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RESEARCH ARTICLE

Valentin R. Troll · C. Henry Emeleus
Colin H. Donaldson

Caldera formation in the Rum Central Igneous Complex, Scotland

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Abstract The Northern Marginal Zone of the Rum Central Igneous Complex in NW Scotland represents part of the early, felsic phase of the volcano. The marginal zone is a relic of the early caldera floor and the infilling of sedimentary and igneous rocks. Its formation has been explored through field examination of the ring fracture system of the Complex and its pyroclastic and epiclastic intracaldera facies. A sequence of magmatic tumescence and chamber growth caused initial doming, followed by the formation of a collapse structure without accompanying volcanism. This collapse structure, circular in plan, is akin in origin to a salt basin formed by crustal stretching above a rising diapir. We call this the proto-caldera. Collapse breccias, which represent the slumping and sliding of megablocks, blocks and boulders of the Torridonian sandstones which form the walls of the basin, were the original infilling. Logs of these deposits reveal considerable variation in thickness of the breccias (from 80–170 m) in the Complex, indicating an uneven floor to the proto-caldera, consistent with piecemeal collapse. Following accumulation of up to >70 m thickness of breccia, thin interbedded rhyodacitic crystal tuffs (10–30 cm) record the earliest eruptions of felsic magma in the caldera. Caldera formation was then interrupted by a period of quiescence, recorded by the presence of an epiclastic sandstone of locally several metres thickness, formed by washout of fines from the breccias. Subsequent resurgence created a fracture pattern characteristic of doming, along which rhyodacite magma rose in dykes and erupted up to perhaps 10 km^3 of rhyodacitic intracaldera ignimbrites. This major eruption caused further incremental subsidence of the caldera floor into a now partly emptied magma chamber. Mafic inclusions in the ignimbrites point to the eruption being triggered by multiple injections of basic magma into a chamber occupied by felsic magma.

Keywords Pre-eruptive caldera collapse · Proto-caldera · Rum igneous complex · Intracaldera stratigraphy · Ignimbrite feeder dykes · Caldera resurgence

Introduction

Calderas and pit craters are common features of volcanoes and can occur at various stages in a volcano's history. It is widely supposed that flat-bottomed calderas develop during collapse of a piston-shaped plug of rock into the underlying magma chamber during and after eruption (e.g. Smith and Bailey 1968); however, it also has been proposed that collapse could occur without accompanying eruption as a consequence of changes in shape of the magma body (e.g. Gudmundsson 1988).

The opening phase of the Paleocene volcano and intrusive complex preserved on the Isle of Rum (Scotland) features a caldera, the infillings of which are exposed in two areas of the island, separated by a layered ultrabasic intrusion.

The purpose of this paper is to describe new observations from one of the two areas, the Northern Marginal Zone, which shed light on the processes that

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V. R. Troll (✉) · C. H. Donaldson
School of Geosciences, University of St. Andrews, St. Andrews, KY16 9ST Scotland
E-mail: vtroll@geomar.de

C. H. Emeleus
Department of Geological Sciences, University of Durham, Durham, DH1 3LE England

V. R. Troll
Department of Volcanology and Petrology, GEOMAR Research Centre, 24148 Kiel, Germany

caused formation of this caldera. Logs through the caldera-infill breccias, sandstones and felsite that covered the caldera floor reveal that the caldera existed, and was being infilled by collapse breccias slumping from the caldera walls, before any magma reached the surface. These observations support the view that onset of volcanism can indeed be preceded by caldera collapse lacking volcanism. The reason for this may be changes in the form of the underlying magma reservoir. There is evidence that the magmatic system was open to periodic magma recharges throughout the lifespan of the Rum Igneous Centre.

This study focuses on the relationship of the ignimbritic deposits to the underlying caldera-fill tuffs and sediments, which are described in detail and interpreted in the context of caldera formation during the early stages of the Rum Igneous Centre. The history recorded in the intracaldera succession and the caldera ring fracture system allows a more refined reconstruction of the events and further consideration of the processes which led to formation of the Rum caldera.

The Northern Marginal Zone (NMZ) predates formation of the Layered Suite, for which a date of 60.5± 0.1 has been obtained (Hamilton et al. 1998), and postdates the Eigg lava formation, which has been dated at 60.56±0.16 (Pringle and Chambers 1999). The nature of the rocks of the NMZ and their structural relations have been debated for more than 100 years. Judd (1874) referred to the felsites as "lavas", whereas Harker (1908) suggested that a supposed Paleozoic shear zone marked by extensively brecciated horizons had been intruded by Tertiary felsite sheets. The shear zone was reinterpreted by Bailey (1945) as part of a major Tertiary ring fracture system termed the Main Ring Fault, within which major central uplift had occurred. Subsequent studies by Hughes (1960) and Dunham (1968) highlighted the close association of the breccias and felsites. They supported Bailey's (1945) view of in situ rock shattering during explosive volatile release from a magma reservoir, brecciating the overlying country rocks to create explosion breccias. The felsites in turn were interpreted as shallow-level intrusives into the explosion breccias with steep intrusive zones in the north of the complex grading into a shallow-dipping sheet towards the south (Dunham 1968). "Elongated lenticular structures" within the felsite were ascribed to devitrification in an intrusive environment (Dunham 1968). Williams (1985) identified these eutaxitic textures as fiamme and the felsites [referred to as rhyodacite or rhyodacite-porphyry (RDP) in this account] as ignimbrites, a view later supported by Bell and Emeleus (1988) who ascribed the breccias to epiclastic deposits filling the caldera basin as a result of caldera wall collapse. The present study supports the interpretations of Bell and Emeleus (1988).

Mechanisms of caldera formation

A variety of causes for caldera collapse have been proposed since Anderson (1936) considered the problem, but as yet no consensus exists. The classical view of collapse of the magma chamber roof due to evacuation of the underlying magma chamber (Williams 1941; Smith and Bailey 1968) has been widely accepted for a long time; however, recent studies have revealed that this cannot be the only mechanism responsible. Thus, caldera formation has also been attributed to magma chamber tumescence (Komuro 1987), chaotic subsidence (Scandone 1990), downsagging (Walker 1984), trap-door subsidence (cf. Lipman 1997), resurgence (Lipman 1984) or regional tectonism (Moore and Kokelaar 1997). Distinction between these possible mechanisms is complicated, since often the caldera fill prevents direct inspection of the ring faults and the pre-collapse caldera floor. Consequently, much of what is commonly regarded as knowledge on caldera formation is still speculative (McBirney 1990; Branney 1995), and interpretation of caldera structures in terms of a continuum of subsidence styles, rather than as end-member types, may best explain many observed features (Lipman 1997).

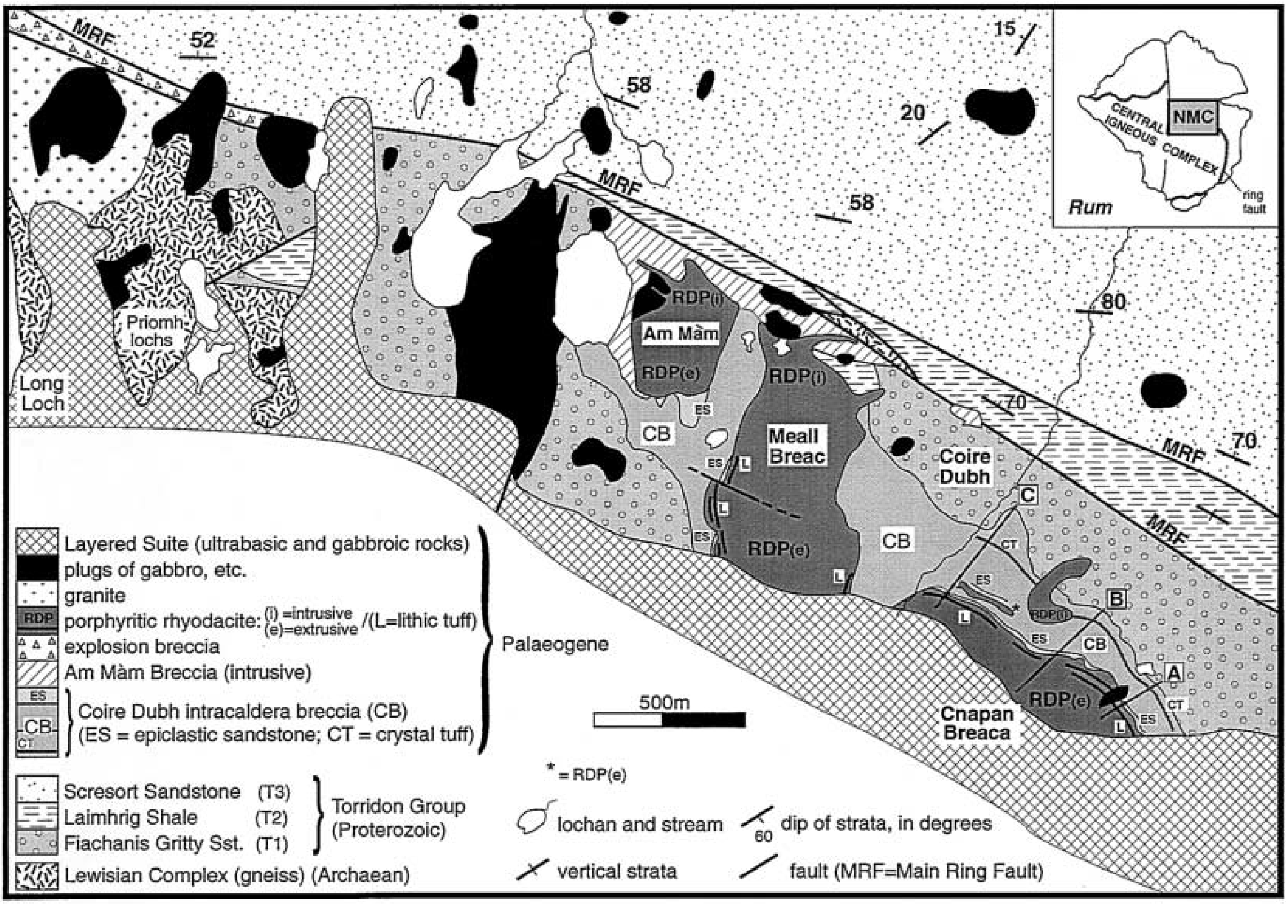
Ring fractures can form due to underpressure on magma chamber evacuation (cf. Anderson 1936; Lipman 1997; Roche et al. 2000) or due to overpressure on doming and chamber inflation (cf. Smith and Bailey 1968; Bahat 1980; Komuro 1987) and are generally thought to develop from the magma chamber upwards. The initial ring fractures created during doming are inward-dipping reverse faults. Only small volumes of magma are able to escape at this stage, since the magma chamber pressure does not greatly exceed the lithostatic pressure (Druitt and Sparks 1984). These initial inward-dipping fractures may get reactivated during collapse to inwards dipping normal faults to accommodate the subsidence at the surface, whereas subsidence at depth may proceed along outward-dipping or vertical fractures (cf. Komuro 1987; Branney 1995; Roche et al. 2000). Alternatively, in the case of extension above an inflated magma system, subsidence may be guided exclusively along the reactivated inward-dipping faults of the doming stage (Komuro 1987; Marti et al. 1994). In contrast, experimental modelling simulating the withdrawal of magmatic support, without precursor tumescence, confirms the development of sharply defined vertical and outward-dipping ring fractures along with piston subsidence (Marti et al. 1994; Branney 1995; Roche et al. 2000).

