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Dating the onset of volcanism at the Rum Igneous Centre, NW Scotland

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Abstract: Major volcanic activity on the Isle of Rum commenced with the eruption of thick (>100 m) intra-caldera rhyodacite ash-flow sheets fed from steep-sided feeder conduits in the proximity of the Main Ring Fault. Twenty plagioclase phenocrysts of the rhyodacite were analysed using single crystal $^{40}Ar/^{39}Ar$ laser dating, yielding a mean apparent age of 60.83 ± 0.27 Ma (MSWD = 3.65). On an age v. probability plot the feldspars do not, however, show a simple Gaussian distribution, but a major peak at 60.33 ± 0.21 Ma and two smaller shoulders at *c.* 61.4 Ma and 63 Ma. These older ages are interpreted to represent recycled and largely re-equilibrated feldspars. The age peak at 60.33 ± 0.21 Ma is interpreted to represent the intrusion and eruption age of the rhyodacites. This new age constraint overlaps with that for the ultrabasic intrusion, implying that the latter was already forming at depth and supplying necessary heat during the early felsic activity phase, and quickly thereafter migrated upwards to shallow structural levels and intruded the volcano's earlier deposits. Combined with previously published ages, these new age data highlight an extremely rapid succession of events at the Rum centre, the whole sequence occurring in potentially <500 ka.

The Isle of Rum has been the subject of intense geological investigation for well over 100 years. Early research (e.g. Geikie 1888; Harker 1908; Bailey 1945; Hughes 1960; Dunham 1968) focused on the identification of the major structures, lithologies and some of the unique igneous features on Rum. Recent work has reinterpreted these early findings and refined the detailed sequence of Palaeocene events (e.g. Donaldson 1974, 1975; Williams 1985; Smith 1985; Emeleus 1985, 1997; Troll *et al*. 2000, 2004; Holness & Isherwood 2003; Holness 2005). This sequence commenced with uplift and erosion of Lewisian gneiss and Torridonian sandstone inside a ring fault zone in response to magma focusing and pushing upwards beneath Rum. This phase was succeeded by felsic ignimbrite eruptions with corresponding caldera collapse and the intrusion of a large, shallow-level microgranite. Finally, there was migration and intrusion of a major ultrabasic magma chamber to shallow crustal levels and also into the lower reaches of the early intra-caldera deposits. Extremely rapid subaerial erosion of the Rum centre followed these events (Emeleus 1985, 1997).

Within this sequence, the thick pile of intra-caldera ignimbrite deposits preserved on Rum are of particular relevance, as they not only provide constraints on the timing of the centre by marking the onset of surface volcanism, but also because they represent possibly the best-preserved example of voluminous, explosive, surface volcanism within the British and Irish Palaeogene Igneous Province. Other, but volumetrically smaller and/or less well-exposed examples include the Donalds Hill Ignimbrite Formation in NW Ireland (Mitchell *et al*. 1999), the Kilchrist vent area on Skye (Bell & Emeleus 1988), the Sgùrr of Eigg (Emeleus 1997), and the Tardree and Sandy Braes complex in NW Ireland (Mitchell 2004.). A significant number of vents and shallow felsic intrusions are preserved on Skye (Harker 1904; Bell 1985), Mull (Bailey 1924; Sparks 1988), Arran (King 1955) and at Slieve Gullion (Richey & Thomas 1932; McDonnell *et al*. 2004), suggesting that explosive felsic volcanism must have been an essential, voluminous and widespread part of the igneous activity in the province as a whole. This study presents the first $^{40}Ar/^{39}Ar$ age dates for the major rhyodacite event on Rum and places these early eruptive events of the Rum volcano within a rapid evolutionary sequence.

Geological setting

The Isle of Rum is located on a NE–SW-trending ridge of Torridonian sandstone, bounded by Mesozoic basins to both the west and east. The initial ponding of magma beneath the region caused doming at the Rum centre. Lewisian gneiss inside the ring fault was uplifted, in places by up to 1.5 km (Emeleus *et al*. 1985; Emeleus 1997), into juxtaposition with the younger Applecross Formation Torridonian sandstone (external to the ring fault). Subsequent dome erosion brought the gneiss to very shallow levels near, or even onto, the palaeo-surface.

Breccias derived from erosion of Lewisian gneisses and Torridonian sediments, and lacking any significant igneous matrix material, were deposited within the Main Ring Fault structure prior to the onset of the main felsic volcanism (Troll *et al*. 2000). These breccias are overlain and cross-cut by extrusive sheets of rhyodacite and associated massive intrusive rhyodacite bodies, well preserved in both the Northern Marginal Zone and the Southern Mountains Zones (Fig. 1). The onset of felsic volcanism was coupled with large-scale caldera collapse (Emeleus 1997; Troll *et al*. 2000, 2004) and the down-faulting of Jurassic limestone and slivers of the Eigg Lava Formation (Fig. 1) by potentially as much as 1 km (Smith 1985; Emeleus 1997). This onset of volcanism is marked by a number of thin, crystal-rich tuffs as observed within the Coire Dubh sedimentary breccias grading up into >100 m thick valley-fill ignimbrite sheets (Emeleus 1997; Troll *et al*. 2000; Fig. 2a and b). The major plutonic system of the layered ultrabasic suite cuts these early rhyodacites and the Western Granite (Emeleus 1997; see

