matrix of the 'flinty crush-rock'. At the contact with the 'flinty crush-rock' some whitish zones are present in the microbreccia, and in places the 'flinty crush-rock' appears to either cross-cut these zones or to have incorporated remnants of them within it. To the SW the flow-banded microbreccia grades (over a distance of 1 cm) into a zone of whitish rock that consists of crushed fragments of quartzite (Clough *et al.*, 1909). Within this crush zone there are two distinct lithologies: one adjacent to the flow-banded microbreccia, which is a mix of light and dark components, and one to the SW, which is characteristically white in colour. To the SW are relatively undisturbed quartzites of the down-faulted inner block with vertical bedding and NNW strike. However, within 40 m of the ring fracture there are crush zones (up to 10 cm wide) that have the same strike and dip as the ring fracture, and that are more abundant nearer to the ring fracture.

Interpretation

Roberts (1974) presented a unifying model of explosive eruptions at the ring fracture producing the ignimbrites that are now preserved within the down-faulted block. However, Moore (1995) has demonstrated that piecemeal subsidence associated with Group 2 ignimbrite eruptions took place within an early graben-controlled caldera, and not at the ring fracture, thus invalidating the model of Roberts. The cataclysmic event that led to late-stage cauldron subsidence (i.e. ring fracture-controlled caldera formation), contrasts with the earlier graben-controlled volcanism and caldera collapse. The ring intrusion probably represents a syncaldera, subvolcanic, non-erupted magma that was associated with cauldron subsidence on the encircling ring fracture(s).

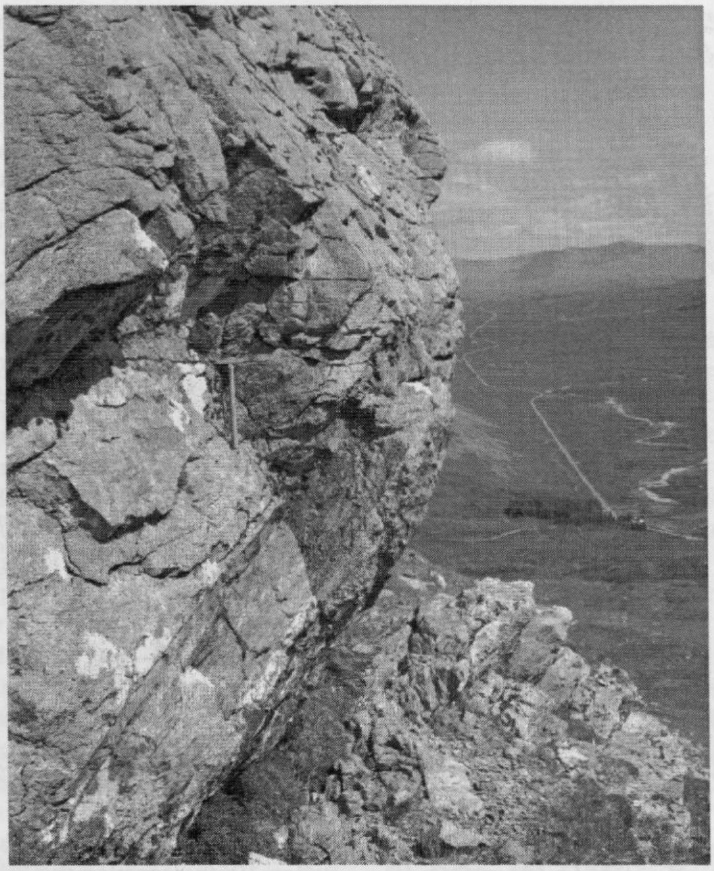

Figure 9.15 The outward-dipping Glencoe ring fracture at Stob Mhic Mhartuin (down-faulted block on the right). The prominent dark band running up to the right is the 'flinty crush-rock', and above it (to its left) is the ring intrusion, here a porphyritic microdiorite, which is chilled at the contact. Between the 'flinty crush-rock' and the low ground on the right (Dalradian quartzites within the downfaulted block) are crushed and brecciated quartzites (see Figure 9.16). The outward-dipping orientation of the contact is probably due to rotation accompanying collapse of the downfaulted block. (Photo: BGS no. D1562.)

While there is good evidence for major subsidence of a down-faulted inner block along encircling ring fractures at Glen Coe (summarized by Clough *et al.*, 1909 and Bailey, 1960), there is uncertainty regarding the magnitude of the subsidence. Bailey (1960), Taubeneck (1967), and Roberts (1974) all placed considerable emphasis on the presence of sedimentary rocks intercalated throughout the volcanic pile, and concluded that episodic subsidence kept pace with the eruption of syncaldera volcanic rocks. Moore (1995) agreed with this conclusion, adding that the subsidence was graben-controlled. Furthermore, Moore has shown that the Group 2 ignimbrites were erupted from vents in the central area of the volcano, whilst Garnham (1988) found no geochemical correlation between the ring intrusion and volcanic rocks of the down-faulted inner block. Thus, any syncaldera volcanic rocks that accompanied *en bloc* subsidence of the down-faulted inner block have since been removed by erosion. If a major eruption accompanied cataclysmic caldera collapse (i.e. cauldron subsidence) – and this would be wholly consistent with ring-fracture-controlled caldera formation elsewhere (see Smith and Bailey, 1968; Smith, 1979) – the ring intrusion could be the remnants of a vent which gave rise to eruptions of ignimbrite.

At the ring fracture itself, subsidence was accompanied by comminution and crushing of the country rocks of the down-faulted inner block. There is a clear progression from crushed country rock quartzite in contact with undis-

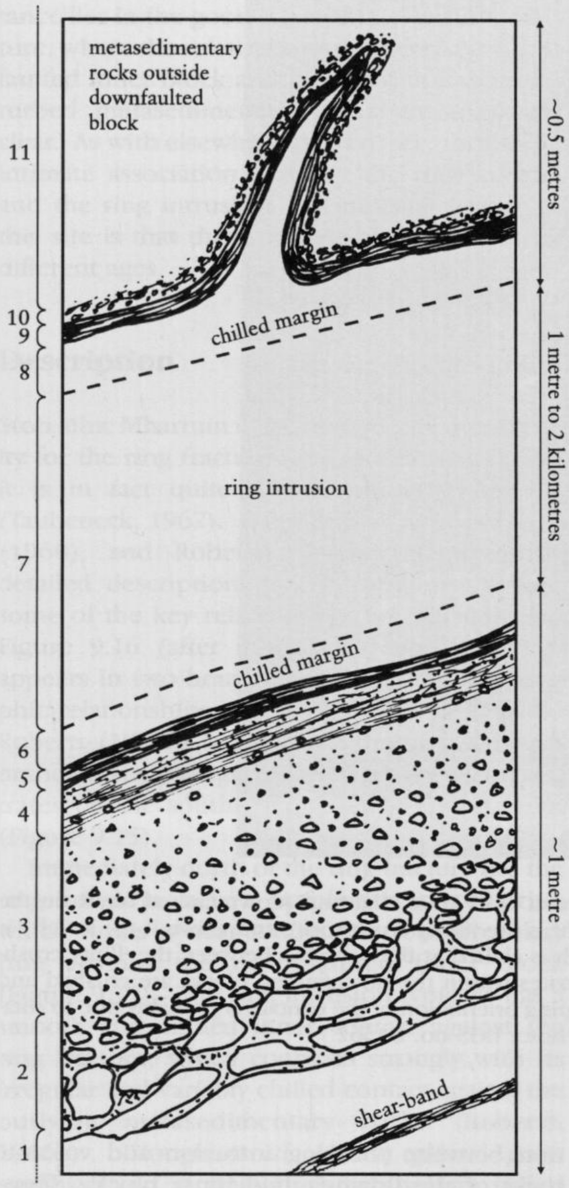

Figure 9.16 Sketch (note variable scale) showing relationships in the Stob Mhic Mhartuin area between the downfaulted block, the ring intrusion, and the undisturbed metasedimentary rocks outside. Note the broad symmetry that is present, with 7 (ring intrusion) flanked by chilled margins (6 and 8), which are in turn flanked by 'flinty crush-rock' (5 and 9) – all of which probably constitute an ancient vent system. The 'flinty crush-rock' is flanked by a complex series of microbreccias to the west (2, 3 and 4), and by a much simpler microbreccia to the east (10), and these are themselves flanked by unbrecciated Dalradian metasedimentary rocks (1 – within the downfaulted block; and 11 – outside the downfaulted block). After Roberts (1966b), and Garnham (1988).
Key: 1, Bedded quartzites within downfaulted block; 2, Quartzites cut by veinlets of granulated quartzite; 3, Quartzite microbreccia; 4, Banded quartzite microbreccia with matrix of 'flinty crush-rock'; 5, 'Flinty crush-rock' (note sharp and straight contact with 6); 6, Chilled margin of ring intrusion; 7, Ring intrusion; 8, Chilled margin of ring intrusion; 9, 'Flinty crush-rock' (note sharp but irregular contact with 8); 10, Quartzite microbreccia; 11, Undisturbed Dalradian metasedimentary rocks outside the downfaulted block.

turbed vertically bedded quartzites of the downfaulted block, through to a bedded microbreccia incorporating progressively lesser amounts of crushed quartzite, through to the dark 'flinty crush-rock'. The incorporation of crushed quartzite into the 'flinty crush-rock' suggests that the 'flinty crush-rock' is younger. Roberts (1966b) presented convincing evidence that the 'flinty crush-rock' is simply a rapidly chilled variant of the ring intrusion, and this suggests that magmatic activity either accompanied or post-dated down-faulting.

The original workers (Clough *et al.*, 1909; Bailey, 1960) regarded the 'flinty crush-rock' as a pseudotachylite (a melt produced by extreme friction). This interpretation was questioned by Reynolds (1956), Roberts (1966b), and Taubeneck (1967), who all proposed a magmatic origin. The veins and tongues of 'flinty crush-rock' that occur away from the ring fracture (Taubeneck, 1967) further support a magmatic origin. Clough *et al.* (1909) did comment on these offshoots of the 'flinty crush-rock', but attributed them to injection of the still-fluid pseudotachylite away from its source. It is significant that Roberts (1966b) also found 'flinty crush-rock' at the outer (irregular) contact, and concluded that the 'flinty crush-rock' is simply a marginal facies of the ring intrusion. Reynolds (1956), Roberts (1966b) and Taubeneck (1967) all regarded the 'flinty crush-rock' as an intrusive tuff. Recent work at Ben Nevis, where there is also 'flinty crush-rock' (Bailey and Maufe, 1916), has further strengthened the case for a magmatic origin. Burt and Brown (1997) concluded that the Ben Nevis 'flinty crush-rock' is an intrusive tuff, and that it represents the remnants of a vent which probably encircled the Ben Nevis volcano (see the Ben Nevis and Allt a'Mhuilinn GCR site report).

The presence of two separate ring fractures, of different ages, suggests two periods of subsidence, although Taubeneck (1967) has questioned this interpretation. The older ring fracture is not found encircling the entire down-faulted block, and its significance is therefore uncertain.

The ring fractures are outward-dipping at this locality, which is atypical. Both Taubeneck (1967) and Roberts (1974) demonstrated that the ring fractures are inward-dipping or vertical at the vast majority of localities, implying that the down-faulted inner block has the shape of an upward-opening cone. At calc-alkaline volcanic centres, major caldera collapse involving chamber roof collapse along concentric, inward-dipping ring fractures (cf. cauldron subsidence) invariably triggers the eruption of substantial volumes of ignimbrite (Druitt and Sparks, 1984). By analogy with caldera complexes elsewhere, it is likely that at least one such late-stage cataclysmic event took place at Glen Coe. Thus Roberts (1974) was partly correct in concluding that there had been a major ring fracture-controlled caldera event at Glen Coe. He did, however, misinterpret the role of the Group 2 ignimbrites, which were erupted during an earlier phase of small-scale, graben-controlled caldera formation, and not during late-stage cauldron subsidence (Moore, 1995).

Conclusions

Rocks exposed around the summit of Stob Mhic Mhartuin in Glen Coe preserve features developed during late-stage cauldron subsidence (cf. ring fracture-controlled caldera collapse), when a down-faulted inner block sank. Without this subsidence the volcanic rocks that form the rugged topography of Glen Coe would not have been preserved. The ring fracture, which separates the down-faulted inner block from the undisturbed rocks outside, is well exposed. By analogy with volcanic centres elsewhere, major subsidence of the down-faulted inner block along concentric, inward-dipping ring fractures, led to cataclysmic eruption of ignimbrites, much of which would have been deposited within the subsiding caldera. Subsequent erosion has removed these deposits, but the ring intrusion that partly encircles the ring fracture is probably the remnants of a concentric vent.

LOCH ACHTRIOCHTAN (NN 132 557 AND 140 575)

D. W. McGarvie

Introduction

This GCR site exhibits two contrasting topographic expressions of the ring fracture that encircles the down-faulted inner block of the Glencoe cauldron subsidence (Figure 9.17), together with good exposures of the metasedimentary rocks that underlie the volcanic rocks. Exposures within the site also reveal marginal tilting of rocks of the inner block immediately adjacent to the ring fracture, demonstrating that the subsidence was accompanied by drag.

The site comprises two areas: one to the north of the River Coe, extending from the banks of the river up to the western end of the Aonach Eagach ridge (Figure 9.18); and a second area to the south of the River Coe that includes the mountain spur of An t-Sron and the west side of Coire nam Beitheach (Figure 9.9).

Description

Rock types

This site is dominated by Group 1 rocks and the

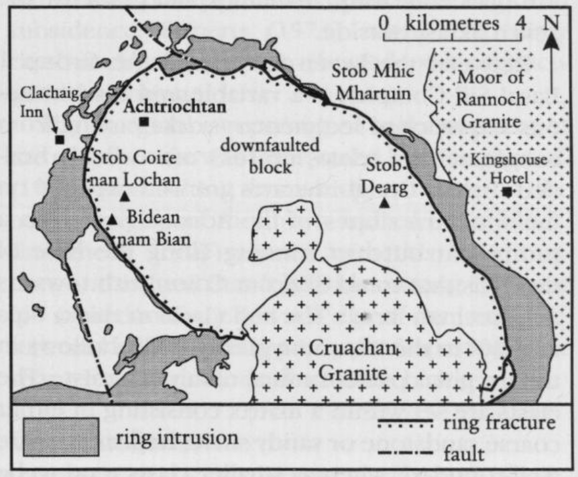

Figure 9.17 Sketch showing the ring fracture and ring intrusion system around Glen Coe. Relationships are less clear in the south where there are difficulties distinguishing the ring intrusion from neighbouring intrusions. Minor outcrops of the ring intrusion (which are numerous) have been omitted for clarity. Redrawn after Clough *et al.* (1909), Roberts (1974) and Garnham (1988).

underlying Dalradian metasedimentary rocks (Leven Schist). Outcrops of groups 2 and 3 occur high on the shoulders of Stob Coire nan Lochan and Stob Coire nam Beith.

The metasedimentary rocks that surround Glen Coe, and that form part of the down-faulted inner block, belong to the Grampian and Appin groups of the Dalradian Supergroup (Table 9.5). In Glen Coe the metasedimentary stratigraphy is complicated by the presence of two ductile slides or lags, the Ballachulish Slide and the Sgurr a'Choise Slide. This has created the structural sequence which is found in the River Coe just west of the Loch Achtriochtan GCR site and is as follows.

Leven Schist
Ballachulish Limestone
Sgurr a'Choise Slide
Ballachulish Slate
Ballachulish Slide
Leven Schist
Glencoe Quartzite

At this site the Leven Schist (a 'phyllite') is predominant, and forms a roughly triangular outcrop within the ring fracture. Clough *et al.* (1909) and Bailey (1960) noted that the low metamorphic grade of the Leven Schist within the down-faulted block contrasts with the higher (i.e. garnet-bearing) metamorphic grade of the Leven Schist outside.

Between the Leven Schist and the Group 1 Basal Sill Complex is a variable and discontinuous sequence of sedimentary rocks varying from conglomerates (clasts up to 3 m) to finely bedded shales. Conglomerates are well exposed on the southern slopes of the Aonach Eagach in a prominent outcrop running along the base of the cliffs that trend SE from Coire Leith towards Achtriochtan farm. The bed (1–20 m thick) dips at *c.* 30° to the SE, and typically infills hollows in the irregular palaeosurface of Leven Schist. The clasts are set within a matrix consisting of either coarse sandstone or sandy shale; larger clasts are well-rounded, whereas smaller clasts tend to be more subangular (Clough *et al.*, 1909; Bailey 1960). The dominant clast type is quartzite, although minor schist, andesite, granite, quartz porphyry, and kentallenite are reported by Bailey (1960).

The Leven Schist outcrop forms fairly subdued topography, in contrast to the more-resistant rocks of the sill complex. Consequently, the rocks of the sill complex form prominent crags that enable its base to be traced with ease throughout the site. On the south side of the River Coe, sheets of the sill complex dip at approximately 15° to the SE.

The ring fracture

South of the River Coe is a striking (and rather atypical) topographical expression of the ring fracture. Much of the impressive and deeply incised gully known as The Chasm of An t-Sron follows the ring fracture, which passes just east of the summit of An t-Sron where it appears as a distinctive notch (Figure 9.9). On the southern slopes of An t-Sron the ring fracture forms a narrow (but pronounced) gully. The subdued topographical expression of the ring fracture just south of the River Coe, and its continuation north of the River Coe up to the summit of the Aonach Eagach ridge, is more typical (Figure 9.18). The line of the ring fracture over such terrain is not obvious from a distance, but it can be traced with ease when walking along the contact. Within this site the ring fracture changes direction abruptly: the strike is almost N–S from An t-Sron north to the River Coe, whereas it strikes NE to the north of the River Coe.

On the slopes of An t-Sron, south of the River Coe, the down-faulted rocks in contact with the ring fracture are Leven Schist up to the 350 m contour, with Group 1 rocks at higher elevations. Throughout the site, the ring fracture dips between 65° and 85° inwards (i.e. towards the centre of the down-faulted inner block), and flinty crush-rock (see the Stob Mhic Mhartuinn GCR site report) is commonly found at the contact between the ring intrusion and the ring fracture.

There is abundant field evidence of marginal steepening of rocks of the down-faulted inner block immediately adjacent to the ring fracture. For example, the primary foliation of the Leven Schist at An t-Sron increases from *c.* 35° some 20 m away from the ring fracture to *c.* 70° immediately adjacent to it. This marginal steepening is observed both in the metasedimentary rocks and in Group 1 rocks adjacent to the ring fracture.

The ring intrusion

At this site the ring intrusion is present outside

Table 9.5 Metasedimentary rocks found in the Glen Coe area.

Group	Subgroup	Formation
Appin	Ballachulish	Appin Quartzite
		Ballachulish Slate
		Ballachulish Limestone
		Leven Schist
	Lochaber	Glencoe Quartzite
Grampian	–	Eilde Flags

the ring fracture, except where it is absent for short stretches north of the River Coe and at the summit of the Aonach Eagach ridge (Clough *et al.*, 1909). At An t-Sron, the ring intrusion has its greatest development anywhere in Glen Coe and forms a large intrusive mass that extends almost 2 km from the ring fracture (Clough *et al.*, 1909). Here, there is an abundance of accidental fragments, especially quartzite, in the ring intrusion. Most of the quartzite fragments are angular to subangular, and they vary from white to red in colour. The provenance of these fragments is unknown, but precise classification would clarify the emplacement mechanism of the ring intrusion.

Interpretation

The Basal Sill Complex (Group 1) is well developed at this site and at the adjacent Bidean nam Bian GCR site (where it is discussed in detail), in strong contrast with its absence from the eastern parts of Glen Coe (see the Stob Dearg and Cam Ghleann GCR site report). This suggests that the sedimentary basin intruded by the sills of the sill complex was restricted to the western part of Glen Coe and may have developed due to precursory subsidence related to Group 1 magmatism.

Clough *et al.* (1909) and Bailey (1960) interpreted the presence of garnet in the Leven Schist outside the down-faulted inner block as indicating a higher metamorphic grade than the non-garnet-bearing rocks of the inner block. Cauldron subsidence then brought rocks with similar lithologies yet contrasting metamorphic grade into juxtaposition. However, it is now known that subtle compositional differences can have a marked effect on index mineral development in metasedimentary rocks (e.g. Yardley, 1989). Consequently, it would be necessary to confirm that the Leven Schist lithologies in juxtaposition are compositionally identical before placing too much emphasis on this original interpretation.

The abrupt change in the strike of the ring fracture at this site was noted by Clough *et al.* (1909) and Bailey (1960). They mapped several persistent N–S-orientated shatter belts throughout Glen Coe (two are exposed on the south slopes of the Aonach Eagach ridge), and conjectured that the prominent N–S strike of the ring fracture at An t-Sron may coincide with one of these. Disruption of the ring intrusion at An t-Sron may also relate to this shattering. The shatter belts apparently pre-date cauldron subsidence and the intrusion of the Etive dyke swarm (Clough *et al.*, 1909), yet there is evidence that the shatter belts were also active after cauldron subsidence; Roberts (1974) noted that 'flinty crush-rock' at An t-Sron showed post-emplacement fracturing.

The marginal steepening of rocks adjacent to the ring fracture was interpreted by Clough *et al.* (1909) as resulting from frictional drag on the outer margins of the down-faulted inner block. Taubeneck (1967) agreed with this interpretation, and argued that it provides strong evidence for a predominant inward dip of the ring fracture and consequently an upward opening cone shape for the down-faulted inner block.

Conclusions

Outcrops at this site reveal spectacular features that accompanied late-stage cauldron subsidence within the Glencoe volcano. Metasedimentary rocks that formed the eroded landscape before volcanic activity began are preserved in the down-faulted inner block. The ring fracture that separates the down-faulted inner block from the undisturbed metamorphic

Figure 9.18 View across Loch Achtriochtan, Glen Coe towards the Aonach Eagach ridge on the skyline. The ring fracture enters the left edge of the photograph about halfway up and runs towards the low point of the ridge at its extreme left. This subdued expression of the ring fracture is typical, and contrasts strongly with that shown in Figure 9.9. The distinctive cliffs running down to the right are Group 1 rocks (Basal Sill Complex), which overlie Leven Schist (Dalradian basement). (Photo: BGS no. B624.)

rocks outside is also well exposed and, in the prominent gully of An t-Sron, it has a particularly impressive topographical expression. While the down-faulted inner block was subsiding, magma rose from depth and intruded the rocks outside the ring fracture. This magma is known as the ring intrusion, which at this site has its most extreme development in the mountain of An t-Sron (where it extends up to 2 km from the ring fracture).

CRAWTON BAY (NO 880 797)

R. A. Smith

Introduction

These coastal exposures are the type locality for the Crawton Volcanic Formation, the youngest formation in the Crawton Group which comprises part of the Lower Old Red Sandstone succession in the Crawton Basin, a precursor to the Strathmore Basin (Figure 9.2). The formation consists of olivine-bearing basalts and basaltic andesites and interbedded conglomerates of late Silurian to Early Devonian age. The inter-relationships between the lava flows and intercalated sedimentary rocks of 'Highland origin' have been recorded from this vicinity since Geikie (1897). Subsequently Campbell (1913), Trewin (1987), Carroll (1994) and MacGregor (1996) have described the locality in detail. Of the four lava flows present in Crawton Bay (Figure 9.19), the lower three contain characteristic large, flow-orientated plagioclase phenocrysts (the 'Crawton type' of Campbell, 1913), whereas the uppermost one is aphyric. The distinctive 'Crawton type' lavas have been traced inland around the hinge of the Strathmore Syncline (Haughton, 1988). Some of the lavas have been analysed as part of a geochemical study of the British Lower Old Red Sandstone lavas (Thirlwall, 1979).

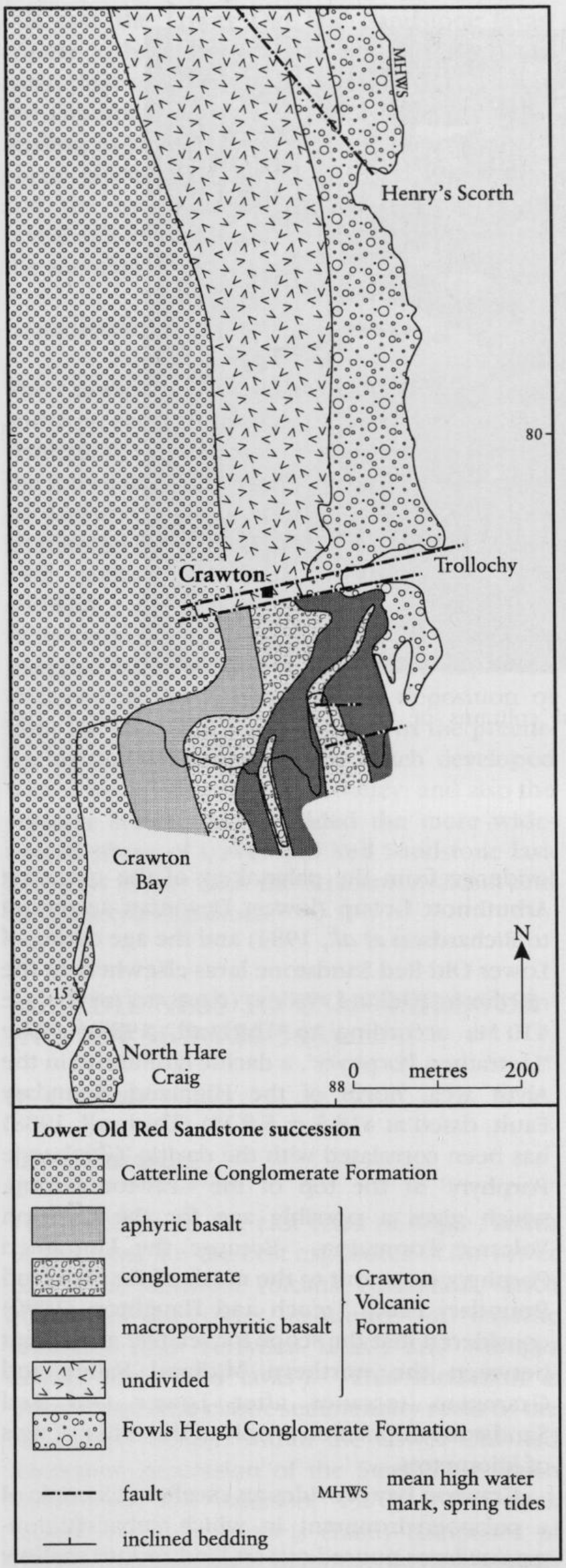

Figure 9.19 Map of the Crawton Bay Volcanic Formation at Crawton Bay.

Description

Carroll (1994) estimated the Crawton Volcanic Formation to be 70 m thick. At Crawton Bay the rocks dip at about 13° to the WSW within the hinge zone of the Strathmore Syncline and are cut by minor normal faults that trend ENE. The parallel alignment of tabular feldspar phenocrysts up to 25 mm in length, gives the macroporphyritic basaltic andesites a platy structure. These flows generally have slaggy upper and lower surfaces. A columnar-jointed central portion commonly has potholes in the centres of the hexagonal columns as the rock close to the cooling joints is more resistant to wave erosion (Figure 9.20).

The base of the lowest flow, exposed near Trollochy (8805 7970), is more vesicular than the main part of the flow and contains disorientated feldspar phenocrysts. Lenses of laminated sandstone and mudstone underlying this flow have been disrupted in places and are baked by the lava (Trewin, 1987). The flow contains large amygdales filled with chalcedony, clear quartz, amethyst and calcite (MacGregor, 1996).

The second and third flows are separated by a few centimetres of sedimentary rock; the top of the second flow is marked by thin, impersistent red mudstones and blocks of altered lava, the reddening being due to a period of subaerial weathering (Trewin, 1987, fig. 1). Both the flows show a well-developed flow orientation of the feldspar laths. The top of the third flow is irregular, and in places the slaggy top was eroded prior to the deposition of the overlying conglomerate in the potholed surface.

The uppermost flow is a purplish massive basalt with scattered vesicles, which are locally over 10 cm in diameter. The vesicles are generally filled with calcite and quartz, but brick red stilbite is also recorded (Trewin, 1987).

Thick interbeds of clast-supported or matrix-supported conglomerate resting upon irregular eroded surfaces of lava are good evidence of penecontemporaneous erosion. These conglomerates consist of well-rounded pebbles of andesitic lava, psammite and quartzite with lesser amounts of metabasalt and greywacke within a matrix of poorly sorted volcaniclastic coarse-grained sandstone. The coarse fraction is of broadly 'Highland' provenance (i.e. Highland Border Complex and probably some Dalradian) although there is a component of locally derived lava.

Figure 9.20 Differential weathering in hexagonal columns of Crawton type basalt, Crawton Bay. (Photo: BGS no. D2454.)

Interpretation

Both types of lava present in the formation contain microphenocrysts of olivine and augite, with the 'Crawton type' also having megacrysts of plagioclase. The few available analyses have SiO_2 in the range 51–53% spanning the basalt/basaltic andesite division (Thirlwall, 1979), and they generally have high K_2O and related elements, making them shoshonitic *sensu* Le Maitre (1989). They are olivine-hypersthene normative, with moderately high alumina (16%), but the one analysed sample of 'Crawton type' shows substantial iron enrichment and hence has tholeiitic tendencies. The variation trends in trace elements may be accounted for by fractional crystallization of the phenocryst phases olivine, plagioclase and clinopyroxene, although some minor opaque oxide may have been involved.