Many calderas are geometrically complex, contain features attributable to various mechanisms and display a succession of caldera cycles that may not be possible to explain by a single end-member mechanism (Walker 1984; Lipman 1997). The deeply eroded cauldron structure of the Rum Centre provides insight into the lower levels of the ring fracture system and of the caldera floor and fill, and allows an evaluation and reconstruction of its development. This case study adds field observations to the foregoing discussion on how calderas can form and develop.

General features of the Northern Marginal Zone

The marginal zones of the Rum Complex (Northern Marginal Zone and the more extensive Southern Mountains Zone [formerly known as the Northern Marginal Complex and the Southern Mountains Complex; the recent memoir for the island has renamed them as zones (Emeleus 1997)] comprise similar lithologies and structural arrangement of the rock types. In this study the focus is largely on the NMZ. This zone comprises an area of approximately 6 km^2. Precambrian Lewisian gneisses are overlain by Torridonian strata, which in turn are overlain by a thick breccia sequence followed by rhyodacitic ignimbrites. The Northern Marginal Zone is bound to the north by the subvertical Main Ring Fault system and is transected by the Layered Suite in the south (Fig. 1).

Fig. 1 Map of the Northern Marginal Zone (*NMZ*) and adjacent areas, based on mapping by Emeleus (1997) and Troll (1998). Lines *A*, *B* and *C* indicate traverses from which the logs in Fig. 2 were constructed



Main Ring Fault system

The ring fault system on the island forms a clear morphological feature of roughly circular shape, largely encompassing the Tertiary igneous complex. Locally the ring fault system is cut by the post-caldera Layered Suite. The ring fault system of the NMZ comprises two essentially vertical major fault zones which brought Lewisian basement and Torridonian rocks of different ages into tectonic contact. These zones are marked by shattered country rock and uplifted basal units of the Torridonian (T1 and T2; Fig. 1), and show quartz-filled tensional fractures parallel to the fault trend. The two fault zones are generally subparallel but have a complex intersection north of Meall Breac (Fig. 1). Elsewhere on the island, the Main Ring Fault shows a vertical to steep inward dip, e.g. in the Western Granite and the Southern Mountains Zone (Emeleus 1997). The occurrence of more than one fault zone in the NMZ is consistent with observations from the Southern Mountains Zone, where there are more than three subparallel, locally intersecting fault zones (Emeleus 1997).

In the fault zones minor folds, lunar steps, slickensides and polished surfaces with striations indicate the sense of slip(s). Evidently, there have been several periods of fault movement, in opposing directions, in agreement with the history of movement inferred by Smith (1985), Emeleus et al. (1985) and Emeleus (1997) from geological relations of the rock units.

Structure and geological history of the Main Ring Fault system

Combining the existing knowledge and new evidence on the ring fault, we identify the following three stages of activity:

1. The earliest movement of the Main Ring Fault (MRF) represents an early doming stage. Direct indications of this movement in the fault zone itself have been largely obscured by later reactivation of the fault system. The ring fault system is thought to have been initiated during doming which brought Lewisian gneiss and lowermost Torridonian strata to the stratigraphic level of the Torridonian Scresort Sandstone (T3; Fig. 1), which forms the country rock to the complex. This represents an uplift of approximately 1–1.5 km, based on sedimentary thicknesses provided by Nicholson (in Emeleus 1997). Large-scale doming is also consistent with the steep dip of the country rock away from the igneous centre in a 1-km-wide belt north of the ring fault (Fig. 1; Emeleus et al. 1985). This contrasts with the uniform dip of approximately 20–25° to the NW in the north of the island. The geometry of the country rocks is consistent with doming caused by forceful emplacement of an igneous body. Further evidence of doming is contained in the attitude of the unconformity between the Lewisian gneisses and the basal Torridonian beds. This unconformity dips towards the northeast near the Priomh Lochs and to the southeast in the Ainshval area in the Southern Mountains Zone (Emeleus et al. 1985). Within the outer part of the folded belt, small en echelon quartz-filled tension fractures occur in T3. Their long axes are orientated perpendicular to the trace of the ring fault indicating extension in a direction parallel to the fault zone.
2. A collapse stage, forming a basin within the igneous centre, is indicated by the absence of the caldera infill succession outside the MRF and is consistent with downthrow of the intra-fault basement prior to breccia and rhyodacite formation. Other evidence for this movement is the Mesozoic sediments, which are caught up in the ring fault system near Allt nam Bà (Smith 1985), and the shear indicators in the fault zones at Coire Dubh. Syn- to post-rhyodacite subsidence is exemplified by downfaulting of rhyodacite towards the caldera's interior (~40 m) along an inwards dipping (~65° to the south) extensional fault at southern Meall Breac (Fig. 1). This is furthermore supported by a marked tilt of the Cnapan Breaca area towards the SW.
3. The final stage is connected with emplacement of the gabbros and ultrabasic rocks of the Layered Suite and represents an upwards movement of the rocks within the fault system. The upward direction is indicated by a dominant trend of shear-sense indicators within the fault system and by the occurrence of lower Torridonian rocks thrust over Jurassic sediments in the Southern Mountains Zone, where these strata are juxtaposed along a reverse fault dipping steeply towards the northwest (Emeleus et al. 1985).

The results and interpretations presented here are exclusively concerned with the first two stages.

The Caldera Infill

The importance of the infill for interpretation of caldera subsidence has been recognised for a long time (e.g. Lipman 1976). Distribution and volumes of collapse breccias vs those of tuffs are commonly considered to provide critical evidence on the timing and geometry of caldera subsidence (Lipman 1976, 1997).

A fairly complete section of the lower caldera infill, reaching from the caldera basement (Precambrian rocks) through epiclastic caldera-fill breccias and fine sediments to the ignimbrite sheets, is best studied in the Coire Dubh and Cnapan Breaca area. There the exposure permits a series of largely complete traverses (Figs. 1, 2), although the top of the ignimbrite has been removed by erosion. The exposed caldera infill dips 30–35° towards the SE; however, the dips are not original as the whole of the NMZ appears to be slightly tilted towards the SE, at approximately 10–15°. The original dip of the infill may thus have been shallower by this amount.