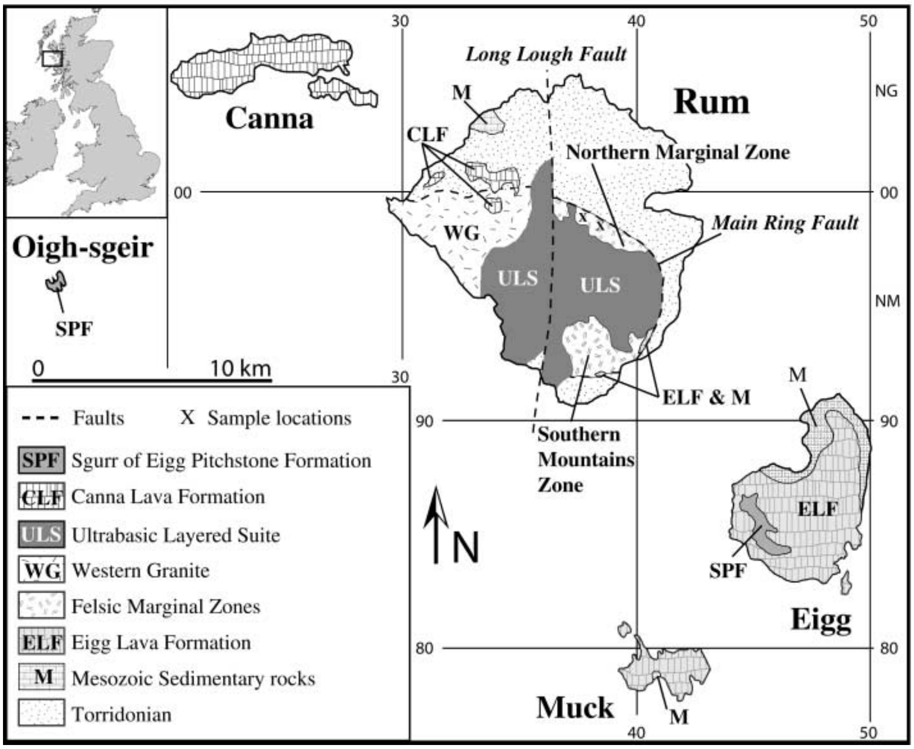

Fig. 1. Map showing the location and simplified geology of the Isle of Rum and the surrounding Small Isles, modified from Emeleus (1997).

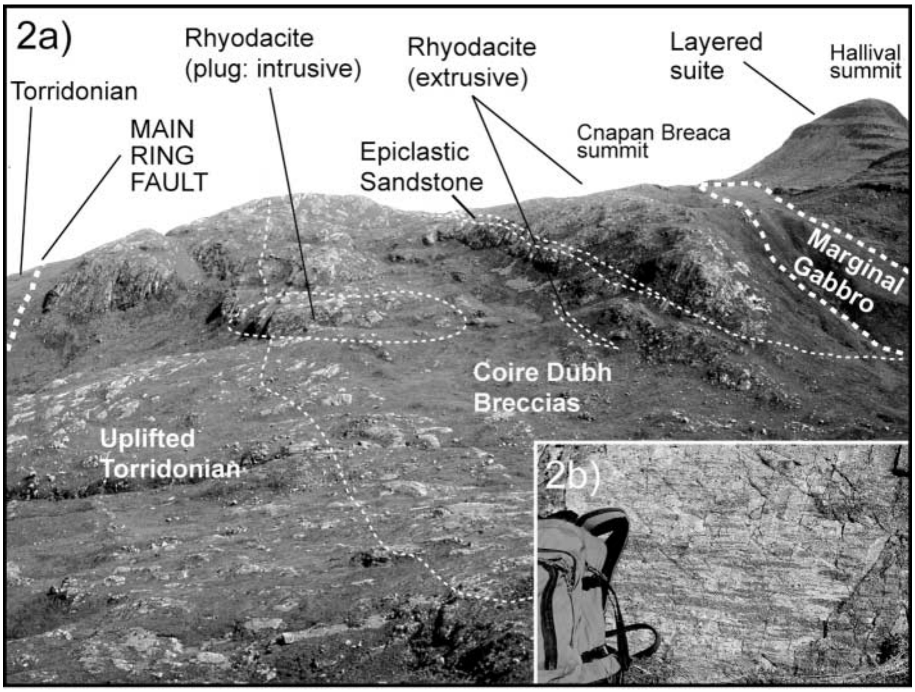

Fig. 2. (**a**) Photograph of Cnapan Breaca and Coire Dubh area showing rhyodacite ignimbrite sheets, Northern Marginal Zone. (**b**) Photograph of fiamme at the base of the rhyodacite ignimbrite sheet at south Meall Breac, Northern Marginal Zone (after Troll *et al*. 2000; Donaldson *et al*. 2001).

Fig. 1). Following cessation of the ultrabasic magmatic activity, vigorous subaerial erosion ensued, evidence for which can be observed in the west of the island where several Palaeocene lava flows, erupted from nearby Canna (Fig. 1) and the Skye Igneous Centre, occupy valleys deeply incising the Western Granite (Emeleus 1973, 1985).

The duration of events was previously defined as *c*. 1 Ma (Chambers *et al*. 2005). The earliest felsic volcanic rocks on Rum, the rhyodacites, have not previously been dated. Our study provides independent age constraints for the onset of volcanic activity within the Rum central complex and, placed within the framework of previous data, a test for the internal consistency of geological events and available radiometric dates.

Analytical methods

Single crystal Ar/Ar age analysis

Large rhyodacite samples, collected from the southern end of Meall Breac and the northern end of Am Màm in the Northern

Marginal Zone (see Fig. 1), were jaw-crushed and 20 plagioclase crystals were selected under a high-magnification binocular microscope for single crystal $^{40}Ar/^{39}Ar$ age determination. The crystals were cleaned ultrasonically to remove any remaining matrix and groundmass. The crystal separates were then washed in ultrapure HF and HCl to remove any low-temperature alteration. The mineral fragments were fused in a single step, with no flux material added, by a 25 W Spectra Physics argon ion laser at the maximum power range. Irradiations were carried out in the 5 MW research reactor at the GKSS Research Centre (Geesthacht, Germany), with crystals in aluminium trays and cans (no Cd liner). The $^{40}Ar/^{39}Ar$ laser analyses were performed at GEOMAR Research Centre, Geochronology laboratory, Kiel, Germany. The argon isotope ratios were determined on a MAP 216 series mass spectrometer fitted with a Baur–Signer ion source and a Johnston electron multiplier, following the procedures outlined by Bogaard & Schmincke (1998). Argon isotope ratios were corrected for mass discrimination, background and blank values, neutron flux gradients and interfering neutron reactions. The applied irradiation monitor standard used was MMhb-1 (520.4 Ma; Samson & Alexander 1987). Single age and error estimates were derived for the sample by calculating the mean apparent age and assuming an initial 'atmospheric' $^{40}Ar/^{36}Ar$ ratio of 295.5 (see Table 1 and Fig. 4). Mean square weighted deviations (MSWD) were determined for the mean apparent age to test for scatter within the single crystal data (see Bogaard 1995, for procedural details). Ages are quoted with a 1σ error, including the uncertainties of the monitor's $^{40}Ar/^{39}Ar$–K relation and procedural blank measurements.