The Crawton Volcanic Formation contains some of the oldest lava flows exposed within the Lower Old Red Sandstone in the northern Midland Valley, and Carroll (1994) considered the formation to be uppermost Silurian in age. This conclusion was reached by combining the evidence from the palynology of the overlying Arbuthnott Group (lowest Devonian according to Richardson *et al.*, 1984) and the age dating of Lower Old Red Sandstone lavas elsewhere in the northern Midland Valley (close to or before 410 Ma according to Thirlwall, 1988). The 'Lintrathen Porphyry', a dacitic ignimbrite in the Alyth area, north of the Highland Boundary Fault, dated at 415.5 ± 5.8 Ma (Thirlwall, 1988) has been correlated with the dacitic 'Glenbervie Porphyry' at the top of the Crawton Group, which gives a possible age for the Crawton Volcanic Formation. Because the Lintrathen Porphyry crops out to the north of the Highland Boundary Fault, Trench and Haughton (1990) considered that the scope for relative movement between the northern Midland Valley and Grampian terranes after Lower Old Red Sandstone deposition is only of the order of tens of kilometres.

Crawton Bay provides an excellent example of a palaeoenvironment in which subaerial/non-marine lavas poured out on land or into shallow water, cooled, cracked and became partially eroded, before being covered by clastic sediment mainly derived from an exotic source. In this case the Lower Old Red Sandstone lavas appear to have accumulated in a subsiding rift basin close to the Highland Boundary Fault, with the Grampian Terrane to the NW of the fault feeding in coarse clastic detritus. Further geochemical studies and age dating of both the lavas and the interbedded 'Highland' clasts could reveal details of the evolution and provenance of the succession.

Conclusions

The Crawton Bay GCR site is the best exposed and type section through the Crawton Volcanic Formation, which forms a significant marker at the top of the Crawton Group. These intercalated Lower Old Red Sandstone lavas and conglomerates have been studied since the end of 19th century because of the fine exposures showing the stratigraphical relationship between volcanic and sedimentary rocks in a marginal rifted basin. They provide important evidence of the environment of deposition of both the lavas and the sediments in the precursor to the Strathmore Basin, which developed within the northern Midland Valley; and also the volcanic setting that heralded the more widespread phase of Lower Old Red Sandstone lava eruption within both the Strathmore Basin and the adjacent Highlands.

SCURDIE NESS TO USAN HARBOUR (NO 734 567–726 545)

R. A. Smith

Introduction

The outcrops on the east coast of Angus, south of Montrose are the best exposures of the lower part of the Montrose Volcanic Formation, which comprises an older sequence of basaltic andesites (the 'Ferryden lavas') and younger basalts (the 'Usan lavas'). This formation is intercalated with clastic sedimentary rocks of the Arbuthnott Group, within the Lower Old Red Sandstone succession of the Strathmore Basin (Armstrong and Paterson, 1970). The thick sequence of lava flows is chiefly composed of olivine basalts and orthopyroxene-feldspar-phyric andesites with few intercalated conglomerates. Structures within the flows and their relationships to penecontemporaneous sedimentary rocks are well exhibited.

This excellent section was first described by Geikie (1897) and later in more detail by Jowett (1913) and Robson (1948). Pillows within the Usan lavas were described as the best examples Jowett had seen along this coast. Heddle (1901) recorded that calcite, chalcedony, agate and chloritic minerals occur within the amygdales. Some of the lavas within this section have been analysed as part of a petrochemical study of the British Lower Old Red Sandstone lavas (Thirlwall, 1979).

Description

The 'Ferryden lavas' are exposed at the north end of the section (733 567) around Scurdie Ness ('scurdie' is the local term for the lavas), and farther south along the coast (732 564) they are faulted against the younger 'Usan lavas' (Figure 9.21). The trace of a large open ENE-trending anticline, the Ochil-Sidlaw Anticline, transects Scurdie Ness, so that the section southwards along the coast passes from the oldest exposed lavas of the Montrose Volcanic Formation, up through the younger flows. The dip on the southern limb of the anticline is about 10° to the SSE. The Montrose Volcanic Formation in this area is estimated to be about 200 m thick with the lava pile thinning out to the NE and SW.

The Ferryden lavas around Scurdie Ness nearly all contain conspicuous feldspar phenocrysts. These lavas were termed enstatite-olivine basalts by Jowett (1913) and were classified as andesites by Robson (1948). Although the lavas are mainly dark-grey in colour, they locally weather greenish, purple or brownish-red. The flows rarely exceed 3 m in thickness and the base of each is irregular with a flinty, chilled zone. In places, the chilled lavas appear to have formed pillow shapes. The coarser-grained centre of the flow is capped by a purplish weathered slaggy, amygdaloidal top, which is commonly fissured. The amygdales and cavities at Scurdie Ness contain green chloritic infill and agates of various sizes. Veins of chalcedony and gypsum are also present. Lenses of hard, green or reddish-brown, fine-grained sandstone have infilled the fissures from an overlying bed. Subsequent lava flows have incorporated and disturbed the fine-grained, slightly calcareous sandstone not only baking it but causing it to buckle, break up and

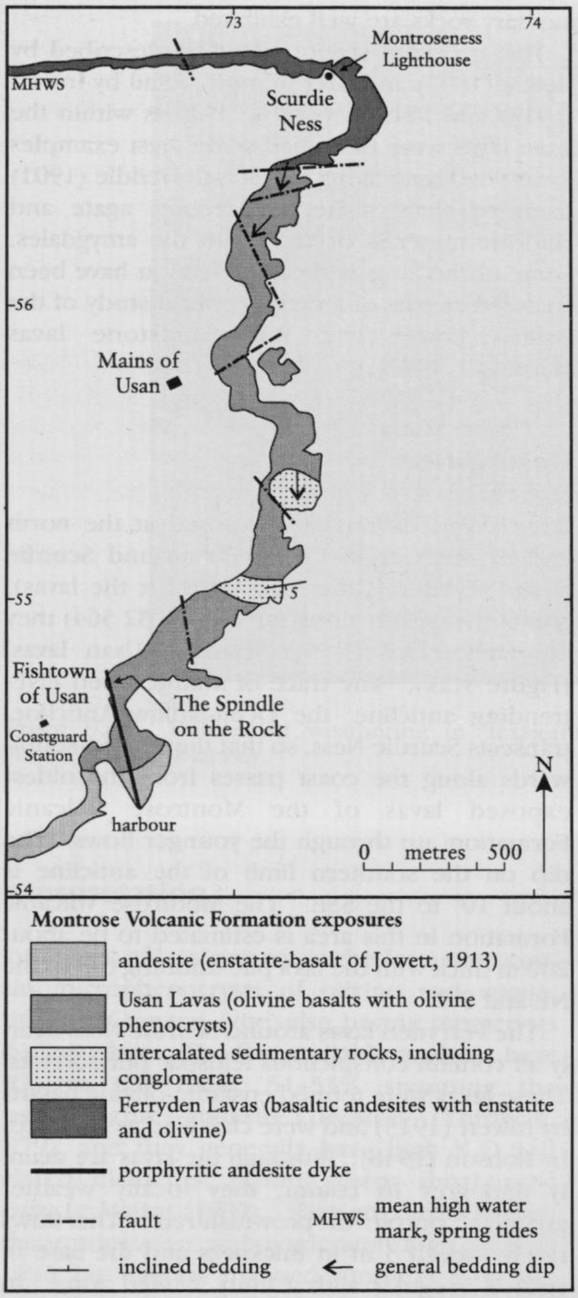

Figure 9.21 Map of coastal exposures of Montrose Volcanic Formation between Scurdie Ness and Usan Harbour, adapted from Jowett (1913).

even produce amygdales within the sediment itself (Jowett, 1913). Just north of the fault that separates the Ferryden from the Usan lavas, an intercalated lens of coarser sandstone is almost entirely composed of volcanic detritus.

The Usan lavas are well exposed on the wave-cut platform and in small sea stacks, which extend from the fault southwards to Usan Harbour. They were described as olivine basalts by Jowett (1913) and as basalts by Robson (1948). These lavas are fine grained with reddish pseudomorphs after phenocrysts of olivine and they lack the conspicuous feldspar phenocrysts of the Ferryden lavas. Fresh 'Usan lava' is dark-grey but depending on the amount of weathering, ranges from shades of purple, brown and red into a lilac colour, particularly in the amygdaloidal tops. Fissures in the slaggy and brecciated tops are filled with sandstone, but locally the base of an overlying flow lies directly on sandstone-filled, fissured, compact lava, which suggests that any slaggy top or conglomerate originally intervening had been removed. Locally, there are intercalated lenses of reddish cross-bedded sandstone and conglomerate containing pebbles of locally derived lava (Figure 9.22).

Jowett (1913) mapped two thicker intercalations of conglomerate and sandstone within the Usan lava sequence. The northernmost, about 500 m SE of Mains of Usan (at 732 554), is a clast-supported, coarsening-upwards conglomerate (Figure 9.22) containing well-rounded boulders of volcanic rock, 0.6–1 m across, with a lens of red sandstone up to 0.45 m thick at its base. The boulders, some of which are feldsparphyric lavas (i.e. not only the local Usan lavas), are set in a matrix of coarse-grained volcaniclastic sandstone. Spheroidal pillows with a concentric arrangement of amygdales occur in the lower part of the lava flow overlying this sedimentary intercalation. The other thick conglomeratic intercalation lies about 700 m SSE of Mains of Usan (at 730 550), and rests on an irregular channelled surface in the lava below. All the boulders in this conglomerate are volcanic rocks with feldspar phenocrysts (? Ferryden type lavas). On the coast, east of Fishtown of Usan, The Spindle on the Rock (725 547) is part of a NNW-trending, 2 m-wide dyke of porphyritic andesite (Jowett, 1913). On the rock-platform to the SE of this dyke, which constitutes the southernmost outcrops of the GCR site (727 544), Jowett mapped some of the lava flows as enstatite basalts; these are characterized by large plagioclase phenocrysts and a lack of olivine.

Interpretation

These lavas are inferred to be some of the earli-

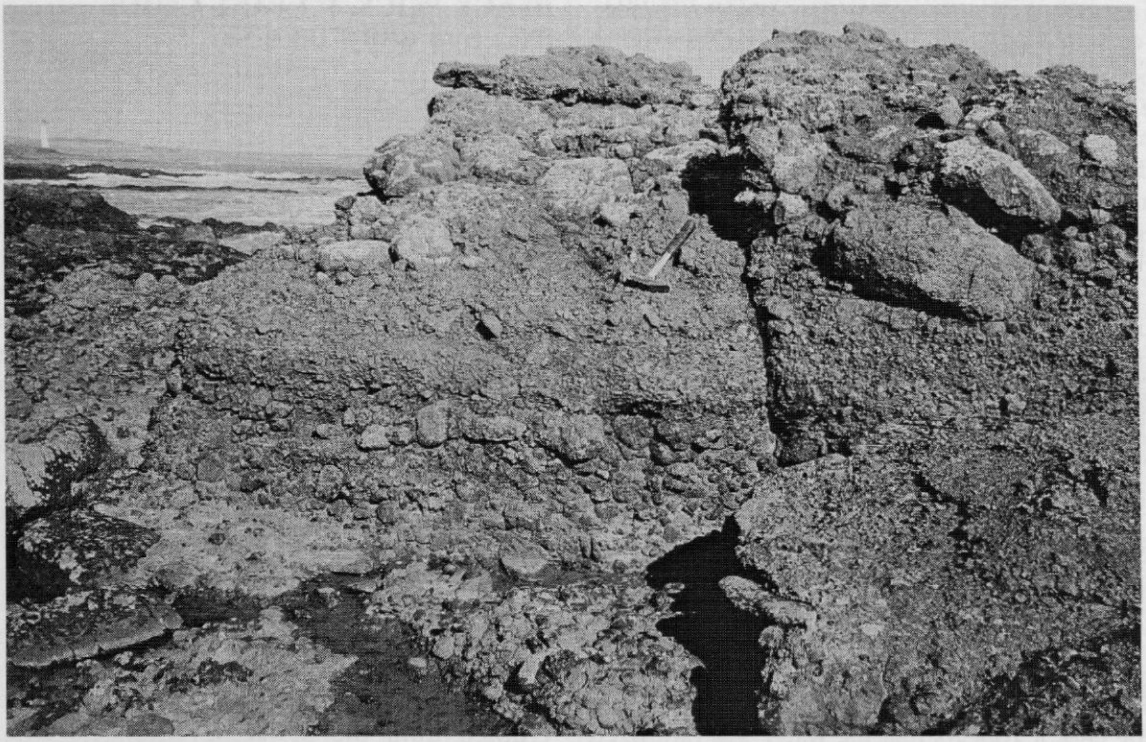

Figure 9.22 Bedded pebble and boulder conglomerate composed of lava clasts in coarsening up intercalation between lavas. Usan lavas, 500 m SE of Mains of Usan (at 732 554). (Photo: R.A. Smith.)

est of the Montrose Volcanic Centre, which lay to the NE, now under the North Sea (Geikie, 1897). The volcanic succession, exposed in the core of the Ochil–Sidlaw Anticline, must be at about its thickest in the Scurdie Ness to Usan Harbour area although its base is not seen. The lack of pyroclastic rocks within this sequence suggests that the eruptions from the Montrose Centre were essentially quiescent.

The Ferryden lavas are chiefly basaltic andesites, containing phenocrysts of labradorite and enstatite; olivine is restricted to the groundmass together with augite and andesine (Jowett, 1913; Robson, 1948). Some of the enstatite is intergrown with augite (?exsolution) but more commonly each phenocryst of enstatite has a border of granular augite. The Usan lavas were described by Jowett as olivine basalts with altered phenocrysts of olivine set in a fine-grained matrix of augite and feldspar. However, Robson (1948) recorded microphenocrysts of andesine and some groundmass feldspar of higher alkali content. A distinct flow-structure is indicated by alignment of feldspar laths and elongation of amygdales. The enstatite basalts without olivine (Jowett, 1913), in the upper part of the Usan lavas, were classed as andesites by Robson (1948) and attributed to fractionation of the more basic magmas.

Some lavas from this site have been analysed by Thirlwall (1979) as part of his 'Ferryden Member', which comprises all the lavas from Ferryden to Lunan Bay (i.e. both the Ferryden and Usan lavas). He divided the lavas into geochemical ranges using Al_2O_3 contents and Zr/Nb ratios. The alumina ranges from 15.8 to 16.1% for the Ferryden lavas as described above, and from 16.9 to 17.3% for the Usan lavas. He concluded from a study of the trace elements that the variation is unlikely to be the result of fractional crystallization.

The Scurdie Ness to Usan Harbour section shows in excellent three-dimensional detail the relationships between the lava flows of both the Ferryden and Usan lavas and the intercalated sedimentary rocks. The intermittent outpourings of fairly fluid gaseous lavas were punctuated by relatively short episodes of local erosion and deposition of fine sediment that accumulated in shallow waters. A slow but steady rate of subsidence is inferred within the Strathmore Basin, for although the lavas were hardly eroded before the deposition of the sediment, there was a considerable amount of penecontemporaneous oxidation (reddening) of the tops of lava flows. The fact that thicker, coarser conglomeratic beds are intercalated with the younger lavas might be due to increasing time intervals between flows as volcanic activity waned, or to changes in local topography as the lava pile built up. The local development of pillows at the bases of flows, as recorded by Jowett (1913), suggests that in places the lavas flowed into shallow water. On the contrary, Robson (1948) stated that pillow-structure is not known from these lavas, which he suggested precluded any suggestion that they formed in deep water. However, Robson agreed that the evidence from the fracturing and infilling of the lavas by sediment implied deposition in shallow water.

Interaction of the molten lavas with wet sediment can be studied in this section; as the wet sediment was ripped up and incorporated into the lava, it appears that the water was vaporized before the sediment was baked so that amygdales eventually developed in the sedimentary rock as well as in the lava. A study of the section could prove examples of fluidization by intrusive magmas as described from rocks of similar type and age from Ayrshire (Kokelaar, 1982)(see the Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray GCR site reports).

Conclusions

The Scurdie Ness to Usan Harbour coastal section is of national importance, both as a representative of the lower part of the Lower Old Red Sandstone, Montrose Volcanic Formation and for its value in reconstructing the environment and evolution of the Montrose Volcanic Centre. The olivine basalt to basaltic andesite lava sequences are excellently exposed along this coast. The main distinction between the Ferryden and Usan lavas is that the former are enstatite-feldspar-phyric with only groundmass olivine, whereas the latter are mainly fine-grained olivine-phyric basalts. Detailed contact relationships with the sedimentary intercalations are of special interest in this section together with possible examples of lava–wet sediment interaction.

BLACK ROCK TO EAST COMB (NO 694 488–703 476)

R. A. Smith

Introduction

This section of the Angus coast exposes the 'Ethie lavas', the upper part of the Montrose Volcanic Formation in the Arbuthnott Group of the Old Red Sandstone succession in the Strathmore Basin (Armstrong and Paterson, 1970) (Figure 9.2). The three-dimensional exposure makes the section eminently suited to detailed study of sediment–lava contacts. These volcanic rocks and interbedded sandstones were first described by Fleming (1818). He used their complex relationships as an argument in favour of the Wernerian hypothesis, which considered that basalt was deposited from an aqueous fluid (see the Forest Lodge GCR site report). Subsequently the lavas were described by Geikie (1897) as sheets of andesite or 'porphyrite' erupted from the Montrose Volcanic Centre. Jowett (1913) produced a more detailed geological description and map (Figure 9.23). The lavas were placed at the base of the former 'Red Head Series' by Robson (1948) but he did not study them in detail. Although down-faulted Devono-Carboniferous rocks intervene between the 'Ethie lavas' and the lower part of the Montrose Volcanic Formation (see the Scurdie Ness to Usan Harbour GCR site report), the 'Ethie lavas' are clearly the younger and are succeeded by clastic red beds of the Red Head Formation of the Garvock Group. Some of the Ethie lavas have been analysed by Thirlwall (1979) as part of a regional geochemical study of Lower Old Red Sandstone lavas.

Description

The lavas are dull purplish-grey to green in colour and vary from compact to extremely amygdaloidal with large cavities. Some have roughly polygonal cooling cracks. Their most striking features are the detailed contacts with the intercalated sedimentary rocks. Fissures and large cavities in the lavas have been filled with pale-green and red sandstone and some of the slaggy lava tops, which can be 3–4 m thick, have interstices filled by horizontally stratified pale-green sandstone.

In his petrological study of the area, Jowett

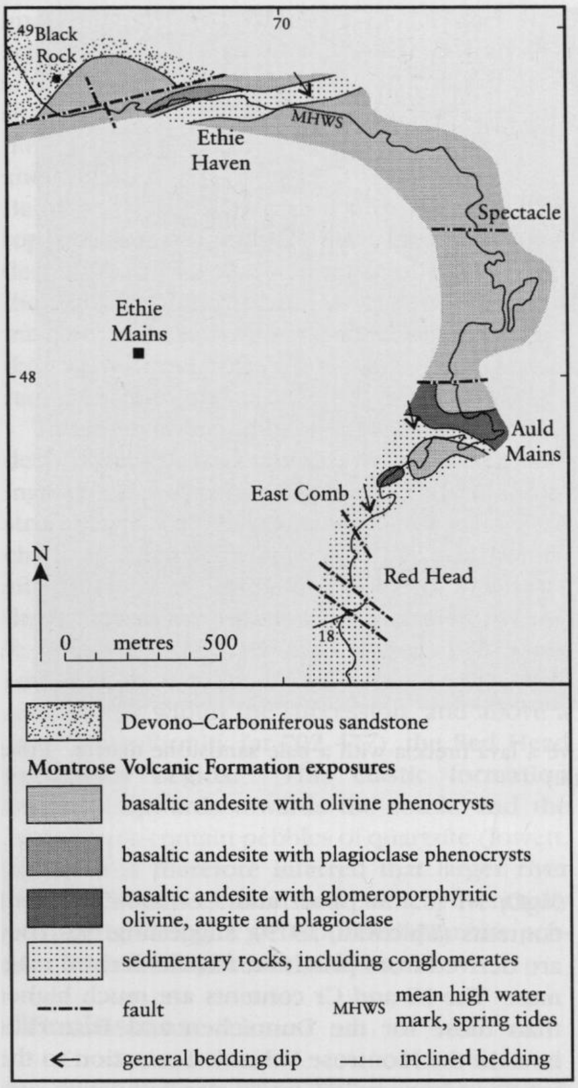

Figure 9.23 Map of coastal exposures of Montrose Volcanic Formation between Black Rock and East Comb, adapted from Jowett (1913).

(1913) described all the lavas as 'olivine basalts', most of which could not be distinguished in the field except for one feldspar-phyric type exposed in the lower part of the cliff at Ethie Haven (698 488) and which continues west for about 300 m. The typical 'Ethie lavas' are probably basaltic andesites; they contain phenocrysts of altered olivine and microphenocrysts of labradorite, augite and magnetite, set in a holocrystalline to partly glassy groundmass. All the olivine has been pseudomorphed by serpentine and haematite. Some of the youngest lavas in the succession, around Auld Mains (706 478) and in the bay to the SW (703 476), are less basic and contain glomeroporphyritic aggregates of olivine, augite and labradorite (Jowett, 1913). No orthopyroxene has been found in the Ethie lavas (cf. the Ferryden lavas of the Scurdie Ness to Usan Harbour GCR site). A flow structure is seen in some of the lavas due to the alignment of small feldspar laths.

The section is here described from north to south, which is generally up the sequence (Figure 9.23). Black Rock is a breccia within red sandstones of Devono-Carboniferous age that are presumed to be unconformable on the Lower Old Red Sandstone lavas. The latter are well exposed in the cliffs to the SE of a major fault trending ENE. Above the basaltic andesites and the feldspar-phyric basaltic andesite at Ethie Haven (699 487), there is a local unconformity overlain by a thick red conglomerate. Within the conglomerate are at least two thin flows of fine-grained basaltic andesite. The top surface of the conglomerate is irregular and it is overlain by fine-grained basaltic andesite.

Rugged coastal scenery has developed to the south, where the softer amygdaloidal zones of the basaltic andesites have been eroded away. The bases of some flows are pillowed and, locally, rounded blocks of highly amygdaloidal lava are set in scoriaceous lava or volcaniclastic breccio-conglomerate. The slaggy and brecciated parts of the flows are commonly paler coloured due to replacement by calcite. Thick beds of conglomerate, comprising lava fragments in a pale-green medium-grained sandstone matrix, are intercalated with the lavas near Spectacle (705 484). North of Kirk Loch (705 481), elongate, flow-orientated amygdales occur within the base of a lava flow overlying a volcaniclastic breccia (Figure 9.24).

South-west of Auld Mains (at 704 477), there are excellent exposures showing the relationship between a clast-supported conglomerate containing large rounded boulders of volcanic rock and an underlying, irregularly eroded lava surface. At Auld Mains (706 478), a resistant flow of lava infills and covers the uneven surface of the same conglomerate. The lower part of this lava is platy with partings parallel to the surface of the conglomerate. The compact part of the lava is at least 10 m thick and has rough columnar-jointing, but the slaggy top has been eroded away locally beneath the next conglomerate. The irregular slaggy top of the uppermost lava flow is overlain disconformably by volcaniclastic conglomerate and red sandstone of the

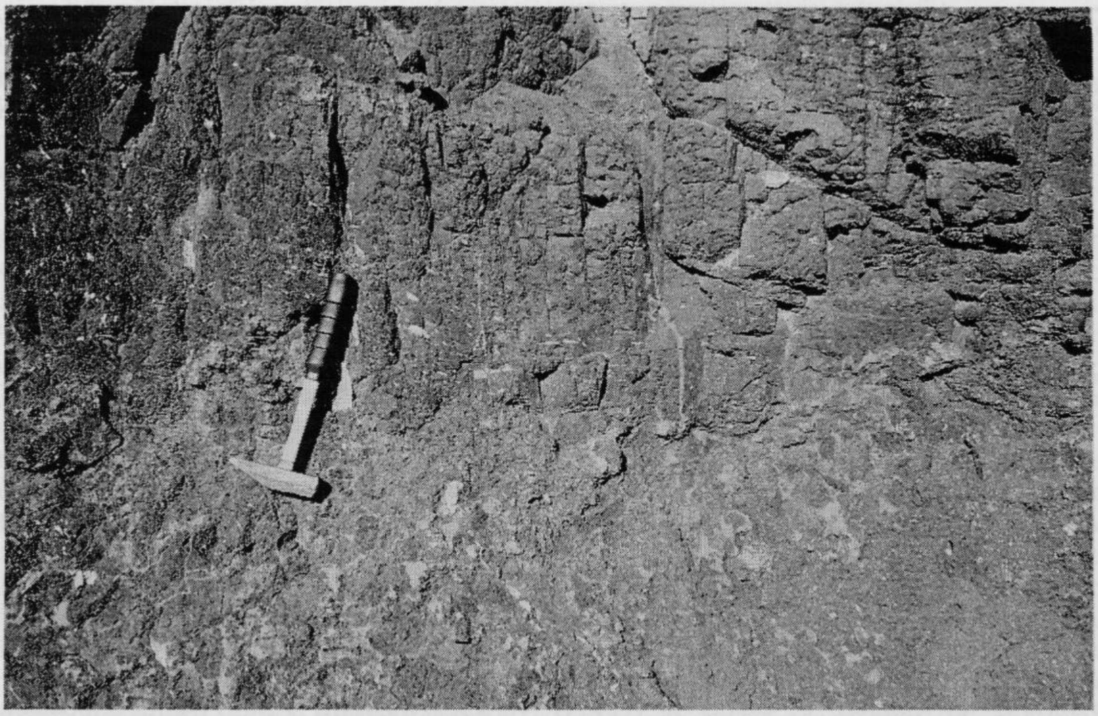

Figure 9.24 Base of lava with elongate amygdales above a lava breccia with a pale sandstone matrix. Ethie lavas, north of Kirk Loch (at 705 481). (Photo: R.A. Smith.)

Red Head Formation; this exposure has been figured by Geikie (1897).

Interpretation

The Black Rock to East Comb GCR site contains a well-exposed section through the lavas at the top of the Montrose Volcanic Formation which means that, except for minor outpourings in the overlying Garvock Group, these lavas are the youngest in the main Lower Old Red Sandstone lava sequences of the northern Midland Valley (Figure 9.2). Spores of Early Devonian age have been found in the intercalated sedimentary rocks of the Arbuthnott Group in Angus (Richardson *et al.*, 1984).

Thirlwall (1979) analysed phenocrysts from the Ethie lavas (his Ethie Haven Member); the olivines are Mg- and Ni-rich, the clinopyroxenes are low-Na diopsidic augites, and all but one of the analysed samples has bytownite–labradorite microphenocrysts. The analysed samples are quartz- or slightly olivine-normative, and the SiO_2 content ranges from 53.8–55% (Thirlwall, 1979). The lavas may therefore be classified as basaltic andesites. The 'Ethie lavas' have high MgO, Ni (*c.* 150 ppm) and Cr (350–540 ppm) contents (Thirlwall, 1979), suggesting that they are derived from primitive, mantle-derived magmas. The Ni and Cr contents are much higher than those for the Dunnichen and East Hills lavas in the Montrose Volcanic Formation to the west, and according to Thirlwall the two lava successions could be related by fractional crystallization with olivine and clinopyroxene as the major crystallizing phases.

The lavas are thought to have emanated from the Montrose Volcanic Centre, which lay to the NE, now under the North Sea, and to have accumulated in a slowly subsiding basin in which the interplay of successive lava flows with the intercalated sediments was complex. The fissured and scoriaceous zones permeated by fine-grained laminated siltstones could suggest that the sediment was washed in by shallow current action after the flow had cooled and cracked. However, the local development of pillow structures and the development of amygdales in the incorporated sediment suggests that the lavas flowed on to wet sediment. Hence, some of the lavas may have locally ploughed or intruded into wet sediment and caused fluidization of the sediment (cf. Kokelaar, 1982; and see the Port Schuchan to Dunure Castle, Culzean Harbour and Turnberry Lighthouse to Port Murray GCR site reports), which would account for the examples where the sediment has been homogenized and forced along a maze of narrow cracks. Because of the widespread reddening of the tops of the lavas and the local unconformities described at their tops, it is thought that most of the basaltic andesites are lava flows and not intrusive sheets into wet sediments, although this is an aspect of the geology that would require future study.

The intercalated conglomerates include boulders of volcanic rock and this indicates that during the longer periods between lava eruptions, strong currents deposited lenticular bodies in channels cut into the lava pile. The sandstones, siltstones and mudstones were probably deposited on the adjacent banks during periodic floods. South of Auld Mains, increasing amounts of mainly volcaniclastic sedimentary rocks occur within the succession, and above a local unconformity (at 702 477), the Red Head Formation begins. This clastic formation coarsens upwards towards the south, and the higher beds contain pebbles of quartzite (Jowett, 1913); it is therefore inferred that larger river systems became established, which eventually managed to bring in well-rounded quartzite pebbles from the Highlands to the north.

Conclusions

The Black Rock to East Comb coastal section is of national importance as a representative of the Ethie lavas, which are the youngest in the Lower Old Red Sandstone Montrose Volcanic Formation. The section provides an excellent opportunity to examine the relationships between the lavas and intercalated sedimentary rocks at the transition between the Arbuthnott and Garvock groups.