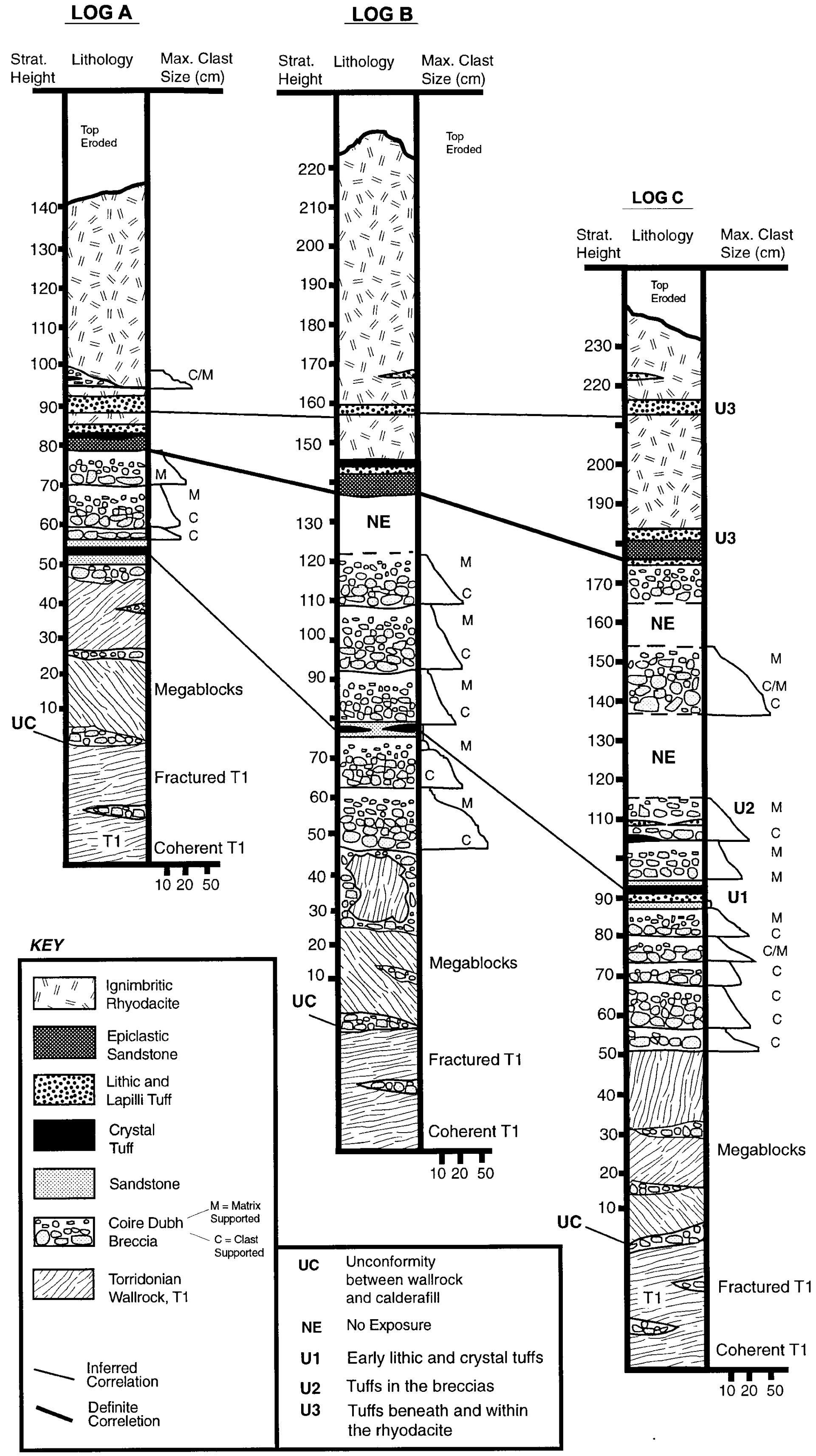
Description and interpretation of the individual units

The caldera infill of the NMZ is essentially a sequence of interbedded breccia and pyroclastic horizons in the lower part, and a variety of pyroclastic rocks in the upper part. The units are described in stratigraphic order.

Caldera basement

The caldera basement comprises Lewisian gneisses, lower Torridonian strata and the early intrusive Am Màm breccia. The major outcrops of the Lewisian gneisses occur near the Priomh-lochs, but Lewisian fault slivers also crop out north of Meall Breac, caught up within the fault zone itself. The fault slivers are thought to have been left stranded along the MRF on collapse following the doming stage (Emeleus et al. 1985). The main mass of Lewisian near the Priomh-lochs is overlain by the basal Torridonian strata (T1)

Fig. 2 Stratigraphic logs of the caldera-infill succession of the Northern Marginal Zone. See also Fig. 1 for position of recorded sections. Note thickness of crystal tuff is vertically exaggerated. Line of correlation is approximately NW–SE



showing an unconformable contact dipping to the NE. Extensional faulting has been observed within the exposed caldera floor east of the Priomh-lochs, where Torridonian beds are downfaulted against Lewisian gneisses.

The Am Màm intrusive breccia

The Am Màm Breccia, although of Tertiary age, is also considered to be part of the caldera basement. The breccia is cut by the inner ring fault zone, implying its emplacement to be related to the early doming stage. The breccia most likely represents an early intrusion into the developing ring fracture. The breccia is made up of a medium-grained granodioritic matrix with clasts and blocks of caldera-floor lithologies together with igneous xenoliths, among which coarse gabbros of centimetre to tens of metre size are very abundant. This is not only compelling evidence for the presence of felsic and basic magmas throughout the early history of the Rum Complex, but it also demonstrates the intrusive nature of the Am Màm breccia. The Am Màm Breccia is cut by later intracaldera ignimbrite feeder dykes, demonstrating that the breccia is of pre-collapse age. The breccia is overlain by caldera infill, signalling a period of erosional unroofing of the updomed rocks before collapse occurred. This implies that the ring fracture has locally permitted intrusion of magma in the vicinity of the chamber roof, but no evidence for corresponding surface volcanism has been detected. Movements on the ring fault therefore occurred prior to any volcanism. Permitted intrusion of the Am Màm Breccia points to extension accompanying the earliest movement in the ring fault zone.

Coire Dubh intracaldera breccias

The breccias occur exclusively within the igneous complex. They are best exposed in Coire Dubh and north of Cnapan Breaca, where they form a succession >160 m thick, including small thicknesses of interbedded pyroclastic units and fine-grained caldera-fill sediments. The breccias show an unconformable contact with the uplifted and strongly deformed basal Torridonian sandstone. The breccias consist of an upper section of mesobreccias and a lower section of megabreccias using the terminology of Lipman (1976; Fig. 2). The mesobreccias consist of angular, subangular or rounded clasts of those lithologies that formed the caldera walls, i.e. Fiachanis Gritty Sandstone (T1) and Laimhrig Shale (T2). Although basalt, dolerite and Lewisian gneiss clasts occur, they are very uncommon. The matrix of the mesobreccias consists of finely comminuted Torridonian lithologies. The maximum clast size ranges from 55 cm down to 2 cm. Grading of the maximum clast size divides the section into several packages (Fig. 2). The breccias lack bedding in the lower part of the succession and show a dominance of clast-support changing to matrix-support upsection (Fig. 3). At an appreciable height above the base of the breccias thin-bedded lithic and crystal tuffs occur in association with coarse sandy layers of the mesobreccia (Fig. 2). These tuffs are the first indication of contemporaneous volcanic activity and divide the mesobreccia into upper and lower units. Above these first volcanics, the angularity of the clasts in the mesobreccia again increases, with clast-support grading into matrix-supported strata (Fig. 2). Above this horizon the volcanic components within the breccias range from glass shards, coated lapilli, scoria and felsic clasts to plagioclase crystal fragments derived from the crystal tuff. Locally restricted and weakly bedded horizons occur within the upper mesobreccias. The breccias dip towards the SSW at 30–35° and show a considerable variation in along-strike thickness (Fig. 2), consistent with an uneven floor to the caldera.

Fig. 3 Portion of a bed of matrix-supported collapse breccia lacking any internal bedding. Southern Coire Dubh. *Hand lens* for scale

According to Lipman (1976), mesobreccias are commonly underlain by megabreccias. The geometry of megablocks and megabreccia zones becomes increasingly difficult to establish as megablock size increases, and is commonly recognised by a lack of structural, stratigraphic or lithological coherence from outcrop to outcrop (Lipman 1976). Megablocks, >25 m across, have been recorded below the mesobreccias of Coire Dubh. Some megablocks are demonstrably enclosed by mesobreccia and have fractures infilled by mesobreccia, e.g. north of Cnapan Breaca at the northern end of Log B (Fig. 1) and in the Southern Mountains Zone (Emeleus 1997). North of Cnapan Breaca, the megabreccias grade into a ca. 150-m-wide belt of coherent T1 countryrock which extends to the ring fault and lacks mesobreccia-infilled fractures. Lipman (1976) reports that the distinction between caldera floor and megabreccia infill is often complicated but generally marked by welded tuff near the contact. In the Rum case this transition is marked by mesobreccia-filled fractures. Pyroclastic rocks are completely lacking within the lower breccia units.

Interbedded pyroclastic deposits

Interbedded pyroclastic materials in the breccias and rhyodacite first occur following the deposition of up to 70 m of mesobreccia (Fig. 2). They indicate that substantial caldera collapse and infilling occurred prior to onset of eruption. They were previously interpreted as tuffisite intrusions (e.g. Hughes 1960; Dunham 1968); however, Williams (1985), Bell and Emeleus (1988) and Emeleus (1997) identified them as pyroclastic deposits of the caldera-fill succession. In this study the interbedded pyroclastic deposits are divided into three subunits.

Unit 1: Early lithic-ash and crystal tuffs (U_1)

The early tuffs show bedding and sorting on a thin-section scale, contain bubble wall and junction shards and are surface deposits (cf. Bell and Emeleus 1988; Emeleus 1997). They are laterally discontinuous but locally traceable over distances of several tens of metres up to more than 100 m. Lateral thickness changes from 10 to 20 cm may be explained by deposition on a palaeotopography and by local reworking.

The lithic-ash tuff contains fine beds of dominantly lapilli-size clasts, mainly of Torridonian lithologies. The lapilli are angular to subangular and represent a combination of early fall and minor flow deposits.

