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Felsites and breccias in the Northern Marginal Zone of the Rum Central Complex: changing views, *c.* 1900–2000

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SUMMARY: As in several other parts of the British Tertiary Igneous Province, breccias and felsite sheets are closely associated on the Isle of Rum. This association has been described and interpreted by several workers over the last 125 years. Opinion has divided into an intrusive origin for both rock types, as explosion breccias and felsite intrusions, versus a sedimentary origin for the breccias and an extrusive origin for the felsite. Evidence is reviewed for both opinions and it is concluded that the latter is substantially correct, as indicated by the presence of sedimentary structures and interbedded tuffs in the breccias and eutaxitic textures in the felsites. The breccias formed by inwards slumping of rocks from the oversteepened walls of a caldera, whereas the felsites formed by eruption of pyroclastic flows which were thick and hot enough to weld. It is inferred that the caldera formed initially and subsided progressively without any accompanying eruptions, and this is attributed to growth of the underlying magma chamber. The breccias accumulated during this stage. There followed a resurgent stage in which caldera collapse occurred in response to repeated ignimbrite eruptions partially emptying the magma chamber. The chamber is inferred to have been chemically and mineralogically zoned.

Ansel Dunham cut his postgraduate research teeth on the Palaeocene central igneous complex of the Isle of Rum, examining the 'Northern Marginal Complex' that fringes the well-known layered basic–ultrabasic intrusion (Dunham 1962). At Oxford University, where his supervisors were L. R. Wager and G. M. Brown, his was one of a succession of investigations of problems in the British Tertiary Igneous Province. Of these, several were concerned with similar associations of rocks as, for example, the 'Southern Mountains Complex' of Rum (Hughes 1960) and the Slieve Gullion Ring-dyke in Ireland (Emeleus 1962). Dunham published several papers on various aspects of the geology, mineralogy and petrology of this complicated and controversial area. His familiarity with the island's geology in general led him, with Emeleus, to publish a detailed synthesis of its Palaeocene igneous events (Dunham & Emeleus 1967) which was a crucial step in the subsequent growth of studies in the next 25 years, following the opening of the island as a National Nature Reserve.

In recent years we have been re-examining much of the Northern Marginal Zone, with a view to understanding its evolution as part of a caldera that was the earliest surface expression of Palaeocene magmatism on the island (Emeleus 1997; Troll *et al.* 2000). Here we highlight Dunham's contributions to the understanding of the enigmatic sequence of volcanic events and processes associated with the caldera which shaped the Northern Marginal Zone. We show how interpretations of these rocks have changed so that, what Dunham and earlier investigators judged to be a sequence of sub-surface explosion breccias and acid intrusions, is now seen as a sequence of sedimentary breccias succeeded by ignimbrite flows, infilling a major caldera that originally covered at least two-thirds of the current area of the island.

The terminology used in this paper broadly conforms with that in the Rum Memoir (Emeleus 1997). The main exception is that the term 'felsite' is retained when describing the earlier work, but the modern terms, rhyodacite or rhyodacite porphyry, are used when describing our own work.

1. SETTING AND PREVIOUS WORK

Rum is one of several well-known Palaeogene igneous centres on the western Scottish seaboard. Magmatism on Rum took place over about 1 Ma, at 60.5 Ma (Hamilton *et al.* 1998) and is considered to be related to the opening of the North Atlantic Ocean.

The pre-Palaeogene rocks of the island include small areas of Archaean Lewisian gneiss, a thick and areally extensive sequence of Proterozoic Torridonian sandstone, Triassic conglomerate and cornstone and a vestige of Lower Jurassic sandstone, limestone and siltstone. Most of the central and southern parts of the island host igneous rocks which include acid, basic and ultrabasic types of both intrusive and extrusive origins. The two principal rock masses are the Western Granite and the peridotite, troctolite and gabbro intrusions of the Layered Suite (Fig. 1). The majority of the igneous rocks are confined within a prominent ring-fault system which can be traced through an arc of about 270°. The remainder of this fault system lies below sea-level, or is cut by later intrusions (Fig. 1).

Harker (1904, 1908) produced the first detailed geological map of Rum and the first memoir for the Geological Survey, building on previous work by Judd (1874) and Geikie (1897). He interpreted the gneisses to be of Tertiary, i.e. Palaeogene, age. However, Tilley (1944) and Bailey (1945) identified them as Lewisian gneisses brought up, together with basal Torridonian rocks, on a near-vertical fault, termed the 'Main Ring Fault' (Fig. 1), by central uplift. Harker (1908) had previously interpreted the fault as a Palaeozoic thrust, slightly modified in the Palaeogene.