Electron probe microanalysis

Samples were prepared as polished thin sections for optical microscopy and electron microprobe analysis. Mineral analyses were performed on a JEOL JCXA 733 at the University of St. Andrews, using wavelength-dispersive spectrometry. Analytical conditions included an acceleration voltage of 15 kV, a beam current of 8–20 nA, and counting times of between 20 and 60 s on peaks. A rastered beam was used for the feldspars (*c.* 12 μm^2). Natural and synthetic minerals were used as standards and monitors.

Results

Prior to age determination, a feldspar separate from the rhyodacite was analysed for oxygen isotopes to test for potential hydrothermal overprint caused by the later ultrabasic material that is found in proximity to the rhyodacites (≥1 km). The analysis was carried out at the University of Cape Town (see

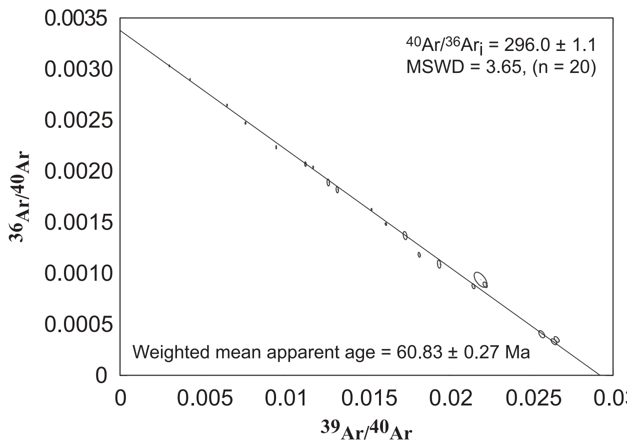

Fig. 4. Isotope correlation diagram of $^{36}Ar/^{40}Ar$ v. $^{39}Ar/^{40}Ar$ isotopic ratios for the 20 Rum rhyodacite feldspar crystals analysed. Isochron calculation (York 1969) yields an isochron age of 60.73 ± 0.27 Ma and an initial $^{36}Ar/^{40}Ar$ ratio of 296 ± 1.1 Ma (MSWD = 3.65); this translates to a weighted mean apparent age of 60.83 ± 0.27 Ma. Single crystal $^{39}Ar/^{40}Ar$ isotope ratios are shown with 1 SD error ellipses. All data are normalized to a common J-value of 1E − 3.

Table 1. *$^{40}Ar/^{39}Ar$ laser dating ages of rhyodacites from Rum*

Sample	Location	Unit type	Mean ± error (Ma)	MSWD	*n*	Isochron ± error (Ma)	Initial ± error (Ma)
UDPNTLH	North Am Màm hill	Dyke		5.6	8	60.6 ± 0.8	294 ± 3
RDP	South Meall Breac hill	Ash-flow		2.3	12	61.0 ± 0.6	296 ± 1
UDPNTLH and RDP	Combined samples		60.83 ± 0.27	3.65	20	60.73 ± 0.27	296 ± 1.1

MSWD, mean square weighted deviation; *n*, number of single crystal analyses used to derive mean and isochron age; 'Initial' is initial $^{40}Ar/^{36}Ar$ ratio.

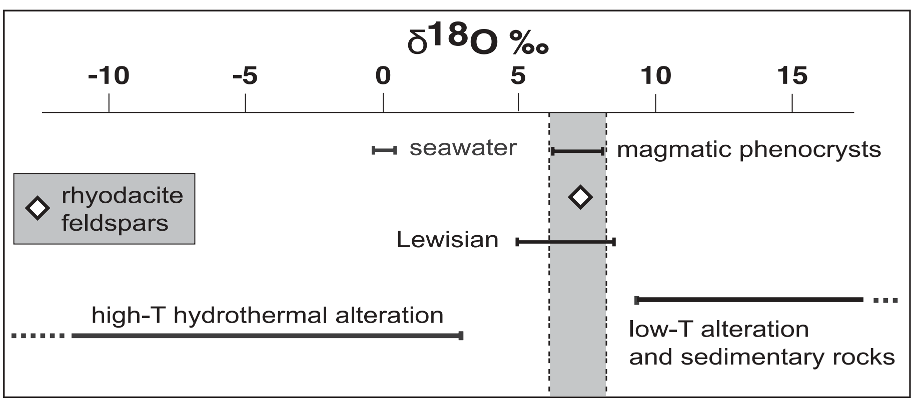

Fig. 3. Oxygen isotope values (δ^{18}O ‰) of analysed rhyodacite feldspars (note that the error is smaller than the symbol size). The ranges of Lewisian gneiss, igneous rocks in general, and high- and low-temperature hydrothermal alteration are indicated.

Harris *et al.* 2000, for analytical procedure). The rhyodacite feldspars give $\delta^{18}O = 6.88 \pm 0.15‰$ (Fig. 3), thus falling within the range expected for magmatic phenocrysts (5.5–7.5‰, Hoefs 1997), as well as that of the Lewisian gneisses in the area (*c.* 5–8‰, Thompson *et al.* 1986). The $\delta^{18}O$ value of the rhyodacite feldspars does not, however, fall within the much lower range that is usually associated with high-temperature hydrothermal alteration ($\ll$5‰), or the much higher range associated with low-temperature weathering ($\gg$9‰) (e.g. Hoefs 1997; Hansteen & Troll 2003). Oxygen isotope data of Emeleus (1997) suggest that some of the Lewisian and rhyodacite whole-rocks have been partially affected by high-temperature alteration. Our new data indicate that, despite this, the feldspars in our rhyodacite samples have largely escaped alteration, indicating that the samples are suitable for age determination (see Cousens *et al.* 1993).