The lavas were probably erupted from a volcanic centre now under the North Sea. Most are probably basaltic andesites but the youngest ones may be less basic; as such they are typical of the calc-alkaline suite of Lower Old Red Sandstone lavas in the northern Midland Valley. They were erupted in a terrestrial shallow-water environment and have complex relationships with intercalated sedimentary rocks, partly due to the interaction of hot lava with wet sediment. The intercalated lenses of coarse conglomerate, composed mainly of volcanic detritus, indicate that initially the local drainage channels were sourced within the Strathmore Basin, but with the cessation of volcanic activity in this area, rivers draining the higher land to the north entered the basin.

BALMERINO TO WORMIT (NO 356 248)

M. A. E. Browne

Introduction

The coastal cliff sections and foreshore beside the Firth of Tay between Balmerino and Wormit provide the most complete section through the Lower Old Red Sandstone, Ochil Volcanic Formation in Fife (Figure 9.25). The GCR site illustrates the nature and environment of this volcanic activity and complements that of the Sheriffmuir Road to Menstrie Burn GCR site at the SW end of the Ochil Volcanic Formation outcrop. The eastern half of this section is described in a field guide by MacGregor (1996). A 350 m-thick sequence of basaltic to andesitic lavas and volcaniclastic sedimentary rocks is intercalated with sandstones and minor claystones of the Dundee Formation. Rocks from the section have provided radiometric ages and micro- and macro-palaeontological evidence, both indicating an Early Devonian (Lochkovian) age.

Description

The stratigraphy of the area has been described by Geikie (1902) and Armstrong *et al.* (1985). The lavas, usually less than 7–9 m thick, consist mostly of basalts and basaltic andesites, which are usually distinguishable only by geochemical analysis (Thirlwall, 1979). They vary from coarsely to finely feldspar-phyric and from fine- to medium-grained aphyric. The feldspar is labradorite–andesine and usually co-exists with small altered phenocrysts of one or more of forsteritic olivine, bronzitic orthopyroxene, titanomagnetite and diopsidic augite. Hornblende has not been reported and phenocryst biotite is restricted to the acid igneous rocks (Thirlwall, 1979). The lavas are commonly heavily altered and weather to a brown, greenish-grey (chloritic), or purplish and reddish-grey mottled appearance. When fresh they are grey

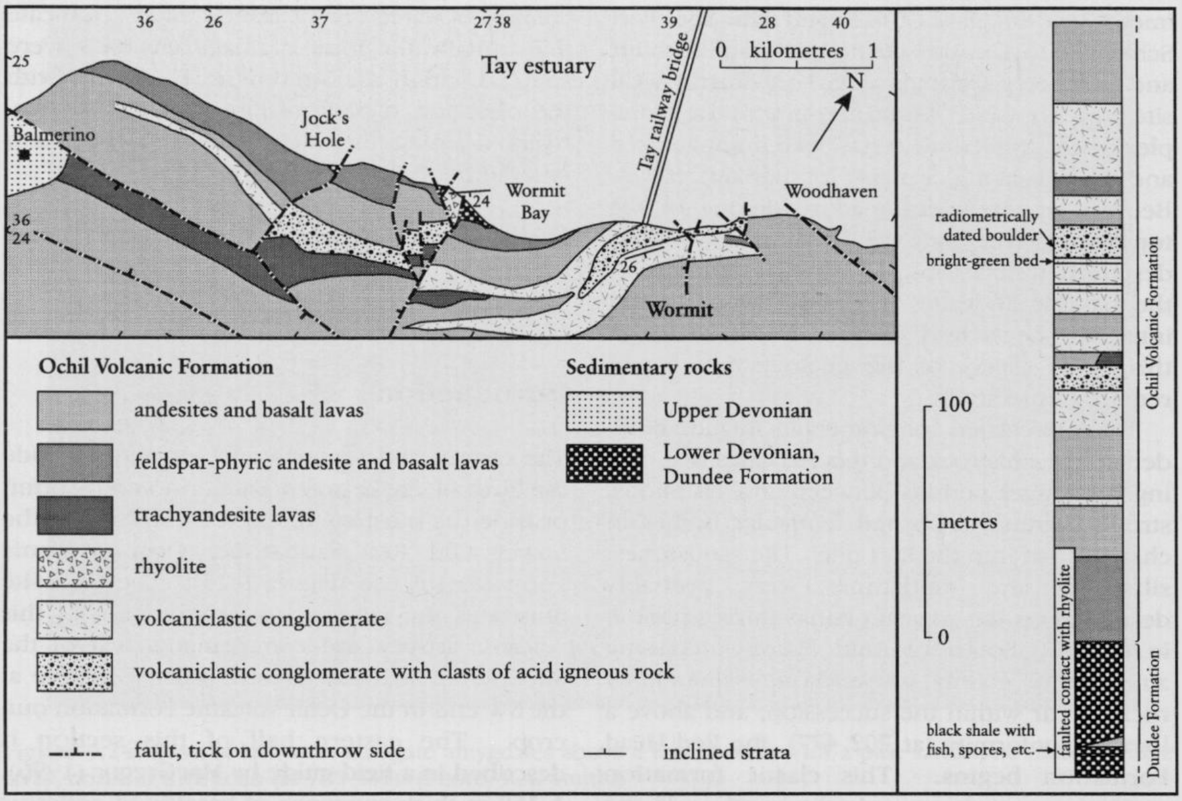

Figure 9.25 Map and generalized vertical section of the Balmerino to Wormit GCR site.

or less commonly brown. They show features such as autobrecciation, amygdales and infiltrated sediment in fissures and between blocks. Possible pillow lavas have been identified. Individual flow bases are not always easy to recognize in the absence of lateritic alteration. However, because the lava flows are interbedded with both volcaniclastic and non-volcaniclastic sedimentary rocks of the Dundee Formation (Arbuthnott Group), the section displays load-cast relationships between flow bases and underlying shales. Uneven, possibly eroded flow tops are infilled by sandstone in places, but elsewhere peperites formed by the interaction of hot magma and wet sediment are clearly seen (MacGregor, 1996) (Figure 9.26).

At Peasehill Point (3832 2580) highly altered and weathered andesite flows are faulted against a pale-grey, fawn and salmon-pink colour-banded rhyolite. On the western edge of the rhyolite outcrop, this thin flow-banding is near-parallel to the adjacent fault plane, but away from this contact it is highly irregular. The eastern contact of the rhyolite is with a rhyolitic breccia, which includes blocks of sandstone and shale. In places the rhyolite appears to intrude the breccia, which itself intrudes the sandstone country rock. Two possible origins have been suggested for the rhyolite. Harry (1956) suggested that it is a vent intrusion with the breccia pre-dating the rhyolite, whereas Geikie (1902) followed by Armstrong *et al.* (1985) suggested that it is a lava within a vent that has been faulted down into its present position.

Probably all the volcaniclastic rocks are sedimentary rather than pyroclastic. They consist predominantly of massive, thickly bedded, poorly sorted conglomerates and breccias in beds up to 9 m thick. The clasts in the conglomerates consist of basalt, basaltic andesite and rhyolitic lavas. The rhyolite clasts are probably not of local derivation and conglomerate units have been distinguished by their absence or presence and relative abundance. The clasts can be subangular to rounded and are usually less than 30 cm, but over 2 m across locally. The matrix is composed of grains of similar materials and quartz. Greenish-grey, cross-bedded, volcaniclastic sandstones are also present as impersistent lenses and beds.

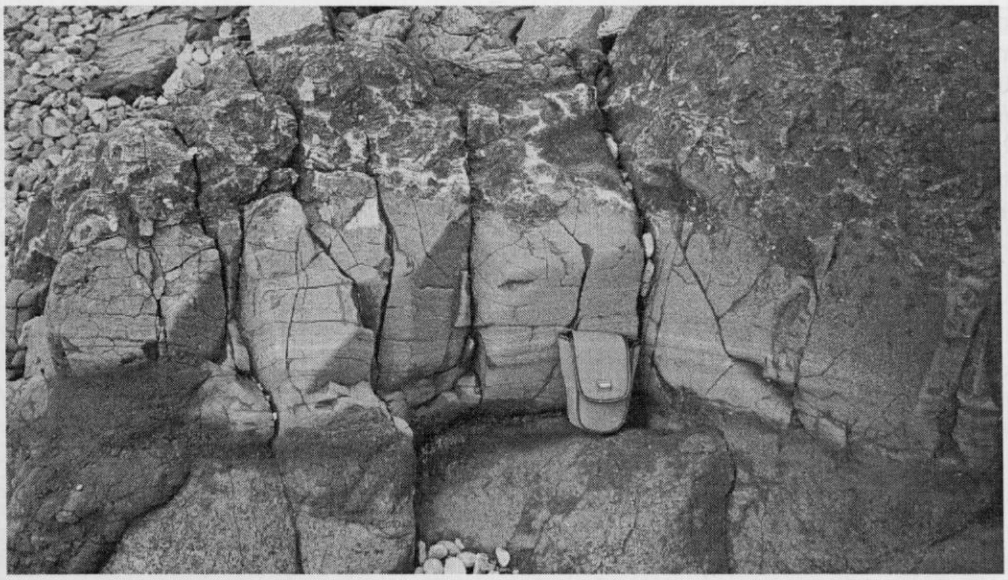

Figure 9.26 Lens of well-laminated sandstone between igneous sheets on the foreshore west of the Tay Bridge at Wormit. The lower sheet has a sharp but irregular, apparently intrusive, contact with the sandstone; the upper sheet shows evidence of magma–wet sediment interaction, with fragments of igneous material separated by irregular veins of pale sandstone and peperitic texture well seen on the right. (Photo: M.A.E. Browne.)

The interbeddded Dundee Formation strata consist of cross-bedded, sometimes graded sandstones and finer-grained beds of siltstone and shale. The colours of these sedimentary rocks range from grey to green to red and also yellow. They are fluvial and lacustro-deltaic in origin and form part of the infill of the Strathmore Basin, which extends south-westward from Stonehaven across the whole of the Midland Valley of Scotland. Marshall *et al.* (1994) have described the vitrinite reflectivity of the carbonaceous shales at Wormit as a small part of a study of the Strathmore region. They concluded that maximum burial of 3–5 km, and therefore thermal maturity occurred during the late Carboniferous. This has major consequences for understanding the nature, depth and number of late Silurian to Early Devonian sedimentary basins in the eastern Midland Valley.

Interpretation

Thirlwall (1983b) analysed trace elements, including rare earths, and Sr, Nd and Pb isotopes of lavas within and around this site. He found all the samples from the site to be primitive basalts and andesites (high Mg, Ni and Cr) in contrast to samples farther south, which are more typical of modern calc-alkaline suites with less than 30 ppm Ni and Cr. He reported Rb-Sr age determinations on biotite and plagioclase separations from a rhyolite boulder in what he described as the lowest conglomerate in the local succession. The age was reported as 406.5 ± 5.6 Ma, later adjusted to 410.6 ± 5.6 Ma (Thirlwall, 1988).

The dark-grey, carbonaceous shales near Peasehill Point have yielded a fish fauna, including *Brachyacanthus, Ischnacanthus* and *Mesacanthus* (Westoll, 1951). The arthropods *Kampecaris* and *Pterygotus* and the plant *Parka decipiens* have also been found. Richardson *et al.* (1984) re-assessed the age of some Arbuthnott Group sedimentary rocks from the Strathmore region on the basis of a re-investigation of spore assemblages. At Wormit, samples associated with, but stratigraphically beneath the rocks dated by Thirlwall (1983b, 1988) as 410.6 Ma, yielded assemblages of Early (but not earliest) Devonian age belonging to the *micrornatus–newportensis* Zone (lower and middle subzones) of the Lochkovian Stage. The Wormit GCR site is possibly the only Lower Old Red Sandstone site where radiometric and biostratigraphical dating methods are so closely related. The radiometric dates are very close to the Silurian–Devonian boundary on most recently published time-scales and until recently may have been regarded as late Silurian. However, the palaeontological data indicate early Lochkovian (Gedinnian) and this is now accepted. Therefore this site not only provides a stratigraphical and radiometric date for the late Caledonian volcanicity in this part of the Midland Valley, but potentially it has even greater implications internationally for the dating of the Silurian–Devonian boundary.

Conclusions

The Balmerino to Wormit GCR site is a particularly important site both nationally and internationally. The former, because it represents a key 350 m-thick succession of the Ochil Volcanic Formation in the eastern Midland Valley, and the latter because of the intimate relationship it shows between the volcanic rocks and the interbedded fossiliferous claystones within the Dundee Formation (Arbuthnott Group). Studies of organic matter in the carbonaceous shales provide estimates of depth of burial and degree of maturity, which have contributed to the understanding of the development of the late Silurian to Early Devonian sedimentary basins in the eastern Midland Valley.

Geochemical studies have characterized the basalts and andesites as primitive calc-alkaline types related to subduction during the final closure of the Iapetus Ocean, and have contributed to more detailed suggestions regarding the magma source. Radiometric investigations on this site and elsewhere in the Midland Valley estimate the age of the late Caledonian magmatism as 415–410 Ma. This has been substantiated by spores which, together with the macrofauna, including fossil fish, show the succession to be early Lochkovian (Early Devonian). Hence there are possible international implications for the age of the Silurian–Devonian boundary.

SHERIFFMUIR ROAD TO MENSTRIE BURN (NS 813 979–852 973)

M. A. E. Browne

Introduction

This well-exposed part of the Ochil Hills shows many of the characteristic features of the volcanic and volcaniclastic rocks of the Lower Old Red Sandstone, Ochil Volcanic Formation. The 600 m-thick sequence in the Ochil Fault scarp, from the summit of Dumyat down to the bottom of Menstrie Glen (Figure 9.28) consists of subaerial lava-flows interbedded with volcaniclastic rocks variously interpreted as being of pyroclastic and sedimentary origin. Detailed descriptions are given by Francis *et al.* (1970) and accounts of the petrology and geochemistry of lavas in the western Ochils in general are given by Taylor (1972) and Thirlwall (1979). A suite of dykes and sills adds to the interest of this site, which complements the Balmerino to Wormit GCR site at the NE end of the Ochil Volcanic Formation outcrop. The site also forms part of the classic Ochil Fault escarpment view, as seen from Stirling Castle and the Wallace Monument.

Description

A measured section of the volcanic succession, derived from this area, has been given by Francis *et al.* (1970, pp. 31–32) (Figure 9.27). It consists of at least 20 lavas, from 3 to 30 m thick, interbedded with volcaniclastic rocks in units up to 50 m thick. In the past the latter rocks have largely been described as of pyroclastic origin.

The lavas are mainly basalts, basaltic andesites and andesites with a few ‘trachyandesites’. The basalts and andesites are normally only distinguished from each other by their geochemistry. They range from fine- to medium-grained and from micro- to macro-porphyritic in texture. Most are feldspar-phyric (labradorite–andesine) but clinopyroxene (diopsidic augite), orthopyroxene (bronzite) and olivine phenocrysts are also present in many rocks, and there are some hornblende-phyric andesites (Thirlwall, 1979). Thirlwall noted that the rocks described as trachyandesites by Francis *et al.* (1970) and classed as dacites by Taylor (1972) are not notably more alkaline than many other Ochil andesites. The term is, however, considered as a useful misnomer to describe these sparsely porphyritic and slightly more siliceous rocks. The lavas are usually grey when fresh but more commonly purplish where altered and weathered. They may be vesicular or amygdaloidal, and autobrecciation is common, but this is difficult to detect unless the voids between blocks or fissures contain infiltrated sediment. Flow texture and jointing are developed in some of the flows.

The volcaniclastic rocks, which form a significant part of this succession, consist of crudely and thickly bedded, massive, commonly matrix-

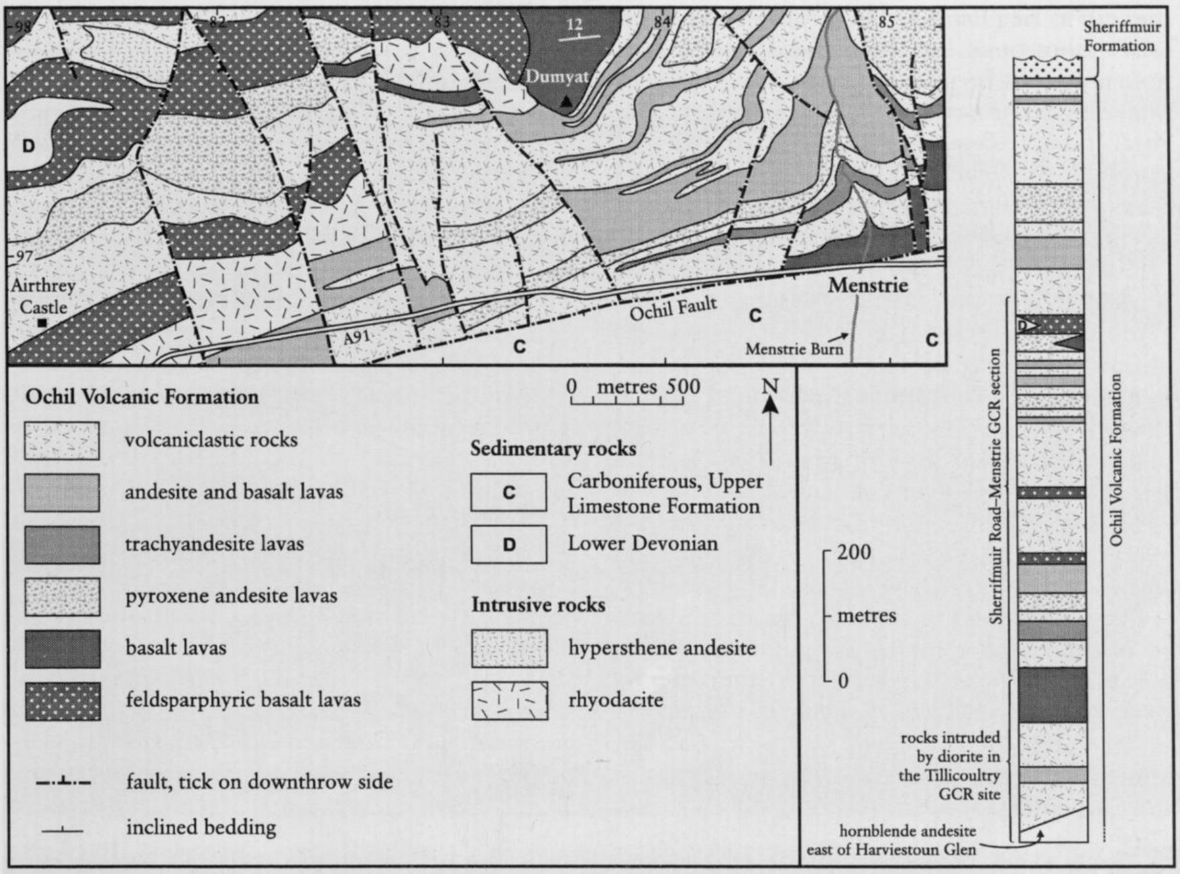

Figure 9.27 Map and generalized vertical section of the Sheriffmuir Road to Menstrie Burn GCR site.

supported breccias and conglomerates with only one example of volcaniclastic siltstone noted. The largest clasts are up to 1.2 m across, with an average size being 30 cm or less. They are extremely poorly sorted, with the matrix consisting mainly of volcanic detritus of sand to silt grade.

A sill of possible rhyodacite, over 100 m thick, forms pink-weathering crags and screes on the main fault scarp and in the foothills NW of Blairlogie. This intrusion forms an important marker as it is displaced upwards by faults to the higher slopes west of Dumyat. The rock in the centre of the sill contains scattered microphenocrysts of albitized plagioclase and altered amphibole and orthopyroxene in a cryptocrystalline matrix of quartz and alkali feldspar. The marginal aphyric rocks are pale and blotchy and show some resemblance to the autobrecciated lavas.

The succession is broken by a number of significant faults, mostly trending NNW. Locally these and related joints are mineralized (Dickie and Forster, 1976); the age of mineralization is possibly early Permian (Hall *et al.*, 1982).

Interpretation

According to Francis (1983), the more-proximal zones of central volcanoes of assumed heights of 1–3 km and diameter 40 km at the time of extinction, would not survive erosion to become buried. He suggested that volcanic outcrops of much greater linear extent are likely to represent overlapping or interdigitating products of more than one volcano. The extent of the linear outcrop forming the Ochil and Sidlaw hills far exceeds that of one edifice (Francis, 1983, fig. 22). The volcanic rocks preserved are suggestive of the lower proximal to distal zone of composite volcanoes (Williams and McBirney, 1979) with both moderately thick lavas and massive to thickly bedded volcaniclastic debris-flow (or

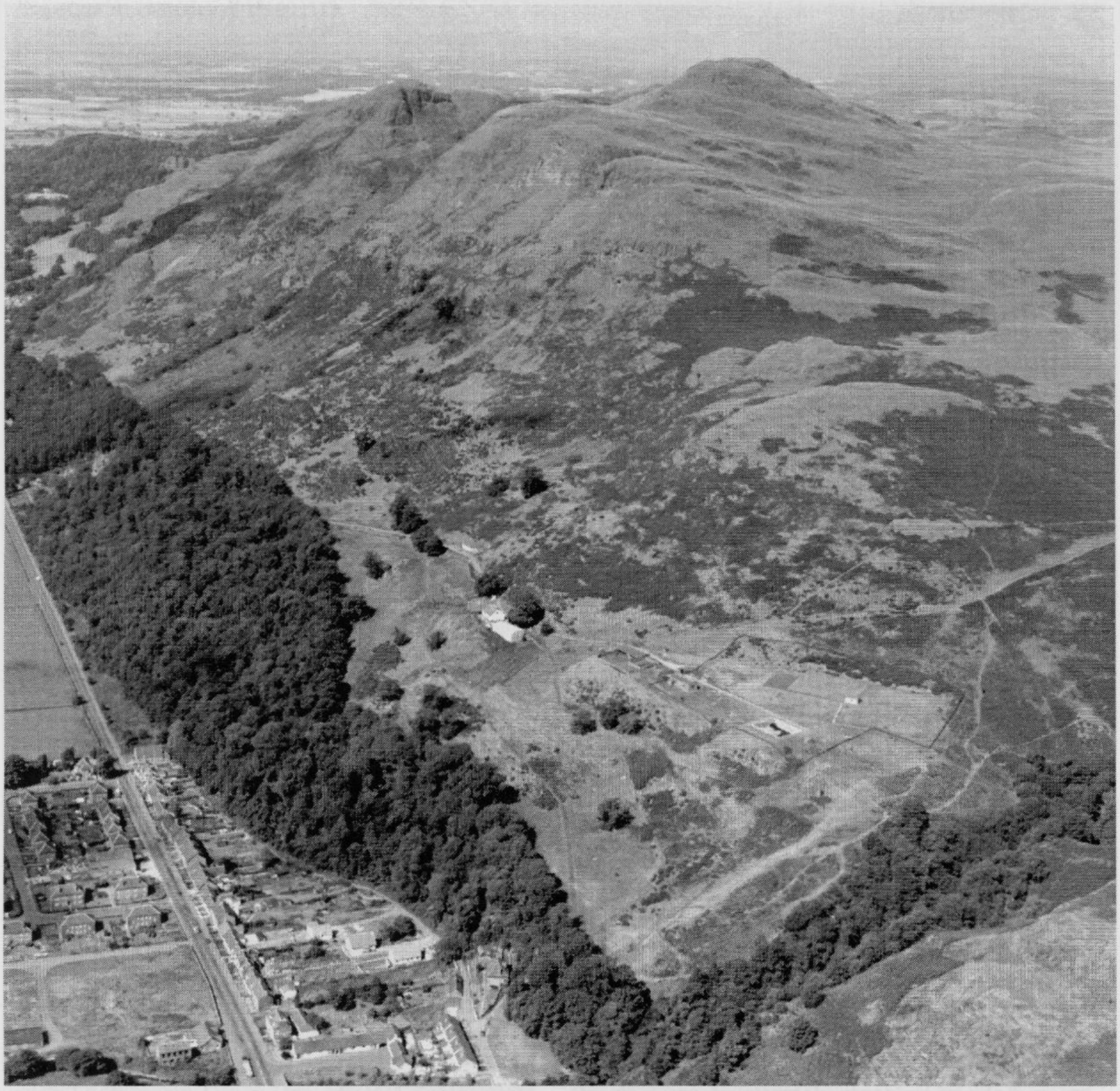

Figure 9.28 The Ochil Fault scarp above Menstrie. The scarp face exposes a 600 m-thick sequence through the Ochil Volcanic Formation, dipping gently to the north (right). Menstrie Glen is in the bottom right and the prominent summit is Dumyat. (Photo: BGS no. D2066.)

laharic) breccias and conglomerates predominant (rather than pyroclastic ash-fall or distal ash-flow tuffs and agglomerates). Only one possible vent structure has been identified in the Ochil Hills (now under the waters of the Upper Glendevon Reservoir) (Francis *et al.*, 1970), and it is uncertain whether the diorites of the Tillicoultry GCR site and elsewhere represent roots of volcanoes or late stage intrusions. In the above context, the Sheriffmuir Road to Menstrie Burn succession of basalts, andesites and volcaniclastic rocks represents at least one 600 m-thick fragment of a composite (or strato) volcano, the whole volcanic pile locally being over 2400 m thick in the Ochil Hills. There is little evidence for the alternative view that the lavas were erupted from fissures.

Thirlwall (1988) reported a clinopyroxene-whole rock Rb-Sr age of 416.1 ± 6.1 Ma from a lava a little to the north of this GCR site (NN 835 019).

Conclusions

The importance of this site lies in the thick sequence of the Ochil Volcanic Formation laid out largely on the scarp face of the Ochil Fault. The succession is of national importance in understanding the origin and architecture of a major volcanic pile and it complements that of the Balmerino to Wormit GCR site at the NE end of the Ochil Hills. On a regional scale, this calc-alkaline assemblage, with its associated geochemical and radiometric data, contributes to the understanding of late Caledonian subduction and closure of the Iapetus Ocean in northern Britain.

CRAIG ROSSIE (NN 980 125)

M. A. E. Browne

Introduction

The acid volcanic rocks around Craig Rossie in the Ochil Hills form only a small part of the outcrop of the Lower Old Red Sandstone, Ochil Volcanic Formation. In general this formation consists of a wide variety of basaltic and andesitic lavas interbedded with volcaniclastic rocks for which the GCR sites of Sheriffmuir Road to Menstrie Burn and Balmerino to Wormit provide adequate reference. In contrast, acidic flows are areally restricted and are confined to high stratigraphical levels within the volcanic pile. The Craig Rossie rhyodacite, on the NW limb of the Ochil Anticline, is well exposed in hillside exposures, in the cliffs of Craig Rossie itself and in a quarry at 9770 1277 (Figure 9.29). The flow is of local distribution and is believed to occupy a topographical low in the pre-existing volcanic landscape. It is a feldspar-biotite-quartz-phyric rock that shows well-developed flow-banding picked out by colour variation.

The hill of Craig Rossie is a good example of an escarpment with dip slope. The summit and the eastern escarpment (Figure 9.30) have been affected by major landslips, formed after the

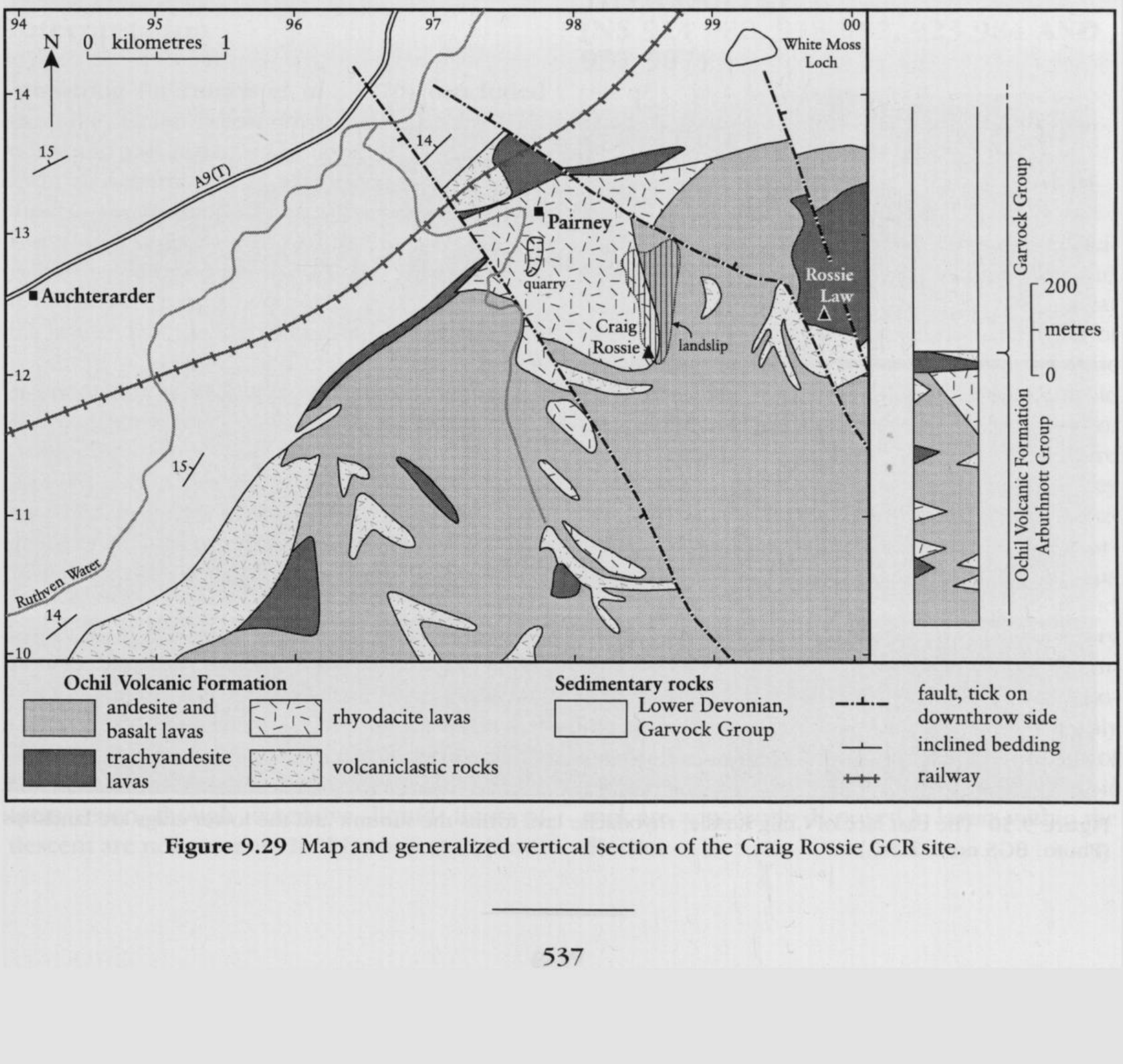

Figure 9.29 Map and generalized vertical section of the Craig Rossie GCR site.

retreat of the last ice sheet from the area less than 15 000 years ago.