The early crystal tuff (ECT) contains abundant plagioclase (An 15–27), along with accessory quartz and alkali feldspar in a fine-grained rhyolitic matrix. Glassy, vesicular, basaltic clasts and fiamme point to the availability of degassing basic magma in the same magmatic system.

Unit 2: Minor bedded horizons within the breccias (U_2)

The breccia succession following deposition of the early crystal tuff contains restricted beds of lithic and crystal tuff, as well as weakly bedded impersistent domains with only minor juvenile igneous components. These components include scoria fragments, coated lapilli, and crystal fragments of plagioclase. The origin of these locally restricted tuffs and bedded domains is ascribed to minor eruptions, including steam and possibly phreatic explosions with little juvenile contribution. These deposits are likely to have suffered reworking, thus contributing to the upper mesobreccias division.

Unit 3: Lithic and crystal tuffs below and within the rhyodacite (U_3)

Bedded tuffaceous horizons at the base of the rhyodacite sheet at Cnapan Breaca comprise a complex suite of continuous lithic, lithic-ash and crystal tuffs (Bell and Emeleus 1988), and have strong similarities with ground-layer deposits of ignimbrites (Williams 1985). The tuffs show evidence of flow deposition and represent the products of the early phases of the rhyodacite eruption.

Lithic-enriched and fines-poor tuffs also occur several metres above the rhyodacite base. These are discontinuous but locally traceable over several tens of metres. They comprise the common Torridonian lithologies and similar igneous contributions as in units 1 and 2, though locally they lack a crystal tuff component. Clear surface depositional features can be identified, including asymmetrical, plastically deformed impact structures of breccia blocks in rhyodacite. Indications of block transport direction are consistent with possible derivation from the rhyodacite plug north of the Cnapan Breaca rhyodacite sheet. Blocks consist of breccia fragments indicating reworking of already consolidated breccias. This allows for a significant time gap between formation of the early breccias and deposition of the main rhyodacite. The impact structures and plastic deformation of the rhyodacite in turn indicate only a short time interval between emplacement of the ignimbritic flow units below and above the intercalated lithic and crystal tuffs.

In summary, the interbedded pyroclastic deposits are small-volume surface deposits of pyroclastic origin. The tuffs are the products of variably violent explosions resulting in different modes of pyroclastic emplacement. The early crystal tuff represents the first ash-flow eruption of the NMZ and marks the end of the initial, eruption-free, collapse episode. During the second collapse episode there was minor volcanic activity and its products were largely reworked. The interbedded tuffs at the base and within the rhyodacite are thought to represent early phases of large-scale ash-flow eruptions of rhyodacite magma and mark the boundaries of individual flow units of the lower rhyodacite ignimbrites.

Epiclastic sandstone

The upper mesobreccias grade into a fine, pale-grey or cream-coloured epiclastic sandstone (ES), which is commonly between 1.5 and 6 m thick. The ES is laterally extensive and major outcrops have been observed within the NMZ, at Cnapan Breaca, Meall Breac and Am Màm (Fig. 1). The sandstone was deposited in valleys and on flat ground representing the palaeotopography of the underlying Coire Dubh-type breccias. It reaches maximum thickness within the palaeo-valleys but is of near-constant thickness elsewhere. The sandstone varies laterally from a medium-grained alkali-feldspar and quartz sandstone to a gritty, quartz-rich, lithology. The quartz grains are rounded and originate most likely from reworked Torridonian rocks. The alkali-feldspar grains are angular to subangular, representing reworked fragments of Torridonian feldspar which have experienced only minor transport. Locally a grading from the collapse-breccia-like lithology into the sandstone lithology has been recorded, suggesting deposition of the latter as a result of washed-out fines from the unconsolidated breccia deposits.

Rhyodacite

Field relations

The rhyodacite comprises the upper units of the pyroclastic succession. Three main outcrops of the rhyodacite are distinguished in the NMZ, i.e. the Western, the Central and the Eastern, but stratigraphic and petrologic features indicate that the three outcrops are part of same body of rock (Troll 1998). The Western outcrop forms the Am Màm hill and shows steep to vertical, intrusive contacts in the north, whereas to the south, it passes into an extrusive sheet up to 40 m in thickness. Locally at southern Am Màm the rhyodacite directly overlies Coire Dubh-type breccia, suggesting the existence of a palaeo-ridge and palaeo-valleys (Fig. 1). The Central outcrop forms principally the Meall Breac ridge and shows a similar outcrop pattern to the Western outcrop, with steep-sided contacts in the north, grading southwards into an extrusive sheet with a southerly dip of ~25–30°. At its southern end the sheet has a thickness of approximately 100 m and is seen to infill a palaeo-valley within Coire Dubh-type breccia. The Eastern outcrop comprises a sheet-like body to the south, which forms the hill, Cnapan Breaca. The sheet has a maximum thickness of 80 m. Also present are an intrusive plug near the ring fault north of Cnapan Breaca and several smaller dyke-like bodies orientated parallel to the ring fault. An additional outcrop to the NW of Cnapan Breaca may be part of the main Eastern outcrop, which possibly fills a palaeo-valley or alternatively represents the deposits of a previous eruption restricted to this valley.

Whereas the extrusive rhyodacite sheet has been mapped as a single unit, it is locally interbedded with restricted lithic tuff horizons and breccia layers, indicating that it includes the products of at least three major eruptions (compare Fig. 8). The interbedded breccia layers represent collapse events following the eruption of the lower flow units of the rhyodacite; thus, the unit can be divided vertically into at least three major flow units, each marked by basal lithic tuff bed. The lithic tuff overlying the two lower flow units is in one location seen to overlie a thin (~40 cm) epiclastic sandstone bed, suggesting a short time gap between the emplacement of the lower and the upper flow units.

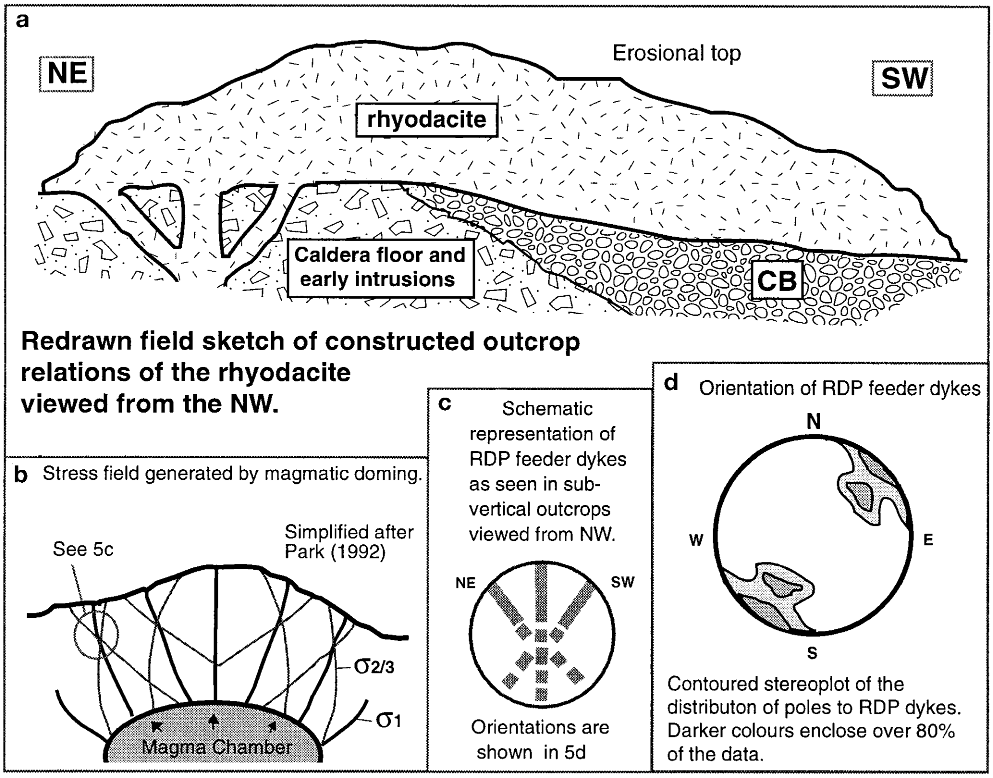
Fig. 4 Fiamme on weathered surface at the base of the extrusive rhyodacite porphyry (RDP). The collapsed pumice fragments die out higher up the extrusive rhyodacite sheets. *Hand lens* for scale

The rhyodacite is characterised by eutaxitic texture, defining a sub-horizontal, and in places folded, foliation. The texture consists of lenticular streaks and fiamme (Fig. 4). The folding occurs dominantly in the lower units of the rhyodacite and is ascribed to post-compactional rheomorphic deformation. Jointing perpendicular to the foliation is observed locally. Fiamme are of two types: a light-grey type which is poor in phenocrysts (<10%) and a darker grey, phenocryst-rich type (>20%). The eutaxitic texture is abundant in the lower two major flow units and becomes progessively less prominent upwards, possibly reflecting the decrease in load pressure upsection.