The results of the $^{40}Ar/^{39}Ar$ single crystal analysis define an isochron that yields a weighted mean apparent age of 60.83 ± 0.27 Ma (see Table 1), showing an error of <1% and a MSWD of 3.65 (Fig. 4). On an age v. probability plot the feldspars do not show a simple Gaussian distribution, however. There are three distinct feldspar populations within the dataset (Fig. 5), with a major peak at 60.33 ± 0.21 Ma and two smaller peaks at *c.* 61.4 Ma and 63 Ma.

In the next section we argue that the smaller peaks represent older, crustal-derived xenocrysts that are probably present beside juvenile feldspar phenocrysts. The Torridonian sandstones on Rum contain alkali feldspar, and the early mafic plutonic rocks, coarse gabbroic intrusions now preserved as isolated blocks within the Am Màm Intrusion breccia (Emeleus 1997; Troll *et al.* 2000), contain calcic plagioclase. Neither type of feldspar is commonly found in the rhyodacite, which contains oligoclase as its dominant feldspar. Hence we focused attention on the Lewisian gneiss as a possible xenocryst source and obtained a substantial number of microprobe analyses of the chemical compositions of plagioclase crystals from the rhyodacite and from Rum Lewisian gneisses (Fig. 6). This dataset is one of very few currently available on the chemical composition of Rum Lewisian gneiss feldspars (see Greenwood 1987) and also regionally for Lewisian feldspars in general (see Table 2 and supplementary data online at http://www.geolsoc.org.uk/SUP18301). Plagioclase in the Rum Lewisian gneiss ranges from An_5 to An_{74} ($n = 85$), with the major peak between An_{26} and An_{29} and a small shoulder at about An_{10}. The majority of the rhyodacite feldspar analyses ($n = 230$) fall within the An_{16} to An_{25} range. Thus the rhyodacite and Lewisian gneiss feldspars show a considerable overlap in chemical composition (Fig. 6). The rhyodacite feldspars frequently show complex zoning patterns (see Troll *et al.* 2004, pp. 724–727) and analyses of rhyodacite crystal cores often show compositions that match the most abundant Lewisian feldspar group (An_{26} to An_{29}). Troll *et*

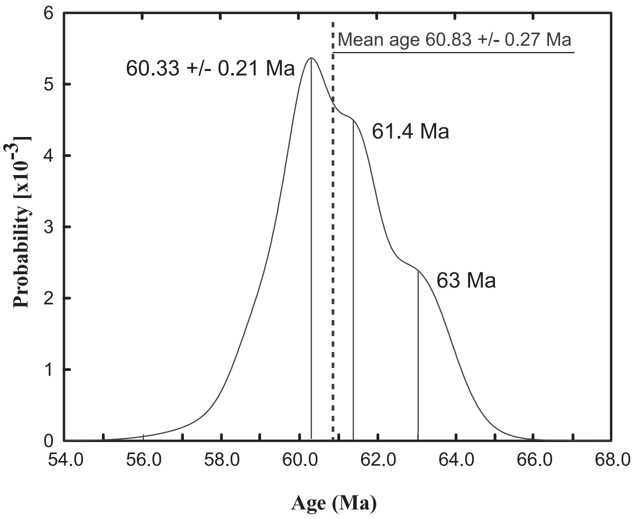

Fig. 5. Probability density function of rhyodacite single grain apparent ages and errors, with discrete maxima at 60.33, 61.4 and 63 Ma.

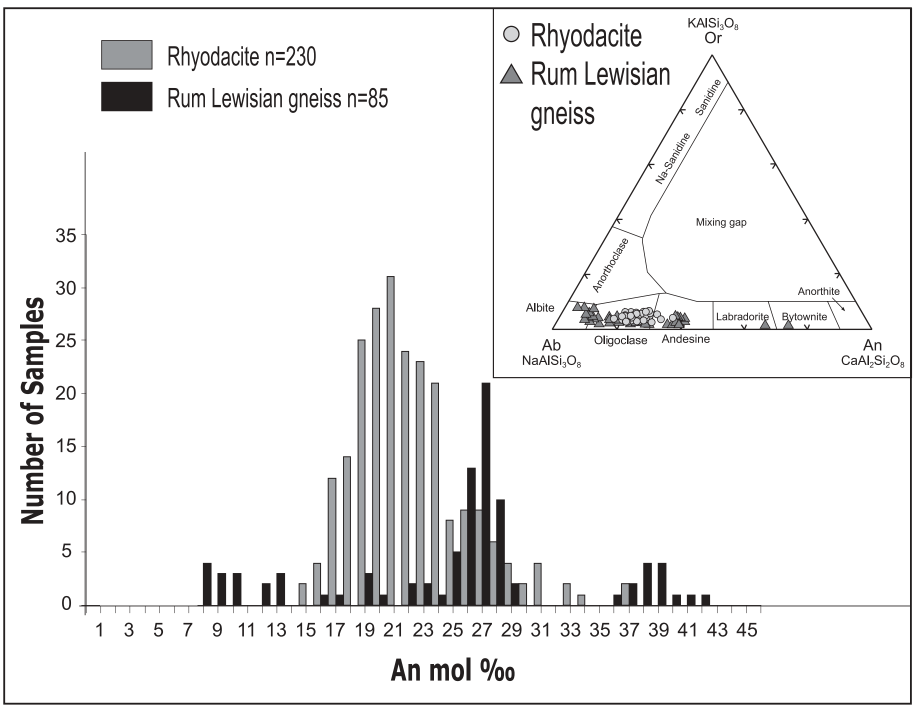

Fig. 6. Histogram showing the distribution and range of An mol.% of both Rum Lewisian gneiss and rhyodacite plagioclase crystals (see Table 2 and Supplementary Publication).