Description

The Ochil Volcanic Formation in the Craig Rossie area generally consists of altered and weathered basalt and basaltic andesite lavas, which are commonly vesicular and autobrecciated (Geikie, 1900; Francis *et al.*, 1970; Taylor, 1972). These rocks are not conspicuously porphyritic but olivine-, feldspar-, clinopyroxene- and hypersthene-phyric types are present as well as aphyric forms. Interbedded in this succession are trachyandesites, rhyodacites and some volcaniclastic rocks. The Craig Rossie rhyodacite is immediately overlain by a trachyandesite which is the youngest flow in the Ochil Volcanic Formation of this area. A unit of volcaniclastic rocks of uncertain origin is present within the succession a little beneath the rhyodacite. It consists of gravel- to pebble-sized clasts of volcanic material, generally of poorly rounded to subrounded shape, in a massive, greenish-grey, poorly sorted sandy matrix. It is not known whether the matrix is entirely derived from volcanic rocks or whether it includes quartz grains derived from sedimentary rocks.

The Craig Rossie rhyodacite is brown, dull red or pink in colour. It contains phenocrysts, particularly of pale-coloured feldspar but also of quartz and biotite, in a fine-grained crystalline matrix. Its petrography and geochemistry are described by Francis *et al.* (1970) and by Taylor (1972). As far as is known, the rhyodacite is a single lava and no separate flow units have been recognized. Its most striking feature is the widespread occurrence of colour-contrasted flow-banding due to subtle mineralogical differences. This flow-banding developed as the cooling magma passed through a viscous phase, developing folds just prior to solidification. The folds

Figure 9.30 The east face of Craig Rossie; rhyodacite lava forms the summit and the lower crags are landslips. (Photo: BGS no. D2181.)

are usually open in form but locally become overfolded. Undeformed flow-banding is seldom parallel to the base of the flow. A feature of the rhyodacite in the quarry (9770 1277) is the presence of xenoliths, 5–10 cm across, of coarse-grained igneous material. These may be of gabbroic or dioritic rock by analogy with those found at the Rossie Braes Quarry (NO 249 120) near Auchtermuchty in Fife, where fragments of layered cumulate have also been found (Thirlwall, in Armstrong *et al.*, 1985, p. 36). Other features noted include amygdales of calcite and red chalcedony near the supposed top of the rhyodacite and patches of fine-grained sedimentary rock, which have have been recorded as infilling fissures or spaces between autobrecciated blocks near the base.

The volcanic sequence at Craig Rossie dips to the NW at between 20 and 30°. It is cut by at least two significant NW-trending faults that throw down the base of the rhyodacite to the SW and NE respectively. Other smaller faults with similar trend are also present, together with related joints. Small crush zones associated with the faulting have voids infilled with chalcedony.

Interpretation

Armstrong (in Francis *et al.*, 1970) concluded that the Craig Rossie rhyodacite occupies a depression in pre-existing lavas, is of lenticular form and thins out both eastwards and westwards. The evidence for the topography is to be found in the Pairney Burn and in an adjacent gully eroded along a NW–SE fault. Here the flow overlies an amygdaloidal basalt and the base can be traced. If the base is parallel to the flow-banding, the underlying basalt should occur along strike in a deeply cut glacial channel a short distance to the NE. Since the basalt does not occur here, the rhyodacite base must descend north-eastwards from the visible outcrops in a manner discordant to the flow-banding and thus presumably occupies a depression.

The rhyodacite forms a minor acidic part of the generally basalt and basaltic andesite assemblage of the Ochil Volcanic Formation. While noting the marked silica gap between the more basic rocks ($SiO_2 < 62\%$) and the rare 'rhyolites' ($SiO_2 > 74\%$), Thirlwall (1983b) believed that the acid rocks could be generated by fractional crystallization from some of the more mafic lavas, even though extensive liquid lines of descent are not present. In this context, it is not surprising that rhyodacitic flows are restricted to high stratigraphical positions in the volcanic pile.

Conclusions

The importance of this site lies in the excellent exposures and geomorphological expression of this rare, flow-banded, acidic lava within the primarily basaltic and andesitic Ochil Volcanic Formation. Craig Rossie thus provides a complement to the areally more extensive GCR sites between Balmerino and Wormit, and in the Sheriffmuir Road to Menstrie Burn area. The pre-existing topography below the flow base is an interesting feature of the site. The rhyodacite is important as a representative end member of fractional crystallization processes which may have operated in the late Caledonian magmas. Further study of the recently found coarse-grained xenoliths may provide information concerning possible parental material and this would add to the conservation value of this site.

TILLICOULTRY (NS 914 980, 918 982, 923 984 AND 931 987)

M. A. E. Browne

Introduction

The cliffs, ravines and hillside exposures associated with the Ochil Fault scarp around Tillicoultry display four diorite stocks that intrude related lavas and volcaniclastic rocks of the Lower Old Red Sandstone, Ochil Volcanic Formation within a 6 × 1 km thermal aureole (Figure 9.31). The stocks are cut by members of a contemporaneous radial dyke-swarm (Figure 9.32) and are truncated by the Ochil Fault. They are also cut by the late Carboniferous quartz-dolerite fault intrusion (Figure 9.33). The diorites are notable for their locally heterogeneous and hybrid character and show both sharp and diffuse contacts with the hornfelsed country rocks. The diffuse contacts, reflecting contamination of the magma by incorporation of xenolithic material, are well seen in the deeply incised Harviestoun Glen where a number of poorly defined enclaves of hornfelsed volcanic rock are apparently disposed in layers within the diorite.

Description

The diorite stocks are intruded into basalt and andesite lavas and volcaniclastic rocks of similar character to those in the nearby Sheriffmuir Road to Menstrie Burn GCR site. There are four masses of diorite; from west to east these are Castle Craig, Mill Glen, Wester Kirk Craig and Elistoun Hill. They are about 30–135 m apart and each is cut off to the south by the Ochil Fault. The Castle Craig and Mill Glen stocks are about 200 m in diameter, the latter with a 350 × 30 m westward-trending dyke-like extension, whereas those at Wester Kirk Craig and Elistoun Hill are 1050 m and 1250 m in diameter respectively. The diorites range in grain-size and colour from fine grained and grey to coarse grained and blue-grey or green with pink mottling. Transitions in grain-size occur on a metre scale and, although margins tend to be of fine-grained grey diorite, the latter's occurrence is not confined to contact zones. The heterogeneous nature of the diorites is further accentuated by the presence of numerous country-rock xenoliths, especially near to margins. As a consequence of the presence of xenoliths, there are only a few localities where the margins of the diorites are sharply defined. Where seen, the walls of the intrusions are vertical or highly inclined outwards. This suggests that the four masses may converge and unite at depth.

The Castle Craig diorite is fine- to medium-grained, with xenoliths of volcanic rock generally confined to the contact zone, some showing various stages of transition from hornfelsed lava to diorite. The Mill Glen rock is coarse grained and is mottled-pink and bluish-green. The dyke-like apophysis varies from fine- to coarse-grained, reflecting the presence of a chilled margin. The Wester Craig diorite is variable, being fine- to medium-grained in the north and west and coarser and of the mottled-pink form elsewhere. The Elistoun rock is also fine- to medium-grained in the west but is usually coarse grained elsewhere. It exhibits the best examples of rapid transition from hornfelsed lava into coarse-grained diorite.

The petrography of the diorites has been described by Francis *et al.* (1970). They are composed largely of plagioclase feldspar with varying proportions of ferromagnesian minerals (clinopyroxene, orthopyroxene, amphibole and biotite), and with sufficient quartz to classify them as quartz-diorites. The coarse-grained diorites may be subdivided into four types, three of which are present in the GCR site. A two-pyroxene diorite with little amphibole occurs within all of the Tillicoultry stocks and a variant with uralitic amphibole but little pyroxene occurs in several. A granodioritic variant, with

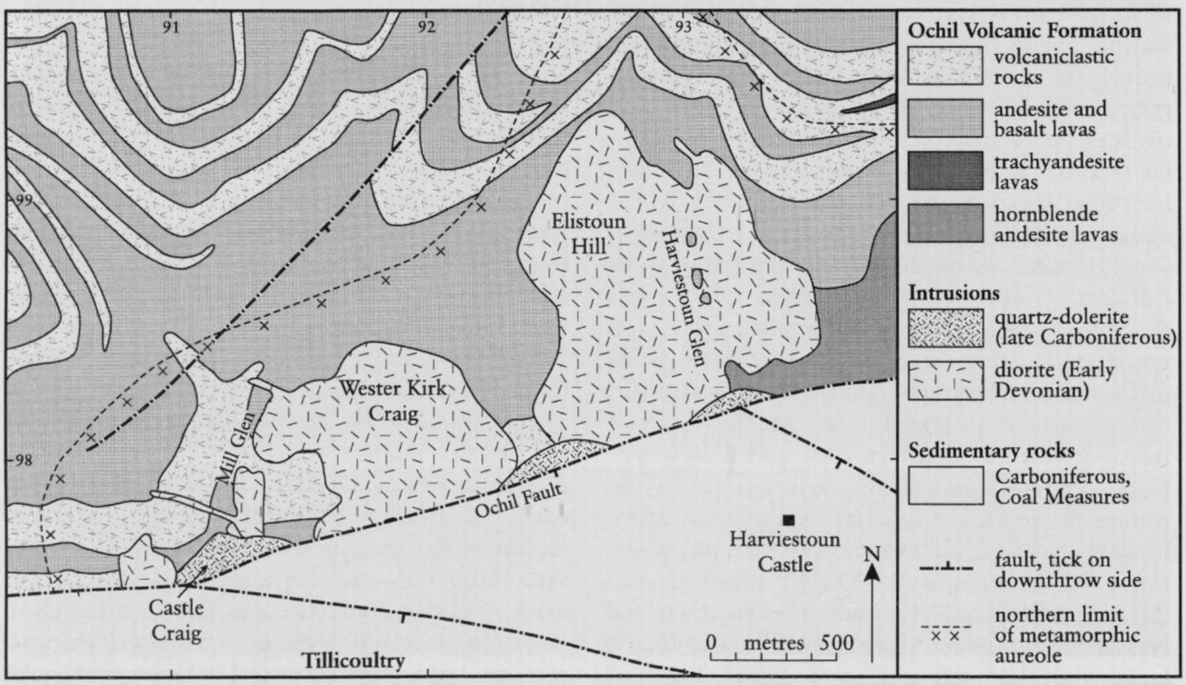

Figure 9.31 Map of the Tillicoultry GCR site. The general succession is similar to that shown on Figure 9.27.

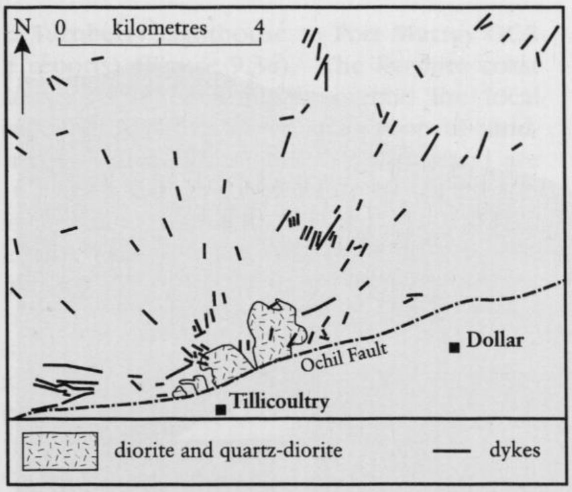

Figure 9.32 Sketch-map showing radial disposition of dykes relative to diorite stocks in the Ochil Hills, after Francis *et al.* (1970).

pink potash-feldspar and no pyroxene, is restricted to parts of the Mill Glen stock and its dyke-like apophysis. Francis described the fine-grained diorites as grey, saccharoidal rocks sharing many of the characteristics of both hornfelsed country rocks and coarse-grained diorites. In varieties most closely related to the hornfelsed lavas, plates of biotite are the only fresh ferromagnesian mineral. These fine-grained variants present some of the best evidence for the formation of some of the diorites by metamorphism of the country-rock lava. In general, the petrographical differences between the igneous and metamorphic/metasomatic varieties are that the former are relatively rich in quartz and potash-feldspar, whereas the latter tend to be richer in pyroxene.

Pink aplitic veins and segregation patches in the diorites and aureole are clearly a late-stage magmatic event. Diorites cut by the aplites show contact alteration but the veins themselves are not chilled and have gradational contacts with the host rock. Similar gradational contacts have been noted with some of the hornfelsed volcanic rocks.

Numerous small andesitic dykes ('porphyrites' and 'plagiophyres' on old maps) show a radial disposition relative to the diorite stocks (Francis *et al.*, 1970) (Figure 9.32). Many are similar in composition to the lavas, consisting of olivine basalts, pyroxene- and hornblende-phyric andesites, trachyandesites and albitized equivalents. Within the diorites, the dykes usually have irregular, gradational and unchilled contacts, indicating near-contemporaneity and their radial distribution probably reflects the stress pattern generated by emplacement of the stocks.

The diorite stocks all occur within a single extensive thermal metamorphic aureole that is always at least 300 m wide. The degree of alteration of the country rocks depends on their permeability and their distance from the diorite. The volcaniclastic rocks and autobrecciated lavas are generally more permeable and they alter to pale-pink, grey or even greenish-grey, partly amorphous rocks. The outlines of clasts become indistinct at an early stage of alteration and pink feldspar porphyroblasts develop. Amygdales in lavas recrystallize to ill-defined pink patches. Some lavas become hackly-looking and, when traced into the diorite, they pass through massive hornfels into metasomatically produced fine-grained diorite.

Interpretation

There seems little doubt that the diorite bodies are genetically linked to the extrusive rocks into which they are emplaced. They are probably of similar age, accepting the radiometric age of 411.4 ± 5.6 Ma for a related small olivine diorite body at Glenfarg, about 20 km to the ENE of Tillicoultry, and of 416.1 ± 6.1 Ma for an andesite lava flow at NN 835 019 just north of the Sheriffmuir Road to Menstrie Burn GCR site (Thirlwall, 1983b, 1988). These, together with other dates from the north Midland Valley, suggest that the late Caledonian volcanic activity in this area occurred during the limited interval of 415–410 Ma (see the Balmerino to Wormit GCR site report).

Large strips of vaguely defined hornfelsed country rock that crop out in the floor of Harviestoun Glen are possibly enclaves within the Elistoun diorite. These enclaves and their associated hybridization underlie non-hybridized, coarse-grained diorite, giving a sub-horizontal layered effect and Francis *et al.* (1970) recorded that the diorites here show differences in composition from one layer to another. Further evidence of hybridization (and metasomatism) cited by Francis *et al.* (1970) is the presence of 'ghost' scarp-featuring inherited from the subsumed lavas on Elistoun Hill. The 'ghosts' dip at about 10° to the NW in conformity

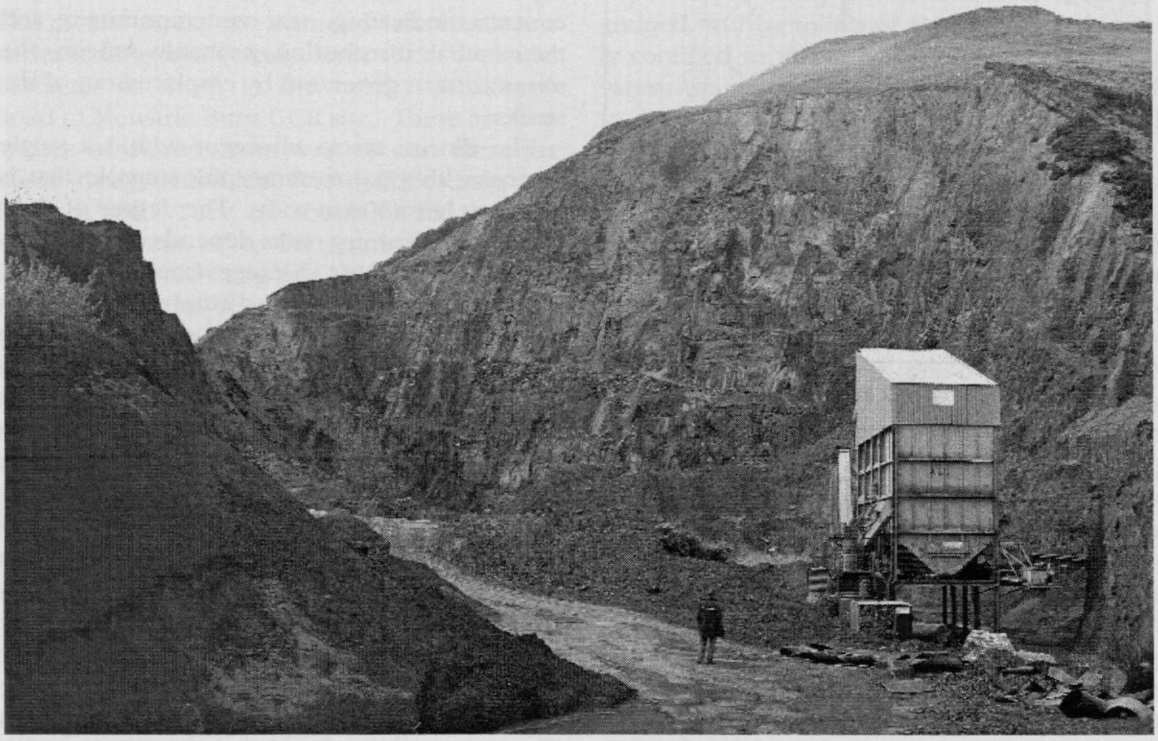

Figure 9.33 Castle Craigs Quarry, Tillicoultry. The quarry is along the line of the Ochil Fault plane; the back face exposes hornfelsed lavas and volcaniclastic conglomerates of the Ochil Volcanic Formation and the crags on the left are quartz-dolerite of the late-Carboniferous fault intrusion. (Photomosaic: M.A.E. Browne.)

with the regional dip of the rocks of the Ochil Volcanic Formation. Francis *et al*. also noted the way in which different topographical and weathering features may be used to map the generally narrow hybridized zones that delimit the outcrop of the diorites; the lava crags are more angular and the non-hybrid diorite crags are more rounded and massive.

Conclusions

The importance of this GCR site lies in the excellent exposures of the late Caledonian diorites that are intruded into the lavas and volcaniclastic sedimentary rocks of the Ochil Volcanic Formation. These include purely magmatic quartz-diorites and hybridized pyroxene-rich diorites. The changes caused by thermal metamorphism of the country rocks are also a feature. In particular the often diffuse contacts between the altered country rocks (hornfels) and the diorites, with ghost-like features within the hybridized diorites, contrasts with those where wholly magmatic diorite is in sharp contact with country rock. It may be concluded that the diorites were emplaced partly by simple intrusion and assimilation, with radial fracturing of the surrounding rocks, and partly by metasomatic replacement of country rocks.

PORT SCHUCHAN TO DUNURE CASTLE (NS 247 152–252 159)

G. Durant

Introduction

Lower Old Red Sandstone volcanic rocks crop out along the Ayrshire coast at Dunure, Culzean and Turnberry where they occupy a total area of approximately 40 km^2. The Dunure coastal exposures are part of the Carrick Hills outcrop; those of Culzean and Turnberry are smaller down-faulted inliers (see the Culzean Harbour and Turnberry Lighthouse to Port Murray GCR site reports) (Figure 9.34). The Ayrshire coast volcanic rocks conformably overlie the local Lower Old Red Sandstone succession of sandstones, conglomerates and cornstones and are in turn overlain unconformably by Upper Old Red Sandstone sedimentary rocks. The volcanic rocks are predominantly calc-alkaline andesites, suggested by Thirlwall (1981a) as being the product of subduction-related volcanism. The basal lavas are interbedded with the topmost beds of the sedimentary succession and sedimentary intercalations occur throughout the volcanic sequence suggesting that the volcanic rocks are the same general age as the sedimentary rocks.

Smith (1910) estimated that the volcanic rocks of the Dunure area are approximately 130 m thick in total, although a much higher figure of 300 m was given by Eyles *et al.* (1949). This section is important because of the complex relationship between volcanic rocks and intercalated sedimentary rocks, which has led to the suggestion that much of the sequence consists of subvolcanic sills rather than lava flows (Kokelaar, 1982). The volcanic units will therefore be referred to as 'sheets' in the following accounts. Petrographically the volcanic rocks are augite-, enstatite-, and pyroxene-olivine andesites with rare basalts near to the base of the sequence. The andesites are commonly markedly feldsparphyric and also highly vesicular. The vesicles are filled by a variety of secondary products, but it is the agates described by Smith (1910) that makes this section of the coast popular with collectors (see Heddle, 1901; Macpherson, 1989).

Description

A well-exposed sequence of andesite sheets with minor intercalations of sedimentary rock is exposed in the low cliffs, the sea stacks and on the wave-cut platform between Port Schuchan and Dunure. A porphyritic, vesicular andesite forms the wave-cut platform immediately west of Port Schuchan and two prominent sea stacks, the Two Sisters, are isolated outliers of the 7 m-thick overlying andesite sheet. At the base of the south-easterly of the Two Sisters (2468 1523), a highly distinctive pillow of vesicular andesite has cut into the finely laminated sandstone between the andesite sheets (Figure 9.35). The lamination within the sandstone remains close to that of the regional dip even when remnants are isolated by the pillowed andesite. Thin sandstone 'dykes' (up to 2 cm wide) cut through the massive central part of the andesite sheet which forms the stacks. The sandstone between the andesite sheets is intimately mixed with the volcanic rock in places; it can infill vesicles or occur within the andesite as irregular structureless patches, some of which are traceable back to larger more laminated patches. This is well displayed in outcrops near the top of the shore just to the east of the south-easterly of the Two Sisters stacks.

The 12 m-thick andesite sheet forming the distinctive cliff at Dunure Point (2473 1532) to the NE of the Two Sisters, is cut by numerous thin sandstone 'dykes', which follow broadly curving paths from the bottom to the top of the sheet.

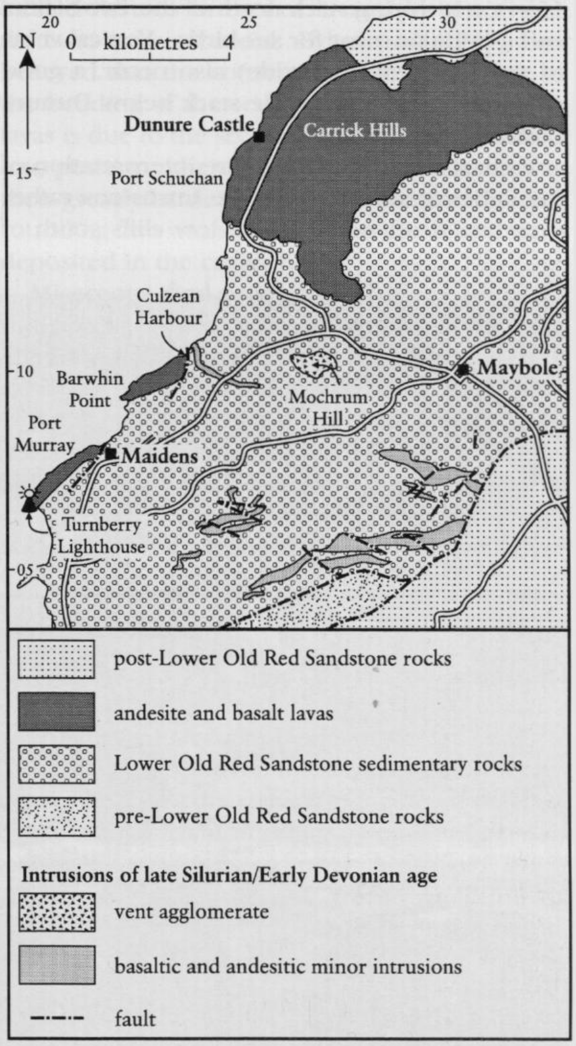

Figure 9.34 Map of the Ayrshire coast outcrops of Lower Old Red Sandstone volcanic rocks.

Where the andesite sheet is seen in horizontal section on the wave-cut platform, the sandstone 'dykes' can be seen to be part of a branching, pseudohexagonal network. The sandstone within the dykes has been hardened and often stands proud, being more resistant than the andesite. This is well displayed to the NE of Broad Crag (2500 1569) and on the shore just below Dunure Castle (2517 1582).

The bases and tops of individual sheets are often markedly amygdaloidal, the original vesicles having been infilled with quartz, agate and calcite. Minor amounts of galena, pyrite, manganese and baryte have been reported as associated minerals (Smith, 1910). Larger irregular masses of quartz and agate also occur within the andesites. A 75 × 50 cm oval mass of quartz occurs near the summit of Mackerel Rock (2471 1544), a low-lying stack north of the Two Sisters and a popular roost for sea-birds. Vertical veins of agate (up to 1 cm wide) also occur, a good example being seen in the stack below Dunure Castle.

Critical exposures for the re-interpretation of the andesite sheets as sill-like intrusions rather than lava flows occur in the low cliffs south of Dunure Castle. A good example of a typical contact between two andesite sheets occurs immediately to the east of Mackerel Rock (2482 1544). In this low cliff section the pillowed and highly vesicular upper contact of the lower andesite sheet encloses and is partially overlain by sandstone, which is laminated in places and structureless elsewhere. Pillows at the base of the upper andesite sheet cut down into the sandstone and sandstone 'dykes' traceable back to this sedimentary enclave run upwards through the upper sheet. This exposure has been figured by Kokelaar (1982, fig. 4B). A good example of the complex upper surface of one of the andesite sheets occurs in a low cliff at the top of the shore to the SE of Scart Rock (2494 1553). Protrusions of andesite from the main mass, penetrate upwards into laminated sandstone. The laminations within a diagonally orientated remnant wedge of sandstone are absent within 2 cm of the contact with andesite (see Kokelaar, 1982, fig. 4C). Such observations led Kokelaar (1982) to postulate a process of sediment removal by fluidization as the lobes of andesite burrowed into wet, unconsolidated sediment. The wet sediment into which the magma was

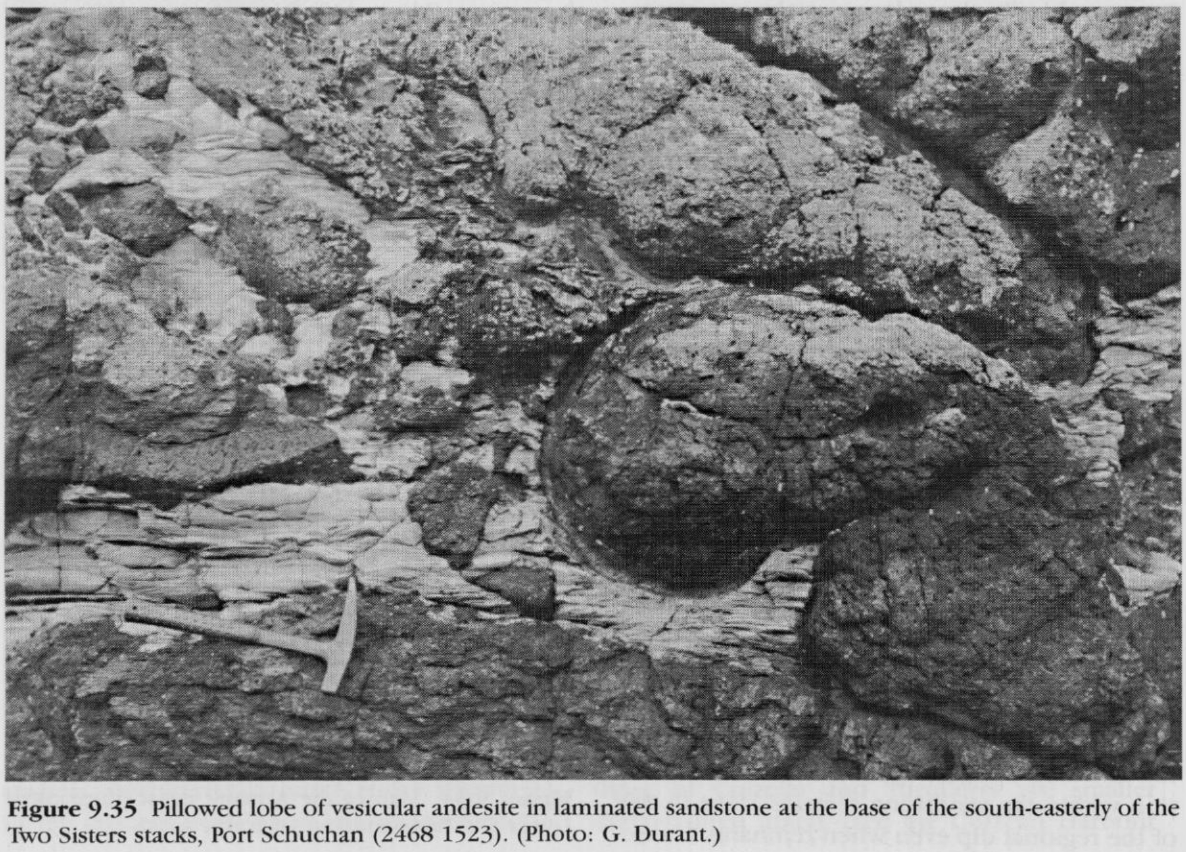

Figure 9.35 Pillowed lobe of vesicular andesite in laminated sandstone at the base of the south-easterly of the Two Sisters stacks, Port Schuchan (2468 1523). (Photo: G. Durant.)

intruded is now preserved in part as vesiculated sandstone. This feature can be seen on the shore just south of Dunure Castle (2518 1583).