Rhyodacite feeder system

Ignimbrite feeder dykes are known elsewhere (e.g. Ray 1960; Cook 1968; Almond 1971; Wolff 1985; Reedman et al. 1987) but are thought to be rare (Almond 1971; Wright and Walker 1977; Wolff 1985). The feeder sheets and dykes in the northern part of the NMZ, which cut through the Am Màm Breccia and the Coire Dubh breccia deposits, show a variance of dip directions ranging from ~60° to the south to vertical to ~60° to the north (Fig. 5). The pronounced foliation within the dykes, picked out by highly attenuated fiamme, is generally parallel to the smooth margins. This is explained by dyke closure after withdrawal of magmatic pressure or by squeezing on further caldera collapse (Almond 1971; Wolff 1985). The fracture geometry resembles that of fault systems ascribed to magmatic pressure in a doming or resurgence stress field (e.g. Almond 1971; Walker 1984; Park 1992).

By analogy, the rhyodacite, including its interbedded pyroclastic deposits, is the result of early resur-



Redrawn field sketch of constructed outcrop relations of the rhyodacite viewed from the NW.

b Stress field generated by magmatic doming.

c Schematic representation of RDP feeder dykes as seen in sub-vertical outcrops viewed from NW.

Orientations are shown in 5d

d Orientation of RDP feeder dykes

Contoured stereoplot of the distributon of poles to RDP dykes. Darker colours enclose over 80% of the data.

Fig. 5 **a** Redrawn field sketch of constructed outcrop relations of the Am Màm and Meall Breac hills viewed from the NW (length of section approximately 0.5–1 km). The intrusive feeder dykes and sheets which grade into extrusive rhyodacite deposits cut through the caldera basement and the infilling collapse breccias (*CB*). The foliation of the rhyodacite swings round from vertical to shallow dip at the transition from intrusive to extrusive character. **b,c,d** The fracture pattern exploited by the feeder dykes follows a vertical (*σ1*) and a conjugate (*σ2/3*) fracture pattern characteristic for magmatic doming. This indicates that the ring fracture of the first collapse phase had been closed during collapse. The rhyodacite magma was consequently rising in a new, resurgent fracture system, which was not exclusively situated along the ring fault

gence, with the rhyodacite exploiting fractures which opened due to renewed magmatic pressure. The exploitation of new pathways which were not restricted to the ring fault confirms that the ring fractures of the first collapse phase had been closed. Creation of new fracture systems during resurgence points to overpressure in the magma chamber (Almond 1971; Bahat 1980; Walker 1984). The lack of intracaldera breccias at the base of the rhyodacite implies sudden opening of the dykes and drainage of the magma reservoir. The resulting chamber evacuation caused cauldron collapse, marked by the interbedded breccia horizons within the extrusive rhyodacite deposits. The closure of the feeder dykes which flattened pumice to produce fiamme parallel to the walls was caused by inwardly directed pressure, probably during collapse following chamber drainage.

Petrography

The rhyodacite contains phenocrysts of plagioclase, quartz, pyroxene and opaque oxides. The microcrystalline to cryptocrystalline groundmass is commonly finely banded with flattened glass shards.

The plagioclase phenocrysts show varying morphology from broken and embayed, to euhedral shapes. Many crystals have pronounced internal oscillatory compositional zoning (An 16–30) which is attributed to the mixing of successive batches of magmas of contrasted compositions (Troll 1998; Troll et al. 1999). Further details on the rhyodacite petrography are given by Emeleus (1997).

Basic inclusions within the rhyodacite

Basic inclusions occur throughout the pyroclastic succession of the NMZ. Whereas they are relatively abundant in the rhyodacite, they are scarce in the earlier pyroclastic units (e.g. the early crystal tuff). Three main types have been distinguished (Table 1). Type-I inclusions are probably accidental plutonic fragments from the walls of the magma chamber. Inclusions of types II and III occur in horizons within the rhyodacite. Type-II inclusions are characterised by a dark aphyric, cryptocrystalline appearance representing magma frozen in the conduit or on eruption. These inclusions occur as blobs, streaks and schlieren (Fig. 6a) and are dispersed through the rhyodacite. Type-III inclusions are always round and differ from type II in having a microcrystalline texture with plagioclase lath morphologies characteristic of quenching (Lofgren 1980) and a chilled margin (Fig. 6b). This type is found throughout the rhyodacite, implying repeated replenishments of the magma chamber by basic magma, and raises the possibility that such replenishments have triggered rhyodacite eruptions (cf. Sparks et al. 1977; Eichelberger 1980; Folch and Marti 1998).

On the east side of Meall Breac there is a composite sheet with a chilled mafic margin and a rhyodacite interior containing type-II inclusions. This implies the

Table 1 Types of basic inclusions

Type	Interpretation
I: Coarse gabbro and peridotite inclusions	Early roof and wall crystallisation
II: Aphyric basaltic to andesitic inclusion with fluid-phase appearance	Basic magma which has been available throughout
III: Marginally chilled basaltic inclusions	Input/replenishment of hot basaltic magma resulting in chilling due to temperature differences

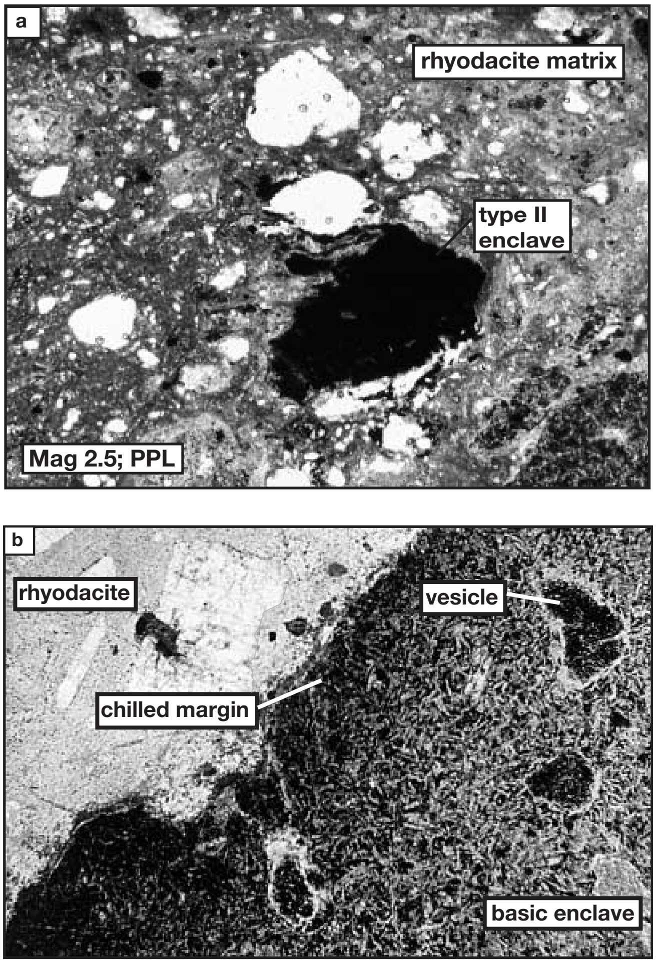


Fig. 6 **a** Photomicrograph of rhyodacite porphyry host and basic inclusions found in the rhyodacite feeder north of Meall Breac (field of view ca. 6 mm; *PPL*). The inclusion-host relationship is indicative of a fluid-fluid relationship of basic "blobs" and the rhyodacite porphyry host. **b** Type-III inclusion in rhyodacite from extrusive sheet, southern Am Màm (field of view ca. 6 mm; *PPL*). The photomicrograph shows the contact of the rhyodacite host to the inclusion. (*Black areas* in the inclusion are vesicles filled with secondary minerals.) The size of the plagioclase laths clearly decreases towards the margin which represents a classical chilled margin in the sense of Eichelberger (1980)

coexistence of basaltic and rhyolitic magmas within the same magma reservoir, and offers a possible explanation for the existence of type-II inclusions in the rhyodacite ignimbrites by entrainment of one magma into the other during ascent of the two magmas in the conduit (cf. Freundt and Tait 1986).

Evolution of the Northern Marginal Zone

As a result of different erosion levels of the intracaldera breccias succession (Fig. 2) insight can be gained into the evolution of the NMZ and the early Rum Caldera.

Coire Dubh intracaldera breccias

Intracaldera breccias can form by either in situ gas shattering or collapse of unstable caldera walls. The former possibility has previously been proposed by Hughes (1960) and Dunham (1968) for the Coire Dubh breccias; however, the occurrence of megabreccia zones in addition to laterally persistent interbedded airfall and ash-flow tuffs in the mesobreccias exclude this possibility. Clast size grading and changes from clast-supported to matrix-supported lithologies define the Coire Dubh intracaldera breccias as epiclastic collapse deposits. These formed due to collapse of unstable caldera walls and inwards slumping and sliding of the debris (cf. Lipman 1976). Slumps, debris flows and lahar deposits are dominant in the upper breccia succession, whereas the lower breccias are characterised by megablocks.

The breccias overlie the relict caldera floor and we have found no evidence for pre-collapse volcanic activity. At least two main episodes of collapse are detected from the caldera-fill breccia. The repetitive nature of the collapse-breccia tuff units together with the lateral thickness changes of the breccia succession supports deposition of an uneven caldera floor.