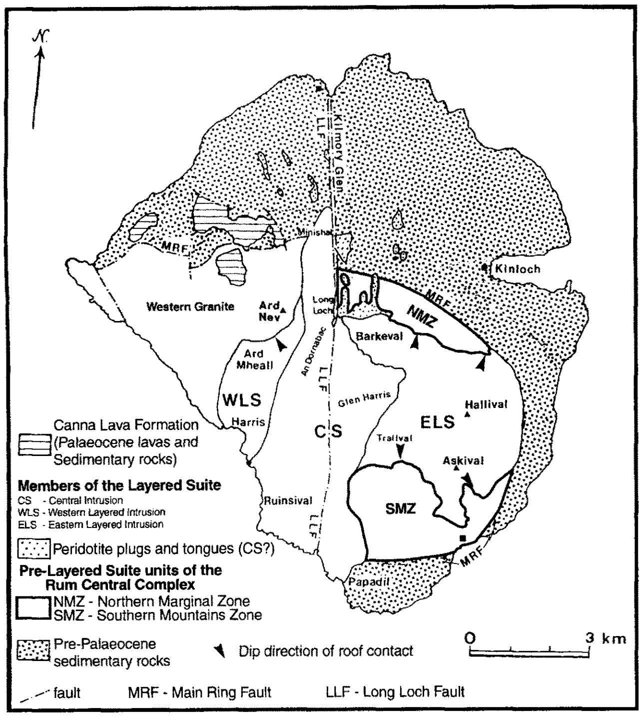

Fig. 1. Simplified geological map of the Isle of Rum. The locations of the Northern Marginal Zone and the Southern Mountains Zone are highlighted.

Other major contributions to documenting the island's igneous geology prior to Dunham's researches were:

- Black's (1952) discovery that basaltic lavas in NW Rum rest upon weathered, and therefore older, Western Granite;
- Brown's (1956) interpretation of the layered basic and ultrabasic rocks as a succession of igneous cumulates in a chamber which had been repeatedly re-injected with basic magma;
- Hughes' (1960) investigation of the igneous breccias and felsites that form the mountainous region on the southern side of the layered suite;
- Wadsworth's (1961) account of the more massive layered ultrabasic rocks and gabbros in SW Rum.

The area assigned to Dunham was the northern counterpart of Hughes' (1960) study area, containing identical lithologies and with comparable structural relationships. He reached broadly similar conclusions about the nature and geological setting of the rocks in the Northern Marginal Zone as Hughes had for those in the Southern Mountains Zone. These were in line with what Bailey (1945, 1956) had deduced about the two areas being sites of violent degassing of acid magma to produce explosion breccias, followed by emplacement of intrusive, degassed sheets of felsite. Prior to the 1960s, the contact relationships of the Layered Suite and acid intrusions were considered to show the younger age of the latter. However, Hughes (1960) convincingly demonstrated that the conspicuous acid net-veining of the marginal rocks of the Layered Suite was due to melting of adjoining acid rocks by the heat of later, basic intrusions with consequent back-veining. Dunham (1964) recognized that similar phenomena are particularly clearly demonstrated in the Meall Breac area of the Northern Marginal Zone.

2. THE NORTHERN MARGINAL ZONE: PRE–1970

The key rock types in assessing the origin of the Northern Marginal Zone are the breccias and the felsites. In this area, and in the Southern Mountains Zone, they are closely associated, as noted by Bailey (1945). This is also the case in the other British Palaeogene igneous centres (e.g. Richey 1940, 1961; Bell & Emeleus 1988). Dunham (1965) published on the textures of the felsites and granophyres and, with Thompson (1967), on the origin of the acid magma by partial fusion of Lewisian and Torridonian rocks, before attending to a detailed account of the felsites, granophyres, tuffisites and explosion breccias and their relationships (Dunham 1968). Figure 2 is a reproduction of the map from his 1965 publication showing the disposition of these rocks within the Main Ring Fault; Figure 3 demonstrates the manner in which the geology controls the topographical features of this area.

2.1. Breccias

The breccias lie entirely within the ring fault and are bound to the south by the marginal gabbro that borders the Layered Suite. Dunham (1968) demonstrated that the breccias predate the ring fault. He recognized two types of breccia: Type 1 consists of sub-angular to rounded blocks of 'Basal Torridonian', now called the Fiachanis Gritty Sandstone (Nicholson in Emeleus 1997), locally with blocks of gabbro, set in a matrix of finely comminuted Torridonian, whereas Type 2 consists of Lewisian gneiss fragments, also with gabbro blocks, in a matrix of comminuted Lewisian gneiss. Fragments are generally from 5 mm to 20 cm in diameter (Fig. 4), but those of gabbro are about 1.5 m diameter with some as great as 55 m. He also recognized a third breccia type in the Long Loch area containing blocks of Torridonian sandstones, gabbro, possible Lewisian gneiss and, in addition, felsite.

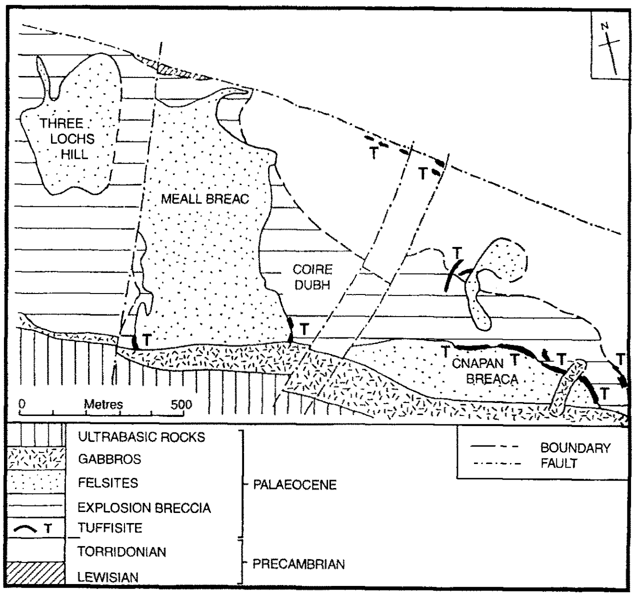

Fig. 2. Simplified map of the Northern Marginal Zone, after Dunham (1965), with the addition of tuffisite bodies (T) mapped by Dunham (1968). Reproduced, with permission, from Dunham, A. C. 1965. 'The nature and origin of groundmass textures in felsites and granophyres from Rhum, Inverness-shire.' *Geological Magazine*, vol. 102 (Cambridge University Press).

