The stratigraphy and eruptive history of the Palaeogene Arran Volcanic Formation, western Scotland: a proximal record of caldera-forming eruptions

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Abstract A Palaeogene caldera system in central Arran, western Scotland, contains a well-exposed proximal caldera-fill succession, the Arran Volcanic Formation. This caldera (formerly known as the Central Ring Complex of Arran) is part of the British Palaeogene Igneous Province and largely comprises highly heterogeneous ignimbrites and minor intra-caldera sedimentary rocks. Exposure across more than 400 m of elevation allows a complex stratigraphy to be determined, which can be linked to changing eruptive styles at a constantly-evolving volcano. Predominantly lava-like to welded tuffs deposited from high temperature, high mass-flux pyroclastic density currents generated from low fountaining columns that retained heat, are preserved. The first recorded phase was eruption of a homogeneous rhyolitic lava-like ignimbrite. A succeeding phase of highly explosive Plinian eruptions, marked by a thick blanket of massive lapilli tuffs, was then followed by caldera collapse and erosion of steep caldera walls. Volcanism then became generally less explosive, with non-homogenous lapilli tuffs interbedded with lava-like ignimbrites, glassy tuffs, and cognate-spatter-rich agglomerates. High topographic relief between distinct units indicate long periods of volcanic quiescence, during which erosive processes dominated. These periods are, in several places, marked by sedimentary horizons and evidence for surface water, which includes a localised basaltic-andesitic phreatomagmatic tuff.

Proximal records of caldera-forming eruptions are relatively rare and the Arran Volcanic Formation provides evidence of these processes. The ignimbrites typically lack the thick autobreccias and lithic-rich lapilli- and block-layers expected of proximal eruptions, indicating that subsidence was relatively gradual and incremental in this caldera, and not accompanied by catastrophic wall collapse during eruption.

Keywords Caldera, volcanic stratigraphy, lava-like ignimbrites, British geology

Introduction

The Isle of Arran in the Firth of Clyde, western Scotland, hosts some well-preserved remnants of the British Palaeogene Igneous Province (BPIP; Fig. 1). The BPIP itself is part of the North Atlantic Igneous Province (NAIP), a predominantly mafic Large Igneous Province (LIP) that developed during the rifting of the North Atlantic Ocean in response to the arrival of the Iceland plume at the base of the lithosphere (e.g., Thompson and Gibson, 1991; Kent and Fitton, 2000; Storey et al., 2007). In the British Isles the NAIP comprises the extensive lava fields of Skye, Eigg (one of the Small Isles), Mull, and Antrim (Emeleus and Bell, 2005), as well as localised intrusive and volcanic centres (Fig. 1). Other Palaeogene remnants of the North Atlantic Igneous Province are preserved on Greenland, the Faroe Islands, and offshore (Saunders et al., 1997).

Although the majority of magmatism in the BPIP is preserved as basaltic lavas and gabbroic and granitic intrusions, there is widespread evidence of extrusive silicic volcanism and explosive eruptions (Bell and Emeleus, 1988; Brown et al., 2009). Due in part to its historical importance and relative ease of accessibility, the BPIP has been the source of many developments in the global understanding of volcanological processes. Pyroclastic rocks are largely found within calderas (on Mull and Rùm, as well as Skye and Arran), often bound by arcuate faults and intrusions, originally interpreted as ring faults, ring dykes, and cone sheets. Recent studies, however, have suggested that the classic model of ring dyke/cone sheet formation by magma injection along-dip from a central magma reservoir is not consistent with geological observations (O'Driscoll et al., 2006; Stevenson et al., 2008; Magee et al., 2012), so these terms should be used with caution.

Detailed studies of the pyroclastic successions on Skye and Rùm have revealed complex histories of caldera collapse in the BPIP (Troll et al., 2000; Brown et al., 2009), but exposures in these areas are limited due to later, cross-cutting layered intrusions. Recently, many silicic extrusive rocks in this province, previously described as lavas or shallow intrusions, have been re-interpreted as welded and rheomorphic lava-like ignimbrites, for example the rhyodacite sheets on Rùm (Holohan et al., 2009) and the Sgurr of Eigg Pitchstone (Brown and Bell, 2013). These studies have allowed us to better understand the processes at work in other lava-like ignimbrite-producing volcanic provinces, for example, the Snake River Plain (e.g., Knott et al., 2016), the Paraná Magmatic Province (e.g., Luchetti et al., 2017), and the Canary Islands (e.g., Sumner and Branney, 2002).

The caldera system in central Arran (previously named the Central Ring Complex; King, 1955) is remarkably well exposed, possibly due to the relatively shallow level of erosion. It contains a caldera-fill sequence of pyroclastic and minor sedimentary rocks, which is better preserved than any other in the BPIP, and many globally. Critically, proximal intra-caldera sequences at modern and ancient volcanoes globally are poorly studied, due to a lack of suitably preserved localities, as they are affected by later intrusions, resurgent volcanism, faulting, and later sedimentation. Therefore, this makes Arran a unique area in which to study volcanic and sedimentary processes, and how these change through time and, in particular, proximal records of ignimbrite deposition at a caldera volcano. Despite these advantages, central Arran has been the subject of few studies since the work of King (1955). In this contribution, this Palaeogene system is named the Central Arran Igneous Complex (CAIC), while the pyroclastic and sedimentary intra-caldera succession is termed the Arran Volcanic Formation.

In this paper, we present new field and petrological data from the pyroclastic rocks preserved in central Arran, propose a volcanological model for the formation and evolution of the caldera, and discuss the nature of eruptions and proximal record of caldera-forming eruptions.

Geological setting

The pre-Palaeogene rocks in the northern part of Arran (Fig. 2) comprise the Neoproterozoic to Lower Cambrian schists, phyllites, and grits of the Southern Highland Group (BGS, 1987), the youngest division of the Dalradian Supergroup (Stephenson et al., 2013). The pre-Palaeogene rocks in the southern half of the island are dominated by Devonian and Permo-Triassic red sandstones and conglomerates (containing clasts of quartzite, vein quartz, and schist – most likely eroded from an exposed Dalradian landscape), separated by a thin succession of Carboniferous sedimentary rocks and lavas (Fig. 2). The basement upon which these sedimentary rocks were originally deposited is not exposed. The Highland Boundary Fault, the major crustal lineament that separates the Dalradian rocks of the Grampian Terrane to the north from the Midland Valley Terrane to the south (Fig. 1), is known to cross Arran, but its exact trace is uncertain (Young and Caldwell, 2012).

The Palaeogene igneous rocks on Arran (Fig. 2) comprise the North Arran Granite (NAG), the CAIC, and a suite of sills and minor intrusions in the south of the island, which vary in composition from dolerite to rhyolite (Fig. 2). In addition, a mafic dyke swarm is exposed largely around the coast of the island and in the mountains in the north of the island. These dykes intrude the Dalradian meta-sedimentary rocks, the Palaeozoic and Mesozoic sandstones, and the Palaeogene intrusions. The North Arran Granite is a roughly circular laccolith that was likely intruded from the south or south-east (Stevenson and Grove, 2014), suggesting that its emplacement could have been structurally controlled by the Highland Boundary Fault. It has been dated by ^{40}Ar-^{39}Ar at 57.85±0.15 Ma (Chambers, 2000). Composite sills, with mafic margins and more highly-evolved cores, are common across much of southern Arran. The most well-known of these (MacDonald et al., 1983) forms cliffs and coastal outcrops at Drumadoon Point (Fig. 2). This intrusion, and adjacent dykes, have been dated at 59.04±0.13 Ma and 59.16±0.17 Ma (Meade et al., 2009).

The CAIC includes a series of pyroclastic rocks and coarse grained intrusions, approximately 4 km x 5 km. It was first mapped by William Gunn of the British Geological Survey at the end of the nineteenth century (Gunn et al., 1901) and has historically been known as the ‘Arran Central Ring Complex’. This term was first used in the Arran Memoir (Tyrell, 1928), in which comparisons were drawn between the granitic intrusions around the edge of the complex and the Loch Bà felsite on Mull, which was interpreted as a caldera bounding ring dyke (Bailey et al., 1924). The complex sits within Devonian red sandstones (to the north and south) and Permo-Triassic red sandstones (to the west and east) (BGS, 1987). The volcaniclastic rocks of the caldera-fill sequence mostly crop out on and around the summit of Ard Bheinn (Fig. 3). King (1955) mapped the western part of the CAIC in detail and suggested that it was younger than the NAG, due to the fact that it appears to have been emplaced into sedimentary rocks that were previously domed during emplacement of the NAG, around 2 km to the north.

The ‘vent agglomerates’ (Tyrell, 1928) of the central ring complex (interpreted here as lapilli tuffs and breccias) were originally thought to represent the products of a single explosive volcanic phase, which was followed by intrusion of ‘felsites’, and the growth of small resurgent volcanoes on the caldera floor (Gregory and Tyrell, 1924; Tyrell, 1928; King, 1955). Large outcrops of basalt, dolerite, and ‘basalt breccia’ were interpreted as the only remains of a Palaeogene lava pile that once covered Arran, which had collapsed into the vent during subsidence (King, 1955). This caldera-collapse has also been proposed to explain the origin of the isolated exposures of Mesozoic sedimentary rocks in the complex (King, 1955). The intrusions, which comprise granites, gabbros, and intermediate hybrids, were thought to be mostly younger than the caldera-fill sequence based on poorly exposed field relationships (King, 1955, 1959).

King (1955) discussed differences within the agglomerates, noting that some seemed to be sedimentary in origin (‘sedimentary agglomerates’) or different in colour due to compositional variation (‘andesitic and basaltic agglomerates’). It is the objective of the present study to frame these observations within the context of well-understood physical volcanological processes.

Sampling and Methods

Fieldwork was carried out on Arran across several field seasons between 2015 and 2017. Most of the information presented in this paper is the result of detailed mapping and stratigraphic logging, however a number of samples were collected for thin section petrography and geochemical analysis. Only ignimbrite samples that we judged to be representative of magmatic compositions (i.e., clast-free) were subjected to whole-rock geochemical analyses.

Nine samples of clast-free ignimbrite from four units were crushed in a Mn steel jaw-crusher and ground to a fine powder in an agate planetary-ball mill. Loss on Ignition (at 900 ^{o}C) was determined gravimetrically, before the samples were prepared using the methods outlined in McDonald and Viljoen (2006) at Cardiff University. Major element analyses were carried out using inductively coupled plasma optical emission spectrometry (ICP-OES). Accuracy was constrained by subjecting international reference materials to the same process, and precision was constrained by duplicates of unknown samples.

Major element maps were obtained using the Zeiss Sigma HD SEM at the Electron Microbeam Facility at Cardiff University on carbon-coated polished thin sections. Spectra were collected on two 150 mm^2 electron dispersive X-ray spectrometry (EDS) detectors, at 20 kV with a beam current of 5 nA and a working distance of 8.9 mm.

The Central Arran Igneous Complex

As part of the present study, the CAIC has been extensively re-mapped (Fig. 3). The most fundamental difference between this new map and those of Tyrell (1928) and King (1955) is the lack of a near-complete ring intrusion. This complex, therefore, cannot be described as a 'ring complex', and is here renamed the Central Arran Igneous Complex (CAIC). Although exposure of the caldera-fill rocks on the slopes of Ard Bheinn and Binnein na h-Uaimh (Figs 3, 4) is excellent, exposure in the majority of the rest of the complex is very poor and largely restricted to stream beds. There is no exposure of a ring fault surrounding the complex, but the juxtaposition of Palaeogene igneous rocks at the same level as Palaeozoic sedimentary rocks indicates extensive marginal faulting.

Intrusive rocks of the CAIC

The north and east of the complex, and the isolated hills of the Sheans (Fig. 3), are dominated by the Glenloig Hybrids, named after the most accessible exposure under the bridge at Glenloig [translation: *glen of the hollow*]. They include heterogeneous amphibole-bearing, fine-grained intermediate rocks, which vary in composition from basaltic-andesitic to dacitic, and lesser amounts of coarser grained granite and amphibole granite. These rock types display intrusive and mingling interaction textures with one another, so the term ‘hybrids’ is retained. In some stream sections, and in the crags on the north side of Gleann Dubh, isolated exposures of quartz-bearing gabbro are found (Fig. 3), however, due to poor exposure, it is not possible to deduce the relationship of these gabbros with the Glenloig Hybrids. A small outcrop of these Glenloig Hybrids, along with a thin outcrop of gabbro, is preserved as an inlier within the caldera-fill succession between Binnein na h-Uaimh and Creag Mhor (Figs 3, 4).

In the stream bed near Glenloig, the oldest exposed pyroclastic rocks of the caldera-fill succession (the Allt Ruadh Member; see below) overlie eroded hybrid rocks, showing that these intrusions were formed and exhumed prior to the explosive volcanism.

Several granitic bodies are found within the CAIC. The largest of these is the Glen Craigag Granite, which is mostly exposed in the upper parts of Glen Craigag [translation: *rocky glen*] and Ballymichael Glen, in the centre of the complex (Fig. 3). Its mineralogy principally comprises medium-grained quartz and perthitic K-feldspar, commonly in granophyric intergrowths, with minor plagioclase, amphibole, and accessory minerals. In Ballymichael Glen, pyroclastic rocks overlie the Glen Craigag Granite on an eroded palaeosurface, suggesting intrusion and erosion of the granite occurred prior to the onset of explosive volcanism.

Five smaller granitic bodies crop out around the margins of the CAIC (Fig. 3). These are collectively termed the Satellite Granites, and all comprise medium- to coarse-grained quartz, K-feldspar and plagioclase, with minor amphibole and biotite, and accessory minerals. They were originally mapped as a near-continuous ‘ring intrusion’, but recent mapping shows that they are isolated from one another. Relationships to the other units of the CAIC are poorly exposed, but the Creag Mhor Granite appears to be a shallowly eastward dipping sheet within the ignimbrites, and the granite in Ballymichael Glen has steeply-dipping, complex contacts, with fingers protruding into the tuffs of the AVF. This suggests that the granites intruded the lower pyroclastic units of the AVF. Their arrangement around the margins of the caldera could be a result of intrusion along a caldera-bounding ring fault.

A large outcrop of fine-to-medium grained basaltic material on the western slopes of Ard Bheinn and Binnein na h-Uaimh (Figs 3, 4) was originally interpreted as the only remnant of an inferred Arran lava field, that had subsided into the caldera (King, 1955). Petrographic work during this study shows that it is, for the most part, an ophitic dolerite. Mineralogy is consistent throughout the outcrop, and consists of small plagioclase laths, commonly embedded in clinopyroxene oikocrysts up to 3 mm in size. Alteration of pyroxene to chlorite is ubiquitous, and common patches of iddingsite presumably replace primary olivine. This unit displays a clear intrusive relationship with several of the pyroclastic units of the AVF, with small fingers of dolerite intruding into the overlying unit (White Tuff Member – see below). There is also one small outcrop of the underlying unit (Allt Ruadh Member – see below) preserved above it. Other than this, it is largely concordant with stratigraphy (Fig. 3, 4), so is reclassified as a sill. In many places, especially near the contacts, the dolerite is heavily brecciated, with peperitic textures visible in several exposures.

A suite of mafic dykes, largely <2 m wide and similar in morphology and composition to the dykes exposed all over Arran, intrudes the Glenloig Hybrids, the Glen Craigag Granite, and the lowest extra-caldera ignimbrites (the Muileann Gaoithe Member; see below) (Fig. 3). No mafic dykes are observed intruding the Satellite Granites or the caldera-fill succession of the AVF. The only dyke seen intruding an intra-caldera ignimbrite is a pitchstone (i.e., vitrophyric) dyke in a tributary to the Glen Craigag stream. One of the dykes intruding the Glen Craigag Granite is composite in nature (Fig. 3), with mafic margins and a silicic core.