Interbedded pyroclastics

Minor pyroclastic eruptions occurred following accumulation of >70 m of breccia. The outcrops are laterally discontinuous, indicating post-depositional reworking. These thin tuff beds represent small-volume eruptions formed while the magma chamber remained over-pressured (lithostatic pressure slightly below chamber pressure; see Druitt and Sparks 1984). The first tuffs were deposited on sandy beds of the breccias, following a time gap between the previous collapse and the tuff eruption. The initial caldera collapse is unlikely to have been caused by evacuation of the magma chamber through volcanic activity, given the clear deficiency in eruptive volume compared with subsidence volume (indicated by the difference in thicknesses of the first tuffs and the collapse breccias). Vesicular basic fragments/inclusions in early lithic and crystal tuffs point towards degassing of probably fresh basic magma as the eruption trigger. The occurrence of alkali feldspar defines the early crystal tuffs as having derived from the most differentiated felsic magmas of the NMZ.

Epiclastic sandstone

Caldera collapse and volcanic activity ceased, allowing deposition of the epiclastic sandstone. This sandstone marks a period of volcanic inactivity and relatively stable conditions when fine material was washed out of the breccias. The maximum thickness of approximately 6 m points to a significant time gap between formation of collapse breccias and the rhyodacite.The epiclastic sandstone is considered to mark the final stage of a first collapse cycle.

Rhyodacite

The rhyodacite is interpreted as a characteristic intracaldera ignimbrite (cf. Cook 1968; Almond 1971; Walker 1984). The feeder dykes can be clearly linked with the extrusive sheets in both the Western and the Central outcrops. Such connections are rare in volcanic terranes (e.g. Almond 1971; Wolff 1985) and represent one further example of intra-caldera feeder dykes grading into extrusive ash-flow deposits. The Eastern rhyodacite outcrops represent a feeder system disconnected by erosion, with a mixed magma filling the feeder conduit to the north of the Eastern rhyodacite sheet. Whereas the Eastern and the Central sheets have comparable successions, only part of the succession is present in the Western outcrop.

A genetic relationship between periodic collapse events and up to four anorthite-enriched zones in the rhyodacite's plagioclase phenocrysts may be inferred. It is proposed that multiple chamber replenishment events caused the physical and chemical changes responsible for the plagioclase zonation within the magmatic system, and possibly magma chamber overpressurisation and growth which triggered accompanying caldera collapse. Caldera collapse into the consequently evacuated magma chamber will have resulted in downfaulting of the rhyodacite towards the caldera's interior (Fig. 1) and tilt of individual blocks (e.g. the Cnapan Breaca block) evident in the current dips of the rhyodacite. Degassing of the basic magma within the replenished chamber is considered to have generated the inferred overpressure (e.g. Folch and Marti 1998), resulting in resurgence of the caldera floor (cf. Marsh 1984).

Timing of events

Cycles of collapse events and episodes within the intracaldera succession can be distinguished (Fig. 7). The first intracaldera episode follows the doming event and is characterised by breccia formation lacking any juvenile volcanic component. This episode, which is here termed the proto-caldera stage, lasted until the first eruption deposited the early lithic and crystal tuffs. Following emplacement of the first crystal tuffs, and until deposition of the epiclastic sandstone, a further episode or possibly two episodes within the first caldera collapse cycle can be demonstrated (Fig. 7). The second caldera cycle followed a period of quiescence marked by the epiclastic sandstone. Eruption of the rhyodacite and its interbedded pyroclastic horizons thus belong to a resurgent phase of activity.

The proposed cycles and episodes (Fig. 7), in combination with the drastic thickness changes of the collapse breccias along strike and the complexity of the fault zone with multiple blocks and slivers, point to incremental growth of the caldera, and support differential (piecemeal) caldera collapse, already occurring during the proto-caldera stage. Syn- to post-rhyodacite collapse is recorded in the ring-fracture-parallel fault at southern Meall Breac, which shows a downthrow of the caldera infill towards the calderas interior, and in a tilt of the Cnapan Breaca block towards the SW. These observations add further convincing evidence in support of a piecemeal collapse style.

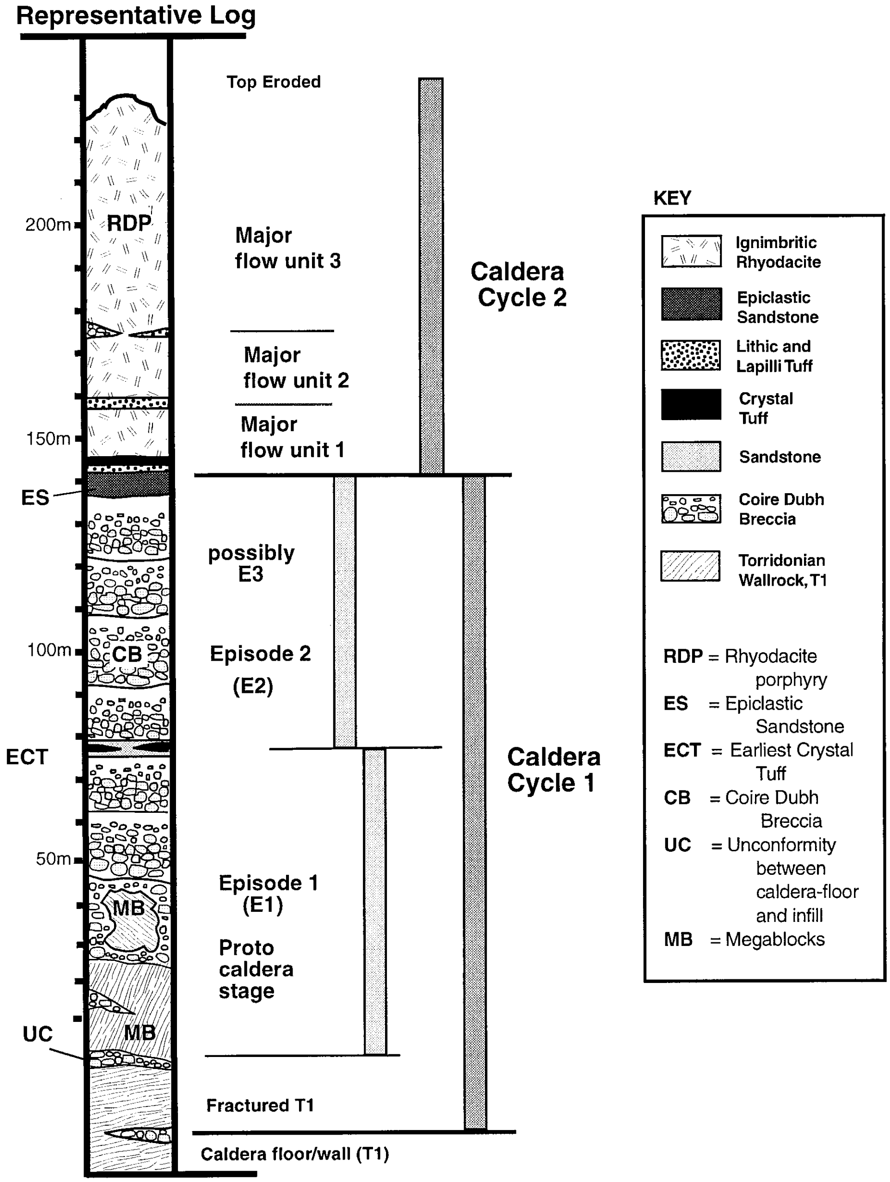
Discussion of caldera-forming mechanism(s)

First caldera collapse cycle

Of the caldera-forming mechanisms mentioned previously, only tumescence is consistent with the observations for the first caldera cycle. This is because of (a) collapse being preceded by doming, (b) the lack of volcanics in the lower breccia succession, (c) the volume deficit of subsidence vs eruptive products and (d) the structure and orientation of the MRF zone. All these features have been identified in laboratory and theoretical modelling of tumescence-causing caldera formation.

Tumescence associated with large shallow magma chambers may cause doming, and tensile stresses which result in caldera formation (Komuro et al. 1984; Komuro 1987; Marti et al. 1994; Henry and Price 1989). Ring-fault formation during initial doming is likely to lead to a vertical or inward-dipping fault system. Chamber tumescence may form radial tension fractures (represented on Rum by en echelon fractures and some radial dykes) until the central region of the dome begins to subside, forming a depression bounded by reactivated concentric and inward-dipping faults of the initial tumescence stage (Marti et al. 1994). It is

Fig. 7 Caldera cycles and episodes marked by the caldera infill



thus the reverse concentric faults of the doming that guide the collapse as reactivated normal faults (in combination with possible new faults). These results demonstrate that collapse may actually begin during the initial tumescence stage, since the central region of updoming is normally always in extension.

A single, sharply defined fault is not created in response to tumescence (Marti et al. 1994). Instead, several ring faults accommodate subsidence, and these are not as well defined as the ring faults of pure piston subsidence. The subsidence associated with tumescence often occurs along a set of concentric faults, and these may even intersect each other. Furthermore, the subsiding centre of the initial dome does not behave as a single block, since it is likely to have already suffered disruption during updoming (Marti et al. 1994). This initial collapse basin (i.e. apical graben) will subsequently fill with sedimentary breccias, followed by tuffs (e.g. Komuro et al. 1984). Tuff erupts as soon as the limit of tensile strength of the country rock is exceeded and rupture of the chamber permits pyroclastic eruptions; thus, the first pyroclastic eruptions may post-date both the formation of the apical graben and its early sedimentary breccia fill. The circular basin may continue to grow in stages in response to shallow-level reservoir changes. Periodic magma replenishments triggering pulses of gas release may produce multiple growth episodes of the associated caldera fault (Gudmundsson 1998). Evacuation of the chamber as a result of succeeding eruptions will lead to further subsidence of the already formed depression, largely guided by reactivation of the fault(s) created during the tumescence stage (Marti et al. 1994). At this stage outward-dipping fractures may develop which also accommodate some of the subsidence.