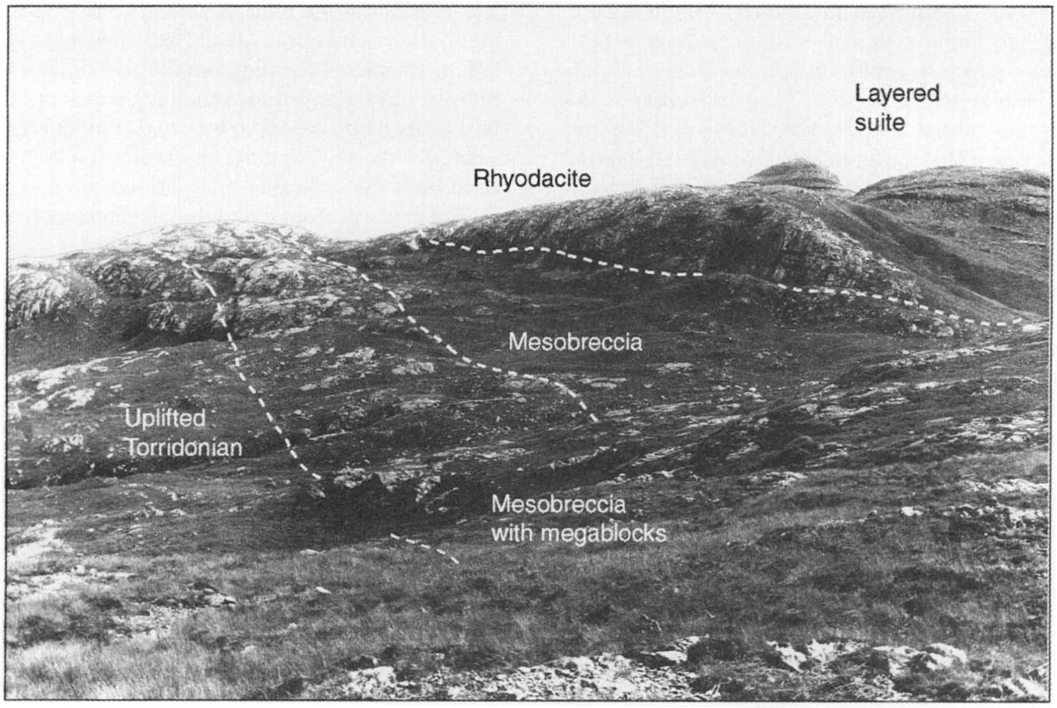

Fig. 3. Coire Dubh and Cnapan Breaca viewed from the eastern slopes of Meal Breac. The principal features within the Northern Marginal Zone are indicated on the photograph. Layered ultrabasic rocks and gabbros of the Layered Suite form the terraced topography on Hallival (top right); immediately below is a dark-coloured area of easily-weathered gabbro which separates the rhyodacite from the Layered Suite.

Judd (1874) interpreted the breccias as agglomerate, whereas Geikie (1897) considered that they were either crush breccias or the result of explosive activity. Harker (1908) adopted Geikie's first suggestion and considered the rocks to be formed during Palaeozoic thrusting, with some Palaeogene reactivation. However, following a visit to the island with J. E. Richey, Bailey (1945) identified the rocks as explosion breccias formed as 'infillings of a volcanic pipe' and demonstrated that what had been interpreted by Harker as thrusts were, in fact, steeply inclined arcuate faults which he termed the Main Ring Fault. Although Hughes (1960) and Dunham (1968) sided with Bailey, they did not interpret the breccias as vent infillings. Rather, Hughes deduced that they formed entirely underground and represented routes of escape for expanding volatiles released from the magma chamber that subsequently fed the felsite sheets and granophyre intrusions. Dunham saw the breccias as of combined fault and explosion origin, and considered that they were emplaced underground.

Fig. 4. Collapse breccias ('Coire Dubh Breccias'), Coire Dubh. The angular to sub-rounded fragments are entirely composed of sandstone derived from the Fiachanis Gritty Sandstone Member (Torridon Group). Scale: lens *c.* 3 cm diameter.

2.2. Felsite

Four areas of felsite were distinguished by Dunham (1968, 1970) in the Northern Marginal Zone (Fig. 2). One to the north of Cnapan Breaca is a plug-like mass of crescentic outcrop plan, cutting Torridonian strata and explosion breccia. The plug contains abundant inclusions of Torridonian sandstones and fine-grained basaltic rocks. In the other three areas the felsite generally forms thick sheets, dipping to the south (Fig. 3), although along the northern margins of the felsite sheets of Meall Breac and Am Màm ('Three Lochs Hill' on Fig. 2) the contact is vertical or dips steeply to the south. Everywhere the top of the felsite has been removed by erosion, whereas the base can be seen in contact with explosion breccias. The thickness of the sheet-like portion of the Meall Breac felsite was estimated at about 100 m.