The Arran Volcanic Formation

The caldera-fill succession is made up dominantly of pyroclastic rocks, with some minor sedimentary packages. We assign all these rocks, as well as pyroclastic units that were deposited outside the caldera, to the Arran Volcanic Formation (AVF).

The Arran Volcanic Formation comprises a number of different mappable pyroclastic units (Fig. 3), separated by erosional unconformities. Exposures of these rocks are found over an elevation change of more than 400m (Fig. 4), giving the best estimate of total preserved thickness. It is impossible to estimate how far the AVF extends below the level of exposure. There was also undoubtedly a large thickness of the AVF that would have extended above the current level of erosion.

The ignimbrites of the AVF are best exposed in the western third of the complex (i.e. west of Glen Craigag), with good exposure on the high ground around Ard Bheinn and Binnein na h-Uaimh (Fig. 4). This is the area that King (1955) described in detail. The general volcanic stratigraphy of the area is shown in Fig. 5. We assign the mappable pyroclastic units as individual members within the AVF. The terminology used to describe the different lithofacies mapped here is given in Table 1 and follows the lithofacies code approach of Branney and Kokelaar (2002).

The Muileann Gaoithe Member

The Muileann Gaoithe Member is exposed in the cliffs on the southern side of Muileann Gaoithe [translation: *windmill*] ridge at the head of Glen Ormidale (Fig. 3; MacDonald et al., 1983). Some small, isolated exposures near the farmhouse at Dereneneach (Fig. 4) also belong to this unit. Its base is not seen, but at Muileann Gaoithe it seems to lie upon the Devonian and Permo-Triassic sandstones outside the caldera, which are exposed nearby.

A stratigraphic log up the south side of Muileann Gaoithe is shown in Fig. 6a. The Muileann Gaoithe Member almost entirely comprises a white-weathering, homogeneous, glassy rhyolitic (77-79 wt.% SiO_2, Table 2, Fig. 7) unit with abundant quartz, plagioclase, and K-feldspar crystals 0.5-2 mm in size (Fig. 6c,d). Throughout the lower half and upper parts of the unit is a well-developed cm-scale flow fabric

(Fig. 6a,b) that we term “flow-banding”. This flow-banding is particularly striking at the base of the unit, where folds on the decimetre to metre-scale are preserved (Fig. 6b). A sub-millimetre flow fabric texture can be seen in thin sections of the glassy parts of the unit (Fig. 6c,d). This fabric is defined by sub-millimetre to near-continuous bands and prolate rods that may have originated as vitroclastic shards or fiamme.

In the lower half of the unit, some layers and discontinuous lenses of non-glassy material containing lithic lapilli of sandstone and dolerite are interbedded with the glassy rhyolite.

Fine, thinly bedded, highly altered red material forms thin layers half-way up the Muileann Gaoithe section, as well as on the upper surfaces of the unit both at Muileann Gaoithe and Dereneneach.

Interpretation

We interpret the Muileann Gaoithe Member as an ignimbrite, due to the lack of visible upper/lower autobreccias, grading between different ignimbrite lithofacies, and the micro-scale parataxitic to lava-like texture. We here use ‘parataxitic’ to describe discontinuous bands and rods, indicating an ignimbrite grade higher than eutaxitic, but not as completely sheared as a fully lava-like texture, seen in Fig. 6c,d. Because of the pervasive micro-scale flow fabric, and obliteration of glass-shard-pyroclasts (Fig. 6c,d), we suggest that the white-weathering rhyolitic portions of the unit should be classed as massive lava-like tuff (mTl-l). The non-lava-like clast-bearing layers are interpreted as lapilli tuffs. Although they form discrete, thin layers, they are internally structureless, so are therefore classed as massive lapilli tuffs (mLT). The fine, red-weathering material is very altered and poorly exposed, but we interpret these layers as non-welded tuffs (T) that were exposed to the atmosphere for some time.

The microtextural features in the rhyolitic portion of this unit suggest that this is a very high-grade ignimbrite of 'Snake River type' (Andrews and Branney, 2011), indicating rapid deposition from a high temperature, (>900˚C) high-mass-flux pyroclastic density current. These ignimbrites are thought to be formed by high-temperature, low-fountaining eruptions that do not entrain much atmospheric air, and therefore retain large amounts of heat (e.g., Branney et al., 1992).

We suggest that the Muileann Gaoithe Member on Muileann Gaoithe (Fig. 6a) is composed of two eruptive units, each capped by a layer of red tuff, representing the surface of the ignimbrite sheet in contact with the atmosphere prior to deposition of the next unit. The layers of lapilli tuff represent changes in flow-boundary conditions within the aggrading ignimbrite, which may reflect increased explosivity at the vent.

The Allt Ruadh Member

The Allt Ruadh Member is the most extensive unit of the AVF at the current level of erosion (Fig. 3), and was possibly one of the most voluminous. Its type locality is the Allt Ruadh [translation: *red stream*, possibly after the orange-weathering ignimbrites exposed in its banks], a small stream in the south west of the complex, in which a near-complete vertical stratigraphy is exposed (Fig. 8a). The Allt Ruadh Member also crops out in Ballymichael Glen, on the hillsides between Dereneneach and Creag Mhor, in the lower parts of Glen Craigag, and on the slopes of A' Chruach (Fig. 3). The lower contact of the Allt Ruadh Member is not seen, apart from a small stream exposure near Glenloig, where it overlies the Glenloig Hybrids. Near Dereneneach, the Allt Ruadh Member overlies the poorly exposed Muileann Gaoithe Member (Fig. 4), although the contact is not directly observed.

The Allt Ruadh Member (Fig. 8a) comprises dominantly massive lapilli tuffs (mLT), with clasts of pre-Palaeogene sedimentary rocks, Palaeogene ignimbrites, and basaltic material (Fig. 8b,c). The clasts of ignimbrite are glassy, white, and contain abundant quartz and feldspar crystals, so presumably come from the underlying Muileann Gaoithe Member. The majority of the mLT in the Allt Ruadh Member displays a distinctive orange weathering (Fig. 8b). In the Allt Ruadh section (Fig. 8a), this coarse orange-weathering lithology makes up about half of the thickness of the unit. In other, less well-exposed areas, it comprises almost 100% of the exposure.

The size and lithology of the lithic lapilli changes both vertically and laterally across the complex, with blocks of ignimbrite over 600 mm in diameter found in the mLT in Glen Craigag. In places, these large blocks dominate the lithic clast population, meaning that the lithofacies in some places approaches massive breccia (mBr). Some thin layers of clast-poor ignimbrite are present. These glassy tuffs and eutaxitic quartz-feldspar crystal tuffs (Fig. 8d) are only exposed in stream sections, so cannot be traced laterally. Fig. 8c shows a photomicrograph of a typical Allt Ruadh mLT. The object on the right (1) is a clast of a Muileann Gaoithe Member ignimbrite.

Interpretation

The Allt Ruadh Member is interpreted as representing a prolonged, highly explosive phase of volcanism in which there was a large volume of material ejected from the underlying magma chamber. This phase of volcanism is suggested to record deposition from a pyroclastic density current at a flow-boundary zone dominated by fluid-escape, with very little turbulent shear-induced tractional segregation (Branney and Kokelaar, 2002). These deposits are thought to record very highly explosive Plinian eruptions. The mBr observed in places within the member suggests occasional higher-energy conditions at the vent. Given the dominance of Muileann Gaoithe lava-like ignimbrite clasts within the mLT and mBr, the lithic clasts are interpreted as being sourced largely from erosion of the substrate by the pyroclastic density current.

The clast-free eutaxitic layers record phases of lower explosivity, in which accidental lithics and atmospheric air were not entrained, leading to higher temperatures within the aggrading pyroclastic density current. The thin, dark, glassy tuffs near the top of the Allt Ruadh section (Fig. 8a) may be basal vitrophyres to the overlying packages of mLT. This would suggest pulses of eruption, rather than a single, sustained pyroclastic density current.

Creag Shocach conglomerates

Directly overlying the Allt Ruadh Member are some isolated outcrops of red sedimentary conglomerates and breccias (Fig. 5). These are found as a thin layer below the dolerite sill west of the Ard Bheinn summit (Fig. 4), and as the prominent crags of Creag Shocach above Glenloig (Fig. 3). The Ard Bheinn outcrop is found at a lower elevation than some of the surrounding exposures of Allt Ruadh mLT (Fig. 4), suggesting deposition on a highly topographical erosional surface. The clasts in these breccias and conglomerates are almost exclusively of the pre-Palaeogene lithologies exposed nearby (i.e. medium- to coarse-grained red sandstones and quartzite conglomerates) (Fig. 9). The matrix is mostly composed of fine- to medium-grained rounded quartz sand. The clasts in the Creag Shocach conglomerate (Fig. 9b) are larger (high proportion of cobbles) and generally rounder than those on Ard Bheinn (Fig. 9c). However, due to their similar stratigraphic position (overlying the Allt Ruadh Member) and similar matrix and clast lithologies, we assign them to the same unit.

Interpretation

We interpret the Creag Shocach conglomerates as representing erosion of Devonian and Permo-Triassic lithologies from topographic highs into the caldera by fluvial or mass wasting processes during the post-Allt Ruadh period of volcanic quiescence. The outcrops on Creag Shocach (Fig. 9a,b) are coarser, and have a massive, largely clast-supported structure. This could indicate that these exposures are proximal to the eroded source and were deposited as high energy debris flows. The Ard Bheinn exposures (Fig. 9c) are generally finer, matrix-supported, and show small channels and lenses of clast-free sandstones. This could indicate a more distal environment dominated by fluvial processes.

Creag an Fheidh Member

The Creag an Fheidh [translation: *deer crag*] Member is named for a small line of crags 500 m south of Glenloig, where it is best exposed and can be traced almost vertically through its succession (Fig. 10a). The volcanic rocks belonging to this unit make up topographic shelves at ~300 m elevation, along both sides of Glen Craigag (Fig. 3). The Creag an Fheidh section exposes a vertical thickness of around 80 m, from the contact with the underlying Allt Ruadh Member to the overlying White Tuff Member. At its western extent, the Creag an Fheidh Member is cut off by the same fault that truncates the intra-caldera outcrop of Glenloig Hybrids (Fig. 3).

The lower parts of this unit (which are only well-exposed on Creag an Fheidh, and may not be laterally extensive) are predominantly lithic-poor tuffs and crystal tuffs (mT and mTcr; Fig. 10c,d). Minor layers of mLT contain clasts of other ignimbrites, presumably from the underlying Muileann Gaoithe and Allt Ruadh members. Some of the lithic- and crystal-poor glassy tuffs (mTv) display bedding-parallel flow fabrics (Fig. 10).

The upper part of the Creag an Fheidh Member consists of a coarse lapilli tuff with abundant clasts of rhyolitic material which resemble the Muileann Gaoithe lava-like ignimbrites. Rounded clasts of sedimentary material are also present. In many places, the upper surface of this unit contains rounded clasts (pebbles and cobbles) of ignimbrite and quartzite.

Interpretation

The massive lapilli tuffs and clast-poor crystal tuffs (mLT and mTcr) record variably highly-explosive eruptions and deposition from a pyroclastic density current at a flow-boundary zone dominated by fluid-escape (Branney and Kokelaar, 2002). The varying degree of lithic clasts may reflect changes in explosivity at the vent or changes in erosive power across the substrate. The eutaxitic crystal tuffs and glassy tuffs displaying flow fabrics record lower explosivity, ‘boil-over’ pyroclastic fountaining, and higher temperatures within the pyroclastic density current. Some of the thin glassy units may be basal vitrophyres to their respective overlying ignimbrite packages.

The rounded cobbles of ignimbrite and quartzite on the upper surface of the Creag an Fheidh Member are thought to be the result of fluvial surface re-working and deposition on the exposed top of the ignimbrite. We therefore infer the presence of surface water on top of the Creag an Fheidh Member in the period of volcanic quiescence before the eruption of the White Tuff Member.

Allt Beith tuff cone

On the upper surface of the Creag an Fheidh Member, just south of the source of the Allt Beith [translation: *birch stream*] are several exposures of a very fine brown-grey thinly banded tuff (Fig. 3). It shows both cross-stratified and planar bedding features on scales of <1 – 50 mm, with occasional graded bedding (Fig. 11). Unlike all other erupted products within the CAIC, it is basaltic-andesitic in composition (54.5 wt.% SiO_2 Table 2, Fig. 7). The surrounding exposures are dominated by the conglomerates that make up the upper surface of the Creag an Fheidh ignimbrite.

Interpretation

We interpret the Allt Beith exposures as the remnants of a small basaltic phreatomagmatic tuff cone or ring. We base this interpretation on several features: 1) It is very fine grained, suggesting intense fragmentation, 2) phreatomagmatism can explain explosive mafic activity and the production of fine basaltic-andesitic ash, 3) its well developed stratification suggest deposition from a fully dilute pyroclastic density current at a traction dominated flow boundary zone (Branney and Kokelaar 2002, Brown et al 2007) and perhaps deposition in surface water, 4) it is surrounded by other deposits of fluvial facies, and 5) it is very localised, being seen nowhere else in the complex. We suggest that between eruption of the silicic Creag an Fheidh and White Tuff Members, there was a small pulse of mafic magmatism that was erupted into a wet environment on the surface of the Creag an Fheidh ignimbrite, causing a relatively small phreatomagmatic event. Other such events are likely to have occurred at this stratigraphic level, but have now been buried or lost to erosion. A similar example of a localised, intra-caldera tuff cone can be seen in the Glencoe caldera, western Scotland (Moore and Kokelaar, 1998).

White Tuff Member

The White Tuff is a very homogeneous, white-weathering rhyolitic lava-like ignimbrite that is mostly exposed in the Ard Bheinn area. It is best exposed in a string of crags to the southwest of the Ard Bheinn summit. It lies on top of the Allt Ruadh Member and Creag Shocach conglomerates to the west of Ard Bheinn (Fig. 4), on top of the Creag an Fheidh Member and Allt Beith tuff cone to the north, and on the exposed Glen Craigag Granite to the east (Fig. 3). There are some small exposures in the Ballymichael Burn tributary 1 km south of the summit of Ard Bheinn. On the western side of Ard Bheinn, the preserved White Tuff is over 100 m thick (Fig. 4, 12a). The lower contact is observed in some small exposures where it overlies the Creag an Fheidh Member. This contact has been mapped as a topographically uneven palaeo-surface in the area between Ard Bheinn and Glen Craigag (Fig. 3).

Most exposures of the White Tuff Member appear structureless, although in places a distinct meso-scale fabric can be seen (Fig. 12a). This is most often sub-horizontal planar banding, but in places it is chaotic. These fabrics are variably expressed as pervasive fractures tens of centimetres apart, or as fine mm-scale colour variations (Fig. 12b). Folding on the scale of tens of centimetres is uncommon, but observed in several places. In places within this unit, autobreccias with a similar petrology are found (e.g., Fig. 12a). The top of the unit comprises a localised conglomerate with rounded clasts of lava-like ignimbrite and quartzite. The White Tuff Member is petrologically and geochemically homogeneous. It is rhyolitic throughout (76-77 wt. % SiO_2 Table 2, Fig. 7), containing abundant plagioclase, K-feldspar, and smoky quartz crystals 1-5 mm in size (Fig. 12c,d).