Dunure Castle sits on top of a raised sea stack composed of enstatite andesite (Tyrrell, 1913) which shows a marked internal fabric parallel to the base of the flow. Loose wave-polished blocks beneath the castle show that this fabric is an internal feature caused by textural differences within the intrusion. Such internal textural differences and consequent differential erosion are also responsible for the pseudo-brecciated appearance of the andesite forming Scart Rock (2800 1560). At the base of Dunure Castle (2519 1586) numerous monolithological blocks of andesite occur within light-coloured calcareous sedimentary rock that form the enclaves between intrusive sheets. A fossil arthropod, *Kampercaris tuberulata*, was found by Smith (1909) in rocks close to Dunure Castle, and was subsequently described by Brade-Birks (1923). Rolfe (1980) places the discovery of these arthropod fossils and tracks in an overall evolutionary setting.

Interpretation

The relationship between the sedimentary rocks and the andesites has interested a number of authors over a considerable period since it was first noted in the Geological Survey Memoir for Sheet 14 (Geikie *et al.*, 1869). The survey authors noted vertical veins of sandstone traversing the 'lavas' and suggested 'that the veins were due to sand being washed into the irregular star-shaped cracks of cooled lava before the flow was covered by the next stream of molten matter'. Smith (1892) who discovered fossil arthropod tracks in the fine-grained sedimentary rocks was sceptical about this interpretation. The tracks figured by Smith (1909) are preserved in fine detail 'owing evidently to the fact that in the quiet recesses within the lavas, there would be no commotion to disturb the surfaces of the sedimentary laminae after the markings had been made on them'. A critical observation by Smith (1909) is that 'the lava has sometimes scoured away portions of the sedimentary beds. This is well demonstrated as sometimes a series of footprints will extend right up to the side of a lava ... where one row had been cut by it and the other left'. Heat blisters identified by Smith (1909) also demonstrate that the wet sediment was baked by the heat of the intruding magma.

Geikie (1897) viewed the lava–sediment relationships somewhat differently, believing that the sediments had entered the fissures from above but in a subaqueous environment. However, he also indicated thoughts of another possible explanation (op. cit., p. 283) 'the first and natural inference which a cursory examination suggests is that the molten rock has caught up and carried along pieces of already consolidated sandstone'. He countered this observation with another, 'that the lines of stratification in the sandstone, even in what appears to be detached fragments are marked by a general parallelism and lie in the same general plane with the surface of the bed of the lava in which the sandy material is enclosed'.

Tyrrell (1913) believed that the sediment infilled fissures in cooled lavas and hence that the lavas were subaerial. Eyles *et al.* (1949) also believed that the constancy of the alignment of the bedding of the sedimentary rock within the lavas is due to the sediment having been washed into position, 'the sediment infilling fissures was then greatly hardened possibly because the surrounding lava was still hot when the detritus was deposited in the cavities'.

Micaceous fine-grained sandstones occur as thin and impersistent intercalations between the igneous sheets and as a series of irregular vertical dykes and fissure fillings. They are commonly finely bedded and this bedding is mostly consistent with the regional dip. However, as was pointed out by Kokelaar (1982), the bedding is absent immediately adjacent to the volcanic rock and is now interpreted as being the original bedding of the sediment into which the magma burrowed, in so doing removing most of the unconsolidated wet sediment by fluidization. The bedded sedimentary rock that is observed in fissures within the andesite is therefore the last remaining vestige of a much greater mass of sediment that has been removed by the proposed fluidization process. This re-interpretation of the lava flows as high-level andesite sills emplaced into unconsolidated wet sediment (Kokelaar, 1982) means that the arthropod trackways found by Smith (1909) were probably formed in fine-grained sediment on the bottom of a shallow lake, prior to eruption, a suggestion which is in keeping with the findings of Pollard and Walker (1984), Pollard (1995) and E.F. Walker (1985) based on detailed examination of the fossil tracks.

The presence of multiple andesite sheets, requires a repetition of the conditions that resulted in the burrowing of magma into wet sediment rather than eruption at the surface. This argues for eruption into an actively subsiding sedimentary basin marked by a lake in which sediment accumulation took place in conditions quiet enough to preserve the arthropod trackways. The fine-grained nature of the sediment suggests that there was low relief around the margins of the lake, which was situated in a generally arid environment (Bluck, 1978b). In spite of the high degrees of vesiculation, the andesite magma seems to have been erupted relatively quietly, possibly from fissures. An earlier, possibly more explosive phase of volcanic activity is indicated by the presence of a breccio-conglomerate exposed at Barwhin Point at the SW end of the Culzean inlier (2185 0946), which contains volcanic rock fragments generally more siliceous than any found elsewhere within the overlying Ayrshire coast volcanic sequence (see the Culzean Harbour GCR site report).

Oxygen isotope studies of agates from both Dunure and Turnberry (Fallick *et al.*, 1985) support the idea of a low temperature (*c.* 50°C) origin for the agates from fluid having at least a component of meteoric water.

Conclusions

The Port Schuchan to Dunure coastal section has engaged the minds of geologists for more that 100 years. This section is of national and international importance because of the complex relationship between volcanic rocks and intercalated sediments. The volcanic rocks, predominantly pyroxene andesites, were originally interpreted as subaqueous flows (Geikie, 1897) or subaerial lavas (Tyrrell, 1913). A re-interpretation of the andesites as intrusions into wet, unconsolidated sediment (Kokelaar, 1982) relied on evidence from this section. Fossil arthropod trackways found in the laminated sedimentary rocks between the volcanic units furnish evidence of life in a Siluro-Devonian freshwater lake and Dunure agates, which form amygdales in the andesites, have been much prized by collectors since Victorian times. This is an enjoyable and instructive section, which has an important part to play in the understanding of Lower Old Red Sandstone times and volcanic processes.

CULZEAN HARBOUR (NS 231 102)

G. Durant

Introduction

A down-faulted inlier of Lower Old Red Sandstone andesites crops out along the coast by Culzean Castle (Figure 9.34). The andesites represent a southerly extension of the Carrick Hills volcanic sequence, which is also exposed at Dunure (Port Schuchan to Dunure GCR site) and Turnberry (Turnberry Lighthouse to Port Murray GCR site). A general description of the overall sequence is given in the Port Schuchan to Dunure site description. These coastal outcrops have been studied for over 100 years (e.g. Smith, 1892) and the spectacular setting of Culzean Castle on top of a 35 m-thick andesite intrusion has been a source of inspiration to artists and geologists alike (Figure 9.36). Evidence from this section has been important in the re-interpretation of some of the lavas as sill-like intrusions into wet sediment (Kokelaar, 1982).

Description

The base of the 35 m-thick andesite sheet which forms the main cliff beneath Culzean Castle is seen in the stack just to the north of the Culzean Harbour slipway (2311 1028). This enstatite andesite (Tyrrell, 1913) overlies a coarse debris flow deposit consisting of blocks of andesite and sandstone in a sandstone matrix (Figure 9.37, and see Kokelaar, 1982, fig. 4A). A highly vesicular basal pillowed zone cuts into the greenish grey laminated sandstone on top of the debris flow deposit. The laminations within the sandstone disappear close to the contact with the andesite and the sandstones are oxidized at the contact with andesite pillows (Kokelaar, 1982). The massive andesite is cut by numerous thin sandstone 'dykes' which can be traced back to a source in the sediment beneath the andesite. The pillowed top of the Culzean andesite intrusion contains pockets of structureless sandstone and is overlain by debris flow deposits similar to those beneath the sheet.

The strongly pillowed base of a vesicular andesite forms the low cliff to the south of the Culzean Harbour slipway (2304 1022) just to the north of Dolphin House which sits on the raised beach. Individual pillows are up to 2 m across.

Pale greyish-green fine-grained laminated sandstone occupies the space between the pillows. The bedding laminations in the sandstone are constant throughout the outcrop and they are consistent with the regional dip. A similar relationship is well displayed in the southern wall of a raised sea-arch close to the southern end of the GCR site (2271 1000), where the pillowed lobes at the base of another andesite sheet protrude into sandstone.

Amygdales and veins of agate and quartz within feldspar-phyric andesite are well displayed on the wave-polished surface immediately beneath the small roundhouse close to the southern end of Dolphin House (2299 1018). Vesicular andesites from this section have been described by Geikie (1897) as being some of the most beautiful volcanic rocks in Scotland. Larger, irregular masses of agate and quartz are seen within andesites a short distance to the south where a 1 m-long mass of agate, quartz and calcite, with quartz crystals lining a drusy cavity is exposed in the low cliff. A coarse breccia containing vesicular andesite fragments represents the particularly fragmented part of one andesite intrusion. The space between the andesite blocks is here filled by coarsely crystalline pink calcite rather than by fine-grained sandstone as elsewhere along the section.

Some compositional variation of the volcanic rocks is present in the area around Culzean Castle. The cliffs immediately beneath the castle are formed of enstatite andesite and an intrusive sheet of augite andesite with olivine occurs at Port Carrick, 1 km along the shore SW of Culzean (Tyrrell, 1913). To the north of Culzean olivine basalt forms a broad dyke which runs inland in the direction of the Mochrum Hill vent (Eyles *et al.*, 1929). At Barwhin Point, at the SW end of the Culzean inlier, a breccio-conglomerate contains fragments of volcanic rock that are generally more siliceous than any others in the Ayrshire coast sequence.

Interpretation

A small number of andesite intrusions into fine-grained sediment are exposed in the cliffs along the coastal section around Culzean Castle. The many detailed features that result from such intrusions are described, interpreted and discussed in a historical context in the section on

Figure 9.36 Culzean Castle from an old engraving by W. Daniell (*c.* 1838). Despite some vertical exaggeration, the spectacular setting of the castle on a cliff formed from a 35 m-thick sill of andesite is well conveyed.

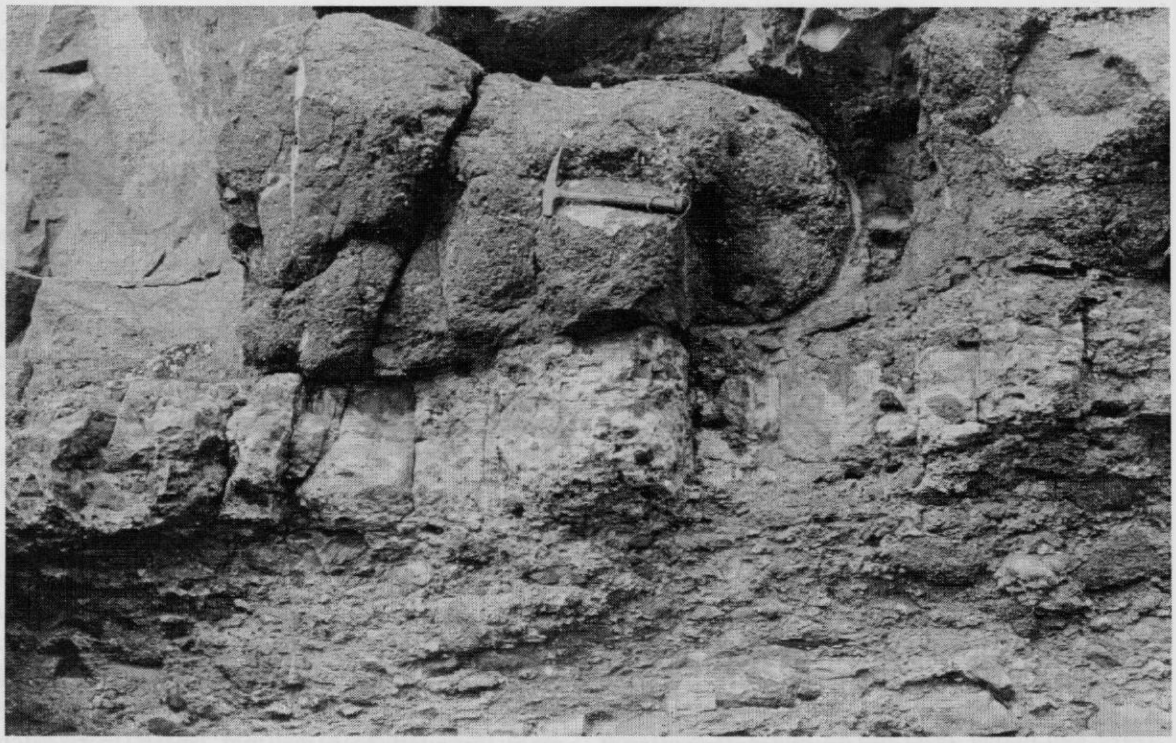

Figure 9.37 Pillowed base of an andesite sheet overlying volcaniclastic debris flow deposit at Culzean Harbour (NS 2311 1028). (Photo: G. Durant.)

the Port Schuchan to Dunure GCR site. In the Culzean section, the typical pillowed bases of andesite intrusive sheets are particularly well-displayed. The laminations in the sandstone between the andesite pillows appear to be generally undisturbed by the intrusion of the andesite magma and all follow the regional dip suggesting relatively passive intrusion of the magma. The debris flow deposits exposed north of the slipway (Figure 9.37) suggest that extrusive andesites existed close by and that these had been re-worked, or that shallow intrusive rocks were subject to penecontemporaneous erosion (Kokelaar, 1982). The exact site of eruption of the andesite magmas is not known but the volcanic vent at Mochrum Hill, 3.5 km east of Culzean, may be a source of some of the magma (Eyles *et al.*, 1949). An earlier, more siliceous and more explosive phase of activity may be represented by clasts in the breccio-conglomerate at Barwhin Point.

Conclusions

Like the other sites on the Ayrshire coast, the Culzean Harbour site is of national and international importance for the evidence critical to the re-interpretation of the Lower Old Red Sandstone lavas as intrusive sheets that have burrowed into wet, unconsolidated sediment. The highly vesicular lower contact of a thick andesite sheet below Culzean Castle shows characteristic well-developed pillow structure and the sheet incorporates sediment-filled veinlets and inclusions of fine sandstone. Laminated sandstone within pillowed andesite is well-exposed in the low cliff to the SW. The situation of this section in the grounds of Culzean Castle makes for a memorable visit.

TURNBERRY LIGHTHOUSE TO PORT MURRAY (NS 196 072–207 081)

G. Durant

Introduction

A down-faulted inlier of Lower Old Red Sandstone andesites crops out along the shore between Turnberry Point and Port Murray just

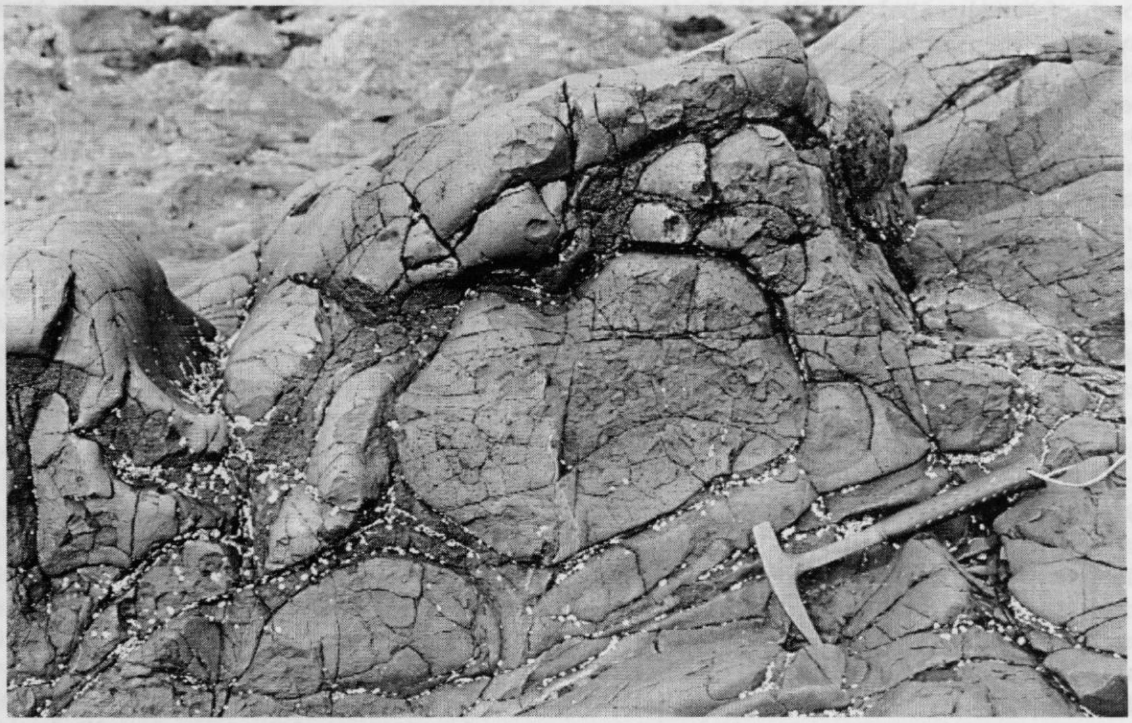

Figure 9.38 Pillow structure in sparsely porphyritic pyroxene andesite south of John o'Groats Port (NS 2032 0780), Turnberry Lighthouse to Port Murray coast section. (Photo: G. Durant.)

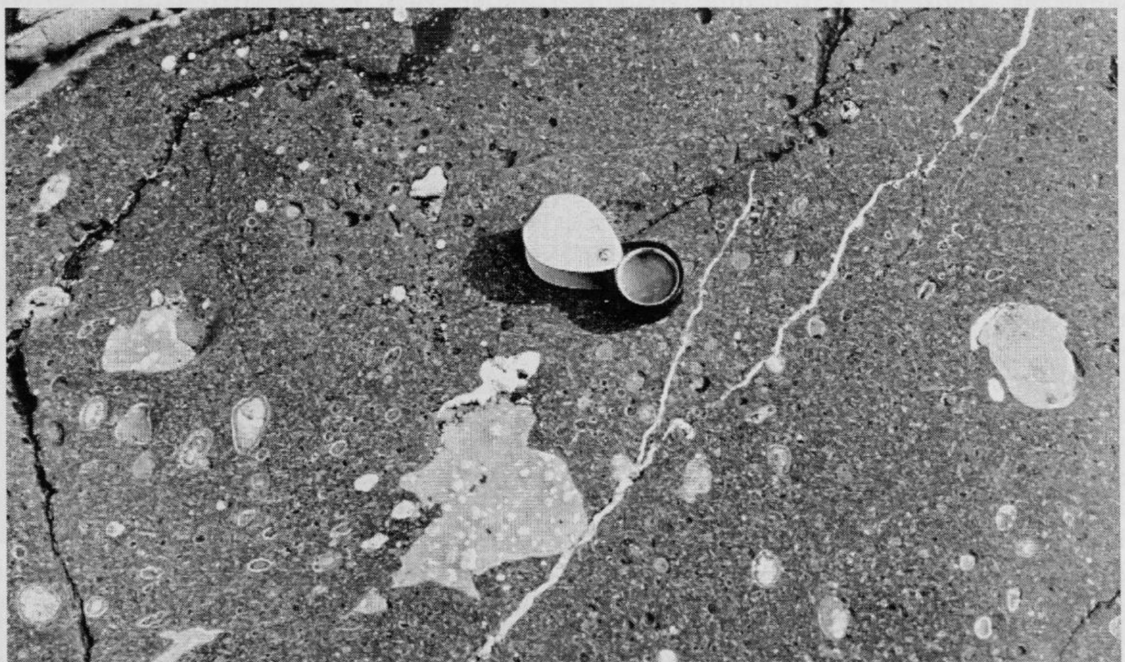

Figure 9.39 Inclusion of vesiculated sandstone in porphyritic andesite, Port Murray (NS 2058 0792). (Photo: G. Durant.)

south of Maidens Harbour (Figure 9.34). The lavas form the southernmost part of the Carrick Hills volcanic sequence and overlie a Lower Old Red Sandstone sedimentary sequence. A general description of the overall sequence is given in the Port Schuchan to Dunure GCR site description. Geikie (1897) identified 30 andesite flow-units within the Turnberry section that have been re-interpreted as sill-like intrusions into wet sediment (Kokelaar, 1982). The andesites crop out along the coast forming the wave-cut platform and low cliffs below the raised beach terrace. Inland exposures are masked by raised beach deposits.

Description

The lowest part of the section is exposed just south of Turnberry Lighthouse (1960 0718) where two andesite sheets occur, separated by a thin zone containing fine-grained sandstone. The pillowed base and brecciated top of one vesicular andesite intrusion is seen on the wave-cut rock platform in the bay immediately south of the lighthouse. The brecciated andesite fragments at the upper contact are locally dispersed within the sandstone, a structure which is known as peperite. The overlying andesite sheet forms the low cliff beneath the lighthouse. The base of this sheet is strongly pillowed and the andesite is partially autobrecciated within the intrusion.

The sequence of broadly similar andesites intruded into fine-grained sandstones continues north-eastwards along the coast. At the southern end of Broad Sands to the east of Castle Port (1978 0728), a strongly amygdaloidal andesite exposed towards the top of the beach, is particularly rich in agates. Sandstone dykes up to 20 cm thick conspicuously cut another andesite sheet exposed in the centre of Broad Sands Bay (1989 0738). The sandstone dykes are interbranching and follow a meandering path through the andesite as seen in horizontal section.

Finely laminated red sandstone is exposed in the northern part of Broad Sands Bay and the northern edge of the bay is defined by a low cliff where an andesite sheet cuts into the sandstone (1993 0753). The andesite sheet has a partially pillowed base and there is local development of a breccia with 10 cm fragments of andesite now supported in a bleached pale-yellow sandstone. The lower 50 cm of the andesite has also been bleached to a pale-grey colour.

Good examples of sandstone-filled joints (sandstone 'dykes') and finely laminated sandstone inclusions within andesite are exposed on the wave-cut platform to the east of the low sea stack Yellow Craig (1997 0760). A rather decomposed enstatite andesite occurs at Cross Ports (Tyrrell, 1913). Just to the SW of John o'Groats Port the strongly vesiculated and pillowed base of a 7–8 m-thick andesite intrusion has been described and figured by Kokelaar (1982, fig. 2) as a typical example of the upper and lower contact features of a moderately thin andesite intrusion into wet unconsolidated sandstone. The base of the sheet, although broadly conformable with the underlying sandstones, is highly irregular with numerous lobate protrusions into sandstone and detached, rounded, more or less irregular pillows. Peperites occur in this basal zone, comprising dispersed andesite fragments within the structureless sandstone. The massive central part of the andesite intrusion is well jointed and some of the joints are filled with sandstone forming sandstone 'dykes'. The upper contact zone is marked by more in-situ hyaloclastite with numerous andesite fragments and detached pillows supported in a structureless sandstone matrix, above which laminated red sandstone is present.

At John o'Groats Port (2030 0777) andesite and sandstone are mixed in a complex way where an andesite sheet lenses out into sandstone (Geikie, 1897; Kokelaar 1982, figs 3A and 3C).

In the upper part of the Turnberry Lighthouse to Port Murray section, the andesite sheets commonly show pillowed zones. Well-developed pillow structure is seen in a sparsely porphyritic pyroxene andesite south of John o'Groats Port (Figure 9.38). The surface of the pillows exposed on the wave-cut platform has a metallic light-brown patina and the surface of individual pillows is crazed with a network of fine joints. A pyroxene andesite with olivine occurs at John o'Groats Port and two flows of augite andesite occur at Port Murray (Tyrrell, 1913). Just south of Port Murray (around 2058 0792) the lower part of an andesite sheet is highly vesicular and encloses a considerable amount of sandstone in irregular patches or as sandstone-filled amygdales. A 15 cm-wide circular inflation structure, conspicuous in the wave-polished rock surface at the top of the beach, is presumably the result of the expansion to steam of water enclosed within the sediment. Immediately adjacent to this an irregular fragment of sediment has been vesiculated following enclosure within the andesite (Figure 9.39, and see Kokelaar, 1982, fig. 3D). The vesicles in the pale-green sandstone fragment are now filled by calcite.

On the northern side of Port Murray the partially pillowed base of an andesite sheet is well exposed at low tide. Immediately to the east of the disused slipway near Maidens at the northern end of the GCR site (2087 0810) a granular-textured vesicular andesite intrusion shows well-developed hexagonal jointing. At the upper contact of this intrusion the joints have opened up to allow a significant amount of sediment to penetrate between joint blocks in the andesite (Figure 9.40). The andesite is also brecciated locally and a striking rock occurs where the angular blocks (up to 15 cm) of strongly vesiculated andesite are set in purple sandstone.

Interpretation

The detailed evidence for the re-interpretation of the andesites as intrusions into largely wet and unconsolidated sandstone has been presented by Kokelaar (1982) (see the Port Schuchan to Dunure GCR site report). Geikie (1897) records 30 separate intrusions along the Turnberry section. It is not clear whether these are the result of 30 separate intrusions or whether there have been a smaller number of multiple sill-like intrusions at different depths within a pile of unconsolidated sediment. It is difficult to correlate individual sheets and hence to quantify the precise number of intrusive events, due to the compositional similarity between intrusions, the variability of character of the andesite within a single intrusion, the rapid changes in thickness of sheets and the presence of minor faulting. However, Tyrrell (1913) reported sufficient petrological variation to suggest that at least some of the andesite sheets were emplaced as separate events. If there were indeed 30 separate intrusions, then the local Lower Old Red Sandstone basin of sedimentation, presumably marked by a lake at the surface, must have been continuously sinking, possibly due to rifting associated with magmatic activity, in order to accumulate sufficient unconsolidated sediment into which subsequent

Figure 9.40 Sandstone infilling expanded cooling joints in andesite, Port Murray (NS 2087 0810). (Photo: G. Durant.)

sheets could be intruded.

As individual andesite sheets were intruded and cooled, a build-up of pressure beneath the intrusion would have caused the sediment to penetrate upwards into the cooling joints of the andesite as they opened. These joints are often curved and must have formed quite rapidly following intrusion. The upper parts of these sandstone 'dykes' are rarely seen and hence the relationship between the sandstone in the 'dykes' within an andesite sheet and that overlying the andesite intrusion cannot be fully evaluated. The fine-grained nature of the sediment and the local preservation of arthropod trackways (found by the author in Broad Sands Bay) argues for quiet depositional conditions.

Conclusions

Like the other GCR sites on the Ayrshire coast, this section is of national and international importance for the evidence demonstrating the high-level intrusion of magma into unlithified wet sediments. A sequence of 30 andesite 'lavas' in this historically significant section has been re-interpreted as a series of shallow intrusions. The basal and upper parts of the andesite sills are well-exposed along the section between Turnberry Lighthouse and Port Murray, and evidence critical to the re-interpretation is present.

PETTICO WICK TO ST ABB'S HARBOUR (NT 909 690–920 674)

D. Stephenson

Introduction

The volcanic rocks around St Abb's and Eyemouth are the best-exposed remnants of late Caledonian extrusive igneous rocks south of the Southern Upland Fault. The only other lava field, in the Cheviot some 25 km to the south, is more extensive but is less well exposed. A number of subvolcanic vents of comparable age and petrological affinity in Kirkcudbrightshire (see the Shoulder O'Craig GCR site report) provide evidence of volcanic activity farther to the SW. Although these volcanic rocks have overall calc-alkaline petrological characteristics, comparable with many modern orogenic suites, they do not conform to the systematic regional variations in geochemistry across the Midland Valley and Scottish Highlands, which have been attributed to the influence of a NW-dipping subduction zone (Thirlwall, 1981a, 1982; Fitton *et al.*, 1982).

Volcanic rocks occur within an outlier of Lower Old Red Sandstone rocks that extends inland from the coast between St Abb's and Eyemouth for some 10 km to the SW (Greig, 1988). The outlier rests unconformably upon an irregular topography of tightly folded greywackes of Llandovery age, and is overlain unconformably by the Upper Old Red Sandstone (Devono-Carboniferous in age). The Lower Old Red Sandstone affinity of the outlier is confirmed by a fragment of the arthropod, *Pterygotus* sp. (A. Geikie, 1863) and basal conglomerates and volcanic rocks are cut by a lamprophyre dyke dated at 400 Ma (Rock and Rundle, 1986). Other igneous intrusions in the immediate vicinity give similar Early Devonian radiometric ages. The sedimentary rocks of the outlier, which predominate to the south and south-west, almost all contain a volcaniclastic component, comprising fragments of fine-grained basaltic and andesitic rock. Reddish-brown sandstones predominate, but conglomerates, siltstones and mudstones occur locally and pedogenic cornstones have been recorded.