Table 2. *Representative plagioclase analyses from rhyodacites and Rum Lewisian gneisses*

	Rhyodacite													Rum Lewisian gneiss							
GPS location:	[3875 9845]					[3969 9400]				[3980 9385]				[3360 0040]				[3939 9294]			
Sample name:	Fsp 45-14 (NMZ)					RDP-BnS-2 (SMZ)				RDP-BnS-8 (SMZ)				Sr 321-4				R-GN-4			
Position:	1(rim)	2	3	5	7(core)	1(rim)	3	4	5(core)	2(rim)	3	6	7(core)	1	2	3	4	293	294	295	296
SiO_2	64.37	63.58	63.55	62.29	62.60	64.74	64.19	61.61	60.59	64.89	64.29	63.22	64.29	61.11	61.25	61.13	60.75	58.96	60.22	59.74	60.08
Al_2O_3	22.90	23.07	23.21	23.59	23.29	24.02	23.26	24.19	24.58	22.34	22.55	23.18	23.17	25.05	24.62	24.87	24.50	26.44	26.03	25.80	26.02
FeO	0.15	0.21	0.33	0.26	0.21	0.06	0.41	0.30	0.53	0.32	0.15	0.35	0.35	0.00	0.02	0.01	0.06	0.22	0.12	0.14	0.21
CaO	3.59	4.21	4.32	5.13	4.68	4.64	4.31	6.01	6.82	4.11	4.00	5.08	4.36	5.95	5.72	5.81	5.78	8.14	6.88	7.58	7.24
Na_2O	9.83	9.09	9.04	8.76	9.02	6.94	7.71	7.75	6.53	8.28	7.84	7.75	7.35	8.06	8.43	8.40	8.45	7.01	7.05	6.95	7.01
K_2O	0.13	0.39	0.51	0.42	0.19	0.37	0.71	0.31	0.56	0.63	0.70	0.83	0.88	0.27	0.18	0.26	0.34	0.20	0.40	0.48	0.16
Total	100.97	100.54	100.95	100.46	99.99	100.77	100.59	100.17	99.61	100.57	99.53	100.41	100.40	100.44	100.23	100.48	99.88	100.97	100.70	100.69	100.72
O	3.043	3.024	3.031	3.009	3.003	3.061	3.036	3.002	2.980	3.035	3.011	3.016	3.032	3.010	3.004	3.009	2.987	3.004	3.013	3.002	3.012
Si	2.817	2.800	2.792	2.757	2.776	2.816	2.816	2.732	2.707	2.847	2.843	2.791	2.823	2.703	2.715	2.705	2.708	2.613	2.661	2.650	2.656
Al	1.181	1.197	1.202	1.230	1.217	1.231	1.202	1.264	1.294	1.155	1.175	1.206	1.199	1.306	1.286	1.297	1.287	1.381	1.356	1.349	1.355
Fe	0.005	0.008	0.012	0.010	0.008	0.002	0.015	0.011	0.020	0.012	0.006	0.013	0.013	0.000	0.001	0.000	0.002	0.008	0.004	0.005	0.008
Ca	0.168	0.199	0.203	0.243	0.222	0.216	0.203	0.286	0.326	0.193	0.190	0.240	0.205	0.282	0.272	0.276	0.276	0.387	0.326	0.360	0.343
Na	0.834	0.776	0.770	0.752	0.776	0.585	0.656	0.666	0.566	0.704	0.672	0.663	0.626	0.691	0.725	0.721	0.731	0.602	0.604	0.598	0.601
K	0.007	0.022	0.028	0.024	0.011	0.021	0.040	0.018	0.032	0.035	0.039	0.047	0.049	0.015	0.010	0.015	0.019	0.011	0.023	0.027	0.009
Total	5.013	5.001	5.007	5.016	5.009	4.871	4.931	4.977	4.945	4.946	4.925	4.961	4.915	4.997	5.009	5.014	5.023	5.003	4.974	4.988	4.971
An mol%	16.8	20.4	20.9	24.5	22.3	27.0	23.6	30.0	36.6	21.5	22.0	26.6	24.7	29.0	27.3	27.6	27.4	39.1	35.03	37.6	36.3

NMZ, Northern Marginal Zone; SMZ, Southern Mountains Zone. A full list of sample numbers and analyses is available online at http://www.geolsoc.org.uk/SUP18301.

al. (2004) also provided evidence for sieve-textured plagioclase crystals associated with rhyodacites from the Northern Marginal Zone. They reported and showed photomicrographs of several plagioclase crystals within the rhyodacite that have sieve-textured zones in the interior of the crystals but with euhedral overgrowth zones. When the Lewisian gneiss is heavily thermally metamorphosed its plagioclase takes on a very distinctive 'sieve texture' (Emeleus 1997). This petrographic line of evidence supports further the presence of xenolithic cores within some of the rhyodacite plagioclases and may give an explanation for the older age dates that would appear to be mixed and partially re-equilibrated ages.