Interpretation

The stratigraphic conformity, and presence of internal stratigraphic variation, along with the presence of autobreccias and conglomerates show that this unit is undoubtedly extrusive. Due to the lack of basal and upper autobreccia, as well as the gradations between parts of the unit with different pervasive fabric characteristics (Fig. 12a), we interpret the White Tuff Member as a rhyolitic lava-like ignimbrite, or series thereof. This is further suggested by the lack of any visible individual pyroclasts (Fig. 12c) which may have coalesced due to agglutination. These features suggest that, like the Muileann Gaoithe Member, this member is a very high-grade ignimbrite of 'Snake River type' (Andrews and Branney, 2011), suggesting rapid deposition from a high temperature, (>900˚C) high-mass-flux pyroclastic density current. The localised conglomerates at the top of the member are interpreted as the result of fluvial surface re-working and deposition on the exposed top of the ignimbrite.

Pigeon Cave Member

The Pigeon Cave Member is exposed extensively on the western and eastern sides of Binnein na h-Uaimh (Fig. 4), and to a lesser extent along the ridge between Ard Bheinn and Creag Dubh, and on Creagan Leana Muic on the eastern side of Glen Craigag (Fig. 3). In the Ard Bheinn area it was deposited on the White Tuff Member. On Creagan Leana Muic, the Pigeon Cave Member was deposited on top of the Creag an Fheidh Member (Fig. 3). This suggests that the White Tuff was not deposited in this area, or was completely removed by erosion prior to eruption of the Pigeon Cave Member.

This member largely consists of massive lapilli tuffs and agglomerates (Fig. 13a,b), most of which weather to a turquoise colour (Fig. 13c). Agglomerates are here defined as ignimbrites which contain elongate bands and streaks of lava-like material in an otherwise non-lava-like matrix (Branney and Kokelaar 2002). Lithic clasts within the ignimbrite consist of pre-Palaeogene country rocks (schist and sandstone) as well as presumably Palaeogene basalt and ignimbrite (Fig. 13). Most layers within the unit contain abundant quartz crystals (Fig. 13d,e). The basalt/dolerite breccias shown in Fig. 13a are interpreted as fingers of the dolerite sill that intruded below the White Tuff Member.

The Pigeon Cave Member contains several sedimentary units within it. The outcrop of 'chalk' at Pigeon Cave on Binnein na h-Uaimh (discussed by Tyrell, 1928) is overlain by the Pigeon Cave Member. Foraminifera fossils suggest a Cretaceous age for this chalk (Tyrell, 1928), and it has been previously interpreted as a subsided megablock (Tyrell, 1928; King, 1955). Some pink-white weathering sandstones are exposed several metres to the south of Pigeon Cave. These were also mentioned by Tyrell (1928), and King (1955) suggested these may also be Cretaceous due to similarities with sediments found on Mull and Morvern, and in Antrim. It is unclear whether these are part of the caldera floor, subsided megablocks, or have a Palaeogene intra-caldera origin.

Interpretation

The presence of thin interbedded layers of lapilli-tuff, agglomerate, and lava-like and vitrophyric tuffs shows a highly dynamic and fluctuating deposition history. The mLT shows deposition from a pyroclastic density current at a flow-boundary zone dominated by fluid-escape, and with very little turbulent shear-induced tractional segregation (Branney and Kokelaar, 2002), while the true lava-like ignimbrites record high temperature deposition from a high-mass-flux pyroclastic density current. These differences would have been linked to processes at the vent, with highly explosive Plinian columns and low-fountaining boil-over eruptions, respectively.

The massive agglomerate lithofacies contains elongate ribbons of lava-like material, interpreted as forming as cognate spatter clasts at the vent, which are then entrained (and stretched) in the pyroclastic density current (Branney and Kokelaar, 2002). The lateral variation within this unit (shown by the differences between Fig.

13 a and b) could be explained by: 1) locally variable amounts of pumiceous matrix; and 2) topographic control of thickness and geographic distribution. These are two of the defining characteristics of the massive agglomerate lithofacies in Branney and Kokelaar (2002) (after Druitt et al., 1989; Mellors and Sparks, 1991). Branney and Kokelaar (2002) suggest that mAg has a similar mode of formation to mBr, with rapid deposition of cognate clasts (with or without lithic lapilli) from a pyroclastic density current rich in ash and dominated by fluid escape.

Binnein na h-Uaimh conglomerates

The exposure on the north slopes on Binnein na h-Uaimh [translation: *hill of the cave*] is dominated by a very coarse clast-supported conglomerate (Fig. 3). This conglomerate forms an almost complete exposure from an elevation of 340 m, where it overlies the Pigeon Cave Member (Fig. 14a), to the summit of Binnein na h-Uaimh (430 m), where it is overlain by the basal breccias of the Ard Bheinn Member (Fig. 4). Clast size is mostly pebbles to large cobbles, with some boulders over 500 mm in length (Fig. 14b,c). The clasts are rounded to angular and mostly comprise country rock lithologies (i.e., sandstone and schist). Some small, rounded pebbles of quartzite are unlike anything observed in the country rocks of central Arran, and may be inherited original clasts from the Devonian or Permo-Triassic conglomerates. The schists (such as the large boulders seen in Fig. 14b) resemble the Dalradian schists, which only crop out north of the Highland Boundary Fault, ~4 km to the north (Fig. 2). Similar schist clasts are found in the Devonian and Permo-Triassic conglomerates throughout Arran, but these are predominantly pebble-sized. There are no other comparable schists exposed south of the Highland Boundary Fault, suggesting that the Binnein na h-Uaimh conglomerates were sourced from the north.

The lower contact of the unit (Fig. 14a) can be traced for over 100 m up the slopes of Binnein na h-Uaimh (Fig. 4). This shows that the conglomerates were deposited on a highly uneven topographical surface.

Interpretation

We suggest that the Binnein na h-Uaimh conglomerates were deposited from a debris flow in a canyon that was eroded into the upper surfaces of the Pigeon Cave Member. The steep canyon sides can be observed in several places along the exposure, with the conglomerates overlying the ignimbrites (Fig. 14a). There are no flow-direction indicators preserved in the conglomerates, but the canyon that they fill appears to slope steeply downhill from the summit of Binnein na h-Uaimh towards the north (Fig. 4). This would suggest that, in the absence of any later large-scale subsidence-related rotation, the flow was towards the north.

Ard Bheinn Member

The youngest exposed unit of the AVF is the Ard Bheinn Member. It is exposed extensively on the summits of Ard Bheinn [translation: *high peak*] and Binnein na h-Uaimh (Fig. 4), with some exposures to the south towards Ballymichael Glen, and to the north east towards Creag Dhubh (Fig. 3). There are also some isolated exposures in the boggy ground 2 km east south east of the Ard Bheinn summit (Fig. 3) which appear to belong to the same unit, although these exposures are isolated and local stratigraphy is impossible to discern.

On Binnein na h-Uaimh the Ard Bheinn Member can be seen directly overlying the Pigeon Cave Member and the Binnein na h-Uaimh conglomerates. On Ard Bheinn it overlies the Pigeon Cave and the White Tuff Members (Fig. 4). In Ballymichael Glen the Ard Bheinn Member appears to cut down into the White Tuff, the dolerite sill, the Glen Craigag Granite, and possibly even the Allt Ruadh Member (Fig. 3).

The Ard Bheinn Member is a heterogeneous dark grey unit (Fig. 15) which displays bedding-parallel and folded flow-fabrics in places. The base of the member varies between the several locations where it is observed. Near the summit of Binnein na h-Uaimh it is a coarse lapilli agglomerate (Fig. 15b), which overlies the Pigeon Cave Member and the Binnein na h-Uaimh conglomerates. In Ballymichael Glen, the lowest parts of the Ard Bheinn Member consist of stratified lava-like coarse crystal tuffs, with a very high content of quartz and feldspar crystals >5 mm in size (Fig. 15e). These sTcrl-l appear to fill valleys on canyons which cut down into the underlying units.

The most complete section of the Ard Bheinn Member extends from the coarse crystal tuff in Ballymichael Glen, up the southern side of Ard Bheinn, to the summit (Fig. 15a). The lower parts of this section, up to a topographic shelf at ˜420 m, comprise a relatively homogeneous lithoidal brown unit (mTv), with crackly weathering, some irregular bands of lithophysae, and pervasive columnar jointing. An analysed sample of a similar lithology from Binnein na h-Uaimh is rhyolitic in composition (77 wt.% SiO_2, Table 2, Fig. 7). Above this topographic shelf the ignimbrite becomes more clast-rich with layers of agglomerate, autobreccia, and lithic-poor tuffs. The lithoidal texture and lithophysae are still seen in places. Clasts are of varying sizes, but are almost exclusively composed of similar lithologies to the rest of the Ard Bheinn Member. One exposure, around 50 m south of the Ard Bheinn Summit, displays eutaxitic texture, clasts of other lithologies, and streaky fiamme of mafic material (Fig. 15d). Around the summit, the top of the preserved part of the Ard Bheinn Member is dominated by fine purple-grey dacitic rock (68-70 wt. % SiO_2, Table 2, Fig. 7) with abundant small plagioclase crystals (Fig. 15c).

Interpretation

The Ard Bheinn Member is interpreted as a series of mostly lava-like ignimbrites, due to completely agglutinated pyroclasts (Fig. 15c,e), pervasive flow-banding in parts, the presence of lithic clasts, and the gradations between units. In the section described in Fig. 15a, the lower part of the unit, up to around 440 m, is thought to represent one single eruption event, with hot (>900°C) ash deposited from a pyroclastic density current at a relatively stable flow-boundary zone. The presence of columnar jointing throughout this lower section suggests it behaved as a single cooling unit.

The upper parts of the member (above 440 m, Fig. 15a) were likely formed from a series of small pyroclastic fountaining eruptions of varying temperature, recording deposition at an unstable flow-boundary zone.

The agglomerate in (Fig. 15b) contains elongate cognate spatter clasts and lithic lapilli (mTv, mTl-l, mTcr) that were deposited rapidly from a proximal pyroclastic density current.

Banded Tuffs

Some isolated exposures around the upper parts of Ballymichael Glen and Gleann Dubh comprise ignimbrites that display flow banding on a variety of scales. These are shown in Fig. 3. Due to their isolated nature, and poor exposure on flat, vegetated ground, it is impossible to discern their relationship with any other of the mapped units. For this reason, we make no attempt to determine their position within the stratigraphy of the AVF.

Discussion

Eruptive History

We have developed a series of schematic cross sections detailing a model for the eruptive history of the AVF (Figure 16).

The first event for which evidence is preserved is the eruption of rhyolitic lava-like ignimbrites (Fig. 16a). These are preserved as the *in situ* Muileann Gaoithe Member on Muileann Gaoithe, where they overlie the pre-Palaeogene sandstones outside the caldera, and at Dereneneach where they underlie the Allt Ruadh Member ignimbrites. Ignimbrites from this phase of eruption are also found as clasts within the mLT of the Allt Ruadh Member and Creag an Fheidh Member. As the base of the Muileann Gaoithe Member is not seen within the caldera, we cannot say whether this was the first stage of volcanism in the area. It is possible that it overlies the erupted products of earlier volcanism that are now buried.

Eruption of the Muileann Gaoithe Member was followed by a period of highly explosive eruptions to form the Allt Ruadh Member (Fig. 16b). These events are recorded as the blanket of mLT with minor lapilli-poor tuffs and lava-like ignimbrites that cover the entire area of the caldera (Fig. 3). The volume of material ejected from the magma chamber, as well as the inferred presence of steep caldera walls in the period following these eruptions, suggests that this phase of volcanism was accompanied by a significant period of caldera subsidence. Collapse may have been piecemeal, with some intra-caldera faults likely to have been reactivated repeatedly (Branney and Kokelaar, 1994; Moore and Kokelaar, 1998). No vents or volcanic edifices are preserved, although it is likely that these tuffs were erupted through vents related to the developing ring fault.

In the period after the eruption of the Allt Ruadh Member, significant transport of country-rock material into the topographically low caldera occurred. This is shown by the presence of the Creag Shocach conglomerates overlying the Allt Ruadh Member at Creag Shocach and on the west side of Ard Bheinn (Fig. 16c). In the Ard Bheinn exposures, interbedded sandstones and conglomerates (Fig. 9c) suggest fluvial processes, whereas the massive and highly unsorted nature of the conglomerates at Creag Shocach (Fig. 9a,b) suggest debris flows. We suggest that these deposits represent rapidly collapsing steep caldera walls, created during the subsidence associated with eruption of the Allt Ruadh Member.

Overlying the Creag Shocach conglomerates and the Allt Ruadh Member in the east of the complex is the Creag an Fheidh Member (Fig. 16d). Because the Creag an Fheidh Member is only exposed in the east of the complex we suggest that it was sourced from a localised vent or series of vents in the surrounding area. The crystal tuffs and lava-like ignimbrites of the Creag an Fheidh Member are truncated by the fault that runs from east of Binnein na h-Uaimh to west of Creag Mhor (Fig. 3). The time-relationship between the fault and the eruption of the Creag an Fheidh

Member is unclear. However, the lack of any exposure of this unit west of the fault suggests that it may already have been a fault scarp against which the Creag an Fheidh ignimbrites were deposited.

The presence of water on the surface of the Creag an Fheidh ignimbrites is inferred from the presence of conglomerates, and the phreatomagmatic Allt Beith tuff cone (Fig. 16e). There may have been a lake in the topographic low adjacent to the fault scarp that truncates the outcrop of the Creag an Fheidh Member, as this is the area in which the conglomerates and basaltic-andesitic tuffs are found.

The White Tuff Member was deposited on top of the Allt Ruadh Member in the west of the complex and the Creag an Fheidh Member in the east of the complex (Fig. 16f). The petrological and textural similarity of the White Tuff Member to the Muileann Gaoithe Member suggest very similar eruption styles, and geochemically similar magma sources. Due to the homogeneous and largely structureless nature of this large unit, it is thought that the White Tuff Member represents the deposits of a small number of large eruptive phases, presumably originating from the same magma chamber. We tentatively propose three eruption events, with unit tops represented by the autobreccia at 380 m elevation and the topographic shelf at 420 m elevation, as shown in Fig. 12a.

The Cretaceous chalk found at Pigeon Cave is overlain by the Pigeon Cave Member ignimbrites, and so may have been transported to its current position immediately prior to ignimbrite deposition. The large size of this chalk block (at least 20 m long) and lack of other blocks of similar lithologies in the surrounding area suggest that it did not travel far. It could be a fragment of the caldera floor faulted relatively upwards as a horst during variable break-up of the floor, or it could have collapsed from a nearby caldera-wall fault scarp during caldera subsidence.

The Pigeon Cave Member tuffs and agglomerates were erupted onto the White Tuff Member (Fig. 16f). The dolerite sill was intruded after deposition of the Pigeon Cave

Member ignimbrites, as it is seen to intrude them (Fig 13a). Given the brecciated nature of the intrusion, and the presence of peperitic textures around the margins, it is likely that the sill intruded at shallow levels into these ignimbrites, and possibly interacted with groundwater. Given that the Ard Bheinn Member appears to erode down into the sill (Fig 3), it must have been erupted after the emplacement of the sill.

The upper surface of the Pigeon Cave Member was heavily eroded to create significant palaeo-topography, including at least one steep-sided canyon on the north face of Binnein na h-Uaimh. It was into these palaeo-canyons that the Binnein na h-Uaimh conglomerates were deposited (Fig. 16g). The source of these conglomerates is not clear, but the large size of clasts suggests that it was quite proximal, while the lack of AVF lithologies shows that it was outside the edge of the caldera.

The last phase of volcanism that is preserved within the AVF is the eruption of the Ard Bheinn Member (Fig. 16h). The coarse crystal tuffs at the base of the Ard Bheinn Member in Ballymichael Glen appear to fill a valley eroded into the White Tuff Member and the dolerite sill (Fig. 3). The highly heterogeneous nature of the upper parts of the Ard Bheinn member (Fig. 15) suggests that it was either deposited from a highly unstable pyroclastic density current, or from many small eruptions.