The volcanic rocks are concentrated in the coastal area, where two major and several minor vents have been recognized, and along the NW edge of the outlier. The GCR site comprises a 600 m-thick sequence of lavas and interbedded volcaniclastic sedimentary rocks that forms St Abb's Head, and a subvolcanic vent to the south, centred upon St Abb's village (Figure 9.41). They were first described by Archibald Geikie (1863) as part of the primary geological survey of Britain, and his account was subsequently expanded, together with a petrographical study by James Geikie (1887). A detailed account appears in the current memoir to Sheet 34 (Greig, 1988) and field guides based on this description have also been published by Greig (1975, 1992). The lavas are almost all autobrecciated and have all undergone extensive hydrothermal alteration, restricting the scope for geochemical investigation. Nevertheless, they were included in a geochemical study of Siluro-Devonian volcanic rocks in northern Britain by Thirlwall (1979) and this has been the basis for some speculation concerning magma genesis and tectonic implications.

Description

The volcanic succession of St Abb's Head is separated from Silurian sedimentary rocks to the SW by the NW-trending St Abb's Head Fault. This fault is marked by a low-lying valley, which at times of higher sea level would have cut off the headland from the mainland. The vertical fault plane, with a 2.5 m-wide breccia zone, is exposed at the cliff top at Hardencarrs Heugh (9176 6803). On the SW side of the fault, at Bell Hill (916 680), at least 120 m of conglomerates and sandstones rest unconformably on Silurian greywackes. The conglomerates contain pebbles of greywacke but, significantly, no volcanic rocks. These are the basal sediments of the local Lower Old Red Sandstone succession and immediately NE of the fault, at the base of the cliff of White Heugh (9185 6801), sandstones and siltstones are overlain by the lowest lava. A lamprophyre dyke (a minette with phenocrysts of biotite and pseudomorphs after olivine) which cuts sandstones on the east side of Bell Hill has been dated at 400 ± 9 Ma by K-Ar on separated biotite (Rock and Rundle, 1986), and a similar dyke cuts volcanic rocks 400 m to the NNE, at Horsecastle Bay.

The lavas at St Abb's Head are mostly fine grained and aphyric or olivine-phyric, with olivine content up to 12%; some are orthopyroxene-olivine-phyric. Phenocrysts are always pseudomorphed by secondary minerals. The groundmass generally consists of flow-aligned laths of plagioclase (labradorite to andesine when fresh), iron oxides and pseudomorphs after clinopyroxene. In some rocks biotite occurs as 'spongy' plates in the groundmass or associated with felsic segregations. Compositions are probably mostly in the range basalt to basaltic andesite, but in general the rocks are so altered hydrothermally that petrographical distinction is unreliable; rocks with over 5% olivine phenocrysts are generally considered to be basalts (Greig, 1988). Major element analyses are also unreliable, particularly because quartz is common in amygdales, as veins and as secondary silicification, exaggerating the silica content; all of the samples analysed by Thirlwall (1979) have silica in the range 54–57%, within the field of basaltic andesite. Feldspar-phyric lavas occur only on the east side of Kirk Hill, at the very top of the succession, but elsewhere in the outlier feldspar-phyric andesites are common and a single flow of dacite occurs near Eyemouth.

The lowest volcanic rocks, totalling at least 100 m in thickness, occur in a NW-younging sequence that extends from the top of the basal sedimentary rocks at White Heugh to Horsecastle Bay. Most of these lavas are red, aphyric, very finely vesicular and autobrecciated. The more massive parts of flows are up to 5 m thick and commonly exhibit good flow-jointing, mostly tabular and parallel to the flow margins but locally curved to bulbous suggestive of viscous flow. Most of the autobrecciation appears to have occurred *in situ* in blocky flows, but locally large tabular blocks of lava, tens of metres long, occur in poorly sorted, crudely bedded clastic units suggestive of down-slope mass movement accompanying the brecciation. This part of the succession is terminated by a NE-trending fault at Horsecastle Bay.

To the north of Horsecastle Bay, lavas and interflow sedimentary rocks dip generally to the SE at 30–40°. The sedimentary rocks, together with rubbly vesicular flow margins, are more easily weathered than the more massive flow centres and form hollows in a marked dip slope and scarp topography that is particularly well seen to the west and south of the lighthouse (Figure 9.42). Between the lowest exposed rocks at Pettico Wick and the highest at Kirk Hill, this part of the succession has an aggregate thickness of over 500 m; it has a different character to the basal flows south of Horsecastle Bay and is assumed to be entirely younger. Here, blocky lavas are up to 50 m thick. The upper and lower parts are vesicular or amygdaloidal, with much brecciation and hydrothermal alteration, and flow foliation is particularly well seen in the lower parts. The tops of flows are commonly marked by brick-red layers, 1–2 m thick. The more massive flow centres are mostly fine grained and purplish, with minute ferruginous pseudomorphs after original phenocrysts. Brecciation is commonly accompanied by ramifying veins and patches of bright-red homogeneous microbreccia with a finely crystalline matrix, which seems to have been auto-injected in a liquid state from the consolidating lava (e.g. in the road cutting around 9095 6905). The interflow volcaniclastic sedimentary rocks are commonly 1–2 m thick but units of up to 30 m occur locally. In places they overlie a planar eroded lava surface (e.g. by the Mire Loch dam (9145 6859)) but elsewhere they rest upon a perfectly preserved top surface of blocky lava and infill cavities to a depth of over 1 m (for

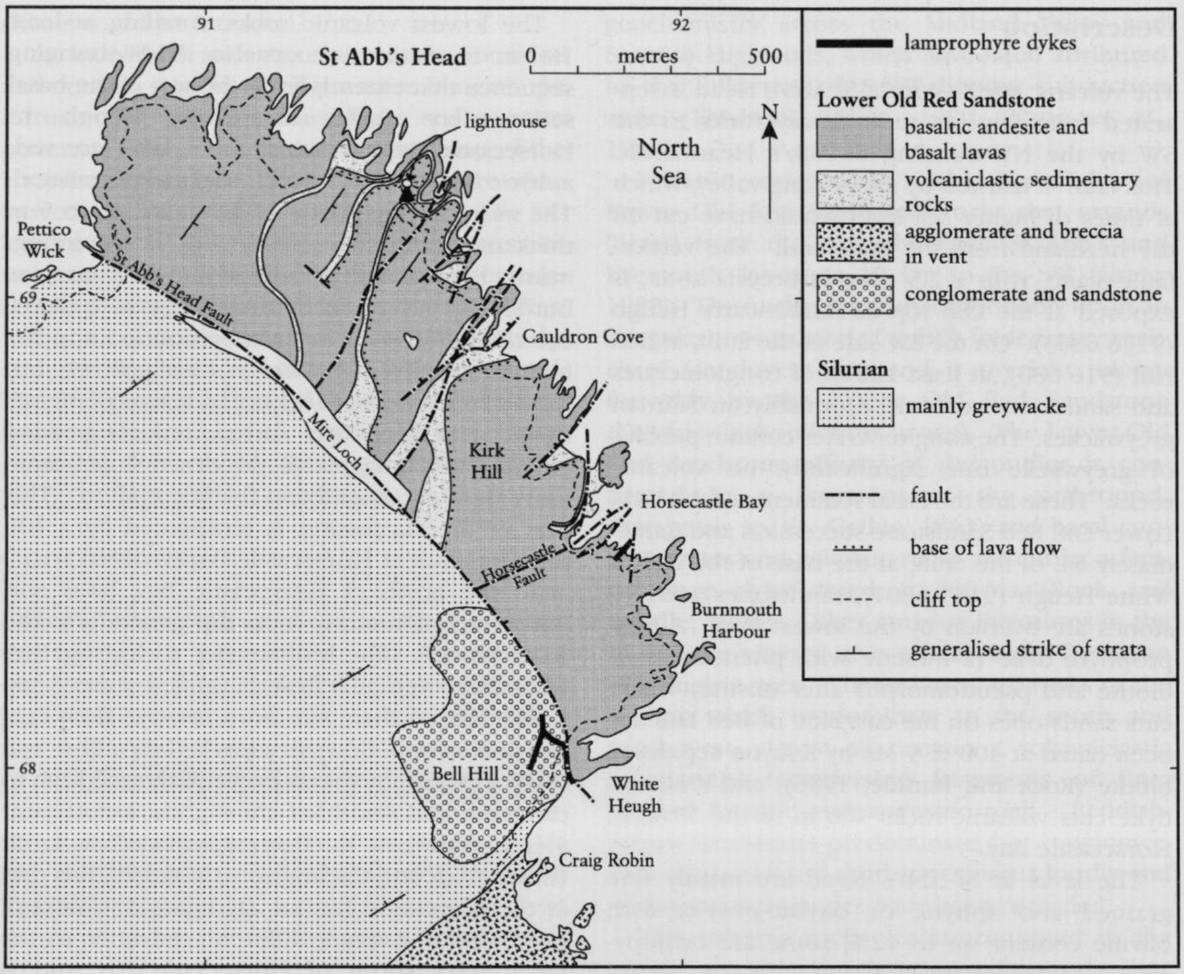

Figure 9.41 Map of the St Abb's Head area, adapted from Greig (1988).

example, below the lighthouse at 9137 6932 and at Cauldron Cove (9162 6889)). They are typically parallel bedded and poorly sorted, but with inverse grading in places. Clasts are angular and up to 20 mm in diameter; they consist entirely of fragments of reworked volcanic rock seemingly of local origin, although pale clasts may be more acid in composition and represent lavas that are no longer exposed. Although the volcaniclastic sedimentary rocks may contain some reworked pyroclasts and rare volcanic bombs, true bedded pyroclastic deposits are not represented in the St Abb's succession.

Shore and cliff exposures in the southern part of the GCR site are of breccia and agglomerate, consisting largely of unbedded, poorly sorted, very large blocks of igneous and volcaniclastic rock up to 2 m in diameter, many of which are moderately well rounded. Some large coherent masses of both lava and bedded volcaniclastic sedimentary rock occur, but their distribution and orientation is chaotic. In places a crude 'bedding' or size grading can be discerned, but this too has no obvious pattern. Many of the lava fragments are similar to those of the St Abb's Head succession, but there are also many that are feldspar-phyric. Some porphyritic andesites were considered by Greig (1988) to be intrusive into the fragmental rocks. At the NW margin of the agglomerates is a 100 m-wide zone of highly brecciated rocks with a marked, coarsely careous weathering that trends NE–SW through Craig Robin. To the north, this zone adjoins sheared Silurian greywackes and the marginal breccia contains blocks of both lava and sedimentary rock, including much yellowish weathering siltstone, in a finely comminuted matrix. Both the marginal breccia and the country rock are cut by

Figure 9.42 St Abb's Head from the north. The volcanic rocks of the headland are separated from Silurian greywackes, forming the smoother topography beyond, by the St Abb's Head Fault; the glacial channel which follows the fault contains the Mire Loch, which is just visible. Note the pronounced scarp and dip slope topography of the volcanic rocks, which dip to the left and away from the camera. (Photo: by kind permission of The National Trust for Scotland.)

abundant thin anastomosing veins of silica, carbonate and haematite. Although not exposed, the contact must be steep or vertical.

Interpretation

Outcrops of coarse breccia and agglomerate extend for almost 1 km on both sides of St Abb's village. Their unbedded, ill-sorted, chaotic nature, the rounding of the fragments and the steep, brecciated and veined margin are all indicative of a subvolcanic vent, as was first suggested by James Geikie (1887). A vent of similar size and nature occurs at Callercove Point between St Abb's and Eyemouth, and a cluster of small vents of a more basaltic nature around Hollow Craig, 5 km NW of St Abb's may also be related. These vents form a NW–SE trend, parallel to the coast, and it is tempting to suggest the presence of a volcanotectonic lineament which controlled the site of a group of small volcanoes and subsequently resulted in faulting on a similar trend. Detailed relationships between the vents and the volcanic sequences are not exposed. There is a general correspondence of rock types, but the St Abb's vent contains blocks of feldspar-phyric lava which are typical of the Eyemouth sequence rather than that now preserved at St Abb's Head.

The basal lavas, between White Heugh and Horsecastle Bay, are viscous autobrecciated flows that probably built up a moderate feature with sufficiently steep slopes to generate syn-eruptive mass-flow breccias on its flanks. Bedded volcaniclastic sediments were not deposited at this stage. Later eruptions, represented by the sequence between Pettico Wick and Kirk Hill, produced more massive, and possibly slightly more basic, blocky lavas up to 50 m thick. Between each eruption, weathering and oxidation of the flow tops occurred to a depth of

1–2 m. Planar-bedded, coarse-grained volcaniclastic sediments accumulated by reworking of debris as the volcanic rocks suffered rapid erosion. Reverse grading in many of these deposits suggests that they accumulated from high-energy flood deposits rather than by settling in areas of still water, and in several places blocky flow surfaces have been perfectly preserved by the rapid burial. If pyroclastic activity did accompany the eruptions of lava, the products must have been destroyed by erosion in a very short time, although obvious reworked pyroclasts, such as pumiceous or scoriaceous fragments are rare in the volcaniclastic sedimentary rocks now preserved.

The St Abb's and Eyemouth volcanoes probably had a limited lateral extent and the volcanic rocks give way to sequences entirely composed of volcaniclastic sedimentary rocks within a few kilometres to the south. Hence they were unlikely to have been connected directly with the Cheviot volcano and there is little compositional overlap between the two areas, although they were broadly contemporaneous.

The general high degree of alteration of the St Abb's and Eyemouth lavas and the consequent small number of samples analysed precludes any detailed geochemical discussion. Thirlwall (1979) describes them as calc-alkaline with relatively high Ni and Cr contents, implying a mantle component to the parental magma. However, they differ in detail from other Siluro-Devonian volcanic sequences and, although two groups of samples are identified, each with very distinct variation trends of many elements, neither of these can be attributed to simple fractional crystallization or progressive partial melting models. Like the Cheviot lavas, they do not fit into the spatial variation pattern of key elements such as Sr, Ba, P, K/Th and La/Y, which led Thirlwall (1981a, 1982) to suggest that the compositions of other Siluro-Devonian lavas relate to their position relative to a subducted slab of oceanic lithosphere. As with the major intrusions and dyke-swarms in the Southern Uplands Terrane (Rock *et al.*, 1986b), the chemistry of the lavas suggests magma generation at depths far greater than would have been possible, given their position relative to the proposed subduction zone. Both St Abb's and Cheviot are slightly later in age (400+ to 390 Ma) than the more northern lava sequences (424–410 Ma), the closure of the Iapetus Ocean, and the implied period of late-tectonic subduction (Thirlwall, 1988). It is therefore possible that they relate to a deeper, slightly later, subduction zone; or in view of their very close proximity to the assumed final position of the Iapetus Suture, they may not be related to subduction at all (see Chapter 1).

Conclusions

This GCR site is of national importance as a representative of the most south-easterly Siluro-Devonian volcanic centres. The lavas were probably erupted some time after closure of the Iapetus Ocean and provide evidence of magma generation in the region of the suture.

The high sea cliffs of St Abb's Head, together with abundant craggy exposures and a marked dip slope and scarp topography inland, exhibit magnificent three-dimensional sections through a 600 m-thick lava sequence associated with a small calc-alkaline volcano. Block flows of basalt and basaltic andesite exhibit a variety of internal features including flow-jointing, vesiculation, auto-injection, autobrecciation and mass-flow brecciation. Volcaniclastic sediments, derived from the local lavas and deposited under high-energy flood conditions, have preserved the top surfaces of several flows. Very coarse agglomerates of a related subvolcanic vent are well exposed on the foreshore NW of St Abb's Harbour and the steep, brecciated and hydrothermally veined margin of the vent can be seen particularly well.

SHOULDER O'CRAIG (NX 663 491)

P. Stone

Introduction

The Shoulder O'Craig GCR site exposes an Early Devonian volcanic vent that cuts Silurian turbidite beds. An intrusion breccia represents the earliest intrusive phase and this is cut by a later intrusion of basalt. Both vent and country rocks are cut by a series of lamprophyre dykes thought to be only slightly younger than the vent itself. The Silurian strata are sandstone turbidites (greywackes) of the Carghidown Formation (Hawick Group) which, although not fossiliferous at Shoulder O'Craig, elsewhere in the region contain a graptolite fauna indicative of a late Llandovery age (White *et al.*, 1992). The tur-

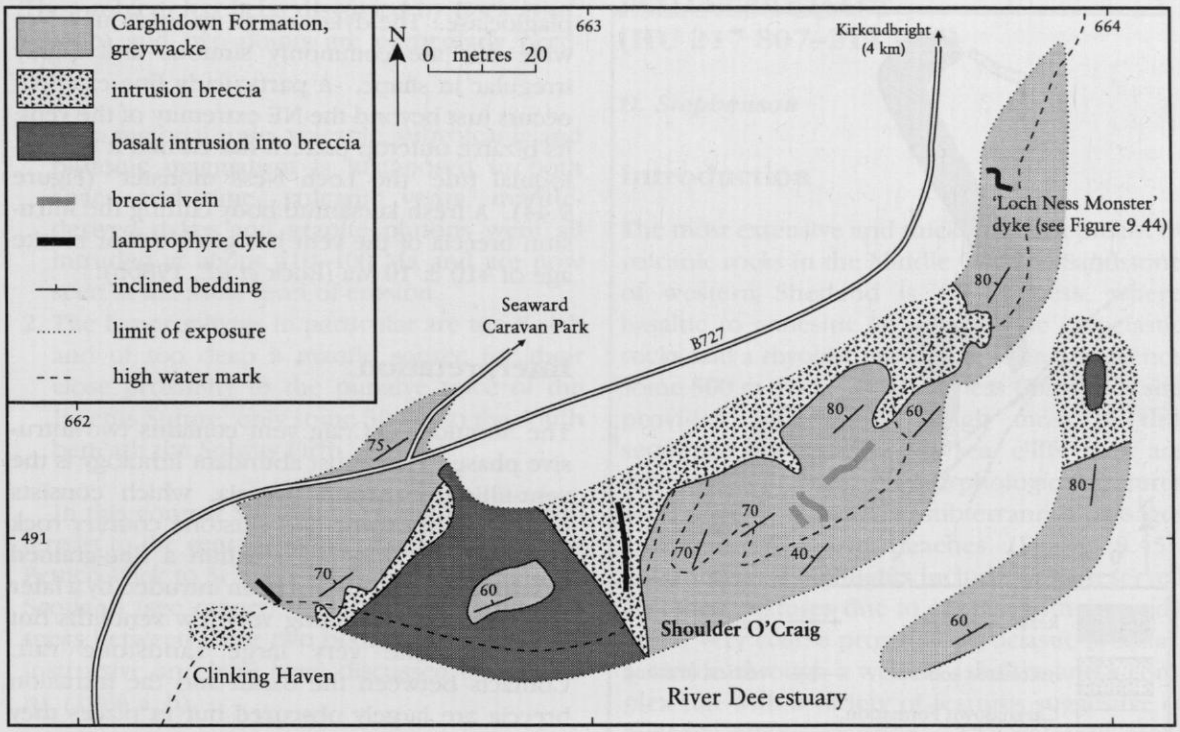

Figure 9.43 Map of the Shoulder O'Craig volcanic vent, after Rock *et al.* (1986a).

bidite beds were deformed and rotated to the vertical during the development of the Southern Uplands accretionary thrust belt (see Chapter 2, Introduction). The later stages of this deformation were accompanied by a range of minor intrusions and igneous activity continued after tectonism had ended, culminating in the emplacement of granitic plutons of the Galloway Suite at about 400 Ma (see Chapter 8). A number of late Silurian or Early Devonian volcanic vents are among the intrusive bodies seen. They appear to be entirely post-tectonic but for the most part are small and poorly exposed. The Shoulder O'Craig vent is one of the larger examples and its coastal locality provides excellent sea-cliff exposures illustrating the varied lithologies and textures within the vent itself, its relationship with the sedimentary country rock, and the morphology of slightly younger, but probably related, lamprophyre dykes. The site thus provides a rare opportunity to examine in detail the characteristics of a Caledonian volcano. A detailed description is provided by Rock *et al.* (1986a).

Description

The outline geology of the Shoulder O'Craig area is shown in Figure 9.43. The vent probably extends for a short distance inland beneath the caravan park. The country rock of the vent consists of beds grading upwards from sandstone to siltstone, each formed by deposition from a single turbidity current. In the immediate vicinity of the vent they strike approximately NE–SW and are vertical or dip steeply towards the NW, with sporadic zones of small-scale tight to isoclinal folding. A penetrative slaty cleavage is widely developed sub-parallel to bedding but terminates at the cross-cutting vent margin. This relationship establishes the vent as a post-tectonic intrusion.

The most striking aspect of the vent is the texture shown by the coarse breccia forming the earliest intrusive component. This is best examined on the wave-polished surfaces to the north of Clinking Haven where both matrix-rich and clast-rich varieties can be identified. The cliff sections provide more extensive exposure in three dimensions and confirm that the breccia consists principally of variably rounded to subangular clasts of sandstone, siltstone and rare basaltic or microdioritic lithologies set in a fine-grained matrix. The latter is pervasively altered to chlorite and carbonate but traces of a relict texture suggest an original igneous (basaltic?)

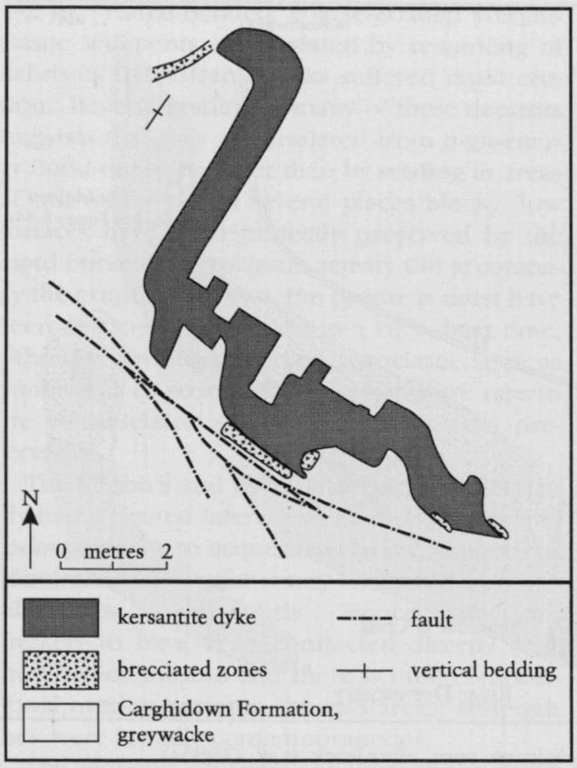

Figure 9.44 Sketch of the 'Loch Ness Monster' lamprophyre dyke, just north of the margin of the Shoulder O'Craig vent, after Rock *et al.* (1986a). (For location see Figure 9.43.)

composition. Most of the clasts seem likely to have been derived from the country rocks and in the cliff sections their size ranges up to rafts several metres in length. This part of the vent fill is an intrusion breccia (*sensu stricto)* although it has been generally referred to in the literature as a vent agglomerate (e.g. Rock *et al.*, 1986a). It is cut by at least two irregular and fractured masses of lamprophyric biotite-olivine basalt, the larger of which occupies much of the western end of the vent. The basalt is generally clast-free and its contacts with the adjacent intrusion breccia vary from sharp to diffuse and gradational. Oval, pillow-like textures and possible flow fractures may suggest intrusion in a semi-solid state (Rock *et al.*, 1986a). Breccia veins up to about a metre across cut the country rock in the vicinity of the vent and seem likely to be related to the intrusive episode.

Both vent and country rock are intruded by a suite of lamprophyre dykes, mostly kersantites in which large phenocrysts of biotite are contained in a melanocratic groundmass rich in plagioclase. The dykes range up to about 1.5 m wide but are commonly sinuous and highly irregular in shape. A particularly fine example occurs just beyond the NE extremity of the vent; its bizarre outcrop pattern has earned it the colloquial title 'the Loch Ness monster' (Figure 9.44). A fresh kersantite body cutting the intrusion breccia of the vent has given a K-Ar biotite age of 410 ± 10 Ma (Rock *et al.*, 1986b).

Interpretation

The Shoulder O'Craig vent contains two intrusive phases. The most abundant lithology is the vent-filling intrusion breccia, which consists largely of sandstone and siltstone country rock clasts carried into place within a fine-grained basaltic matrix. This has been intruded by a later basaltic mass containing very few xenoliths but enclosing one very large sandstone raft. Contacts between the basalt and the intrusion breccia are largely obscured but in places they appear to be gradational suggesting a continuum of intrusion rather than two separate episodes. Pillow-like textures and some possible flow-fractures could arise from emplacement of the basalt as a semi-solid mush (Rock *et al.*, 1986a). The basalt intrusion is altered, with chlorite generally replacing olivine, but some relict olivine remains together with a little biotite and augite. From this petrography and the abundances of trace elements such as Ti, Y and Zr, Rock *et al.* (1986a) classified this rock as a calc-alkaline basalt. The basaltic matrix of the earlier intrusion breccia is much more pervasively altered suggesting that this intrusive phase was more hydrous and volatile-rich. Breccia veins cutting the country rock close to the vent margin have been described as explosion breccias by Rock *et al.* (1986a) and may also relate to the earliest intrusive phase. However, they have an ambiguous relationship with the lamprophyre dykes which are demonstrably intrusive into the intrusion breccia. The dykes themselves are biotite-rich kersantites and most have highly irregular forms thought to reflect high volatile pressure during emplacement. They are an expression of deep-seated K-rich magmatism.

The calc-alkaline nature of the intrusions suggests subduction-related magmatism. However, that is difficult to reconcile with either of the proposed tectonic models for development of the Southern Uplands Terrane (see Chapter 1).

The problem has been discussed by Rock *et al.* (1986b) and two points are particularly pertinent:

1. On a regional scale, volcanic, subvolcanic and plutonic magmatism is juxtaposed in both space and time; volcanic vents, mantle-derived dykes and granite plutons were all intruded at about 410–400 Ma and are now seen at the same level of erosion.
2. The lamprophyres in particular are too K-rich and of too deep a mantle source for their close proximity to the putative trace of the Iapetus Suture, only some 30 km to the south beneath the Solway Firth.

In this context Shoulder O'Craig is the counterpart to the vent intrusion of similar age at the Pettico Wick to St Abb's Harbour GCR site in SE Scotland (see report); the similarities and contrasts between these two bodies are particularly instructive and have been discussed by Rock *et al.* (1986 a, b).

Conclusions

The Shoulder O'Craig locality provides the largest and best-exposed example in SW Scotland of a late Caledonian volcanic vent. The vent contains at least two components, an earlier intrusion breccia of country-rock sandstone clasts in a highly altered basaltic matrix, and a later basaltic plug-like intrusion. Possible explosion breccia forms veins cutting the country rock adjacent to the vent. Both vent and country rock are cut by lamprophyre dykes, which may assume highly irregular intrusive forms. A radiometric age of about 410 Ma from one lamprophyre dyke provides a minimum age for vent intrusion. The maximum age is constrained by the late Llandovery age (about 430 Ma) of the country rocks. These are turbidite sandstones and siltstones that were folded and cleaved prior to the emplacement of the intrusion breccia. Textures within the vent and its relationship with the country rock are exposed with unusual clarity.

The late Caledonian intrusive suite, of which the Shoulder O'Craig vent complex is a particularly fine example, is of regional tectonic significance in respect of subduction models for the closure of the Iapetus Ocean.

ESHANESS COAST (HU 217 807–211 775)

D. Stephenson

Introduction

The most extensive and thickest development of volcanic rocks in the Middle Old Red Sandstone of western Shetland is at Eshaness, where basaltic to andesitic lavas, andesitic pyroclastic rocks and a rhyolitic ignimbrite form a sequence some 500 m thick. The Eshaness Coast GCR site provides a section through most of this sequence, in spectacular sea cliffs that are renowned for their geomorphological features such as geos, blowholes, subterranean passages and cliff-top storm beaches (Figure 9.45). Volcanological highlights include well-preserved lava tops, textures due to contact with wet sediment, very coarse proximal pyroclastic breccias, a section through a welded ash-flow and a complex tuff with a variety of features suggestive of hydromagmatic eruption. The volcanic rocks were first described by Peach and Horne (1884) and subsequently in more detail by Finlay (1930). A succession modified from that established by Finlay forms the basis of the Geological Survey map by J. K. Allan (Wilson *et al.*, 1935) and of the summary by Mykura (1976). Some petrographical and geochemical details are given by Flinn *et al.* (1968) and Thirlwall (1979).