The felsite is a hard, dark-grey rock, containing prominent quartz and plagioclase phenocrysts up to 3 mm in size, and scarcer ferroaugite and pigeonite phenocrysts up to 1 mm. These are set in a glass-free groundmass of quartz, alkali feldspar and accessory opaque oxides and amphibole. The euhedral crystals of plagioclase are commonly broken and may also have resorbed, embayed outlines, whereas individual quartz phenocrysts are bound by both perfect faces and faces with rounded embayments.

The felsites were originally interpreted as lavas by Judd (1874), then as intrusions by Geikie (1888), Harker (1908) and Bailey (1945). In the absence of an upper contact to the felsite sheet(s) in the Northern Marginal Zone, Dunham assumed they had been intruded, because in the Southern Marginal Zone Hughes (1960) had found complete felsite sheets with both upper and lower contacts to explosion breccia. Dunham interpreted the felsite plug to the north of Cnapan Breaca as the feeder for the sheet on that hill. Likewise, at Meall Breac and Am Màm he envisaged that the felsite magma had risen through a steep feeder (or feeders) in the north before intruding southwards into the explosion breccias (Dunham 1968, 1970).

Dunham (1965) regarded the felsite in the Northern Marginal Zone as the faster cooled equivalent of the granophyre (microgranite) that crops out at the western end of the Northern Marginal Zone. Both rocks contain phenocrysts of oligoclase that display oscillatory zoning (e.g. Fig. 8). In the 1968 paper he ascribed the zoning to fluctuations in water-vapour pressure in a body of acid magma that was crystallizing at depth. (The depth to the magma body was estimated to have been 10 km, assuming that it was saturated with H_2O.) The pressure fluctuations were attributed to rapid release of vapour from the body with the formation of explosion breccias, followed by a significantly longer time interval as the pressure gradually built up again.

In a key observation about the Cnapan Breaca outcrops, Dunham (1968, p. 331) stated that 'Flow-banding and elongate lenticular structures are present from the base of the sheet, but they tend to die out upwards'. In thin section the banding was reported as 'layers with poorly developed micropegmatitic structure, while the lozenge-shaped areas are slightly coarser micropegmatitic patches. These may well be flattened drusy cavities' (cf. Emeleus & Smith 1959; Dunham 1965). The flow-banding had previously been reported by Harker (1908), Bailey (1945) and Hughes (1960) for the Rum felsites. This banding (Fig. 5) is critical in the interpretation of the origin of the felsites and the nature of the Northern Marginal Zone.

Another key observation relates to the base of the Cnapan Breaca Sheet (Figs 2, 6), where Dunham reported the presence of a layer up to 2 m thick of banded tuffisite (i.e. intrusive tuff) due to 'the alternation of coarse and fine material'. He found the same material, within the felsite, 4.5 m above the base, in a 0.3 m-thick layer. The basal layer was found to run along most of the base of the felsite and to follow

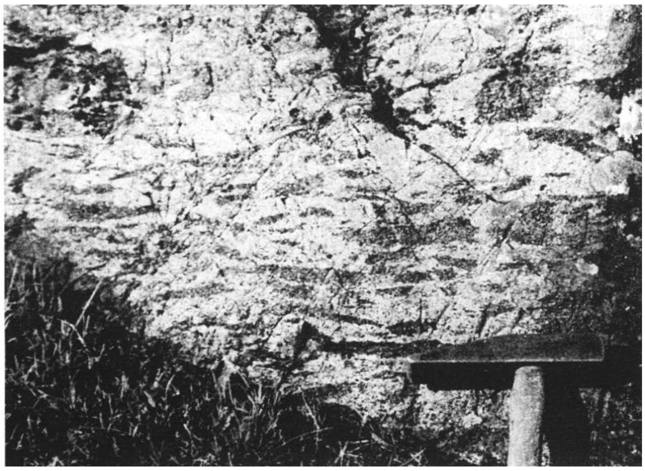

Fig. 5. Dark fiamme in porphyritic rhyodacite at the east end of Cnapan Breaca. Differential weathering of attenuated, aligned of fiamme commonly imparts a 'flow-banded' appearance to the rhyodacite outcrops. Scale: hammer head *c.* 20 cm long.

irregularities at the base. A similar rock type was reported at the southern end of the Meall Breac felsite. In addition to containing fragments derived from the Torridonian sandstones, the tuffisite was described as containing bands of plagioclase crystals. Glass blebs were also reported. These tuffisites were considered to be the products of fluidization of material derived from both the explosion breccias and the felsites, as volatiles moved upwards from the underlying magma chamber.

3. POST 1960s PERSPECTIVES

A milestone in research progress on Rum geology was the publication in 1985 of a special issue of the Geological Magazine (Vol. 122). Most of the articles were concerned with the Layered Suite, but two reported on the tectonics associated with the Palaeogene magmatism, and another reinterpreted the felsites and hinted at an entirely new explanation for the explosion breccias.

New information about movement on the Main Ring Fault, based on the discovery of slivers of Jurassic rocks and Palaeocene basalt lavas in the fault zone, was provided by Smith (1985). This gave crucial evidence for a phase of central subsidence in the early history of the igneous centre. The second paper (Emeleus *et al.* 1985) used these and other observations on the rocks within and outside the ring fault to deduce that initial doming of central Rum, due to progressive uprise of magma, was succeeded by ring faulting. This was followed by creation of a caldera which was infilled during progressive subsidence. Resurgence and doming followed when the Layered Suite was constructed. The nature of what may have filled the caldera was left unanswered although a new idea was suggested, namely that the felsites of the Northern Marginal Zone might be 'the remains of domes, perhaps covered by a blanket of explosion breccias' (Emeleus *et al.* 1985, p. 455).