In summary, several features of caldera initiation due to tumescence and/or chamber growth are not satisfactorily covered by the pure evacuation model:

1. The ring faults are vertical to inward-dipping and form a set of faults, not a sharply defined single ring fault.
2. No pre-collapse volcanics need erupt since the caldera forms as an extensional basin, whereas the evacuation model requires pre-collapse drainage of the chamber to withdraw roof support.
3. Periodic caldera growth may be connected to growth or replenishments of a shallow level, low-aspect-ratio magma chamber, resulting in differential caldera subsidence and very probably a piecemeal caldera floor, although piston/plate collapse is possible but unlikely.
4. The eruption volume associated with caldera formation can be significantly less than the volume formed by subsidence of the caldera floor, because a caldera formed mainly by extensional faulting as the result of chamber tumescence does not require an equivalent withdrawal- to subsidence volume.

The ring-fracture system of the Rum Caldera is believed to have grown from the magma chamber upwards during the doming stage (cf. Smith and Bailey 1968; Komuro 1987), which explains the vertical to inward-dipping ring fractures. Early intrusive breccias (Am Màm Breccia) were emplaced at this stage. Doming, until a degree of instability was reached, led to collapse of the overburden, producing a volcanogenic depression (proto-caldera). The formation of this depression may have started as a downsag structure, but it appears more likely that the subsidence was guided along the pre-existing structural weakness of the ring-fault zone. The initial collapse episode (E1 on Fig. 7.) was dominated by the deposition of megablocks, slides and stone falls from the oversteepened caldera walls, and was followed by episode 2, which began with pyroclastic eruptions. Thus, initiation of the caldera collapse took place without volcanic eruption, i.e. without magma chamber evacuation. The pyroclastic eruptions were followed by the formation of further collapse mesobreccias of episode 2, locally with interbedded thin pyroclastic deposits (Fig. 2). This supports an episodic, and consequently incremental, growth of the caldera during the first cycle; hence, the caldera formation started with a collapse event and ended with a series of pyroclastic eruptions, which may have been triggered by the collapse (cf. Gudmundsson 1998). A piston collapse may be excluded for the first caldera cycle; instead, the caldera floor collapsed in a piecemeal manner as already proposed.

An approximation of the overall caldera subsidence can be obtained by considering the occurrence of Jurassic strata in the ring fault zone of the Southern Mountains Zone. A subsidence of of up to 1.5 km has been tentatively estimated (cf. Bailey 1945; Emeleus et. al. 1985). Smith and Bailey (1968) pointed out that the subsidence volume of calderas formed by evacuation is often approximately equivalent to the eruption volume. This observation was used to imply a genetic relationship between magma chamber evacuation and caldera collapse. However, caldera fault slip is not neccessarily associated with an eruption, as shown by the 1968 fault movement on Fernandina (Galapagos Islands) where a 350-m slip did not lead to large eruptions (Gudmundsson 1998). The eruptive volume of the intracaldera pyroclastics of the first collapse cycle of the Rum caldera can hardly be regarded as even an approximate equivalent of the subsidence volume represented in part by the thick breccia units. Even when considering the relative subsidence along the MRF zone as partially resulting from upward movement of the caldera walls, subsidence cannot be caused by evacuation of the chamber at this stage producing the crystal tuff with maximum thickness of just 20 cm. The proto-caldera can be defined as a circular, large-scale apical graben above the initial dome with subsidence along a complex ring-fracture system. Its origin is believed to bear similarities to basin formation above a rising salt diapir (cf. Talbot and Jackson 1987).

The caldera-slip model of Gudmundsson (1997, 1998) might explain some of the observed features: calderas with steep to inward-dipping ring faults are likely to develop in areas with precursor doming above a sill-like, felsic magma chamber which may have excess magmatic pressure. Slip at the ring faults allows partial decompression of the magma chamber which results in volatile exsolution and bubble growth, thus causing local overpressure which leads eventually to eruption. The eruptive volume during this stage is comparatively low, implying reduction of overpressure but only to lithostatic pressure (Druitt and Sparks 1984).

The balance of field evidence for the first collapse phase is consistent with subsidence due to extensional faulting as a result of magma chamber tumescence and possible growth. This supports views that in many cases it may be the collapse which triggers the eruption, and not vice versa (e.g. McBirney 1990; Gudmundsson 1998). The cause of magma-chamber tumescence, on the other hand, is most likely the replenishment of the shallow-level magma chamber. Two to three replenishments of the Rum chamber during the first collapse cycle are recorded in the caldera infill and suggested by plagioclase zonations (Troll 1998).

Second caldera collapse cycle

The rhyodacite feeders were initiated during resurgence caused by a tensile stress field. The opening of these tensile fractures occurred suddenly and permitted eruption of the main volume of the rhyodacite. It is plausible that the rhyodacite feeders represent the surface extension of pre-existing basement fractures, created by disruption during initial doming and episode-1 collapse. In the experiments of Marti et al. (1994) resurgence of a simulated caldera that experienced tumescence and collapse showed that no new fractures were formed during resurgence. Pre-existing faults of previous stages were simply rejuvenated. In the case of the rhyodacite it is assumed that such pre-existing fractures are present in the caldera basement but would not have been present in the fill which formed in response to the first cycle of caldera collapse. The overall orientation of the rhyodacite feeders could reflect the presence of subparallel concentric faults within the caldera floor, hidden by the caldera infill. For the rhyodacite to penetrate through the caldera floor and the caldera fill, a new fracture system needs to be created within the caldera infill.

Lithic tuffs at the base of the rhyodacite are an indication of volatile exsolution in the early stage of rhyodacite resurgence. No collapse breccias are found between the rhyodacite and the epiclastic sandstone; hence, there was no sudden fault slip on the MRF prior to initiation of the major rhyodacite eruption. The rhyodacites of the second collapse cycle comprise a significantly greater volume than the pyroclastic deposits of cycle 1, with a minimum thickness of 100 m. The evacuation of the rhyodacite therefore represents a volume (possibly >10 km^3) consistent with caldera collapse due to chamber evacuation. Subsidence contemporaneous with the rhyodacite eruptions was caused by classical magma chamber evacuation; hence, the existence of collapse breccias interbedded with the rhyodacite. Collapse breccias occurred after the deposition of at least two flow units of the rhyodacite, indicating that collapse resulted from removal of significant volumes of rhyodacite from the shallow-level reservoir (see Fig. 2, log A). The occurrence of these breccia horizons, as well as the thin epiclastic sandstone, which locally underlies the lithic tuff of major flow Unit 3, implies eruptive pulses and consequent collapse events. Collapse also occurred after rhyodacite emplacement, as seen in the downfaulting of rhyodacite at the southern end of Meall Breac and the tilt of the Cnapan Breaca block towards the caldera's interior.

Druitt and Sparks (1984) proposed that only small volumes of magma can erupt from an overpressurised magma chamber until the chamber pressure reduces to below the lithostatic pressure. At this stage the roof would subside to form a caldera and large-volume ignimbritic eruptions could commence. The evidence of collapse Cycle 2 in the NMZ is consistent with this model. Major flow units 1 and 2 show small volumes of rhyodacite interbedded with a tuffaceous unit some metres above the base of the succession. These contrast with the much larger volume of the ensuing major flow unit 3 (Fig. 7). The interbedded lithic tuffs grading into the main ash-flow deposits may therefore record the change from resurgent overpressure to a lower-pressure regime (e.g. Scandone 1990), which permitted roof collapse.

The vertical to inward-dipping ring fractures observed on Rum will have guided the relative subsidence of the blocks of the first and second collapse cycles within the ring fault system. This may be ascribed to reactivation of the initially reverse ring faults created during doming to inward-dipping normal faults on subsequent chamber evacuation. Subsidence will, however, also have occurred along faults now covered by the caldera infill, since tilting of individual blocks has demonstrably occurred (Cnapan Breaca block tilted towards the SSW). Some of these intracaldera-floor faults may have been outward dipping, but this remains speculative.

Magma chamber replenishments and growth as the eruption trigger and the driving force for caldera formation

Changes of magma chamber shape with time, e.g. on emplacement of fresh magma into a chamber, or on melting and incorporation of wall rock into the chamber, are thought to be a common feature in the British Tertiary Centres (e.g. Walker 1975; Donaldson 1983). The size and geometry of a shallow-level magma chamber are considered to strongly influence the caldera subsidence (e.g. Gudmundsson 1988, 1997, 1998; Marti et al. 1994; Lipman 1997) and thus the intracaldera deposits. Tumescence of a chamber for whatever reason would result in updoming of the roof and/or the caldera floor. A cause of tumescence pointed out by Marsh (1984) and Tilling et al. (1987) is the replenishment of a chamber with basic magma and its subsequent degassing. Evidence for replenishments of the early Rum magma chamber includes: (a) close association of felsic and basic magma; (b) basic inclusions, clearly chilled against the rhyodacite magma within the chamber; (c) oscillatory zoning in rhyodacite plagioclase phenocrysts; and (d) phenocrysts of the rhyodacite in mixed rocks of the rhyodacite plug near Cnapan Breaca show resorption in proximity to basic batches but reaction rims inside the basic batches, both features which necessarily formed prior to eruption (Troll 1998). Further evidence for multiple basaltic and picritic replenishments has been recorded in the well-known layered ultrabasic rocks (e.g. Tait 1985; Renner and Palacz 1987). Although the Layered Suite post-dates the caldera stage, the occurrence of multiple replenishments points to periodic magma injection as a major process during the lifetime of the Rum Igneous Centre.