The Old Red Sandstone rocks of Shetland occur in three distinct structural blocks, differing in age, depositional and volcanological development, tectonic history and effects of igneous intrusion and low-grade metamorphism (Mykura, 1976). These blocks are separated by major N- to NNE-trending faults. The volcanic rocks of Eshaness, together with those of the island of Papa Stour and smaller outcrops at Melby on the western tip of the Walls Peninsula, all occur to the west of the Melby Fault (Figure 9.46) and hence are probably related temporally, if not magmatically (see Interpretation). The Eshaness outcrop, consisting almost entirely of volcanic rocks, is bound to the east by the probable northern extension of the Melby Fault, which juxtaposes the Northmaven plutonic complex. The rocks are folded into a shallow NNE-trending syncline, which plunges to the NNE in the northern part of the outcrop and to the SSW in the south. The GCR site (Figure 9.47) is entirely on the western limb of this syncline,

Figure 9.45 The cliffs of Eshaness, looking NE from the lighthouse. The nearest headland (the North Head of Caldersgeo) comprises andesitic pyroclastic breccias of unit 6 resting on andesites of unit 4. Most of the cliffs of the middle distance are andesites of unit 4; and the prominent dip-surface of the Grind of the Navir ignimbrite is just visible in the distance above the prominent stack (Moo Stack). (Photo: BGS no. D1660.)

which dips to the SE at 10–12°.

Description

The volcanic succession of Eshaness has been divided into nine units (Mykura, 1976), but the lowest two crop out only on the eastern limb of the syncline. Within the GCR site there is a continuous section from the ignimbrite of unit 3 in the north, to the pyroclastic rocks of unit 8 in the south (Figure 9.47).

1. and 2. The basal units, seen on the west side of Brae Wick (245 786) outside the GCR site, consist of reddish-purple micaceous sandstones and tuffaceous sandstones, overlain by olivine basalts and andesites with lenticular tuffaceous beds.
3. The well-jointed ignimbrite of unit 3 is responsible for the spectacular geomorphological feature of the Grind of the Navir (2127 8042). Here, large angular blocks have been, and still are being, excavated by the waves to form a natural passage and 'staircase' and then piled up on top of the cliff to form a high-level storm beach. Most of the outcrop consists of a relatively homogeneous pinkish-purple rhyolitic welded tuff with a well-developed eutaxitic fabric accentuated by flattening of the clasts. Broken and corroded crystals of pink alkali feldspar, commonly with a hollow core, are typically up to 10 mm long, but some are up to 150 mm; smaller fragments of collapsed pumice, shards of glass and rounded darker basic fragments are also abundant, with less common plagioclase, quartz and magnetite-rich aggregates that are presumably pseudomorphs after mafic minerals. All are etched out and well seen on weathered surfaces (Figure 9.48). The fine-grained grey matrix consists largely of devitrified glass with trails of opaque 'dust' and with elongate angular cavities. All parts of the rock are heavily altered, with the feldspars replaced by sericite and/or carbonate and pervasive secondary silicification throughout. The base of the ignimbrite is not exposed, but the top forms an extensive flat surface that dips inland behind the Grind of the Navir. A very sharp junction is well exposed between ignimbrite

with few clasts and a very fine-grained matrix and an overlying soft, yellow-brown-weathering tuff. The poorly sorted base of the tuff contains angular feldspar clasts up to 20 mm long similar to those of the ignimbrite, but it is generally fine grained above. Vesicles and cavities up to 20 mm long are flattened, but otherwise the tuff lacks the fabric of the underlying ignimbrite. Some of the cavities are filled by quartz, but others are hollow. The tuff is well bedded in parts and some beds have convolute flow structures with some brecciation. Coarser-grained beds up to 1 m thick contain large ragged fragments of very vesicular basic-looking rock.

4. Between Gruna Stack (213 802) and Drid Geo (209 790) are several sheets of aphyric andesite (Finlay recorded three), with distinctive vesicular, slaggy and autobrecciated tops. The vesicles are commonly elongated in the direction of flow. The central parts of the sheets have irregular to flaggy, flow-parallel jointing, commonly with a rather lenticular appearance. They are described as 'mugearites' on the Geological Survey map and by Mykura (1976), but the original designation as augite andesites is more appropriate for these essentially calc-alkaline rocks. Most are highly altered. At Brei Geo (2125 7975), the top surface of a sheet is spectacularly domed, the domes and hollows having an amplitude of 2–3 m. This surface can be examined in detail at the cliff top some 100 m to the north, where it is seen in contact with a remnant of bedded brown sandstone. Detached lobes and subangular patches of vesicular andesite, up to 20 cm across, cut across the bedding in the sandstone at a high angle and with a sharp contact (cf. peperite), suggesting intrusion of the magma into wet sediment. Undisturbed sandstone is not present between the sheets.
5. Andesites of unit 5 occur on the eastern limb of the syncline where they are highly silicified and oxidized. On the western limb they have been correlated on the map with a thin flow that rests upon green-, purple- and yellow-weathering clays developed on an amygdaloidal lava at the top of unit 4 (2083 7885). The thin flow, which is also yellow-brown weathering, is very flaggy at the base and has very strong flow-banding that is folded and convoluted in parts. Some layers are vesicular, with slightly elongate, lined vesicles 1–2 mm in diameter. Other layers contain angular pink fragments that could be silicified. The general impression is that this was a very viscous flow, more acid in composition than the underlying andesites.
6. Very coarse andesitic pyroclastic breccias, which are over 100 m thick in the GCR site, increase in thickness and overall clast size northwards (Finlay, 1930). Vertical sections are well seen around Calder's Geo (209 786) (Figure 9.45), but the breccias are best examined on the cliff top SW of the lighthouse (around 205 784), where all traces of soil and superficial deposits have been swept away by high-level wave action. The clasts are largely andesitic, but fragments of felsic rock, sandstone and metamorphic rocks are not uncommon. The larger blocks are up to 1 m in size and mostly angular. Some are slightly rounded, but there are no obvious bombs. The unit as a whole is very poorly sorted, but the relatively finer-grained beds are crudely bedded and crudely graded; more marked rounding of clasts suggests some reworking in parts.
7. The top surface of the pyroclastic breccias is remarkably planar and forms a prominent ledge around the north side of the headland 400 m SW of the lighthouse. It is overlain by a feldspar-phyric hypersthene andesite, which is homogeneous throughout most of its thickness with few vesicles and little development of rubble or visible hydrothermal alteration. For the most part it is massive and blocky, although the central part has spheroidal jointing, well seen at The Bruddans. At its base (2040 7825) it has a definite 5 cm chill. Its top surface forms the SE-dipping land surface on headlands to the north and south of The Cannon (a horizontal blowhole in the cliff). In contrast to the lower parts, the top of the flow has quite large elongate vesicles and some inclusions of sandstone, although it remains quite coarsely porphyritic, with no chill. There are abundant fissure fillings and some wider areas of poorly bedded yellowish-brown sandstone that seem to post-date the cooling of the lava. An overlying flow of pyroxene andesite, which crops out between the Bruddans and Stenness is less porphyritic and more scoriaceous with intense hydrothermal alteration in places. Finlay (1930) reported that this unit thickens towards the north where up to four flows occur.
8. A unit of very coarse andesitic pyroclastic breccias with subordinate interbedded sand-

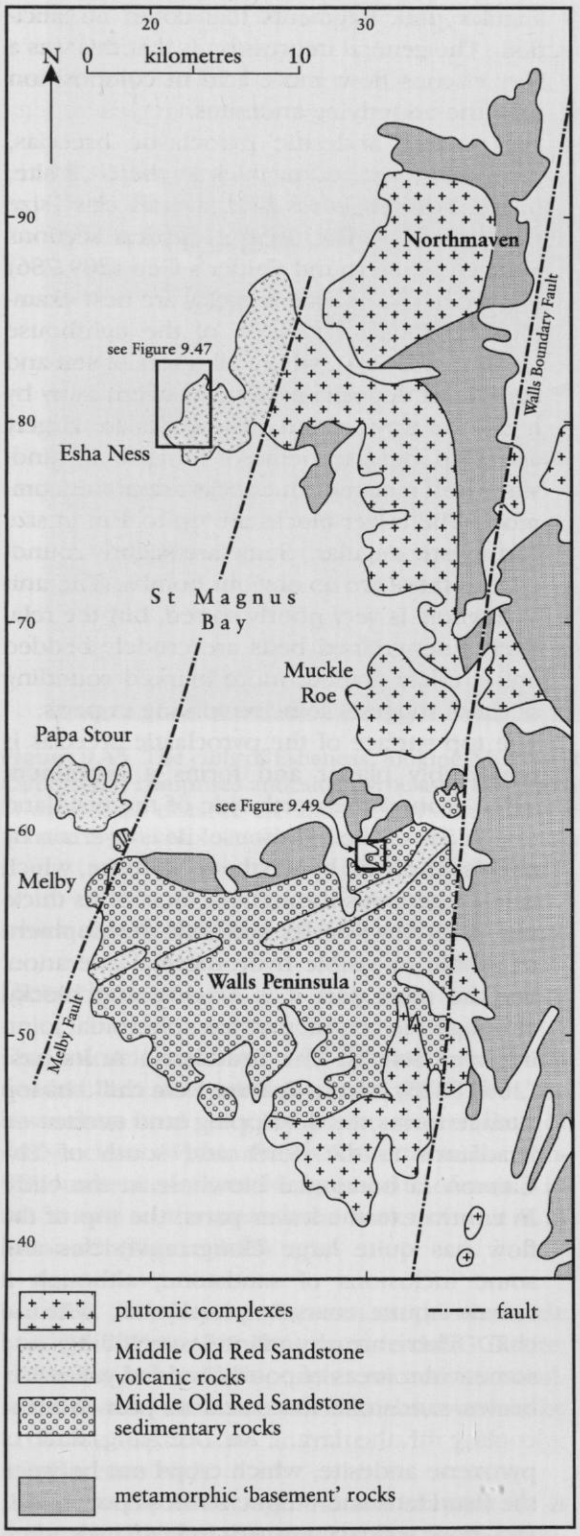

Figure 9.46 Location of Middle Old Red Sandstone volcanic rocks, major intrusions and major faults in western Shetland, after Mykura (1976).

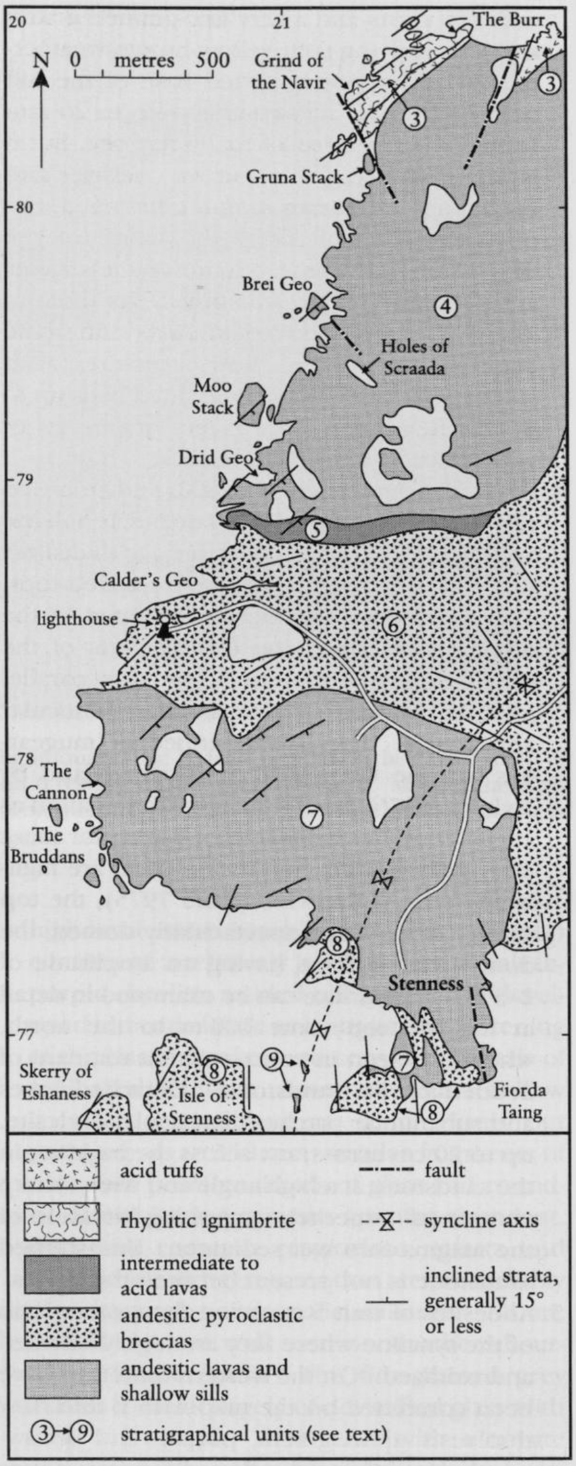

Figure 9.47 Map of the Eshaness coast, adapted from Geological Survey 1:10 560 sheets Shetland 19 and Shetland 23 (1959).

stone and conglomerate crops out in the core of the syncline at Stenness and on islands just offshore. The junction with the underlying lava is irregular and fissures and hollows in the lava surface are filled by tuff and sandstone. Much of the unit is massive, with blocks up to 1 m in size, but bedding occurs in places.

9. The highest unit is a flow of vesicular fine-grained andesite, which forms two skerries, 500 m SW of Stenness, just outside the GCR site boundary.

Interpretation

Because of the lack of intercalated sedimentary rocks in the Eshaness succession, there is little direct evidence of the environment in which the volcanism took place. However, by analogy with successions west of the Melby Fault at Melby and on Foula (Mykura and Phemister, 1976; Mykura, 1976, 1991), it seems reasonable to assume an arid or semi-arid alluvial plain with temporary lakes. The sediment was derived from the W or WNW and the area was close to the NW margin of the main Orcadian Basin where alluvial fans may have been developed. According to Mykura, post Mid-Devonian dextral movement of 60–80 km on the Melby Fault has transposed these outcrops from much farther south than the other structural blocks of Shetland, and confident correlations have been made with successions on Orkney (see below).

The eruptions were almost entirely subaerial, and the lack of sedimentary intercalations at Eshaness could be interpreted as evidence that the volcanic rocks accumulated rapidly, with such sediment as did accumulate between eruptions being removed by subsequent flows. There is good evidence at Brei Geo for interaction of magma with wet sediment, suggesting that at least some magma was emplaced as high-level sills in thin unconsolidated sediments, possibly on a lake bed. However, it is difficult to imagine this as the dominant mechanism in view of the general lack of intercalated sediments. The lowest andesite of unit 7 has many sill-like features (planar base with preserved chill, homogeneity, lack of alteration and flow-brecciation, inclusions of sandstone near the top). If it was emplaced as a sill, its top surface must have been uncovered for the cooling cracks to be filled with sediment prior to the eruption of the next flow.

The very coarse pyroclastic breccias of units 6 and 8 are clearly the products of large-scale eruptions and are relatively proximal, although there is no indication of where the source may have been, apart from the observation that some units thicken and coarsen northwards (Finlay, 1930). In addition to juvenile material, the vents sampled both sandstones and metamorphic basement, which is consistent with a site close to the margin of the sedimentary basin. Some reworking is apparent within the pyroclastic units, but a lack of volcaniclastic sedimentary rocks within the sequence in general suggests that the volcanism did not result in a pronounced topography.

The rhyolitic rocks of the Grind of the Navir probably represent a number of distinct types of pyroclastic eruption. The ignimbrite exhibits classic features of a welded pyroclastic flow with broken crystals, collapsed pumice and a classic eutaxitic texture. Mixed lithofacies in the overlying, dominantly well-bedded tuffs suggest the involvment of several eruptive styles; the basal, very poorly sorted lapilli-tuff and the finer-grained vesicular tuffs are probably the result of hydromagmatic eruptions that may have included pyroclastic surges and ash-falls, whereas the beds with large, ragged vesicular clasts suggest a more dominantly magmatic, possibly strombolian type.

The complete succession at Eshaness includes a wide range of compositions and Thirlwall (1979) has identified basalts, andesites, dacites and rhyolites. Several geochemical and mineralogical features suggest that the rocks are best classified as transitional between calc-alkaline and tholeiitic, in marked contrast to the calc-alkaline suites that characterize the Old Red Sandstone volcanic province in general. Thirlwall (1979) also presented good evidence that the Eshaness sequence could have been derived by multistage low-pressure fractional crystallization from a parental magma close in composition to an olivine tholeiite and relatively low in incompatible elements, features which are also atypical of the province as a whole.

There is no direct evidence of the age of the Eshaness sequence, although Flinn *et al.* (1968) did obtain a Rb-Sr isochron age of 365 ± 2 Ma (recalculated from 373 Ma using new constants) from the Grind of the Navir ignimbrite; in view of the pervasive alteration, this age is probably a minimum (Thirlwall, 1983a). Several authors have proposed correlations on lithological

Figure 9.48 Ignimbrite of the Grind of the Navir, Eshaness coast. The larger clasts are of alkali feldspar, commonly with a hollow core; smaller clasts are mainly collapsed pumice, glass shards and basic fragments. (Photo: BGS no. D1662.)

grounds between the volcanic successions at Eshaness, Melby and Papa Stour (Finlay, 1930; Flinn *et al.*, 1968; Mykura, 1976), but Thirlwall (1979) identified geochemical differences. Although the Papa Stour rocks seem to be significantly distinct to have formed from a separate centre, he did conclude that the Eshaness and Melby sequences could be related. The volcanic rocks of Melby occur above the Melby fish beds, which have been reliably correlated with the middle Eifelian Sandwick Fish Bed of Orkney and palynological evidence has confirmed the Papa Stour and Melby volcanic rocks as late Eifelian (Marshall, 1988; Rogers *et al.*, 1989, fig. 2).

Despite their Mid-Devonian age, Thirlwall (1979, 1981a) attributed the Eshaness and other volcanic rocks of Shetland to the same late Caledonian, WNW-dipping subduction zone that was responsible for late Silurian and Early Devonian volcanic and plutonic activity in northern Britain. He pointed out that their geochemical characteristics are even closer to those of modern arcs than are those of the earlier volcanic rocks in the main part of the province, and attributed their transitional tholeiitic nature to a closer proximity to the surface trace of the subduction zone. Although the magmas do have features that could be related to a subducted slab of oceanic lithosphere, by Mid-Devonian time the tectonic environment was one of post-orogenic extensional basins. Indeed, most of the volcanic activity in Shetland and Orkney was coeval with, and hence was probably controlled by, extensional faulting in the Orcadian Basin (Astin, 1985, 1990; Enfield and Coward, 1987; McClay *et al.*, 1986; Rogers *et al.*, 1989).

Conclusions

The volcanic sequence at Eshaness is representative of several in the most westerly structural block of Old Red Sandstone outcrops in Shetland. Their late Eifelian age is significantly later than Old Red Sandstone volcanism elsewhere in northern Britain, but it is the earliest late Caledonian volcanism in Shetland and Orkney. Although the rocks have subduction-related characteristics, their eruption was probably related to a major phase of extensional faulting during the development of the Orcadian Basin.

The mainly andesitic and rhyolitic rocks of the GCR site have transitional calc-alkaline to tholeiitic petrological features and may be related by fractional crystallization. Proximal pyroclastic breccias are intercalated with subaerial lavas and some high-level sills intruded into wet sediment, although inter-volcanic sediments are rarely preserved in the sequence. The ignimbrite and overlying hydromagmatic tuffs at the Grind of the Navir constitute one of the best preserved records of continuous rhyolitic pyroclastic eruption in Britain, which would well merit further detailed study.

These and many other volcanological features, are well seen in magnificent sea cliffs that are also noted for their geomorphological structures.

NESS OF CLOUSTA TO THE BRIGS (HU 305 584)

D. Stephenson

Introduction

The Clousta volcanic rocks, which form an ENE-trending outcrop across the centre of the Walls Peninsula in western Shetland (Figure 9.46), comprise mainly basic and acid pyroclastic rocks, with some basaltic and andesitic lavas and shallow sills, rhyolitic lava domes and ignimbrites, and concordant intrusions of felsite. These are scattered as relatively thin and localized lenses within Middle Old Red Sandstone alluvial fan and lacustrine sequences. The Ness of Clousta to the Brigs GCR site (Figure 9.49) exhibits a variety of volcanic products but is particularly noteworthy for the evidence of interaction between magma and water-saturated, unconsolidated alluvial sediments, possibly giving rise to phraeatomagmatic explosions. The composition, internal structures and three-dimensional geometry of the pyroclastic accumulations in particular have been compared to those of maars and tuff-rings.

The volcanic rocks were first noted by Peach and Horne (1884) and were described briefly by Finlay (1930). The Walls Peninsula was mapped by the Geological Survey in the 1930s (Wilson *et al.*, 1935) and re-examined in detail in the 1960s, resulting in the current map and a detailed description of the volcanic rocks by Mykura (in Mykura and Phemister, 1976). A detailed, mainly sedimentological, study of the peninsula by Astin (1982) resulted in a radical re-appraisal of some of the volcanic rocks and their relationship to sedimentation. Some petrographical and geochemical details are given by Thirlwall (1979) and Astin (op. cit.).

The Old Red Sandstone rocks of Shetland occur in three distinct structural blocks separated by major N- to NNE-trending faults. The successions within each block differ in age, depositional and volcanological development, tectonic history and effects of igneous intrusion and low-grade metamorphism (Mykura, 1976). Most of the Old Red Sandstone of the Walls Peninsula occurs in the central block, bound to the west by the Melby Fault and to the east by the Walls Boundary Fault (Figure 9.46). Within this block, the Old Red Sandstone rocks rest unconformably on Precambrian metasedimentary rocks to the north and are intruded and hornfelsed in the south by the Sandsting plutonic complex (K-Ar mineral dates of 369 ± 10 and 360 ± 11 Ma by Snelling in Mykura and Phemister, 1976). They have been involved in two phases of intense folding with cleavage development, and have suffered low-grade regional metamorphism, locally up to low greenschist facies. Palynological data indicate a Givetian age (Rogers *et al.*, 1989, fig. 2), making the volcanic rocks younger than those of the western block (see the Eshaness GCR site report) and comparable in age to those of Orkney (see the Point of Ayre and Too of the Head GCR site reports).

In the Walls Peninsula, the Old Red Sandstone outcrop is divided by the ENE-trending Sulma Water Fault into areas of markedly different sedimentary facies that were assigned to two separate formations of different ages by Mykura and Phemister (1976). Astin (1982) recognized four diachronous sedimentary formations which, together with the Clousta volcanic rocks, comprise a single coherent sequence that can be correlated across the Sulma Water Fault. To the north of the fault, sedimentary rocks assigned to the Sandness Formation of Mykura and Phemister represent all four of Astin's forma-

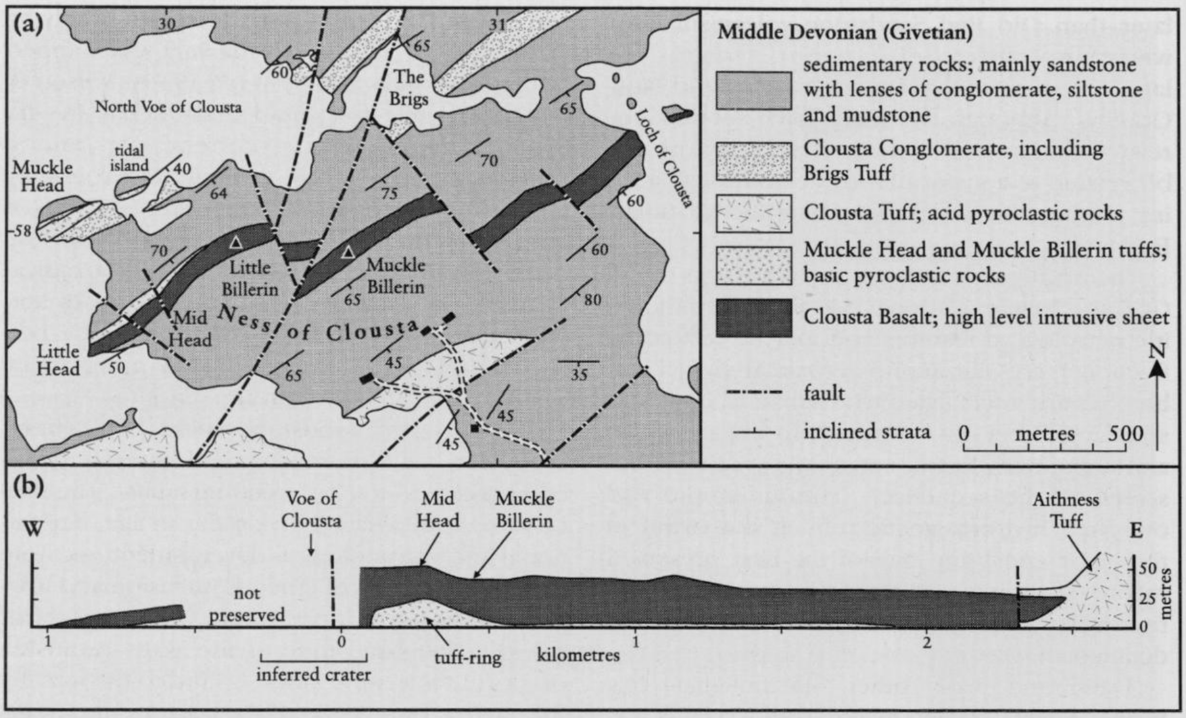

Figure 9.49 (a) Map of the Ness of Clousta to The Brigs GCR site, adapted from Geological Survey 1:10 560 sheet Shetland 42 (1967) and Astin (1982). (b) The Muckle Billerin Tuff and Clousta Basalt: reconstructed cross section based on measured sections, showing the different thickness either side of the Voe of Clousta. Vertical exaggeration ×2.5. (From Astin, 1982.)

tions. The strata dip generally to the SSE at moderate to high angles and the Clousta volcanic rocks are interbedded with the upper part of this sequence, adjacent to the fault.

Description

The GCR site (Figure 9.49) occurs towards the eastern end of the outcrop of Clousta volcanic rocks, which are here intercalated with medium- to coarse-grained sandstones locally with lenses of conglomerate and minor siltstones and mudstones, all assigned to the Vatslees Formation by Astin (1982). The Clousta Conglomerate, which is up to 70 m thick and can be traced for 5 km, forms a good topographical feature (Figure 9.50) and is a stratigraphical marker throughout the area. Within the GCR site there are two lenses of basic pyroclastic rocks, the Muckle Head Tuff and the Muckle Billerin Tuff; the latter is overlain directly by a sheet of basalt, termed the Clousta Basalt (the Muckle Billerin Basalt of Astin). Astin also identified a thin lens of acid volcaniclastic rocks within the Clousta Conglomerate, which he termed the Brigs Tuff. These volcanic units are described in stratigraphical order, combining the observations of Mykura (in Mykura and Phemister, 1976) and Astin (1982) with those of the author.

The Muckle Head Tuff

Muckle Head is formed from a lens of poorly sorted basaltic lapilli-tuff up to 35 m thick, which thins markedly north-eastwards over a strike length of 350 m. Only 2 m are preserved west of the Voe of Clousta. The tuff rests upon conglomerate, which may be the basal part of the Clousta Conglomerate, capping a coarsening upward sequence of slumped alluvial sandstones. Large blocks of conglomerate and sandstone occur in the base of the tuff, but their size and abundance decrease upwards. Clasts of magmatic material, mostly of basic to intermediate composition form up to 70% of the tuff and become more dominant towards the top of the lens. Most are scoriaceous or vesicular, some are flattened and some are glassy and enclose small quartz grains. Clasts of fine-grained acid igneous material are rare. The matrix is com-

Figure 9.50 View of the Ness of Clousta to The Brigs GCR site, looking east from Muckle Head. The Muckle Head Tuff forms the rocks of the foreground; the Brigs Tuff forms the extreme right of the tidal island beyond; the upper part of the Clousta Conglomerate, dipping to the right (SSE), forms the prominent feature crossing the tidal inlet in the middle distance; and the right skyline is the ridge of Muckle Billerin, formed by the Clousta Basalt overlying the Muckle Billerin Tuff. (Photo: D. Stephenson.)

posed mostly of quartz and feldspar derived from the underlying sediments, but garnet, epidote and titanite have also been recorded. The grains are commonly well rounded, but others are fractured and angular. The tuff is well bedded throughout its thickness and cross-bedding has been recorded. Overlying the tuff are well-bedded siltstones, which pass upwards into conglomerate. Astin has correlated these siltstones with a 2–3 m-thick lacustrine unit within the fluvial Clousta Conglomerate.

The Brigs Tuff

Immediately above the thin fine-grained lacustrine unit that divides the Clousta Conglomerate, is a sheet-like, coarse-grained volcaniclastic unit, up to 12 m thick, which thins only gradually to the ENE over a distance of 3 km. The unit consists largely of subrounded to angular lithic clasts of feldspar porphyry and less abundant flow-banded felsite in a finer-grained quartzofeldspathic matrix. Pumice, or other evidence of a magmatic eruption, is conspicuously absent. The lithic clasts are up to 40 cm across, there is little lateral variation in the size of clasts and, in general, the deposit is well sorted and largely clast supported. The unit is either massive or parallel-bedded and locally it has low-angle cross-bedding, with sets up to 20 cm thick that are well seen on the tidal island (at 2990 5811).