The third article reported on new observations on the felsites of the Northern Marginal Zone. Williams (1985) reassessed the lenticular structures (Fig. 5) that pick out the flow banding and identified them as fiamme, i.e. flattened pumice fragments. He also recognized small Y-shaped fragments representing flattened glass shards from bubble wall junctions of disrupted pumice. It is the combination of these flattened shards and the fiamme that constitute the banding, and Williams pointed out that these are features which are also characteristic of welded tuffs, i.e. ignimbrites.

So, once again the felsites were judged to be extrusive but of an explosive origin compared with Judd's lava flow interpretation. The tuffisites which Dunham had reported at the base of the Cnapan Breaca and Meall Breac felsite sheets, and about 1 m within the felsite, were seen by Williams as pyroclastic breccias, possibly representing ground layer deposits from pyroclastic flows. Williams also proposed that the breccias beneath the Cnapan Breaca felsite represent *in situ* explosive disruption of country rocks forming the caldera floor beneath the ignimbrite. However, he also advanced the idea that the close association of felsites and breccias might imply that the breccias were also of surface origin, specifically that they might be caldera-collapse breccias formed by material spalling off the inner walls of the caldera as the floor subsided. This was a radical suggestion that prompted a reinvestigation of the Northern Marginal Zone from an entirely new petrogenetic perspective.

The initial results of the reinvestigation appeared in an article on silicic pyroclastic magmatism throughout the Scottish and Irish Palaeogene igneous provinces (Bell & Emeleus 1988). Williams' findings about the presence of fiamme and bubble-wall shards, and about pyroclastic breccias at the base of felsite sheet on Cnapan Breaca were confirmed and it was agreed that the felsites are indeed welded tuffs that were immediately preceeded by lapilli-, lithic- and crystal-tuffs, of several metres thickness. Fifty metres below the Cnapan Breaca sheet another zone of bedded tuffs was reported in the breccias, which lent support to Williams' (1985) speculation that the rocks hitherto interpreted as 'explosion breccia' had formed at the Earth's surface.

Further mapping of the Northern Marginal Zone and the Southern Mountains led to the conclusion that most of the 'explosion breccias' in both areas are not of igneous but rather of epiclastic origin (Emeleus 1997). The case rests on the recognition that the matrix to much of the breccia lacks juvenile igneous material, consisting of just comminuted sandstone, and that although 'generally chaotic, rough bedding occurs sparingly and finer tuffaceous rocks are commonly bedded'. The rocks were proposed to have formed either as landslips from steep caldera walls following successive subsidence events, or from the reworking of landslip deposits. They were identified, therefore, as caldera-collapse breccias. In recognition of the close temporal and spatial association of the breccias with felsite intrusions and ignimbrites, Emeleus (1997, p. 46) suggested that some of the breccias probably originated as explosion breccias, as envisaged by previous investigators, but were reworked by sedimentary processes. From their major development north of Cnapan Breaca, these rocks have been called the Coire Dubh Breccias (Fig. 3) (Emeleus 1997). A pale coarse-grained sandstone that surmounts the breccias, separating them from the felsite, was attributed to the washout of finer particles from the breccia matrices, whereas the bedded tuffs within the collapse breccias were viewed as tephra from small volume pyroclastic eruptions.

In summary, interpretation of the breccias and felsites (or rhyodacites) has now changed from intrusive origins for both, relieving pressure on an underlying magma chamber, to volcanic events and epiclastic activity in a subsiding caldera. This has significant implications for several other sites in the British Tertiary Igneous Province as well as Rum.