Discussion

The trimodal distribution and the high MSWD of 3.65 imply the presence of up to three feldspar populations and point to significantly older xenocryst material amongst juvenile feldspar phenocrysts of the rhyodacite. The small age peak formed by three (15%) of the analysed crystals, at approximately 63 Ma, is pre-British Palaeogene Igneous Province in age (Emeleus & Bell 2005), and certainly predates igneous activity on Rum (see Chambers *et al*. 2005). The argon content of these xenocrysts may have been modified by interaction with pre-eruptive acid magma of the rhyodacite rocks now exposed on Rum. This oldest peak is interpreted to represent partially re-equilibrated feldspars, perhaps present as cores in rhyodacite feldspar, derived from a crustal source. For a xenocryst to retain measurable quantities of 'old' argon the residence time within the magma must have been very short (of the order of several years, Gansecki *et al*. 1996). For example, Singer *et al*. (1998) reported 374 Ma crustal xenocrysts having lost radiogenic argon to give apparent ages of 46 Ma in no fewer than 20 days of magma residence. Small Lewisian clasts are frequently observed within the rhyodacite and previous studies, by Geldmacher *et al*. (2002) and Troll *et al*. (2004), showed that the rhyodacite is composed of up to 70% of a Lewisian amphibolite-facies-gneiss-derived component. Those workers reported that plagioclase separates from the rhyodacites are more radiogenic in Sr and Pb isotopes than the already very radiogenic whole-rock samples and suggest the presence of Lewisian-derived xenocrysts. Such foreign crystals may have been picked up late, during magma ascent through the crust or even at very shallow levels. We suggest that these 'old' feldspar crystals resided only very briefly in partial melt pockets within the country rock that eventually coalesced into a major magma reservoir or were picked up from conduit walls on ascent. Xenocrysts present were erupted while the process of equilibration to new chemical conditions was under way and probably acquired new feldspar overgrowths within the early rhyodacite chamber system established on Rum (see Troll *et al*. 2004). In addition, Figure 6 highlights the overlap and similarity of chemical compositions for both the Lewisian and rhyodacite feldspars. This close chemical association between the feldspars of the rhyodacites and the Lewisian gneiss complex on Rum is another line of evidence for the Lewisian being a main source for rhyodacite magma genesis. The larger middle age peak, at *c*. 61.4 Ma, formed from around eight (40%) of the analysed crystals, probably representing crustal feldspars that resided for slightly longer periods within pre-eruptive and ascending rhyodacite magmas. It is conceivable, however, that this age may represent xenocrysts related to the intrusion of the earliest Palaeocene igneous rocks (see Fig. 8b), thus perhaps giving a proxy for the initiation of doming and magma generation at the Rum centre. However, the possibility of excess argon trapped within inclusions in the feldspars cannot be fully ruled out as another possible source for some of these older ages. The major peak at 60.33 ± 0.21 Ma, formed from nine (45%) of the analysed crystals, we interpret to represent the actual age of the intrusion and eruption of the rhyodacites, marking the onset of voluminous felsic volcanism at the Rum Igneous Centre.

To evaluate the timing of events within and around the Rum volcano, the ages for the rhyodacite are compared, in Figure 7, with previously published dates for the Rum Igneous Centre. The ‘lifetime’ of Rum igneous activity is bracketed by two separate lava formations, both of which are related to other Palaeocene igneous centres (Fig. 1). Down-faulted slivers of lower Jurassic sediments and Palaeocene basalts are found within the Rum Main Ring Fault in the Southern Mountains Zone, with the basalts thought to represent lavas of the Eigg Lava Formation (Emeleus 1985), dated at 60.65 ± 0.07 Ma (Chambers *et al.* 2005). This basaltic eruptive event was followed on Rum by violent rhyodacite eruptions and caldera collapse at 60.33 ± 0.21 Ma (this study); thus as little as 40 ka or as much as 600 ka would have separated the Eigg lavas and the onset of volcanism on Rum. However, given the well-established field relationships between the rhyodacite and ultrabasic intrusions, this figure is probably closer to the lower value (see Fig. 7). The rhyodacite eruption age, when taken in conjunction with the overlapping age for the cross-cutting, and therefore younger, layered ultrabasic suite (60.53 ± 0.04 Ma; Hamilton *et al.* 1998), implies a rapid migration and emplacement history for these ultrabasic magmas. A large basaltic volcano superimposed on the earlier caldera structure (see Fig. 8) was probably constructed concurrently with this renewed intrusive phase, over as little as 100 ka or less. Textural (Holness & Isherwood 2003; Holness 2005; O’Driscoll *et al.* 2007) and isotopic (Tepley & Davidson 2003) studies have pointed independently to a rapid emplacement and cooling history for the layered ultrabasic suite, which cross-cuts both the rhyodacites and micrograntes of the early felsic phase.

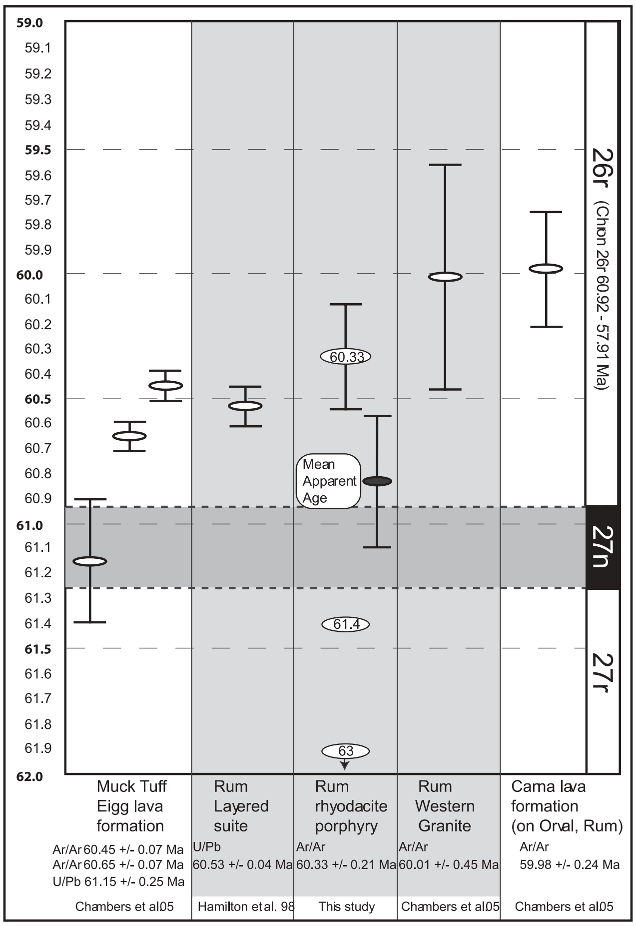

Fig. 7. Time line showing the age of the Rum rhyodacites (including the three age peaks obtained and the weighted mean apparent age), and existing ages from Rum and the Small Isles.