An unknown thickness of the upper Ard Bheinn Member has been lost to erosion, and the total thickness of later AVF units that have been eroded away could total hundreds of metres.

Nature and significance of eruptions, and the proximal record of caldera collapse

The AVF provides the first detailed record of an intra-caldera sequence in the BPIP, and one of only a few globally. Although examples have been described from Mull

(Bailey et al., 1924), Rum (Troll et al., 2000; Holohan et al., 2009) and Skye (Bell and Emeleus, 1988; Brown et al., 2009), this is the first study in the BPIP to define multiple ignimbrite members, which record a variety of eruption styles in the caldera. The ignimbrites are accompanied by sedimentary rocks recording intra-caldera fluvial, mass flow, and lacustrine deposition, which attest to significant eruption hiatuses. The ignimbrites are preserved almost exclusively as intra-caldera units, with only one example, the Muileann Gaoithe Member, extra-caldera. The general absence of extra-caldera ignimbrites is presumably due to rapid erosion of units that may have been relatively thin in more distal areas.

Although the CAIC/AVF is relatively small (~5 km across) compared to more well-known modern calderas (e.g. Long Valley, Valles, Yellowstone; typically ~10-25 km across), they provide an excellent opportunity to investigate an intra-caldera sequence. The AVF is well incised and exposed in places, is not disrupted by later intrusions, resurgent volcanics, and/or filled by later sediments or water, and has not been heavily faulted (e.g., Ordovician Scafell Caldera, English Lake District, Branney and Kokelaar 1994; Silurian Glencoe Caldera, Scotland, Moore and Kokelaar, 1998), unlike many similar modern and ancient calderas. Where intra-caldera sequences are preserved (e.g. Las Canadas Caldera, Tenerife; Smith and Kokelaar, 2013) they have typically received less attention compared to extra-caldera deposits, potentially due to access difficulties associated with steep caldera walls.

The ignimbrites of the AVF are dominated by high grade lava-like and welded units. Although the full extent of the formation is unknown, the Allt Ruadh Member appears to represent the only product of a dominantly Plinian eruption, and perhaps a catastrophic period of caldera collapse. The other members typically record rapid deposition from high temperature (>900˚C), high-mass-flux PDCs generated from low-fountaining columns that do not entrain much atmospheric air, and therefore retain large amounts of heat (e.g., Branney et al., 1992). The members do however, show considerable variation and typically transition from lithoidal and flow banded lava-like tuffs, through eutaxitic tuffs and cognate spatter-bearing agglomerates, to occasional poorly to non-welded lapilli-tuffs. These variations indicate that the PDCs were sustained but unstable and subject to variations in mass-flux and temperature.

Although some examples are recorded, there is a general paucity of autobreccia, and this indicates that little slumping and sliding of cool(ing) ignimbrite units occurred during pauses in deposition. Furthermore, lithic-rich lapilli- and block-layers are rare, indicative of a general absence of climactic subsidence events and associated caldera wall/floor destabilisation, which may be anticipated in intra-caldera proximal successions (Smith and Kokelaar, 2013). Together, these data suggest that although deposition occurred rapidly, caldera subsidence was relatively incremental and considerable topographic barriers to flow may not have been present. In eruption hiatuses however, subsidence continued and exotic material was introduced from outside the caldera by background and extreme sedimentary processes.

Conclusions

The Central Arran Igneous Complex is an excellent example of a well-exposed caldera volcano. Its caldera-fill succession, the Arran Volcanic Formation, is the best preserved in the British Palaeogene Igneous Province, having been eroded to a relatively shallow level, and escaped fragmentation by later intrusions and significant faulting. Given the erosion levels the intra-caldera sequence provides an outstanding record of proximal ignimbrite deposition, which is often unavailable at other ancient calderas that have been heavily intruded and faulted, or modern calderas that are filled with later sediments and/or water, and have not been incised sufficiently. Detailed mapping and field observations have allowed us to reconstruct the volcanological history of this caldera, and propose a model for its evolution:

1. Muillean Gaoithe Member: Eruption of a homogeneous rhyolitic lava-like

ignimbrite deposited from a high temperature, granular fluid based pyroclastic density current.

2. Allt Ruadh Member: Highly explosive Plinian eruption deposited massive lapilli-tuffs from a high particle concentration granular fluid-based PDC, accompanied by catastrophic caldera collapse.
3. Creag Shocach conglomerates: Fluvial and mass flow deposition of debris flow conglomerates and sandstones, sourced from outside the caldera.
4. Creag an Fheidh Member: Lava-like and crystal-rich rhyolitic tuffs locally deposited from a high temperature, high particle concentration, granular fluid based PDC, and ponded against intra-caldera fault.
5. Allt Beith tuff cone: Fluvial-lacustrine system developed in this region of the caldera and reworked subjacent ignimbrite. Basaltic-andesitic magma interacted with ground/surface water and erupted tuff cone, comprising stratified tuffs deposited from low particle concentration, fully dilute PDC.
6. White Tuff Member: Eruption of a homogeneous rhyolitic lava-like ignimbrite deposited from a high temperature, granular fluid based PDC.
7. Pigeon Cave Member: Variable sequence of tuffs, lapilli-tuffs and cognate-spatter-bearing agglomerates, deposited from high temperature, variable mass flux, high particle concentration, granular fluid-based PDC.
8. Binnein na h-Uaimh conglomerates: Palaeo-canyons develop on ignimbrite surfaces and are filled by debris flow conglomerates.
9. Ard Bheinn Member: Variable sequence of crystal-rich tuffs, vitrophyric tuffs, eutaxitic lapilli-tuffs and cognate-spatter-bearing agglomerates, deposited from high temperature, variable mass flux, high particle concentration, granular fluid-based PDCs.

The AVF provides a remarkably complex record of proximal ignimbrite deposition. The typical absence of lithic-rich lapilli- and block- layers and autobreccia, indicates that subsidence was more gradual, and that eruption of high grade ignimbrites can occur without catastrophic collapse. Eruption hiatuses record further subsidence and background sedimentary processes.

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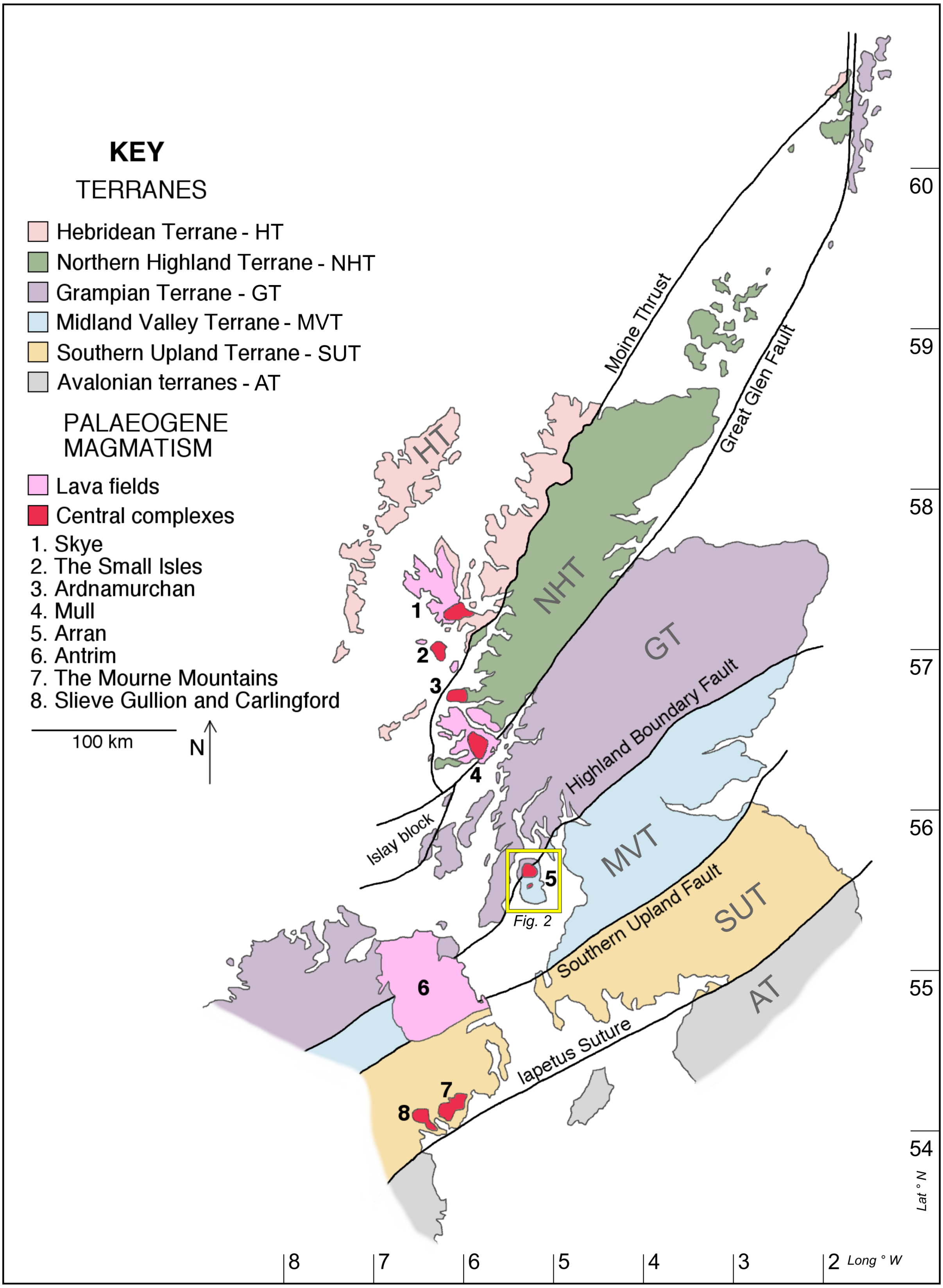


KEY
TERRANES
Hebridean Terrane - HT
Northern Highland Terrane - NHT
Grampian Terrane - GT
Midland Valley Terrane - MVT
Southern Upland Terrane - SUT
Avalonian terranes - AT
PALAEOGENE MAGMATISM
Lava fields
Central complexes
1. Skye
2. The Small Isles
3. Ardnamurchan
4. Mull
5. Arran
6. Antrim
7. The Mourne Mountains
8. Slieve Gullion and Carlingford
100 km
N
Moine Thrust
Great Glen Fault
Highland Boundary Fault
Southern Upland Fault
Iapetus Suture
Islay block
HT
NHT
GT
MVT
SUT
AT
Fig. 2
60
59
58
57
56
55
54
Lat ° N
8
7
6
5
4
3
2
Long ° W

Figure 1

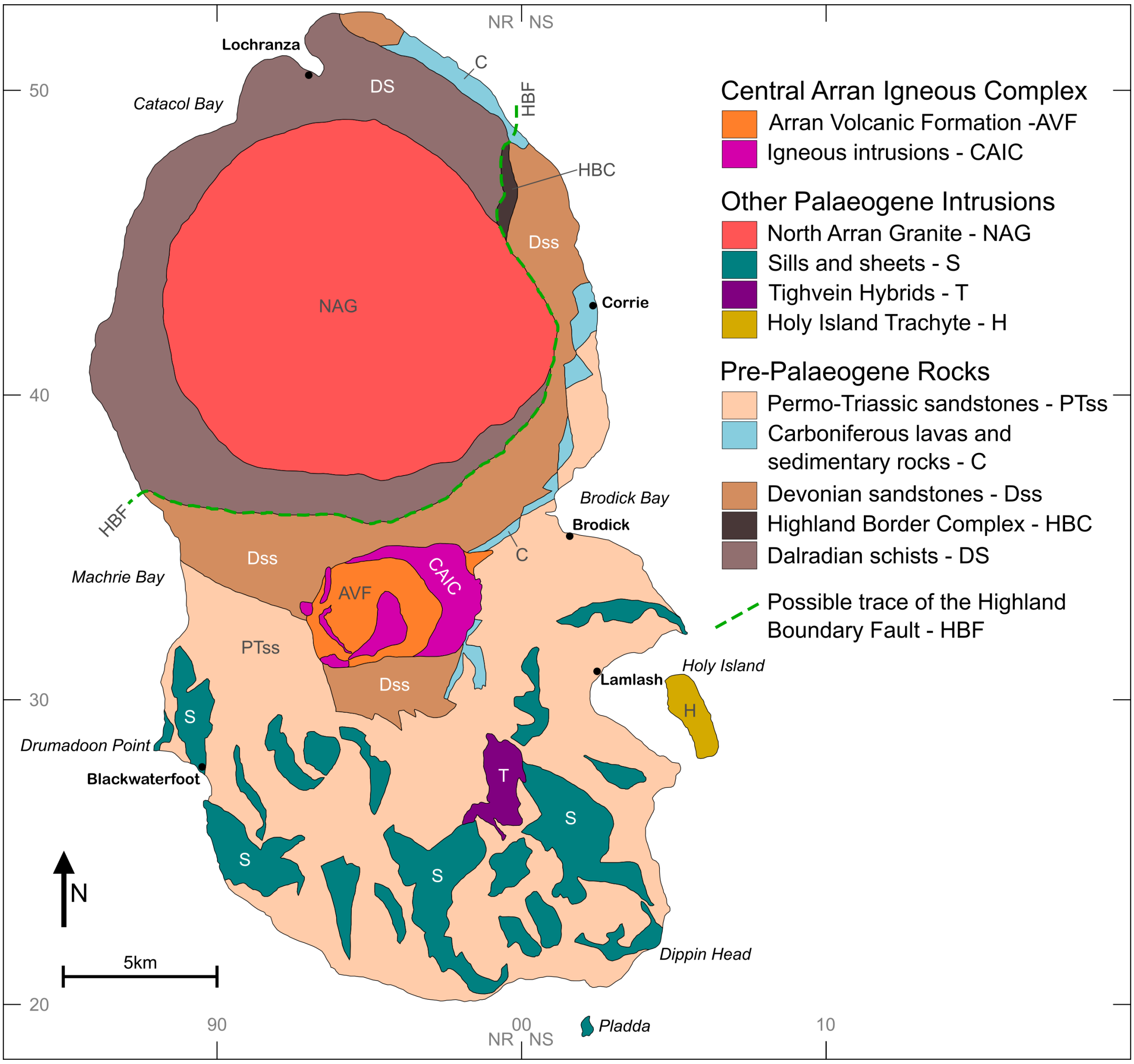

Central Arran Igneous Complex
Arran Volcanic Formation -AVF
Igneous intrusions - CAIC
Other Palaeogene Intrusions
North Arran Granite - NAG
Sills and sheets - S
Tighvein Hybrids - T
Holy Island Trachyte - H
Pre-Palaeogene Rocks
Permo-Triassic sandstones - PTss
Carboniferous lavas and sedimentary rocks - C
Devonian sandstones - Dss
Highland Border Complex - HBC
Dalradian schists - DS
Possible trace of the Highland Boundary Fault - HBF
Lochranza
Catacol Bay
Machrie Bay
Drumadoon Point
Blackwaterfoot
Corrie
Brodick Bay
Brodick
Lamlash
Holy Island
Dippin Head
Pladda
NAG
DS
Dss
HBC
HBF
C
AVF
CAIC
PTss
S
T
H
NR NS
50
40
30
20
90
00
10
N
5km