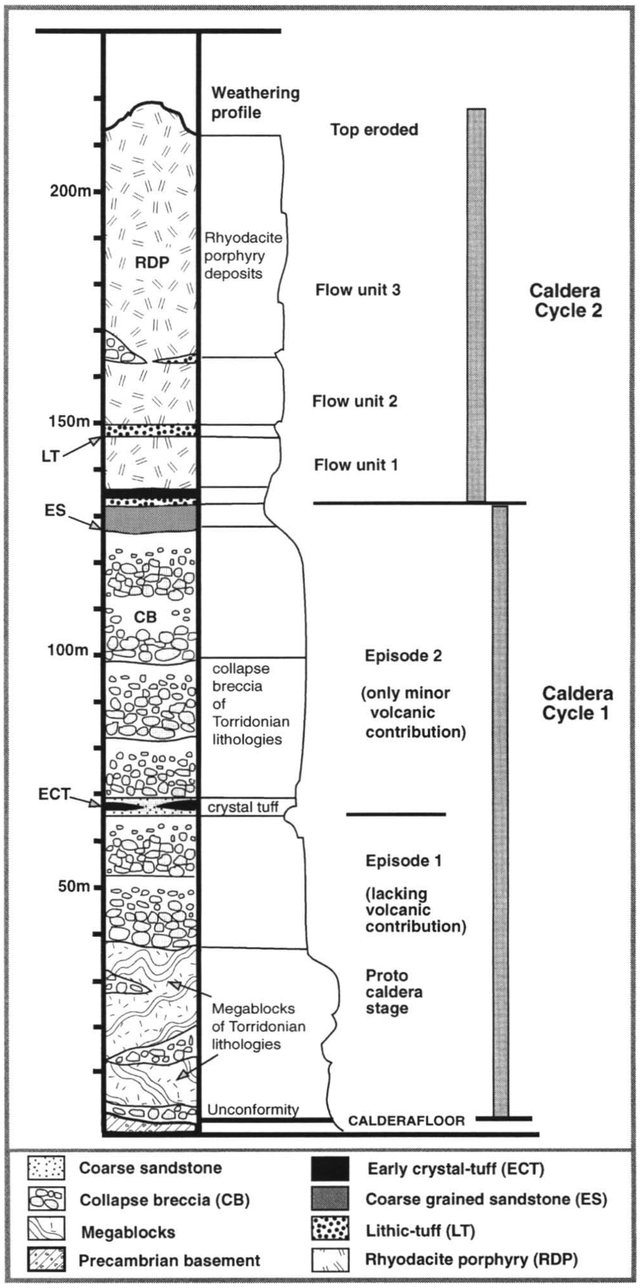

Fig. 6. Generalized graphic log of the caldera-infilling in Coire Dubh.

4. FURTHER INVESTIGATIONS OF THE NORTHERN MARGINAL ZONE BRECCIAS AND FELSITES

4.1. The caldera fill

We have recently re-examined the breccias and rhyodacites (formerly 'felsites') of the Northern Marginal Zone closely with a view to unravelling the volcanological events of the caldera. Graphic logs have been constructed for vertical sections in the eastern part of the Northern Marginal Zone (e.g. Fig. 6) (Troll *et al.* 2000). These extend from the undisturbed caldera floor, upwards through breccias, the pale coarse-grained sandstone (ES on Fig. 6), and the Cnapan Breaca rhyodacite.

Figure 6 is a representative log for the Cnapan Breaca area. Collapse breccia occupies the lower reaches of the section from the contact with the basal Torridonian sandstone. The rock types present as blocks include all the lowermost Torridonian lithologies and very scarce Lewisian gneiss. The breccias are unbedded low in the section and change from clast-supported to matrix-supported macro textures up-section. These are 'mesobreccias' in Lipman's (1976) terminology for caldera-collapse breccias. Some 70 m of collapse breccia accumulated before the first magmatic material was erupted. This material (ECT on Fig. 6) takes the form of lithic and crystal tuffs deposited in coarse sandstone layers of the breccia. With a return to collapse breccia accumulation, the angularity of the blocks increases and clast-support grades into matrix-support upwards. Beneath the tuff there is no juvenile pyroclastic material, whereas above it the breccia matrix contains sparse glass shards, armoured lapilli, scoria, felsic clasts and plagioclase and (rare) orthoclase crystal fragments. Detailed logging reveals that the breccia thickness varies along strike, pointing to an uneven floor to the caldera. This indicates that the roof of the caldera probably collapsed in a piecemeal fashion, as a series of fault blocks, rather than as a single piston unit. The collapse breccias are inferred to be the products of slumps, slides, debris-avalanches and mass flows from oversteepened walls into a developing caldera.

The considerable thickness of collapse breccias that accumulated before any volcanism occurred is striking, as is the observation that the first tuffs in the breccias are a minimal proportion of its thickness. These observations are contrary to the classic model of cauldron subsidence (Williams 1941; Smith & Bailey 1968) which predicts that caldera subsidence takes place as a consequence of the release of some magma from the underlying chamber, and that there should be approximate correspondence between the thickness of accumulated volcanic rocks and the extent of collapse. It is believed that this evidence for an initial stage of caldera collapse, without accompanying eruption, is an indication that the magma chamber was continuing to expand due to the addition of magma (Fig. 7a). This possibility has been predicted from laboratory and theoretical models of caldera formation (e.g. Komuro 1987; Gudmundsson 1988). We call this stage in which a depression develops by collapse, without magma evacuation, a '*proto-caldera*'.

The first tuff and the subsequent thin tuffs, in addition to the traces of juvenile magmatic material above the level of the first tuff, indicate that the underlying acid magma body periodically 'boiled over', emitting small volumes of pyroclastic material. However, after an interval during which there was apparently no collapse nor evidence for eruptions, when the pale coarse-grained sandstone was deposited by winnowing of fines from the breccias, volcanic activity recurred. Initially, this resurgence erupted pyroclastic fall and flow deposits, locally preserved as the bedded lithic tuffs underlying the rhyodacite (felsite), and subsequently as major rhyodacite ignimbrites (Fig. 6).

The trigger for what was the first major eruption in the Northern Marginal Zone area was the emplacement of basaltic magma into the rhyodacite chamber (Fig. 7b). Mixed rock enclaves of fine-grained basic rock, between 1 and 20 cm in diameter, provide the evidence for this inference. These are of two kinds. One has a dark aphyric cryptocrystalline appearance, occurs as blobs, streaks and schlieren, and is andesitic to basaltic in composition. The lobate and embayed outlines of these inclusions suggest a liquid–liquid contact with the rhyodacite host. This material is assumed to have quenched on eruption. The other enclaves are basic and have chilled margins against the rhyodacite host. They are considered to be fragmented basaltic melt injected into the rhyodacite magma chamber and which chilled against the latter (cf. Eichelberger 1980). Some of these enclaves contain flattened vesicles, and it is the gas released from this magma, and the exsolution of gas from the rhyodacite magma due to its heating by the basic magma, that probably initiated the ash-flow eruptions (cf. Sparks & Sigurdsson 1977).