The Western Granite (Fig. 1) is unconformably overlain by basaltic lavas of the Canna Lava Formation (59.98 ± 0.24 Ma; Chambers *et al.* 2005), that are related to the Skye Lava Group (Emeleus & Bell 2005). Interbedded within these basaltic lava flows are several conglomerate units that contain clasts derived from the ultrabasic layered series, the Western Granite and the rhyodacites of Rum (Emeleus 1973, 1985, 1997). This emphasizes that the Rum Igneous Centre had ceased activity and already been unroofed by erosion prior to the eruption of these lavas at 59.98 ± 0.24 Ma.

On face value, a direct comparison of the eruption age for the rhyodacite, which marks the onset of igneous activity, against the previously established age dates (Fig. 7) shows that the duration of the ‘igneous lifetime’ for the Rum Centre was potentially 800 000 years or less. However, it has been argued (Renne *et al.* 1998) that the constants used for Ar/Ar dating generally yield ages 1% younger than those from U/Pb dating. For example see Figure 7, Muck Tuff data (Chambers *et al.* 2005). Taking this descrepancy into consideration, when comparing the age dates available for Rum and the surrounding area (Chambers *et al.* 2005; Hamilton *et al.* 1998; this study), the lifetime for Rum igneous activity may be as short as 500 000 years or less. This also potentially resolves the apparent disparity between the ages for the rhyodacite (this study) and the clearly younger ultrabasic intrusions (Hamilton *et al.* 1998).

Besides the short-lived nature of the Rum Centre, a question that arises from our rhyodacite eruption age is the spatial and structural connection between the ultrabasic suite and the felsic igneous rocks of Rum. The field relationships show beyond doubt that the layered ultrabasic suite postdates the Western Granite and the rhyodacites (Emeleus 1997, and references therein). The presence of coarse gabbroic and rare feldspathic peridotite inclusions in the pre- to syn-caldera felsic Am Màm-type intrusions (Emeleus 1997; Troll *et al.* 2000) provides incontrovertible evidence that basic to ultrabasic magmas were already available at depth during the early felsic phase of activity. It is these ultrabasic to basic magmas that supplied the necessary heat to produce the range of felsic rocks. These were generated by combining the products of extreme fractionation of these basic magmas with melts derived by partial melting and assimilation of significant volumes of the surrounding country rocks. This permitted the incorporation of melts that were considerably more ‘evolved’ than the bulk composition of the affected country rocks (Emeleus 1997; Troll *et al.* 2004). We thus argue that the ultrabasic intrusion was already forming at depth during the early felsic phase and quickly thereafter migrated upwards to shallow structural levels, intruding the products of the lower caldera succession, while contemporaneously a basaltic volcano built up. The suggested close temporal association between the mafic plutonic rocks and the felsic eruptive rocks may be explained by a magma plumbing system of separate but concurrent mafic and felsic magma chambers (Fig. 8a, model 1) or by the coexistence of felsic and mafic magmas in a larger chamber (Fig. 8a, model 2), with felsic