Figure 2

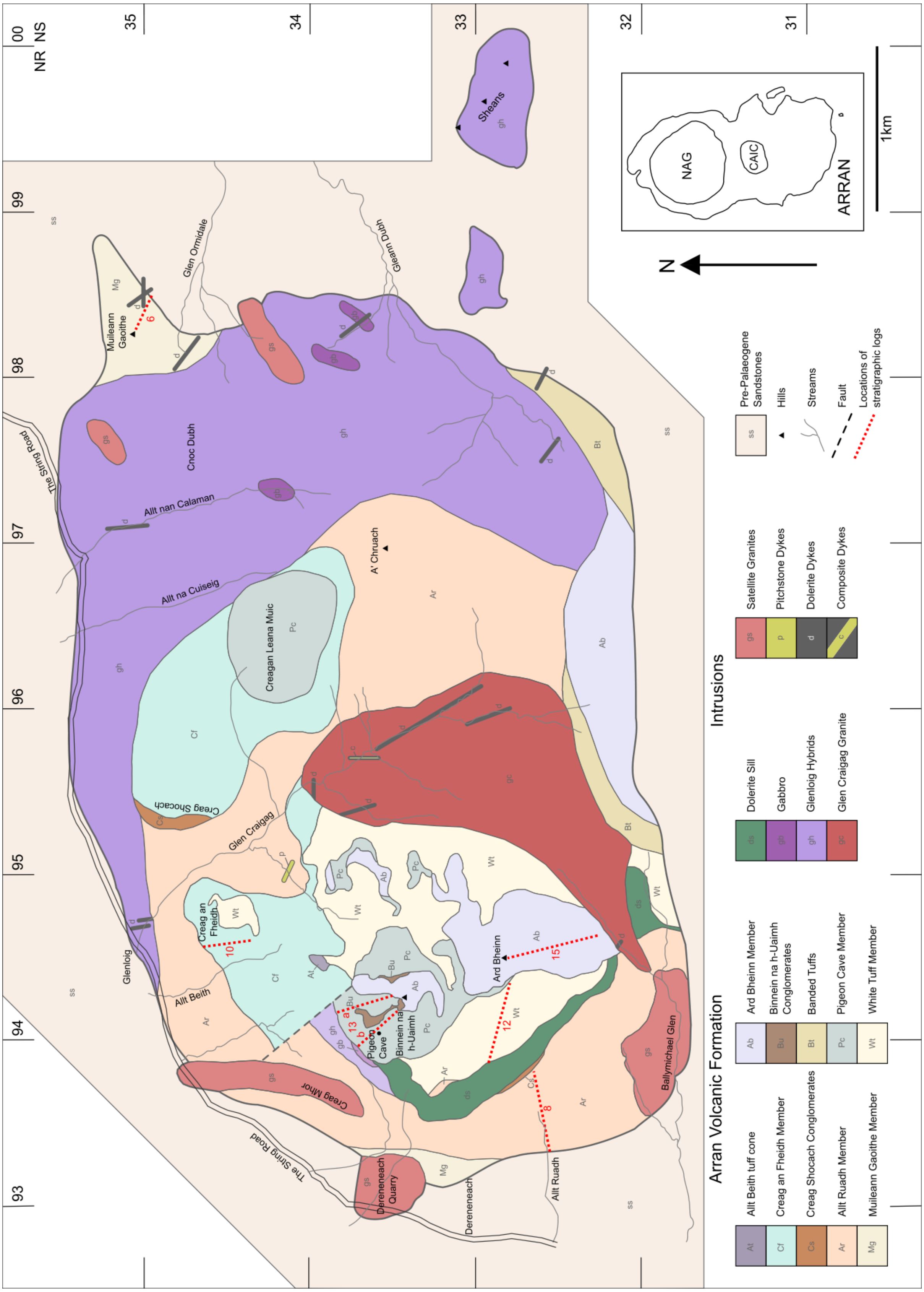
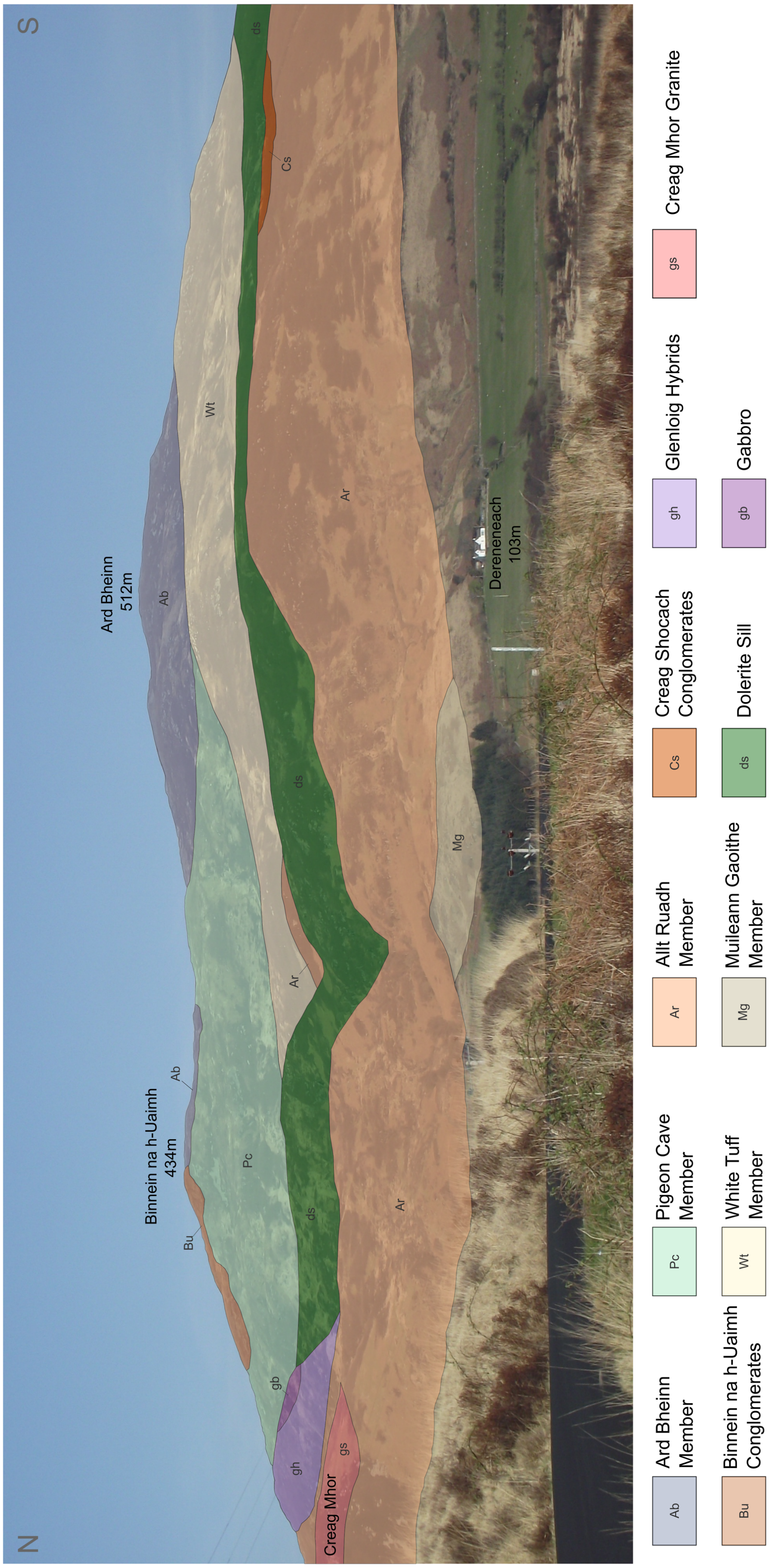
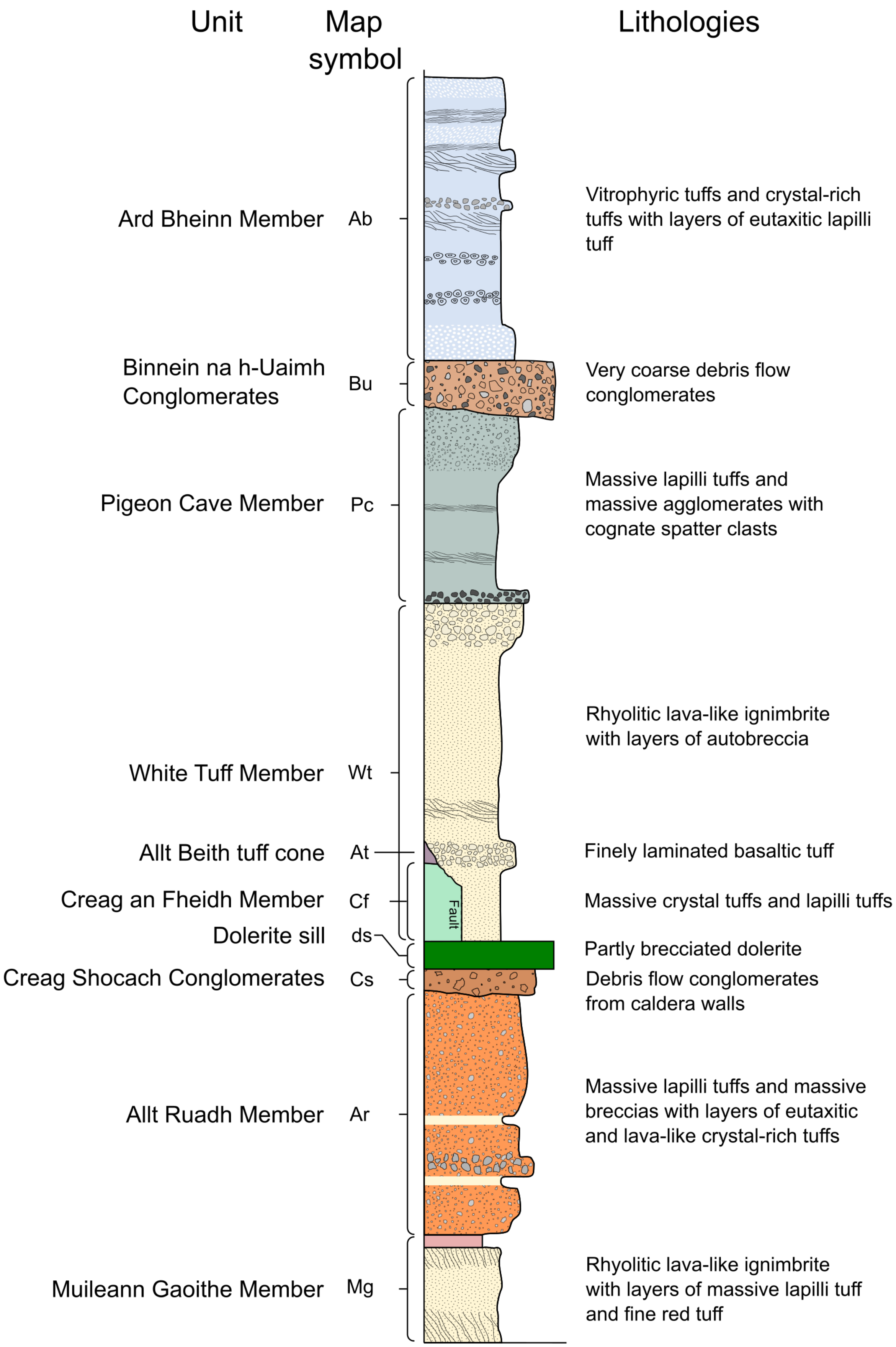

Arran Volcanic Formation
At Allt Beith tuff cone
Cf Creag an Fheidh Member
Cs Creag Shocach Conglomerates
Ar Allt Ruadh Member
Mg Muileann Gaoithe Member
Ab Ard Bheinn Member
Bu Binnein na h-Uaimh Conglomerates
Bt Banded Tuffs
Pc Pigeon Cave Member
Wt White Tuff Member
Intrusions
ds Dolerite Sill
gb Gabbro
gh Glenloig Hybrids
gc Glen Craigag Granite
gs Satellite Granites
p Pitchstone Dykes
d Dolerite Dykes
c Composite Dykes
ss Pre-Palaeogene Sandstones
Hills
Streams
Fault
Locations of stratigraphic logs
N
NAG
CAIC
ARRAN
1km
NR NS
00
35
34
33
32
31
99
98
97
96
95
94
93
Sheans
Glen Ormidale
Gleann Dubh
Muileann Gaoithe
Cnoc Dubh
The String Road
Allt nan Calaman
Allt na Cuiseig
A' Chruach
Creagan Leana Muic
Creag Shocach
Glen Craigag
Creag an Fheidh
Glenloig
Allt Beith
Ard Bheinn
Binnein na h-Uaimh
Pigeon Cave
Creag Mhor
Dereneneach Quarry
Dereneneach
Allt Ruadh
Ballymichael Glen

Figure 3



S
N
Ard Bheinn
512m
Binnein na h-Uaimh
434m
Dereneneach
103m
Creag Mhor
Ab
Wt
Cs
ds
Ar
Mg
Pc
Bu
gb
gh
gs
Ab Ard Bheinn Member
Pc Pigeon Cave Member
Ar Allt Ruadh Member
Cs Creag Shocach Conglomerates
gh Glenloig Hybrids
gs Creag Mhor Granite
Bu Binnein na h-Uaimh Conglomerates
Wt White Tuff Member
Mg Muileann Gaoithe Member
ds Dolerite Sill
gb Gabbro

Figure 4



Unit
Map symbol
Lithologies
Ard Bheinn Member
Ab
Vitrophyric tuffs and crystal-rich tuffs with layers of eutaxitic lapilli tuff
Binnein na h-Uaimh Conglomerates
Bu
Very coarse debris flow conglomerates
Pigeon Cave Member
Pc
Massive lapilli tuffs and massive agglomerates with cognate spatter clasts
White Tuff Member
Wt
Rhyolitic lava-like ignimbrite with layers of autobreccia
Allt Beith tuff cone
At
Finely laminated basaltic tuff
Creag an Fheidh Member
Cf
Massive crystal tuffs and lapilli tuffs
Fault
Dolerite sill
ds
Partly brecciated dolerite
Creag Shocach Conglomerates
Cs
Debris flow conglomerates from caldera walls
Allt Ruadh Member
Ar
Massive lapilli tuffs and massive breccias with layers of eutaxitic and lava-like crystal-rich tuffs
Muileann Gaoithe Member
Mg
Rhyolitic lava-like ignimbrite with layers of massive lapilli tuff and fine red tuff