This view of magma mixing is supported by the oscillatory zoning in the phenocrysts of plagioclase, previously recognized by Dunham (1968). In contrast to Dunham's interpretation of the zoning as being due to periodic magma degassing, it is now interpreted to be the result of a combination of magmatic replenishment, which increased the anorthite content, followed by degassing which gradually decreased the anorthite content (Fig. 8).

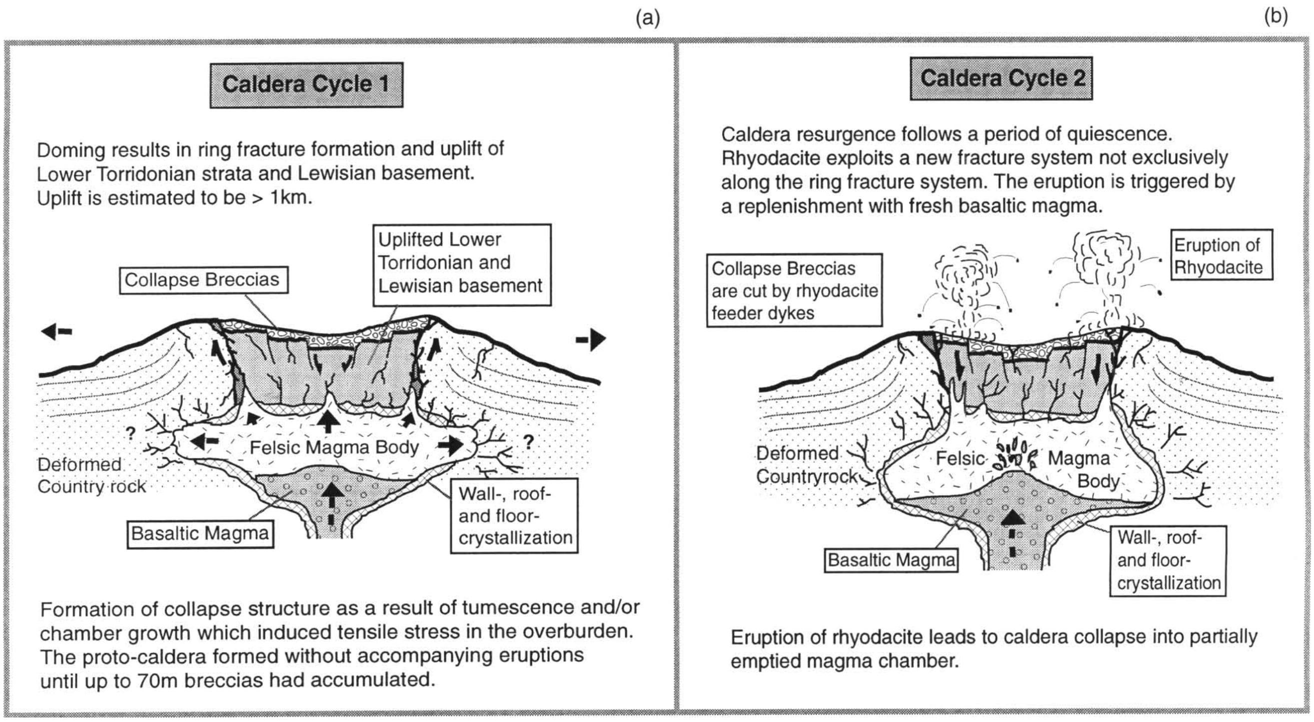

Fig. 7. Evolution of the Rum caldera:
(a) shows the infilling of the caldera by collapse breccias, and emphasises the inflation of the chamber causing formation of the caldera without accompanying eruptions.
(b) shows a later stage when rhyodacitic ash flow eruptions occur, each accompanied by collapse of the caldera floor into the void created.

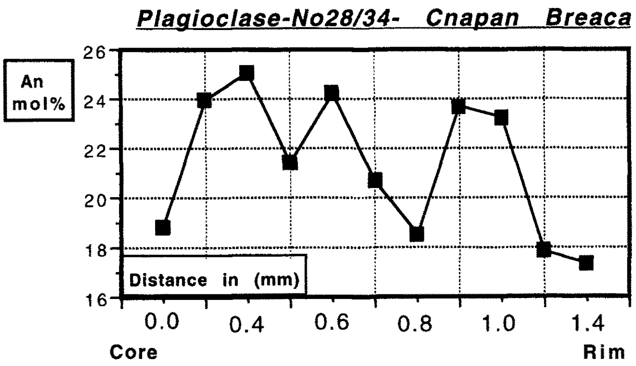

Fig. 8. Evidence of mixing of magmas of contrasted composition: zoning in a plagioclase phenocryst determined by electron microprobe analysis. More than one episode of magma replenishment is indicated by the multiple zoning.

Work in progress suggests that the magma chamber from which the rhyodacite magma was erupted was chemically and mineralogically zoned, with basalt overlain by rhyodacite which itself graded upwards into more evolved compositions (cf. Blake 1981). This conclusion is based on:

- the presence of alkali feldspar only in the early crystal tuffs, indicating derivation from a more evolved magma;
- the occurrence of two types of fiamme, with lighter-coloured and relatively crystal-poor ones present only in the lower flow units of the rhyodacite, whereas dark-coloured, more crystal-rich fiamme occur throughout the rhyodacite;
- decreasing incompatible trace-element abundance upwards through the units;
- the increased proportion of basic enclaves in the upper parts of the felsite (rhyodacite) deposits.