Replenishments of basic magma are commonly thought to de-gas in the lower-pressure environment of a shallow level reservoir and to result in magma chamber tumescence and growth. Evidence for volatile release is provided by vesicles in chilled basic inclusions.

There is convincing evidence of lateral growth of the magma chamber elsewhere in Rum presented by

Greenwood et al. (1990) who describe large-scale partial remelting and incorporation of felsic country rocks by basic melts of the layered suite. Sideways chamber expansion is also evident in the transgression of the MRF by layered ultrabasic rocks on the eastern margin of the centre (Emeleus 1997). Whereas these events post-date the early caldera, they demonstrate that magma chamber growth was common during the history of the Rum Complex and is therefore a reasonable expectation of the early stages of its development. The view of growth/tumescence of the magma chamber may be reinforced, considering a scenario for the crystal-rich rhyodacite magma reaching a density equilibrium within the crust (cf. Marsh 1989) and creating horizontal as well as lateral spread of the magma chamber.

Evolved felsic melts are known to be able to cause caldera-forming eruption solely on their own due to volatile release and separation of vapour phases (e.g. Blake 1984; Tait et al. 1989; Stix and Layne 1996). Influx and underplating of basic magma beneath felsic magma in the chamber would most probably enhance tumescence (e.g. Tilling et al. 1987), since the effects of the volume change imposed by the input will largely be compensated by compaction of country rock, updoming of the chamber roof and possibly lateral growth. The extra magma introduced to the reservoir is, however, unlikely to be the direct cause of eruption; instead, degassing of the injected magma and superheating of the felsic magma can result in sufficient overpressurisation of the chamber to trigger eruption (Folch and Marti 1998). Movements along the already existing ring fractures and the opening of tensional fractures above such an inflated magma system are the surface expressions of the processes in the underlying chamber. In the Rum Caldera a growing and overpressured magma chamber is likely to have initiated the eruptions of the first and second caldera cycle. The subsidence during the first cycle is considered to be the direct result of tumescence and the cause for the eruption. Collapse of the roof into the magma chamber would lead to eruption (cf. Gudmundsson 1998). The second collapse cycle was also initiated by overpressure resulting in the opening of tensile fractures which permitted initial rhyodacite eruptions. Further subsidence, however, will largely have occurred due to evacuation of the magma reservoir by the voluminous rhyodacite eruptions.

It becomes apparent that a simple model which assumes magma-chamber evacuation resulting in caldera collapse cannot account for the formation of the Rum Caldera as a whole. A mechanism is required for initiation of collapse without necessarily involving magma-chamber evacuation and which additionally explains vertical to inward-dipping ring fractures, incremental growth and a piecemeal caldera floor. It further must explain the difference in eruptive volume and subsidence volume during early collapse stages.

Komuro et al. (1984), Komuro (1987), Marti et al. (1994) and Gudmundsson (1988; Gudmundsson et al. 1997, 1998) provided model views on calderas explaining caldera formation due to tumescence with vertical to inward-dipping ring fractures, incremental growth histories and most importantly the ability to explain collapse events without evacuating the magma chamber.

Applying these model views of caldera collapse caused by tensile stress accompanying tumescence of a magma chamber satisfactorily explains the following observations on the Rum Caldera:

1. The vertical to inward-dipping ring fractures.
2. The complex subparallel structure of the fault zones as distinct from a sharp single ring fault.
3. The lack of volcanics at the base of the intracaldera succession.
4. The incremental episodic collapse due to chamber growth events.

Furthermore, if the first-cycle collapse was caused by extension, no difficulties in explaining the discrepancies of subsidence and eruption volumes arise, since collapse is not associated with chamber drainage.

The second collapse phase was initiated due to resurgence after a period of volcanic inactivity. Magma was guided to the surface along fractures which opened due to overpressure caused by degassing of injected basic magma into a probably zoned felsic chamber. The balance of field evidence and geometrical considerations favours syn-eruptive subsidence during the second cycle. A simple synthesis of the sequence of major events is illustrated in Fig. 8.

Conclusion

Formation of the early Rum Caldera featured an initial doming stage followed by two caldera cycles, each initiated by magmatic overpressure. Doming and magma-chamber growth resulted in ring-fracture formation, followed by incremental (piecemeal) caldera formation during caldera collapse cycle 1. Collapse cycle 2 includes resurgence of the caldera, with subsequent collapse into the evacuated magma chamber. The presence of basic magma can be demonstrated in both caldera cycles. When this is combined with the evidence from the later layered ultrabasic intrusion, it is apparent that periodic replenishments by magma may have been the key magmatic process throughout the history of the Rum igneous centre.

Collapse breccia deposits and intracaldera volcanics form in response to shallow-level chamber processes. The lack of volcanics in the lower breccias may be used as an indicator for pre-eruptive collapse events and the style of collapse. Evidence is presented of intracaldera dykes that fed ash-flow deposits, a feature which has been described from only a few other places.

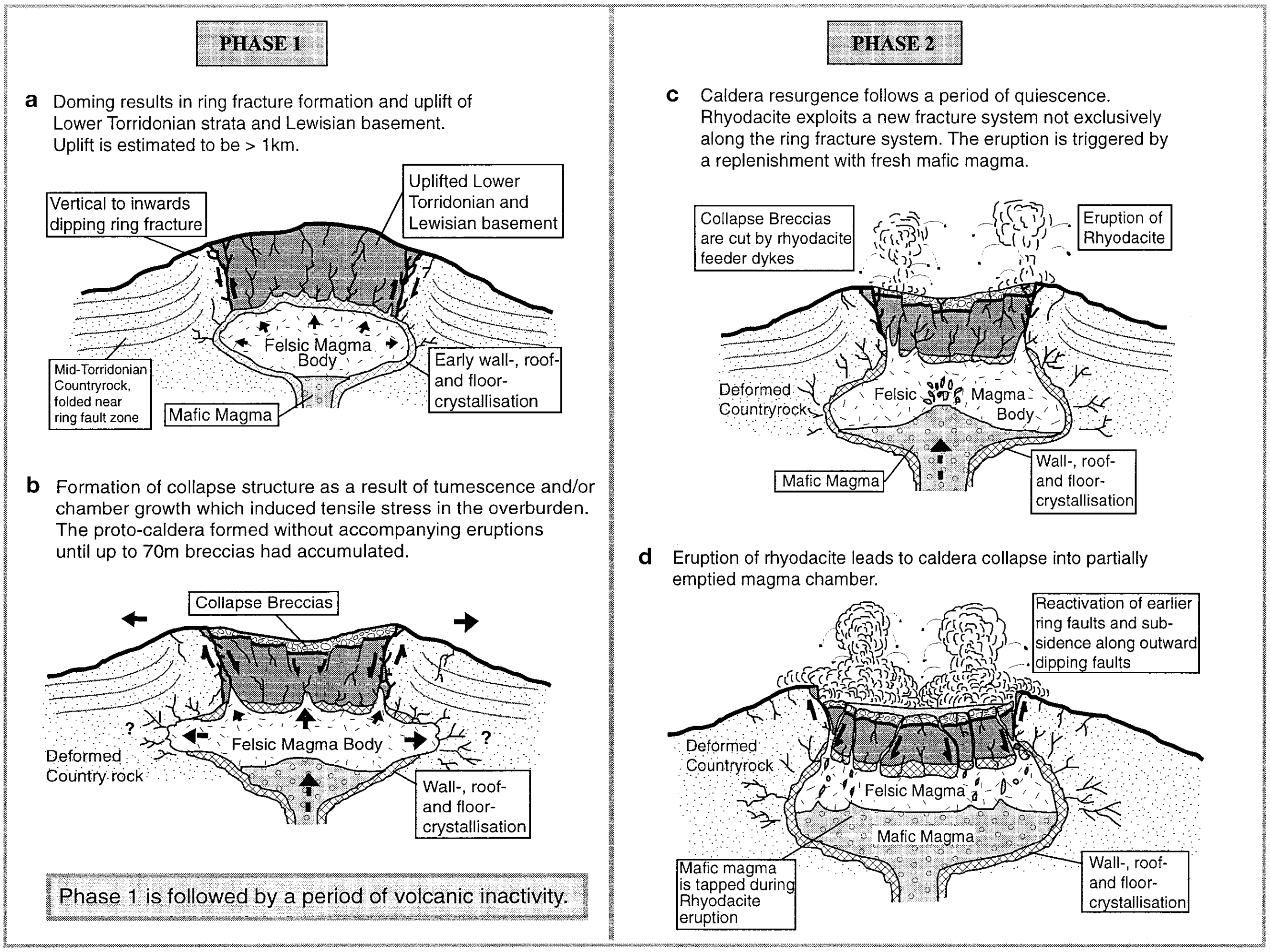


Fig. 8 Sequence illustrates the major events in the formation of the early Rum caldera

This study supports the validity of theoretical considerations and experiments on alternative mechanisms of caldera formation and filling, such as the caldera-slip model, and underlines that it may often be a combination of processes and mechanisms which can best explain the formation of an individual caldera.

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