Figure 5

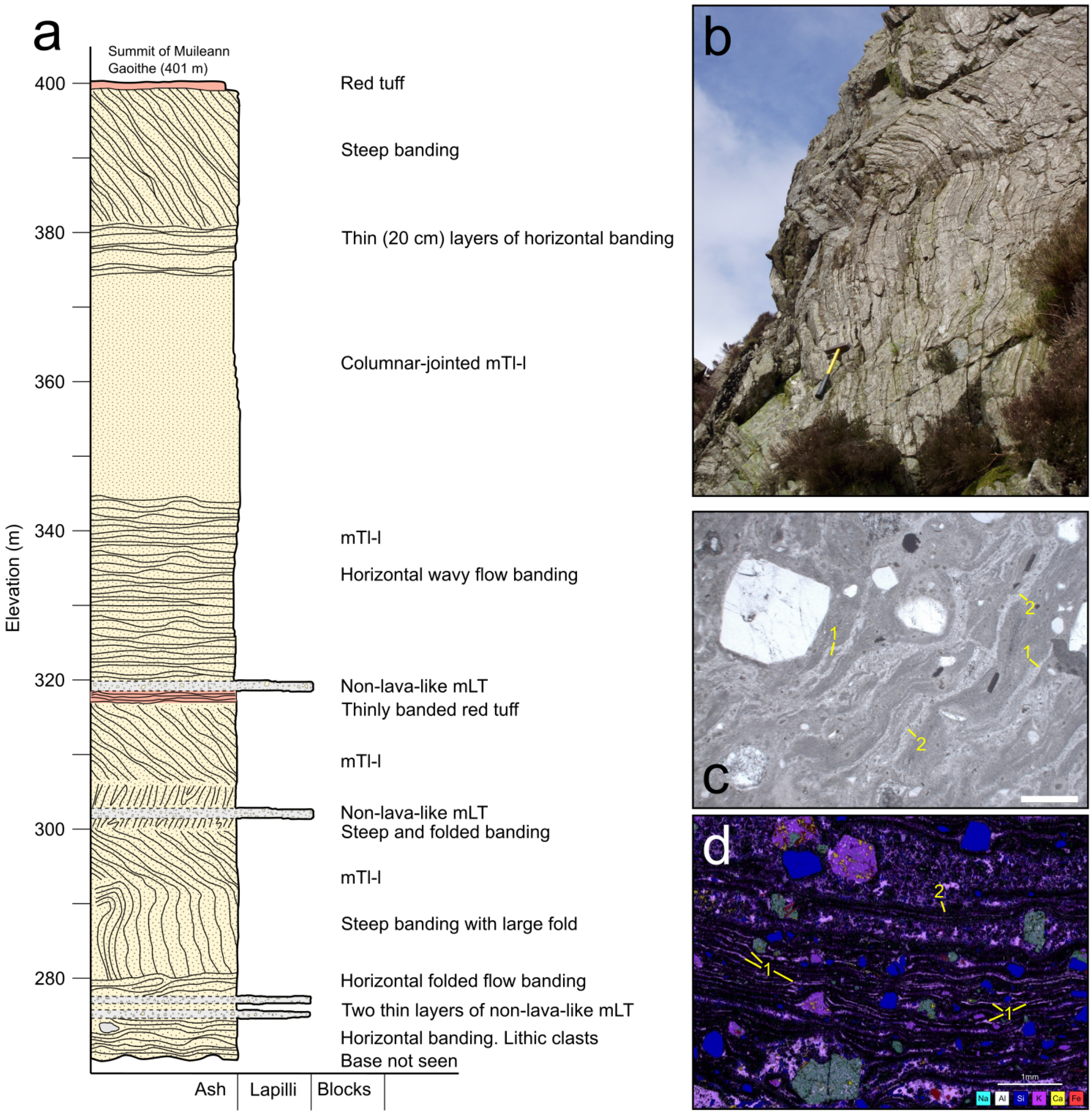
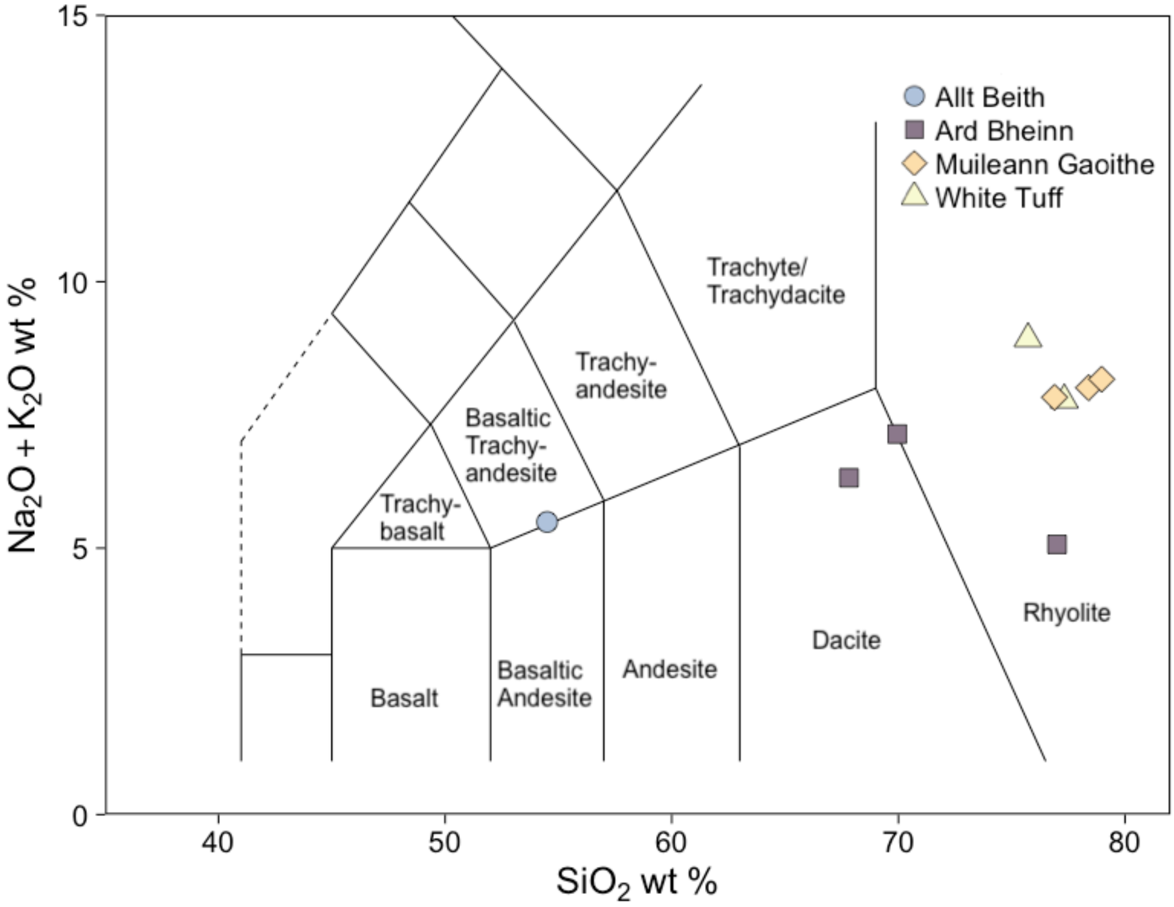

a
Summit of Muileann Gaoithe (401 m)
400
380
360
340
320
300
280
Elevation (m)
Red tuff
Steep banding
Thin (20 cm) layers of horizontal banding
Columnar-jointed mTl-l
mTl-l
Horizontal wavy flow banding
Non-lava-like mLT
Thinly banded red tuff
mTl-l
Non-lava-like mLT
Steep and folded banding
mTl-l
Steep banding with large fold
Horizontal folded flow banding
Two thin layers of non-lava-like mLT
Horizontal banding. Lithic clasts
Base not seen
Ash
Lapilli
Blocks
b
c
1
2
d
1
2
1mm
Na
Al
Si
K
Ca
Fe

Figure 6



15
10
5
0
40
50
60
70
80
$Na_2O + K_2O$ wt %
SiO_2 wt %
Allt Beith
Ard Bheinn
Muileann Gaoithe
White Tuff
Trachyte/
Trachydacite
Trachy-
andesite
Basaltic
Trachy-
andesite
Trachy-
basalt
Basalt
Basaltic
Andesite
Andesite
Dacite
Rhyolite

Figure 7

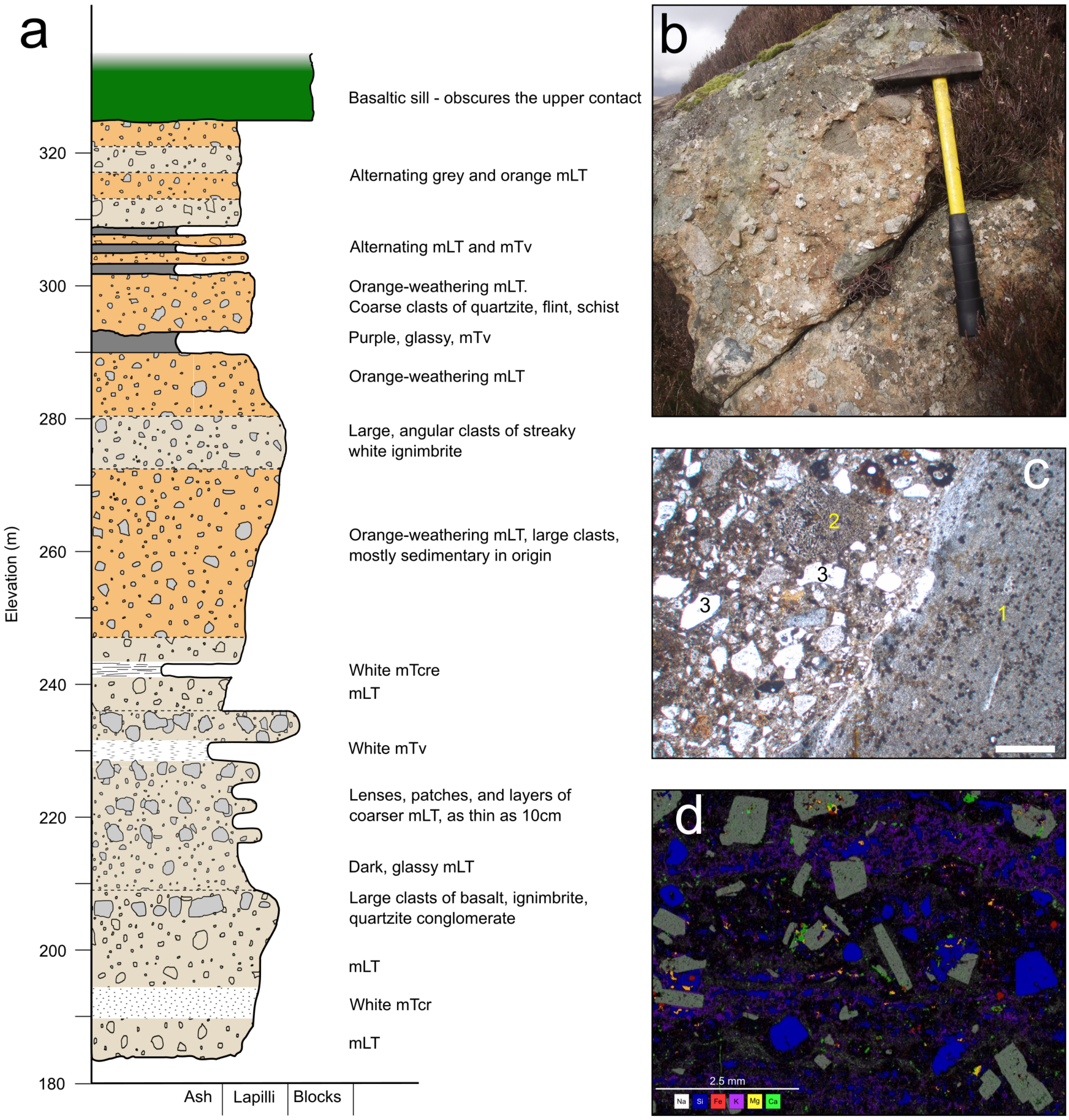

a
b
c
d
Basaltic sill - obscures the upper contact
Alternating grey and orange mLT
Alternating mLT and mTv
Orange-weathering mLT.
Coarse clasts of quartzite, flint, schist
Purple, glassy, mTv
Orange-weathering mLT
Large, angular clasts of streaky white ignimbrite
Orange-weathering mLT, large clasts, mostly sedimentary in origin
White mTcre
mLT
White mTv
Lenses, patches, and layers of coarser mLT, as thin as 10cm
Dark, glassy mLT
Large clasts of basalt, ignimbrite, quartzite conglomerate
mLT
White mTcr
mLT
Elevation (m)
320
300
280
260
240
220
200
180
Ash
Lapilli
Blocks
2
3
3
1
2.5 mm
Na
Si
Fe
K
Mg
Ca