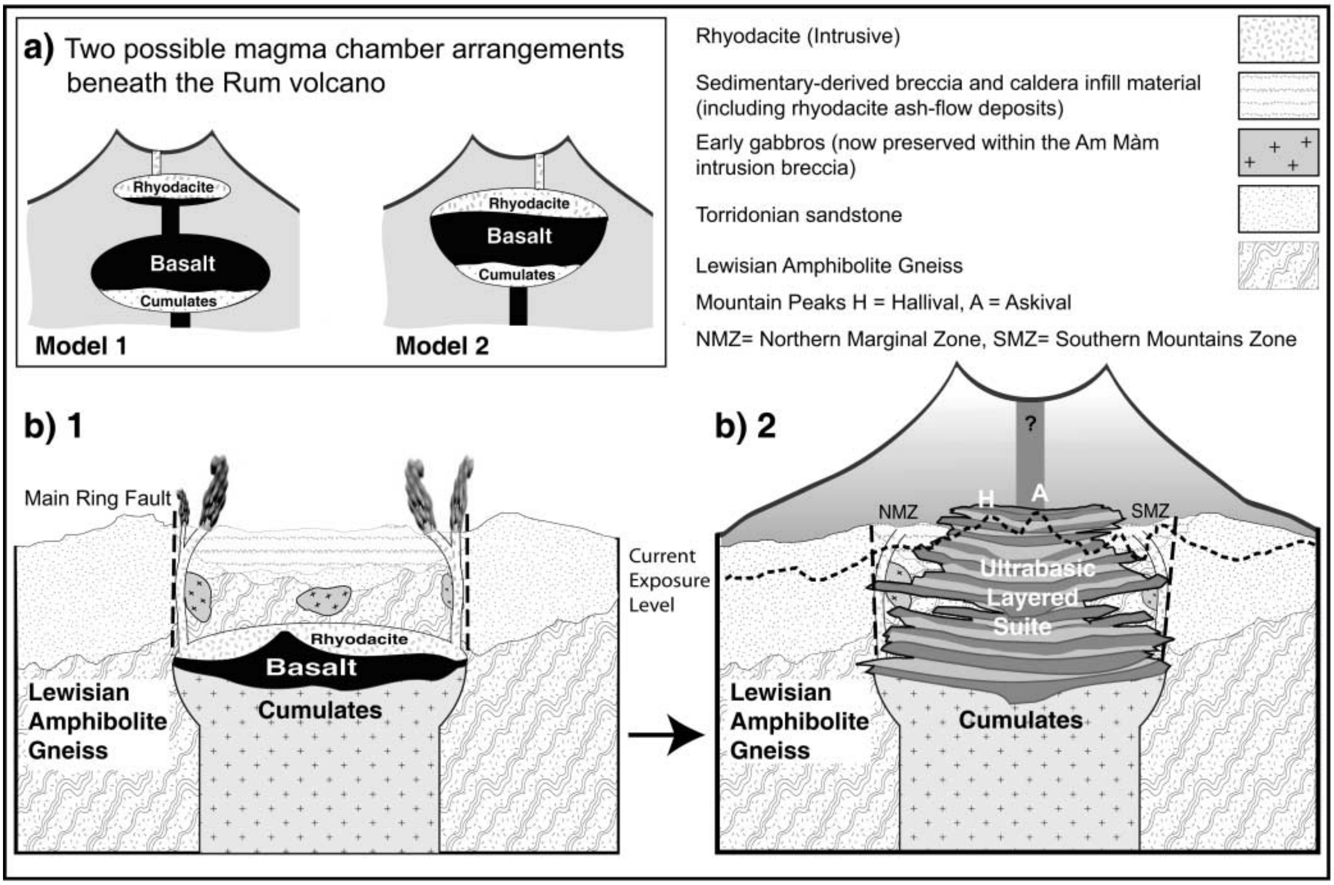

Fig. 8. Proposed volcanic and sub-volcanic evolution of the Rum Igneous Centre (**a**) shows two possible magma chamber models. (**b**) (1) Eruption of voluminous felsic ash-flow tuffs during the early caldera stage followed by (2) upward migration of the underlying ultrabasic magmas, to shallow structural levels intruding the caldera infill products of the earlier felsic phase while constructing a significant basaltic volcanic edifice above the igneous centre and the earlier caldera complex.

magmas residing in the cupola of such a system (see Walker 1975; Sparks 1988).

Several lines of evidence support model 2. First, felsic magma is most effectively produced near or in contact with a large heat source (e.g. Hobson *et al*. 1998; Holness 2002); in the Rum case this is the layered ultrabasic intrusion. Second, Troll *et al*. (2004) presented Sr and Pb isotope data on the rhyodacite and enclosed mafic enclaves. Some of the enclaves' isotopic ratios are equivalent to essentially uncontaminated mantle magma compositions, whereas the rhyodacites are 50–70% crustal in origin. Contamination of the Rum ultrabasic cumulates by Lewisian gneiss is also well documented (Renner & Palacz 1987; Tepley & Davidson 2003), thus prolonged residence of the mafic magma(s), preserved as enclaves in the rhyodacite, in a deeper, separate chamber or chambers seems unlikely. In addition, small-scale examples of model 2 (e.g. partial melting and rheomorphic mobilization) can be observed frozen in the marginal intrusion breccias that exist between the mafic or ultramafic rocks and the Western Granite, rhyodacite, Torridonian sandstones and Lewisian gneisses in several locations around the igneous centre (Greenwood 1987; Greenwood *et al*. 1990; Emeleus 1997). It remains not fully resolved, however, as to which model in Figure 8 is more applicable to the large-scale magmatic system of the Isle of Rum, with the possibility of both occurring in succession over a period of time. We show model 2 in our simplified sequence (Fig. 8b) to suggest the conceivable alternative of a single, larger and intricate chamber system, instead of the more traditional two-chamber model in which chambers are separated not only in space but also in time.

Several workers have previously postulated a very shallow emplacement depth (1–2 km) for the layered ultrabasic suite that intruded the products of the earlier caldera phase, on the basis of structural and petrographic constraints (Greenwood *et al*. 1990; Emeleus 1997; Holness & Isherwood 2003), implying the possibility that the highest peak on the island, the summit of Askival (812 m OD), is only a few tens or hundreds of metres below the former roof of the layered ultrabasic intrusion, within the heart of a major basaltic volcano (Fig. 8). For eroded pebbles from the Rum Igneous Centre to be found in conglomerates interbedded within the Canna lavas (Emeleus 1985), erosion rates after the cessation of magmatic activity at the Centre must have been very high. This erosion must have removed a significant amount of overburden (the basaltic volcano) from above the currently exposed ultrabasic intrusions (the former magma chamber) and the Western Granite (see Fig. 8). This, possibly taking the form of landslides and deeply dissecting fluvial erosion, removed all evidence for the putative basaltic volcano. Intense initial erosion rates (1–3 mm a^{-1}) at volcanic edifices have been emphasized by Ruxton & McDougall (1967) and Ollier & Brown (1971), with comparable rates observed in the Himalaya today (2–3 mm a^{-1}, Galy & Christian 2001), representing some of the highest erosion rates in the world. If we suppose similar rates for the Rum centre during the Palaeocene and bear in mind the time constraints of the analytical errors between 0.27 and 0.83 Ma (see Fig. 7) for the rhyodacite (this study), the ultrabasic intrusion (Hamilton *et al*. 1998) and the Canna Lava Formation (Chambers *et al*. 2005), then a thickness of rock in the range of *c*. 0.7–2 km has to have been eroded from above the former ultrabasic magma chamber, adding a further constraint to its depth of intrusion. Given the time constraints implicit in the ages obtained from these varying rocks, significantly slower erosion rates would require an even smaller overburden, which is considered unlikely, given the well-established plutonic character of the ultrabasic layered rocks.

Conclusions

Our results highlight the need for care when dealing with single crystal Ar/Ar age data. Distinguishing phenocrysts from xenocrysts is of critical importance to fully understand the detailed sequence and timing of events on Rum. We suggest that the 60.33 ± 0.21 Ma crystal age represents the rhyodacite eruption–intrusion event. This event overlaps, within error, the clearly younger ultrabasic layered intrusions. Ultrabasic and basic magmas are, however, shown to have been present throughout the lifetime of the Rum igneous complex. They are thus effectively coeval with the rhyodacites and could have provided the heat necessary for melt generation during the early felsic phase of activity. The ultrabasic magmas rapidly migrated upwards through the country rock and intruded the lower caldera infill deposits shortly thereafter, contemporaneously constructing a basaltic volcano in potentially less than 100 ka. The combination of our ages with constraints imposed by previously published age data and detailed field observations underpins the very rapid succession of events that occurred on the Isle of Rum and suggests a very close temporal, and spatial, link between the felsic and ultrabasic magma systems previously considered as separate episodes. The sequence of events on the Isle of Rum, from violent ignimbrite eruptions, intrusion of granite and the ultrabasic layered suite, to the rapid erosion of 0.7–2 km of overburden down to the heart of the Rum volcano, occurred potentially within as little as 500 ka or less.

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