It is certainly tempting to view the Rum magma chamber as having closely resembled the zoned chamber which developed below the Mull centre at the time of emplacement of the well-known Loch Bà Ring-dyke (Sparks 1988).

There is clear evidence in the Northern Marginal Zone that the pyroclastic flows were erupted from sites close to, or on, the Main Ring Fault system. The felsite plug in Coire Dubh is one such feeder, and the steeply-inclined intrusive sheets on Am Màm and Meall Breac are more westerly feeders. The presence in the latter two bodies of highly attenuated fiamme flattened parallel to the feeder dyke contacts suggests that vesiculation and fragmentation occurred before the magma reached the surface and that upon completion of the eruption the fissures were compressed, presumably due to collapse of the caldera following partial emptying of the magma chamber (cf. Almond 1971; Wolff 1985).

Assuming that the extrusive rhyodacite preserved in the Northern Marginal Zone extended to the same thickness over the entire caldera floor, a compacted eruption volume of at least 10 km^3 is estimated. Within the Southern Mountains Zone a number of rhyodacite sheets are preserved showing that those now exposed in the Northern Marginal Zone are likely to have been overlain by the products of additional pyroclastic flows. Perhaps tens of cubic kilometres of magma were erupted during this progressive collapse stage on the magmatic system, making it a prolific source of acid eruptions in the Palaeocene landscape.

In summary, our assessment of the caldera's infilling in the Northern Marginal Zone reveals that two mechanisms of caldera collapse operated on Rum. The earliest stage of collapse involved essentially no concomitant volcanic eruption and is characterized by the accumulation of epiclastic breccias, most of which were derived from instabilities of the caldera walls. The later stage of collapse is associated with eruption of the rhyodacite and may be viewed conventionally as a response to chamber evacuation. Prior to both stages, major intrusions entered the developing ring-fault, bringing up blocks up to 55 m across of very coarse gabbro, accompanied by Lewisian gneiss, Torridonian sandstone and scarce peridotite, in an igneous matrix of granodioritic composition. This intrusive unit corresponds to Dunham's Type 2 breccia, and is now termed the 'Am Màm breccia' (Emeleus 1997).

4.2. Tuffisites and degassing sheets

Apart from bedded lithic tuffs at the base of the Cnapan Breaca and Meall Breac rhyodacite sheets and 4.5 m above the base of the Cnapan Breaca sheet, which Dunham (1968) identified as tuffisites (Fig. 2), he also identified several steeply-inclined, narrow pyroclastic sheets, about 0.7 to 1.1 m in thickness. These black to dark-grey rocks may be texturally uniform or display banding involving alternating coarse and fine material. The sheets are cut by the rhyodacite but penetrate Torridonian sedimentary rocks and the collapse breccias. In addition to country-rock fragments, they contain pieces of rhyodacite, blebs of devitrified basic glass and, in some, abundant plagioclase crystals typical of those in the rhyodacite. Evidently, gas with entrained juvenile ash did locally escape upwards through the floor of the caldera and the overlying intracaldera deposits.

Recent fieldwork has now revealed a further type of fragmental, sub-vertical sheet in Coire Dubh. These sheets are up to 0.6 m thick and traceable for at least 20 m. They cross-cut the felsite and comprise a high proportion of rounded fragments of Torridonian sandstone up to several centimetres in diameter, in a felsitic matrix. From preliminary observations it is suggested that the sheets formed following emplacement of the ash-flow over water-saturated collapse breccias and that locally the pressure of steam generated was sufficient to force a fissure open in the overlying partially consolidated welded tuff. Fluidization of collapse breccia blocks and of rhyodacite caused mixing of the two lithologies within each sheet. Similar features have been reported by Fisher & Schminke (1984) and Cas & Wright (1987) and have been referred to as 'degassing sheets'.

5. CONCLUSIONS

The rocks of the Northern Marginal Zone of the Rum Central Complex have been variously interpreted since they were first described by Judd (1874). All investigators have recognized that the breccias and rhyodacite are associated, and therefore interconnected in origin. However, distinguishing between an above-ground (extrusive+sedimentary) origin or a below-ground (intrusive) origin has been problematic. As has been shown above, prevailing ideas have changed, most notably since Ansel Dunham's proposal that these rocks formed when a volatile-rich rhyodacite/microgranite magma body vented high-pressure gas through its roof, massively disrupting the

Lewisian and Torridonian overburden. Subsequently, some of the remaining gas-poor magma intruded the now brecciated roof in a series of rhyodacitic sheets. The critical events which necessitated reassessment of this view were the case made for a resurgent caldera volcano, the identification of eutaxitic texture in the rhyodacite as fiamme and flattened bubble-wall shards, essential features of welded tuffs, and the recognition of sedimentary structures and interbedded tuff units in the breccias.

The concept of the resurgent caldera was not widely known in Great Britain and Ireland until the 1970s, and it was only following a major period of investigation of modern pyroclastic deposits that recognition of the rhyodacite as pyroclastic deposits has been possible. This provides a good example of how interpretation of ancient sequences is constrained by the prevailing contemporary understanding of geology. It also shows how, following a change in interpretation, it is possible to investigate rocks in quite a different way, from which novel insights emerge.

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