Figure 8

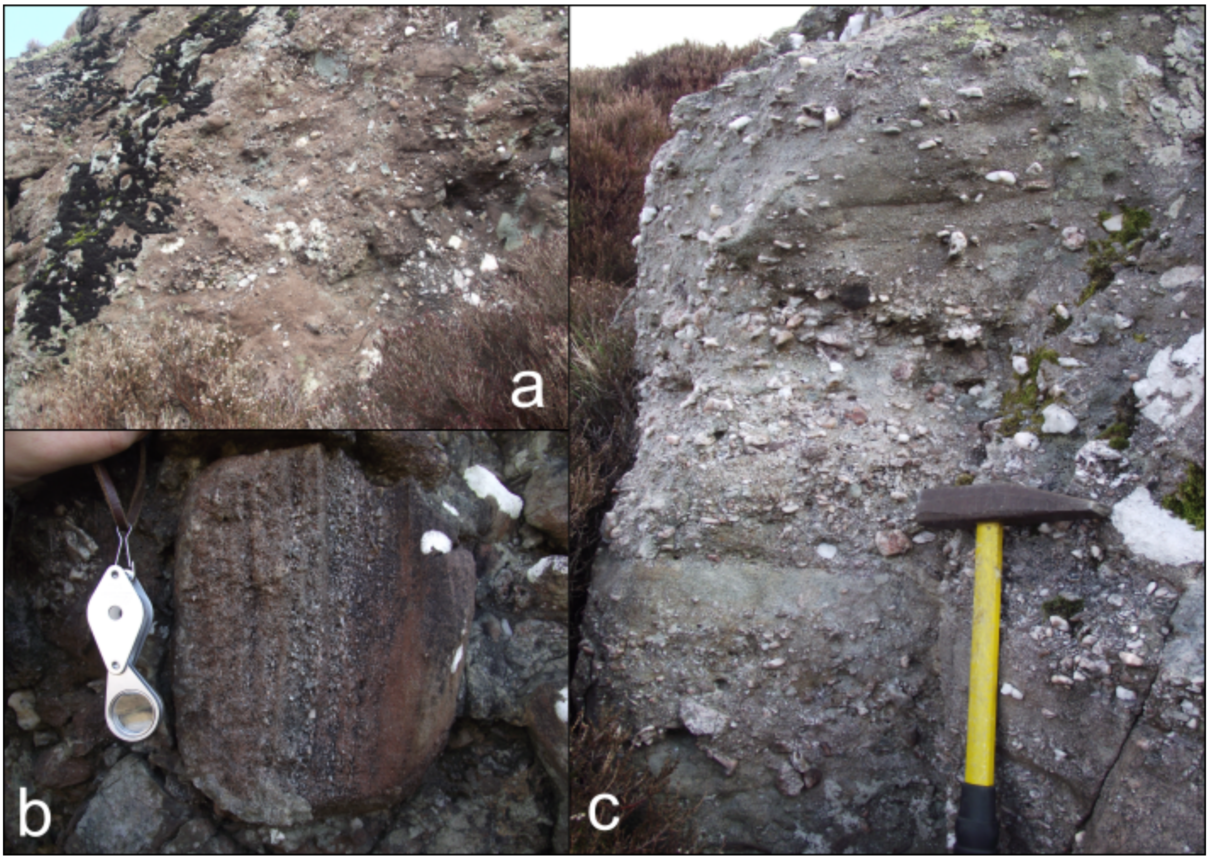


Figure 9

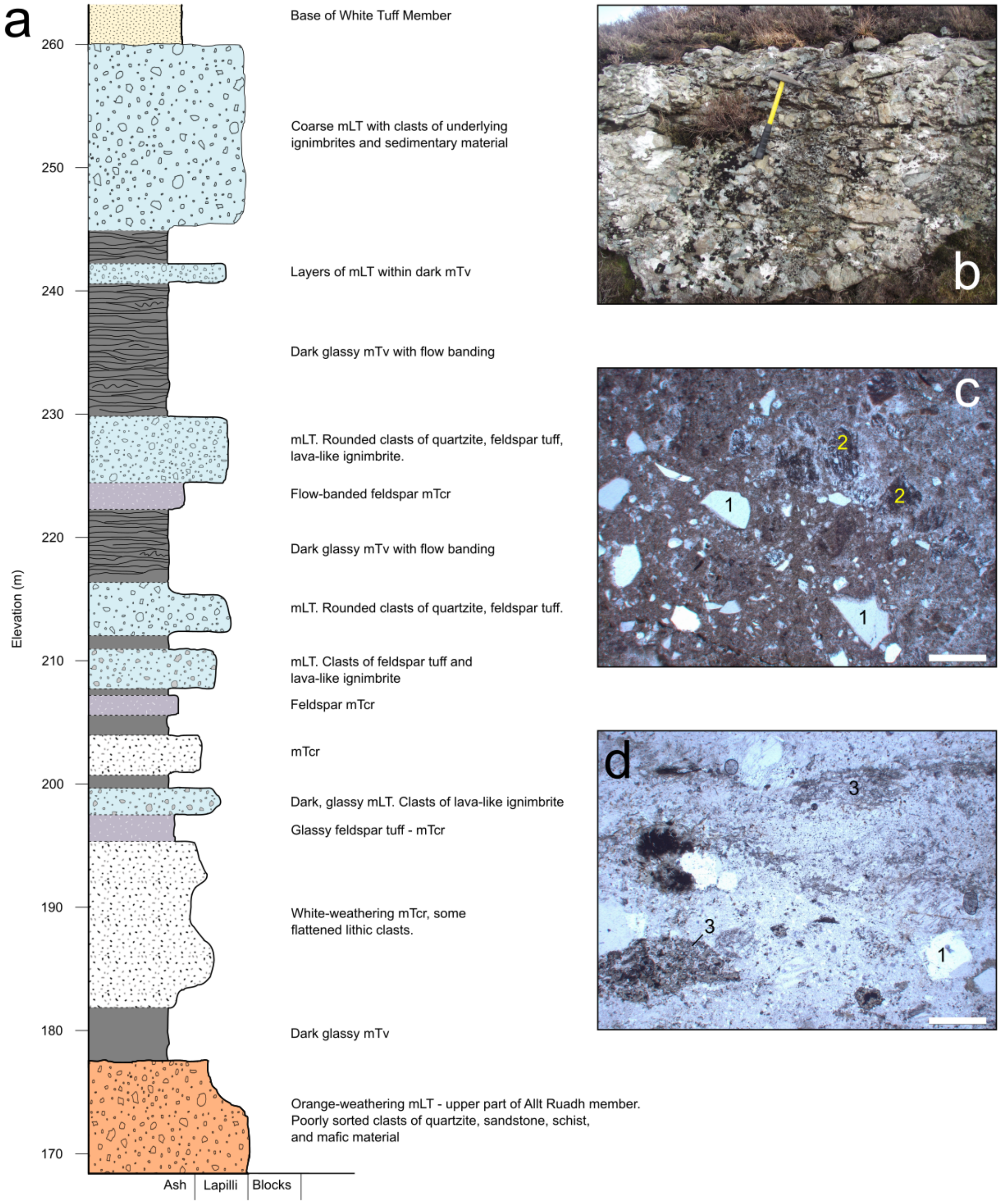

a
Base of White Tuff Member
Coarse mLT with clasts of underlying ignimbrites and sedimentary material
Layers of mLT within dark mTv
Dark glassy mTv with flow banding
mLT. Rounded clasts of quartzite, feldspar tuff, lava-like ignimbrite.
Flow-banded feldspar mTcr
Dark glassy mTv with flow banding
mLT. Rounded clasts of quartzite, feldspar tuff.
mLT. Clasts of feldspar tuff and lava-like ignimbrite
Feldspar mTcr
mTcr
Dark, glassy mLT. Clasts of lava-like ignimbrite
Glassy feldspar tuff - mTcr
White-weathering mTcr, some flattened lithic clasts.
Dark glassy mTv
Orange-weathering mLT - upper part of Allt Ruadh member. Poorly sorted clasts of quartzite, sandstone, schist, and mafic material
Elevation (m)
260
250
240
230
220
210
200
190
180
170
Ash
Lapilli
Blocks
b
c
1
2
d
3

Figure 10

Figure 11

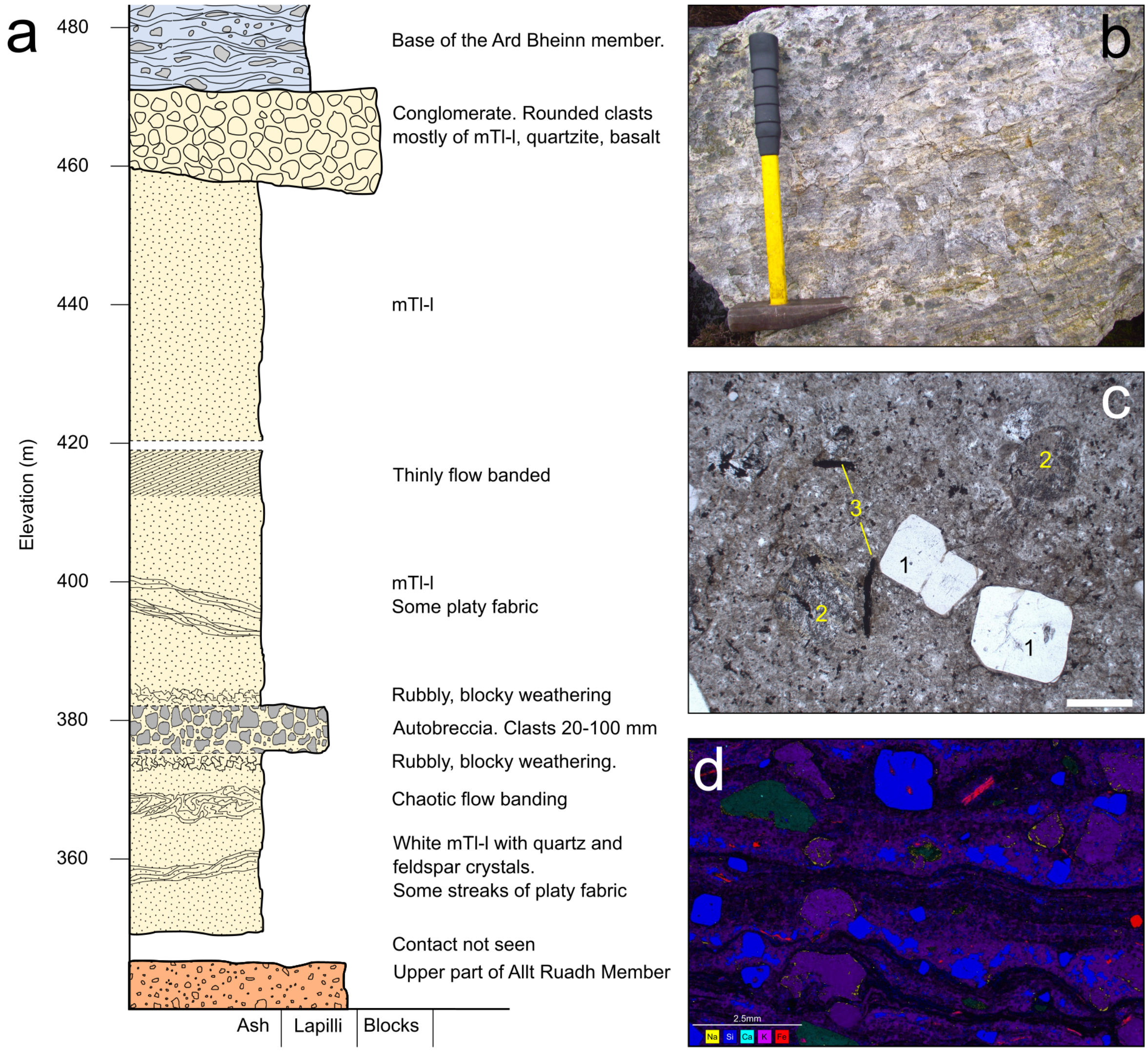

a
480
460
440
420
400
380
360
Elevation (m)
Base of the Ard Bheinn member.
Conglomerate. Rounded clasts mostly of mTl-l, quartzite, basalt
mTl-l
Thinly flow banded
mTl-l
Some platy fabric
Rubbly, blocky weathering
Autobreccia. Clasts 20-100 mm
Rubbly, blocky weathering.
Chaotic flow banding
White mTl-l with quartz and feldspar crystals.
Some streaks of platy fabric
Contact not seen
Upper part of Allt Ruadh Member
Ash
Lapilli
Blocks
b
c
1
2
3
d
2.5mm
Na
Si
Ca
K
Fe

Figure 12

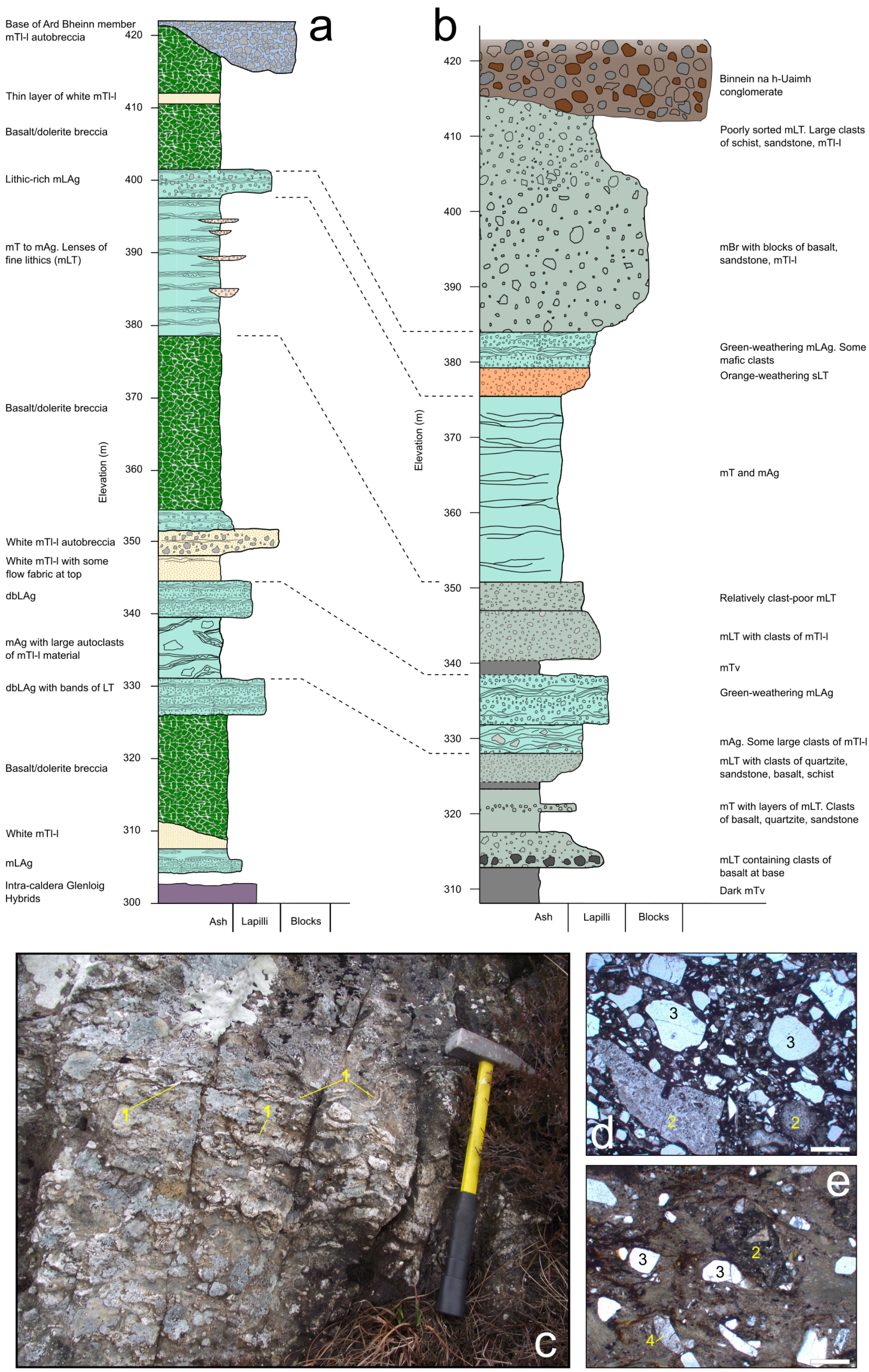

a
Base of Ard Bheinn member
mTl-l autobreccia
Thin layer of white mTl-l
Basalt/dolerite breccia
Lithic-rich mLAg
mT to mAg. Lenses of
fine lithics (mLT)
Basalt/dolerite breccia
White mTl-l autobreccia
White mTl-l with some
flow fabric at top
dbLAg
mAg with large autoclasts
of mTl-l material
dbLAg with bands of LT
Basalt/dolerite breccia
White mTl-l
mLAg
Intra-caldera Glenloig
Hybrids
Elevation (m)
420
410
400
390
380
370
360
350
340
330
320
310
300
Ash
Lapilli
Blocks
b
Binnein na h-Uaimh
conglomerate
Poorly sorted mLT. Large clasts
of schist, sandstone, mTl-l
mBr with blocks of basalt,
sandstone, mTl-l
Green-weathering mLAg. Some
mafic clasts
Orange-weathering sLT
mT and mAg
Relatively clast-poor mLT
mLT with clasts of mTl-l
mTv
Green-weathering mLAg
mAg. Some large clasts of mTl-l
mLT with clasts of quartzite,
sandstone, basalt, schist
mT with layers of mLT. Clasts
of basalt, quartzite, sandstone
mLT containing clasts of
basalt at base
Dark mTv
c
d
e