The Muckle Billerin Tuff

Poorly sorted basaltic pyroclastic breccia and lapilli-tuff are exposed on the northern side of Little Head (2976 5765) at the base of the Clousta Basalt and can be traced for about 2 km along the NW flank of the Muckle Billerin ridge. The lens is up to 24 m thick around Mid Head, but this proximal development only extends for about 450 m along strike. Farther to the NE there is only a thin distal fringe and to the SW, on the opposite side of the Voe of Clousta, there are 8 m (Figure 9.49b). The maximum clast size shows a systematic fining from blocks up to 30 cm around Mid Head to under 2 cm distally. The rock is composed of large amounts of quartzofeldspathic sand and basaltic to intermediate magmatic material, with less abundant blocks of acid igneous rock. The juvenile material varies in amount from 10–70%; it is commonly scoriaceous and vesicular and some clasts are flattened and welded, especially in proximal areas. The quartzofeldspathic and acid material is commonly fractured and angular and is more abundant in the proximal area. The whole deposit is very well bedded, dominantly parallel-bedded, but with some cross-bedding, low-angle discordances and shallow scour and fill structures. The set height of the cross-bedding varies systematically from up to 15 cm proximally to a few centimetres distally.

The Clousta Basalt

This sheet of basalt, which rests directly on the Muckle Billerin Tuff, is the most extensive of several in the eastern outcrops of the Clousta volcanic rocks. It forms a prominent, fault-stepped ridge extending for 2.5 km from Little Head to the shore of the Loch of Clousta and onwards, forming a string of small islands in the loch. The thickness varies from 25–40 m on the Ness of Clousta, but west of the Voe of Clousta, only 8–9 m are preserved. The basalt is aphyric and is pervasively altered, with small feldspar laths in a chloritic matrix that is replaced in parts by aggregates of green biotite, actinolite and epidote as a result of the regional metamorphism. It is vesicular throughout and has well-developed pipe amygdales at its base in places (for example on Muckle Billerin at 3064 5801). Partly remelted inclusions of tuff are also found in the base. The top surface of the sheet is well exposed on the east side of Little Head (2982 5763). Here, the contact is highly irregular, with bulbous protrusions and isolated globular to subangular pods of scoriaceous basalt in sharp contact with the overlying sediment (cf. peperite). Immediately overlying the basalt in places is a volcaniclastic coarse sandstone with quartz, feldspar and some dark igneous clasts that may be slightly flattened; it could therefore be a tuff. More generally, the contact is with purple siltstone and mudstone, the latter having large elongate vesicles. All the signs are that the basalt was intruded at a very shallow depth into the junction between tephra deposits and overlying unconsolidated wet sediments.

Interpretation

The volcanic rocks in the Clousta area were erupted on to the sands and gravels of braided river channels in an alluvial fan derived from metamorphic basement to the north (Astin, 1982). This fan bordered a shallow lake with beach ridges to the SW, which may have encroached north-eastwards at times, depositing finer-grained sediments such as those preserved in the middle of the Clousta Conglomerate. In this environment, volcanic activity is likely to have been phreatic or phreatomagmatic as a result of interaction of rising magma with groundwater or surface water, just below or at ground level. Astin has interpreted many of the pyroclastic deposits as the products of such eruptions.

The basic pyroclastic deposits of the Muckle Head and Muckle Billerin tuffs (and the Hollorin Tuff, 3 km to the WSW of the GCR site) have the composition, bedforms and geometry of phreatomagmatic deposits. The high content of detrital quartz and feldspar and the larger blocks of sandstone and conglomerate reflect the explosive excavation of a vent crater in the underlying alluvium. Indicators of lateral transport, such as cross-bedding, which characteristically decreases in set height away from the vent, coupled with finer-scale planar bedding are typical of pyroclastic surge deposits. But the high proportion of planar bedding suggests that much of the deposit resulted from ash-fall.

Astin reconstructed the original geometry of the basaltic tuffs from measured sections (Figure 9.49b). These formed very shallow cones, 700–1000 m in diameter, with approximate height to width ratios in the range 1:18 to 1:40. Allowing for possible incomplete preservation of the original height, these are comparable with those of modern tuff-rings (1:10 to 1:30; Heiken, 1971). The Muckle Head and Muckle Billerin tuffs each show their maximum thickness, maximum clast size and greatest proportion of sediment-derived clasts close to the Voe of Clousta. Although these features imply close proximity to the vents and possible craters, there is little direct evidence to indicate their sites. Astin did however point out that the lacustrine sediments that directly overlie the Muckle Head Tuff imply a horizontal surface. Hence the thickness variation of the tuff must have been accommodated in the substrata soon after eruption, possibly by slumping and subsidence on the site of the crater. He pointed to the slumped and chaotic sandstone beds below the tuff and steep normal faults restricted to the tuff and immediately underlying sediment, as further evidence for this mechanism. Only thin representatives of the tuffs, with limited lateral extent, are found on the SW side of the Voe of Clousta and the intervening sedimentary sequence is attenuated from about 200 m in the east, to less than 20 m in the west. Astin suggested that this is evidence for active syndepositional faulting on a N–S line along the Voe, which also acted as a magma conduit and controlled the positions of the vents and possible craters.

The Muckle Billerin Tuff is overlain directly by the Clousta Basalt, which has a similar lateral extent (Figure 9.49b). Astin (1982) interpreted this as a lava erupted immediately following the tephra, a transition that is commonly observed in modern phreatomagmatic eruptions as groundwater becomes excluded from the magma conduit. However, the peperitic features at Little Head and the vesiculation (= fluidization) of the overlying mudstones provide convincing evidence that the basalt was intruded into wet, unconsolidated, fine-grained sediments deposited on top of the tuff.

Acid pyroclastic rocks are a major feature of the Clousta volcanic rocks in general, forming large complex lenses such as the Clousta Tuff, west of the Voe of Clousta, and the Aithness Tuff to the east. These larger bodies are built almost entirely from ash-fall tuffs with a large magmatic component, much of it erupted in a plastic state and commonly welded. In the GCR site, only the Brigs Tuff is dominantly acid. This thin lens contains hardly any erupted magmatic material; angular clasts of feldspar porphyry and flow-banded felsite were interpreted by Astin as having originated from the break-up of small pre-existing lava domes or shallow intrusions, such as are found elsewhere among the Clousta volcanic rocks. Some clasts are quite rounded and may have come from the underlying alluvial gravels, along with the quartzofeldspathic sand that forms the matrix of the deposit. Clearly this was generated almost entirely by phreatic eruptions. The well-bedded and sorted nature suggests dominant ash-fall, but the cross-bedding indicates some pyroclastic surge. Measured sections suggest a height to width ratio of about 1:50, notably shallower than the basic tuff-rings and more comparable with modern day maars.

The compositions of the Clousta volcanic rocks are notably less varied than the volcanic sequences elsewhere in Shetland at Papa Stour, Melby and Eshaness (see the Eshaness Coast GCR site report), and Astin (1982) drew attention to the compositional gap between the basaltic and rare andesitic rocks and the more voluminous acid rocks. Thirlwall (1979) concentrated on analyses of the basic rocks, concluding that they have similar characteristics to those at Eshaness, transitional between calc-alkaline and tholeiitic, and were derived from similar parental magmas. Variation in these rocks was explained by low-pressure fractionation of olivine, clinopyroxene and plagioclase. Astin studied the acid rocks in more detail and concluded that, in view of the compositional gap and the presence of only K-feldspar, the acid rocks are more likely to have originated by partial melting of crustal rocks.

As with the other Mid-Devonian volcanic rocks of Shetland and Orkney, the Clousta volcanic rocks were erupted in an extensional basin setting, while retaining geochemical characteristics that are possibly attributable to earlier subduction (see the Eshaness Coast GCR site report). However, being located in the Walls structural block and slightly younger than the other sequences, they are more demonstrably related to the western Shetland plutonic complexes, both temporally and spatially (see Chapter 8: Introduction). These plutons are themselves closely related to the compressive deformation and metamorphism that affected the Old Red Sandstone rocks of the Walls block soon after deposition; Mykura and Phemister (1976) attributed the lack of deformation in rocks close to the Sandsting pluton to pre-deformation hornfelsing, but Astin (1982) implied that this hornfelsing resulted from early crystallization of the outer part of the pluton, which was followed by the main deformation and metamorphism as a result of continuing diapirism and isostatic rise of the plutons. So, it is possible that the volcanism, like the plutonism, may have been related to this Mid- to Late Devonian compressive event, the last phase of Caledonian folding in Britain, which post-dates the main extensional event(s) responsible for the development of the Orcadian Basin.

Conclusions

This GCR site represents the Clousta volcanic rocks of the central, Walls structural block of Old Red Sandstone outcrops in Shetland. Their Givetian age means that they, along with less extensive outcrops on Orkney, represent the youngest Caledonian volcanism in Britain. Although the rocks have subduction-related characteristics, they were erupted in an extensional basin setting, shortly before a reversion to compressive deformation and pluton emplacement.

The rocks were erupted onto an alluvial fan bordering on a lake margin, an environment that resulted in a preponderance of eruptions that involved the explosive gasification of ground and/or surface waters. Measured sections have enabled the three-dimensional form of the deposits to be determined which, together with the sedimentological and compositional features of the volcanic rocks, have suggested the presence of basic tuff-rings and an acid maar. Such features have not been described elsewhere in the Old Red Sandstone volcanic province of Britain and indeed are rarely well preserved in the geological record. An associated basaltic sheet has been intruded into wet unconsolidated sediments at a shallow depth and exhibits good textural features at its upper contact, comparable with those of many other sites in the province.

POINT OF AYRE (HY 590 038)

N. W. A. Odling

Introduction

On the Deerness Peninsula of eastern mainland Orkney, and on the neighbouring island of Shapinsay, volcanic rocks of the Deerness Volcanic Member (formerly known as the Eday volcanic rocks) occur within the Middle Devonian, Eday Flagstone Formation (Peach and Horne, 1880; Flett, 1898; Wilson *et al.*, 1935). Exposures of the volcanic rocks are generally very poor, but good exposures occur on the foreshore at Point of Ayre in the SE of Deerness. Here, the member consists of a vesicular basalt flow that was extruded on to wet lake sediments. The basalt has been substantially altered, which led to an original 'alkaline' classification (Kellock, 1969), but later geochemical studies have shown that it has similar calc-alkaline characteristics to other volcanic rocks of the Old Red Sandstone volcanic suite (Thirlwall, 1979; Fitton *et al.*, 1982). The lava has also provided significant palaeomagnetic information (Robinson, 1985).

Description

There are two outcrops of lava at Point of Ayre (Figure 9.51). The larger outcrop, in the north of the GCR Site, consists of the upper 7 m of an altered greenish-black basalt flow, which forms the foreshore and low cliffs above the Misker rocks. A second outcrop, on the upper shore 30 m to the SW, consists of the top 0.5 m of a vesicular lava. As the two exposures appear to be faulted against each other it is impossible to ascertain whether they represent different flows or different portions of the same flow. However, T. R. Astin (pers. comm., 1997) considers that the two exposures demonstrate a lateral reduction in thickness that occurred at the margin of a single flow.

The top 30 cm of the flow, exposed in low cliffs above high-water mark, contains numerous pipe amygdales up to 20 mm in diameter that are orientated perpendicular to the flow top. Although, most of the amygdales are filled with carbonate and zeolites, some now form hollow voids and so have either lost their filling or are simple vesicles. The pipes terminate at least 25 mm from the flow top and none connect with the upper surface. Below the amygdaloidal zone, the flow exhibits spectacular spheroidal weathering. Near the top of the flow the spheroidal masses are separated by a grid of sediment-filled fractures originating from the overlying Eday Flagstone Formation, indicating that the weathering occurred prior to burial. On the foreshore, cross-bedded tuffaceous sandstones fill hollows in the upper surface of the flow (Kellock, 1969, pl. 1B) and undisturbed laminations in the sediment can be traced to within 5 cm of the top of the igneous rock. The sediments filling the veins and immediately overlying the basalt show no evidence of thermal alteration.

Beneath the amygdaloidal zone the lava is composed of an intimate association of two types of basalt. The more abundant, massive component contains microphenocrysts of olivine and plagioclase set in a groundmass of lilac-coloured clinopyroxene, plagioclase, analcime and carbonate. The primary mineralogy has been subjected to extensive alteration, much of the olivine now being replaced by serpentine and bowlingite. The second component consists of pegmatitic veinlets and patches within the massive basalt. In the veins and patches, olivine up to 0.5 mm and feldspars up to 2 mm are ophitically enclosed by lilac-coloured clinopyroxenes up to 10 mm in diameter. The feldspars are mantled by clear rims of sanidine–anorthoclase and the olivines are substan-

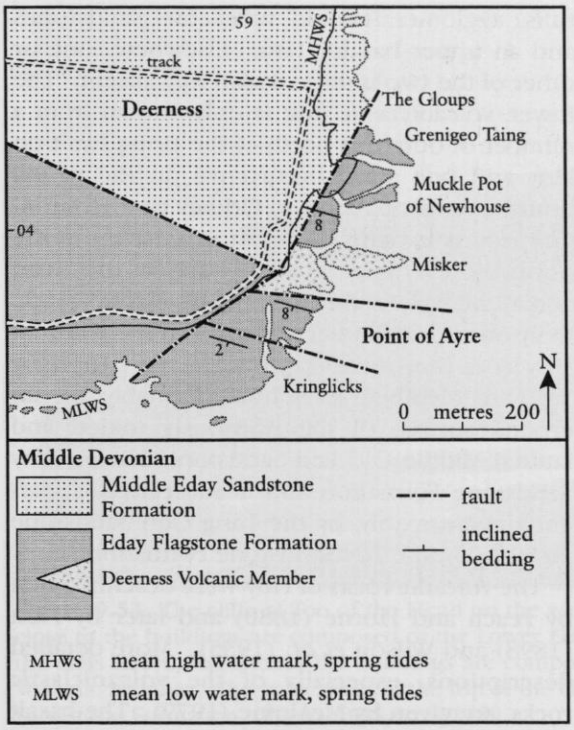

Figure 9.51 Map of the Point of Ayre GCR site, Orkney.

tially altered to serpentine. Analcime, carbonate and zeolite are present as interstitial patches.

Interpretation

The Point of Ayre basic rocks have been subject to a number of differing interpretations in the past (Peach and Horne, 1880; Flett, 1898; Wilson *et al*., 1935). However, more recently Kellock (1969) has suggested that the lack of thermal alteration and disruption of the overlying sediments, and the presence of sediment-filled veins are evidence that the flow became inundated by sediment only after it had cooled significantly. As the base of the flow(s) is not exposed it is impossible to tell what the nature of the underlying sediment was at the time of the basalt eruption. However, T. R. Astin (pers. comm., 1997) has reported synsedimentary, dish-shaped loading structures in the sediments below the flow and has suggested that these are the result of seismic tremors associated with the eruption of the lava. If so, the lava must have been erupted onto unconsolidated, possibly wet sediments.

The Deerness Volcanic Member occurs within the Eday Flagstone Formation, which is of Givetian age (Westoll, 1977; Marshall, 1996) and can be correlated throughout eastern Orkney (Astin, 1985). It has been suggested that the formation can be correlated on sedimentological grounds with the lower part of the Hoy Sandstone Formation of Hoy (D. Rogers, pers. comm. in Astin, 1990, p. 150; Marshall *et al*., 1996, p. 459) and hence it is possible that the Deerness Volcanic Member is near-coeval with the Hoy Volcanic Member. In a study of the palaeomagnetism of the 'Eday Group', Robinson (1985) found that most samples of sedimentary rock have been affected by a widespread remagnetization, possibly attributable to deep sub-unconformity weathering and oxidation in the Late Palaeozoic. The basalt of the Point of Ayre and sedimentary rocks in the contact zone, however, give a consistent remnant pole position of 8°N 167°E (present-day grid). Thus the Point of Ayre rocks are significant in preserving a late Mid-Devonian magnetic signature from the Orcadian Basin.

Kellock (1969) noted that the Deerness lava has many geochemical and petrographical features in common with the alkali basalts of the Carboniferous of the Midland Valley. However, Thirlwall (1979) (and in Fitton *et al*., 1982) noted that, although the major element bulk composition of these substantially altered rocks is that of an alkali basalt, their trace element signature is more allied to calc-alkaline rocks and is similar to the volcanic rocks of Shetland (see the Eshaness Coast GCR site report). It seems probable, therefore, that the apparent alkaline nature of these rocks is due to alteration, in particular the large amount of secondary analcime present in the groundmass. Thus, although the Deerness lava is possibly near-contemporaneous with the Hoy Volcanic Member (see the Too of the Head GCR site report), its inferred primary composition contrasts with the alkaline nature of the Hoy lava and shows that these two lavas cannot be related. The Deerness Volcanic Member comprises the youngest calc-alkaline rocks known in the Orcadian Basin, and hence marks the last possibly subduction-influenced magmatism in this area. The Hoy Volcanic Member shows geochemical features that are transitional between calc-alkaline and alkaline trends, which Francis (1988) considers to mark a change to an extensional tectonic regime. If so, these two GCR sites on Orkney mark an important time when magmatism ceased to be influenced by subducted Iapetus oceanic lithosphere, and became characteristic of the extensional tectonics that were to dominate Carboniferous times in Scotland.

Conclusions

The Point of Ayre GCR site is representative of the poorly exposed Eday volcanic rocks (the Deerness Volcanic Member). The basalt flow and surrounding sedimentary rocks are particularly interesting as they contain many features characteristic of lava extrusion in a subaerial environment. Although the alteration of the basalt has imparted an apparent alkaline character to the rock, the trace element geochemistry preserves evidence of an original calc-alkaline nature. These rocks therefore provide evidence of the last calc-alkaline volcanism associated with the closure of the Iapetus Ocean. Together with the Hoy Volcanic Member (see the Too of the Head GCR site report), the Eday volcanic rocks are significant in preserving a Mid-Devonian magnetic field, unmodified by the widespread late Palaeozoic remagnetization event which affected most of the associated sedimentary rocks.

TOO OF THE HEAD (ND 184 992–196 990)

N. W. A. Odling

Introduction

The coastal exposures at Too of the Head, on the west side of Rackwick Bay, Isle of Hoy show the most extensive section through the Hoy Volcanic Member (Figures 9.52, 9.53). Here, the member comprises a lower volcaniclastic unit of ash-fall tuffs, agglomerates and tuffaceous sandstones and an upper basaltic lava. Elsewhere, one or other of the two units is commonly absent. The lower, volcaniclastic unit is only known from a number of outcrops north of the Bring Fault on Hoy and one small occurrence on the neighbouring coast of Mainland Orkney near Houton. The Hoy lava crops out most extensively in the north of Hoy, in particular at Too of the Head and at the base of the Old Man of Hoy sea stack. Only one limited outcrop occurs in the south of Hoy near the township of Melsetter. The Hoy Volcanic Member rests unconformably on an eroded surface of the previously folded and faulted Middle Old Red Sandstone, Lower Eday Sandstone Formation and is succeeded, apparently conformably, by the Lang Geo Sandstone Member of the Hoy Sandstone Formation.

The volcanic rocks of Hoy were described first by Peach and Horne (1880) and later by Flett (1898) and Wilson *et al.* (1935). More detailed descriptions, especially of the volcaniclastic rocks, are given by McAlpine (1979). The basalt from Too of the Head has been included in a geochronological study by Halliday *et al.* (1977, 1979b, 1982), and its geochemistry has been discussed by Thirlwall in relation to other Siluro-Devonian volcanic rocks of northern Britain (Thirlwall, 1979, and in Fitton *et al.*, 1982). The lava has also been the subject of a palaeomagnetic study (Storetvedt and Petersen, 1972; Storetvedt and Meland, 1985). The Hoy volcanic rocks are of particular interest because they are one of the youngest preserved representatives of the Old Red Sandstone volcanic suite and appear to represent a transitional phase between the dominantly calc-alkaline volcanism of Silurian and Devonian times and the alkaline

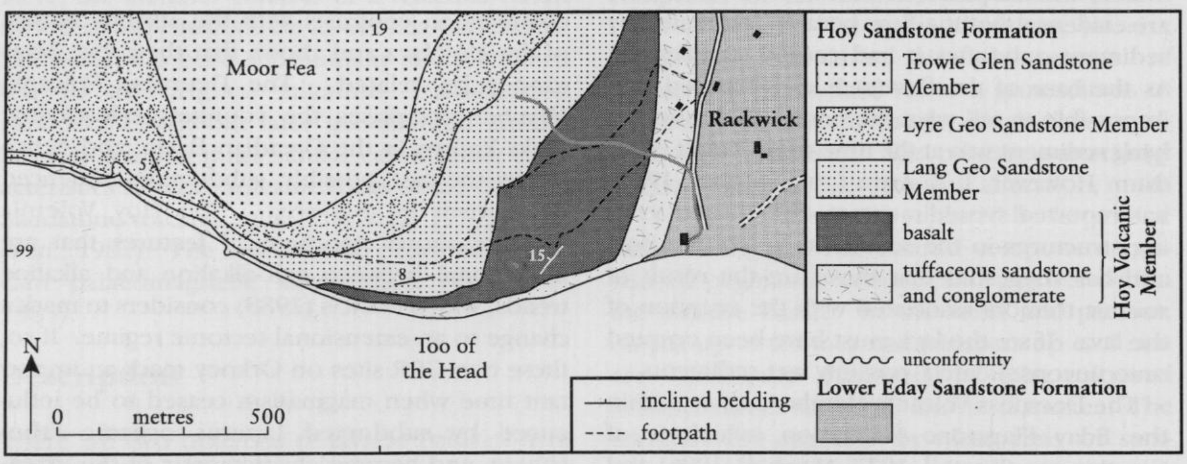

Figure 9.52 Map of the Too of the Head GCR site, Hoy, Orkney.

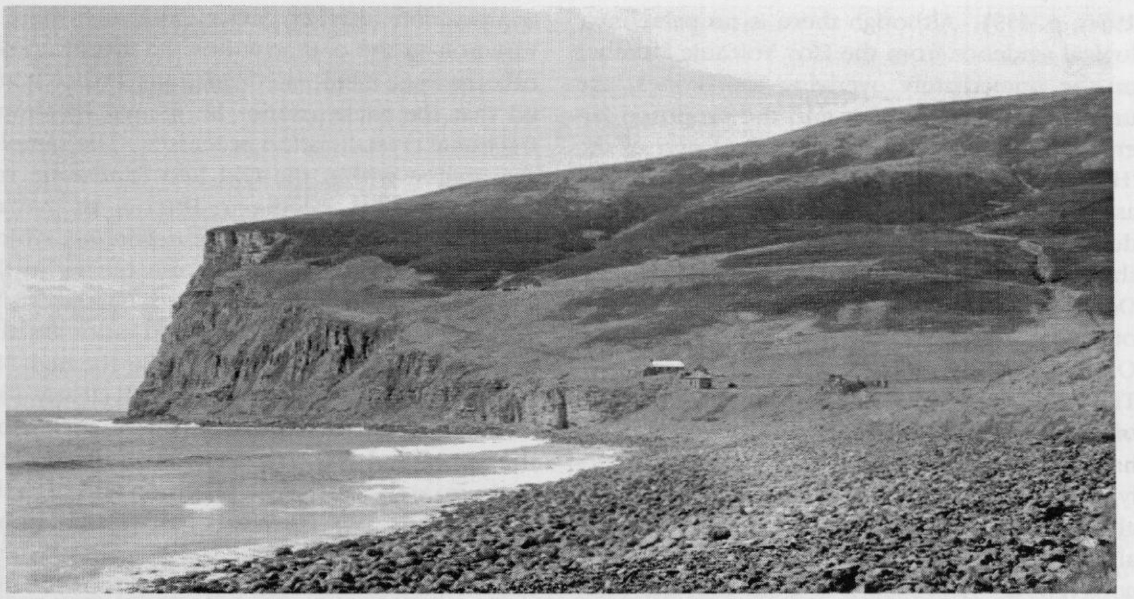

Figure 9.53 The cliffs of Too of the Head on the west side of Rackwick Bay, Hoy. The pale rocks of the cliffs close to the buildings are composed of the Lower Eday Sandstone Formation. The lower and middle parts of the cliffs above and behind the buildings are composed of the basal volcaniclastic rocks and lava of the Hoy Volcanic Member. The paler rocks at the top of the cliff belong to the Lang Geo Sandstone Member of the Hoy Sandstone Formation. (Photo: BGS no. D1489.)

volcanicity characteristic of the Carboniferous in Scotland.

Description

The basal unit at Too of the Head consists of an ash-fall tuff that contains numerous angular blocks and lapilli of basalt and rounded volcanic bombs, and a brownish-red, locally cross-bedded tuffaceous sandstone. In the east of the GCR site, the unit is 20 m thick, but it thins to only a few metres and becomes finer grained in the west, below the headland of Moor Fea. The overlying columnar-jointed lava also thins markedly westwards from over 60 m at Rackwick, and it wedges out completely about one kilometre west of Rackwick Bay. The lava is a porphyritic basalt that contains phenocrysts, up to 4 mm, of euhedral to subhedral bytownite, euhedral or anhedral forsteritic olivine and anhedral sodic augite. All of the phenocryst phases are zoned and are variably resorbed. The groundmass consists of aligned laths of bytownite–labradorite with intergranular olivine, clinopyroxene, magnetite, K-feldspar and devitrified glass. The primary mineral assemblage is variably altered and analcime and calcite are significant secondary minerals.

Interpretation

As the outcrop of the Hoy Volcanic Member is discontinuous it is not known whether it is the result of a single eruption or is composed of several separate flows. The three-dimensional geometry of the volcaniclastic unit in the north of Hoy cannot be reconstructed, but the presence of large blocks and bombs at Too of the Head and the westward thinning implies that the eruption centre was located only a short distance away. A likely location for the centre was close to or along the WSW-trending Bring Fault, which cuts across the north of Hoy and was one of the major faults active during the formation of the Orcadian Basin.

As the unfolded Hoy Volcanic Member rests unconformably on an irregular surface of gently folded Middle Old Red Sandstone rocks, the volcanic rocks and the succeeding 'Hoy Sandstone' have formerly been regarded as Upper Old Red Sandstone (e.g. Mykura, 1976, 1991). However, it is now considered that the unconformity, although marked on Hoy, is of local extent only (Rogers *et al.*, 1989). It has further been suggested, on sedimentological grounds, that the 'Hoy Sandstone' is laterally equivalent to the 'Eday Group' of eastern Orkney (Rogers, pers. comm., in Astin, 1990, p. 150; Marshall *et al.*, 1996, p. 459). Although there is no palaeontological evidence from the Hoy Volcanic Member or the immediately overlying sandstones, the underlying strata on Hoy and the proposed laterally equivalent strata to the lower part of the 'Hoy Sandstone' in eastern Orkney, are both assigned to the Givetian on palynological evidence (Marshall, 1996). Hence it seems likely that the Hoy Volcanic Member is of Mid-Devonian age and possibly near-contemporaneous with the Eday volcanic rocks of eastern Orkney (see the Point of Ayre GCR site report). The geochronological study of the basalt of Too of the Head (Halliday *et al.*, 1977, 1979b, 1982) has yielded an Ar-Ar age of 379 ± 10 Ma, broadly consistent with this biostratigraphical age, although the uncertainty in the date and the altered state of the rocks does not allow precise correlation. However, it is clear that the Eday and Hoy volcanic rocks of Orkney are the youngest expressions of Old Red Sandstone volcanism in Britain.

The basalt at Too of the Head has been examined by Storetvedt and Petersen (1972) and Storetvedt and Meland (1985) as part of a palaeomagnetic study of the Devonian rocks of Hoy. Storetvedt and Petersen (1972) found that the lava contains a two-polarity magnetization structure consisting of a high-temperature remanence associated with spinel and a lower temperature remanence associated with haematite. They concluded that the spinel reflects the geomagnetic field at the time of eruption as it is a product of high-temperature alteration soon after the solidification of the lava. Analysis of the spinel remanence indicated a consistent remnant pole position of 23°N 146°E (present-day grid). This compares tolerably well with a pole position of 8°N 167°E obtained by Robinson (1985) for the near-contemporaneous Eday volcanic rocks of Mainland Orkney (see the Point of Ayre GCR site report). As the haematite was formed at a much lower temperature, it is likely that its remanence has recorded a significantly later geomagnetic field.

Thirlwall (1979) reported four analyses of the Hoy lavas, of alkali olivine basalt to hawaiite composition (48–52% SiO_2). Although there is variation in the compositions, he found no significant trace element correlations and concluded that the rocks cannot be related by simple fractional crystallization processes. The samples are unique within the Old Red Sandstone volcanic suite of northern Britain in having between 3 and 5% normative ***nepheline***, which, because of the presence of fresh olivine in the rock, is believed to be a primary characteristic. Trace element concentrations and ratios are also typical of alkali basalts, in particular the high Nb, P and light rare earth elements. The clearly alkaline nature of the Hoy basalt sets it apart from the more calc-alkaline character of volcanic rocks from the rest of the province, although the relatively low TiO_2 is typical of arc-related, rather than continental alkali basalts elsewhere. Francis (1988) has suggested that this is the first evidence of a change from compressional, subduction-related tectonics to the extensional regime that was later to produce the voluminous alkaline volcanic rocks of Scotland during the Carboniferous.

Conclusions

The Too of the Head GCR site is of national importance as it contains the most complete section through the Hoy Volcanic Member. It is of international importance because the volcanic sequence provides a rare potential time-marker within the Devonian successions of Europe. A radiometric age of 379 ± 10 Ma from the lava is consistent with the Givetian age extrapolated from plant spores in the underlying strata and lateral correlation of the overlying strata on sedimentological grounds. Studies of the magnetic field preserved by the lava show that at this time the north magnetic pole was situated at 23°N 146°E (present-day grid). The markedly alkaline character of the Hoy lava contrasts with other volcanic rocks of the Middle Devonian of Orkney and Shetland and provides important evidence of the transition to the extensional tectonic regime that characterized Scotland during the Carboniferous.