Figure 13

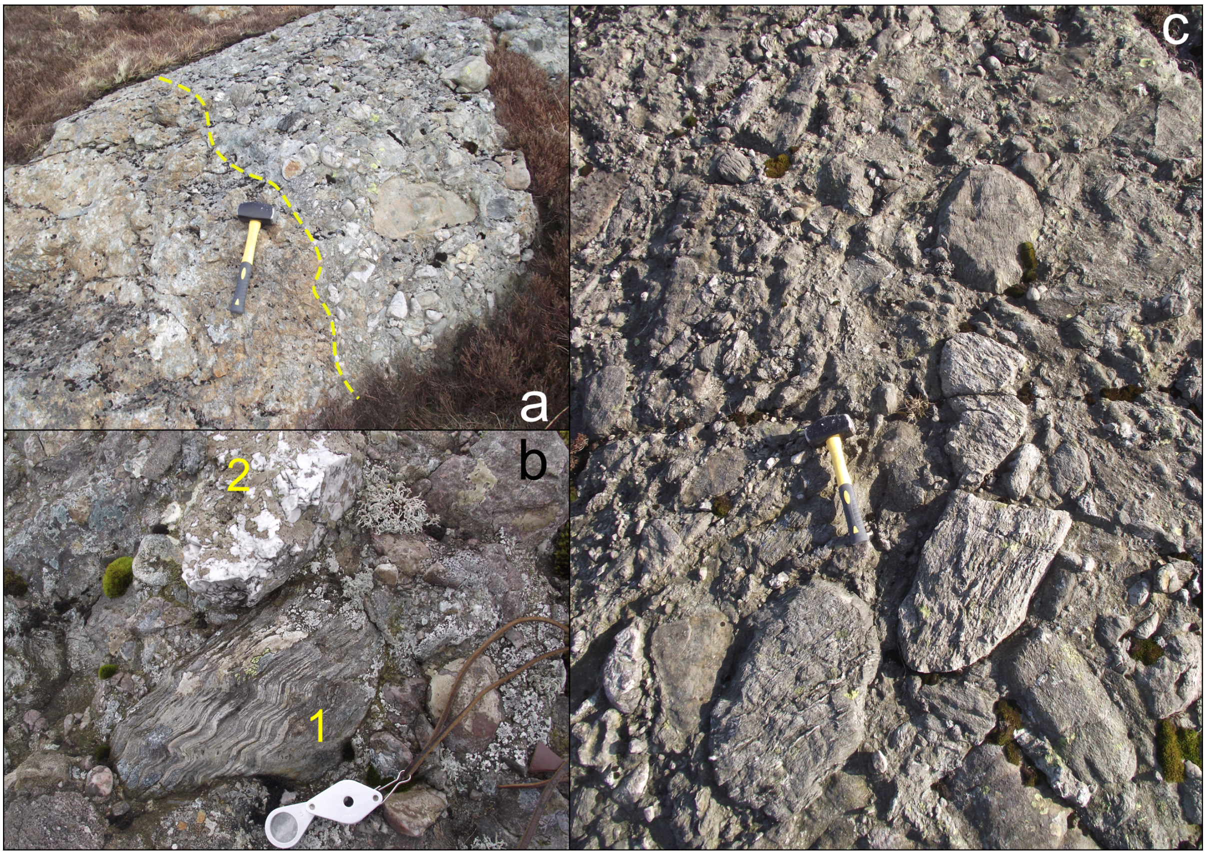


Figure 14

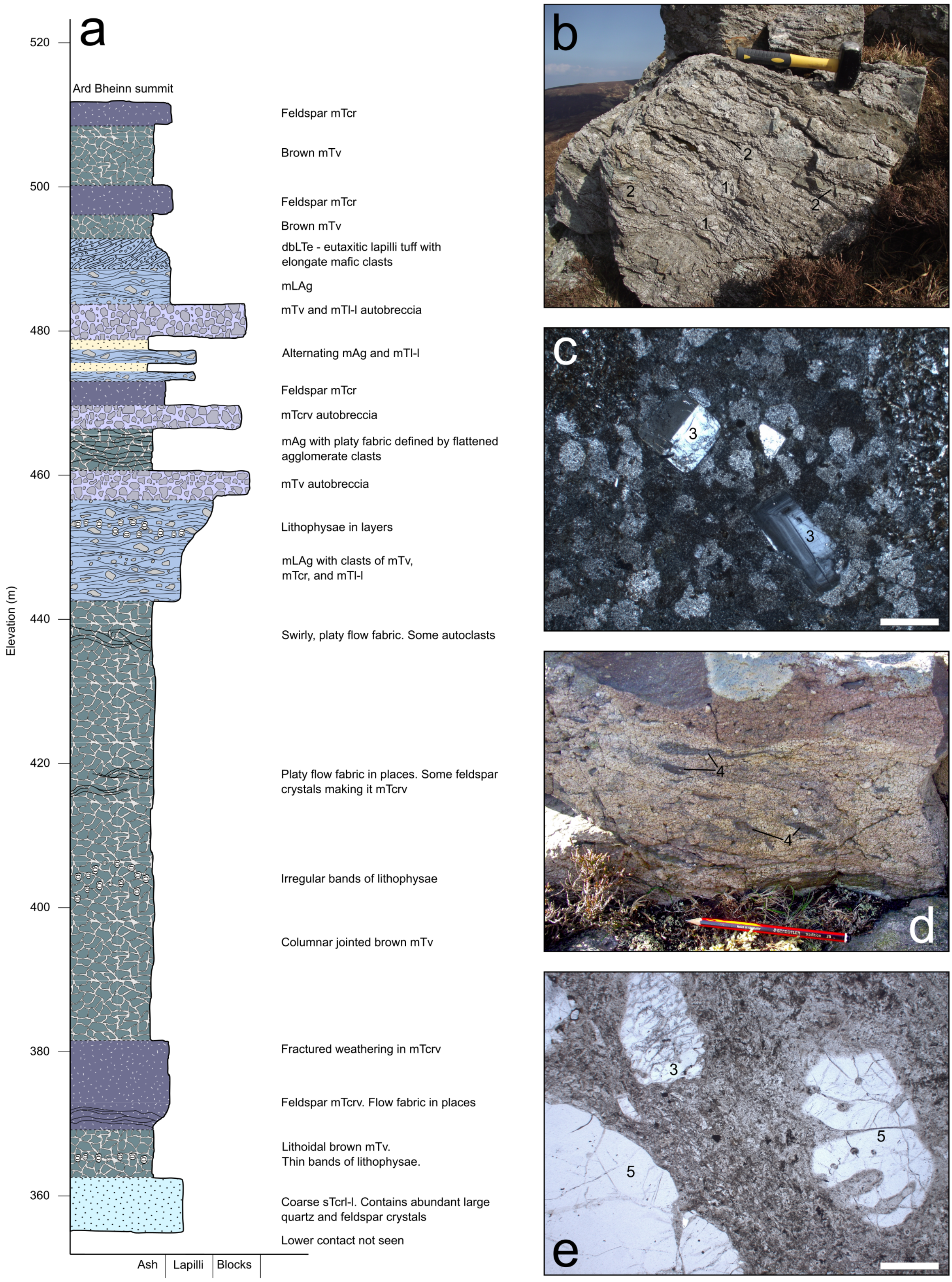
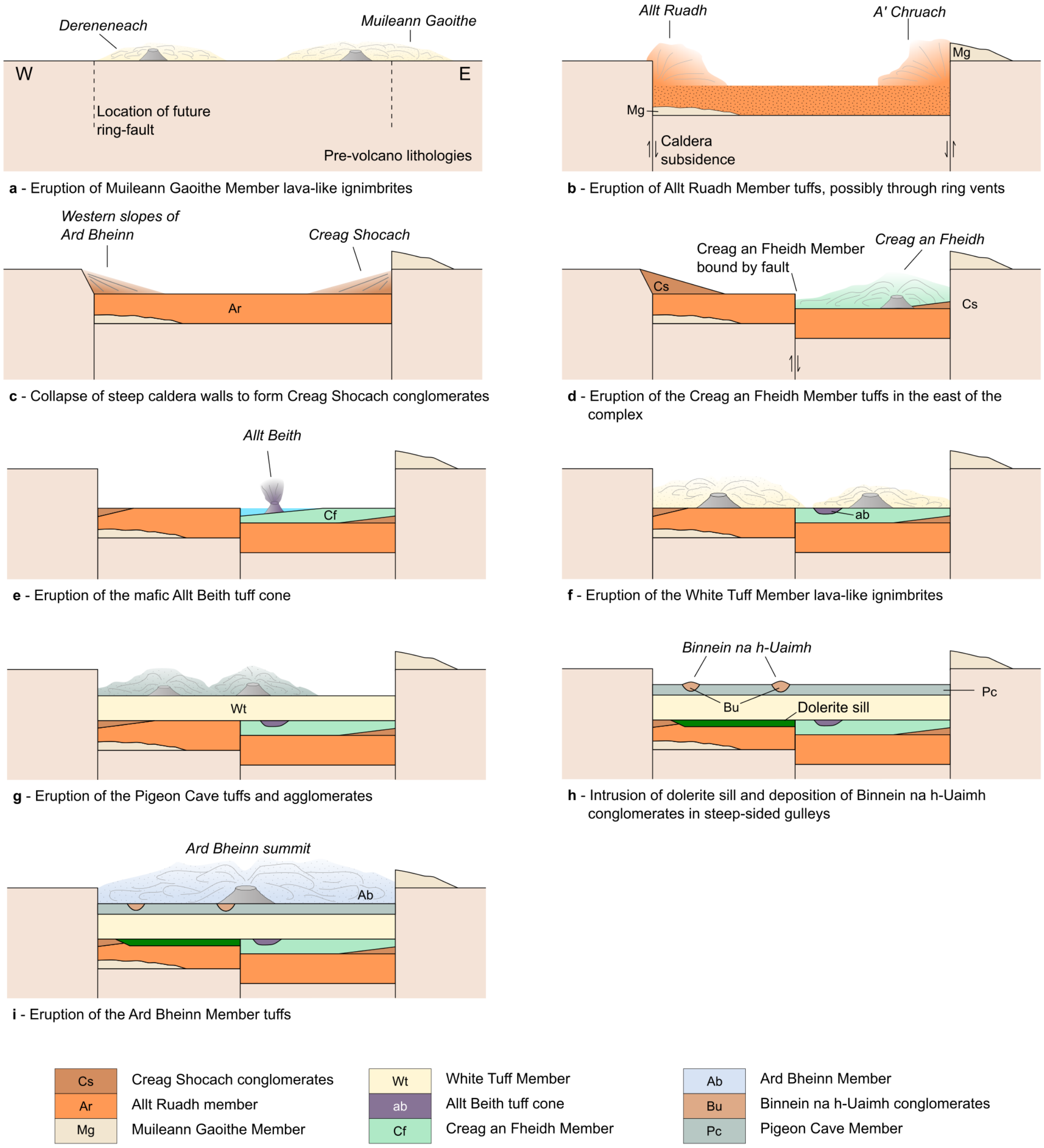

a
520
500
480
460
440
420
400
380
360
Elevation (m)
Ard Bheinn summit
Feldspar mTcr
Brown mTv
Feldspar mTcr
Brown mTv
dbLTe - eutaxitic lapilli tuff with elongate mafic clasts
mLAg
mTv and mTl-l autobreccia
Alternating mAg and mTl-l
Feldspar mTcr
mTcrv autobreccia
mAg with platy fabric defined by flattened agglomerate clasts
mTv autobreccia
Lithophysae in layers
mLAg with clasts of mTv, mTcr, and mTl-l
Swirly, platy flow fabric. Some autoclasts
Platy flow fabric in places. Some feldspar crystals making it mTcrv
Irregular bands of lithophysae
Columnar jointed brown mTv
Fractured weathering in mTcrv
Feldspar mTcrv. Flow fabric in places
Lithoidal brown mTv.
Thin bands of lithophysae.
Coarse sTcrl-l. Contains abundant large quartz and feldspar crystals
Lower contact not seen
Ash
Lapilli
Blocks
b
c
d
e

Figure 15



Dereneneach
Muileann Gaoithe
W
E
Location of future ring-fault
Pre-volcano lithologies
a - Eruption of Muileann Gaoithe Member lava-like ignimbrites
Allt Ruadh
A' Chruach
Mg
Mg
Caldera subsidence
b - Eruption of Allt Ruadh Member tuffs, possibly through ring vents
Western slopes of Ard Bheinn
Creag Shocach
Ar
c - Collapse of steep caldera walls to form Creag Shocach conglomerates
Creag an Fheidh Member bound by fault
Creag an Fheidh
Cs
Cs
d - Eruption of the Creag an Fheidh Member tuffs in the east of the complex
Allt Beith
Cf
e - Eruption of the mafic Allt Beith tuff cone
ab
f - Eruption of the White Tuff Member lava-like ignimbrites
Wt
g - Eruption of the Pigeon Cave tuffs and agglomerates
Binnein na h-Uaimh
Pc
Bu
Dolerite sill
h - Intrusion of dolerite sill and deposition of Binnein na h-Uaimh conglomerates in steep-sided gulleys
Ard Bheinn summit
Ab
i - Eruption of the Ard Bheinn Member tuffs
Cs Creag Shocach conglomerates
Ar Allt Ruadh member
Mg Muileann Gaoithe Member
Wt White Tuff Member
ab Allt Beith tuff cone
Cf Creag an Fheidh Member
Ab Ard Bheinn Member
Bu Binnein na h-Uaimh conglomerates
Pc Pigeon Cave Member

Figure 16

Table 1

Symbol	Meaning	Example Lithofacies
m	massive	mT - massive tuff
s	stratified	sLT - stratified lapilli tuff
db	diffusely bedded	dbTcr - diffusely bedded crystal-rich tuff
L	lapilli	mLT - massive lapilli tuff
T	tuff	mT - massive tuff
Br	breccia	mBr - massive breccia
Ag	agglomerate	mLAg - massive lapilli agglomerate
l-l	lava-like	mTl-l - massive lava-like tuff
cr	crystal-rich	mTcr - massive crystal-rich tuff
v	vitrophyric	mTv - massive vitrophyric tuff
e	eutaxitic	mLTe - massive eutaxitic lapilli tuff

Table 2

Sample	BJG/15/95	BJG/15/78	BJG/15/133	BJG/15/135	BJG/15/31	BJG/17/3	BJG/17/23	BJG/15/8	BJG/15/14
Unit	Allt Beith	Ard Bheinn	Ard Bheinn	Ard Bheinn	Muileann Gaoithe	Muileann Gaoithe	Muileann Gaoithe	White Tuff	White Tuff
Easting	194494	194504	194276	194335	198373	198490	198376	193937	194242
Northing	633982	632829	633467	633297	635029	634980	634970	632857	632457
SiO_2	54.50	67.82	77.00	69.95	76.89	78.39	78.97	77.32	75.72
TiO_2	0.92	1.18	0.53	0.77	0.08	0.07	0.07	0.10	0.11
Al_2O_3	25.30	13.26	9.94	12.31	12.30	12.29	12.54	12.62	12.63
FeO^T	13.89	7.63	4.21	7.13	1.84	1.20	1.22	1.68	1.73
MnO	0.11	0.25	0.15	0.14	0.09	0.03	0.03	0.07	0.09
MgO	0.18	0.67	1.93	0.80	0.36	0.07	0.07	0.12	0.01
CaO	0.46	3.21	1.39	1.22	0.29	0.17	0.18	0.34	0.34
Na_2O	2.52	3.48	2.11	3.88	2.88	2.47	2.52	2.56	2.44
K_2O	2.97	2.84	2.96	3.26	4.95	5.54	5.65	5.22	6.49
P_2O_5	0.24	0.30	0.09	0.10	0.01	0.03	0.03	0.03	0.01
Total	101.10	100.65	100.32	99.56	99.70	100.25	101.27	100.07	99.58
LOI	2.10	0.59	1.00	1.40	0.71	1.15	1.15	0.97	0.90

Fig. 1 The terranes of the northern British Isles with the main onshore locations of magmatic rocks that make up the British Palaeogene Igneous Province. Box shows location of Fig. 2

Fig. 2 Simplified geological map of the Isle of Arran, adapted from BGS (1987), with additional information from this study. The grid shows the 10 km eastings and northings of the British National Grid

Fig. 3 Geological map of the Central Arran Igneous Complex. Approximate locations of stratigraphic logs presented in this paper are shown in red. Numbers refer to Figure number of that log: Muileann Gaoithe Member – Fig 6a. Allt Ruadh Member log – Fig 8a. Creag an Fheidh Member log – Fig 10a. White Tuff Member log – Fig 12a. Pigeon Cave Member north and south logs – Fig 13a,b, respectively. Ard Bheinn Member log – Fig 15a. The grid shows the 1 km eastings and northings of the British National Grid. Inset shows the location of the CAIC on Arran in relation to the North Arran Granite (NAG)

Fig. 4 Overview of the hills Ard Bheinn and Binnein na h-Uaimh taken from the west. The coloured overlay shows the underlying geological units of the AVF. The uncoloured parts show areas underlain by the pre-caldera country rock. Horizontal width of the field of view is ~1200 m

Fig. 5 Generalised stratigraphic log of the Arran Volcanic Formation, showing the relationships between the pyroclastic and sedimentary units. Vertical thicknesses are not to scale. Map symbols are consistent with those in Fig 3

Fig. 6 a) Stratigraphic log of the Muileann Gaoithe Member on the south side of Muileann Gaoithe. b) Folded flow-banding in the lower part of the unit, looking north west. c) Photomicrograph of the rhyolitic lava-like ignimbrite from the summit of Muileann Gaoithe. Scale bar = 500 µm, viewed in plane-polarised light. The micro-scale flow fabric is defined by compositionally distinct (different colours) sub-mm (1) and near-continuous (2) bands and prolate rods. d) Major-element map of the rhyolitic lava-like ignimbrite from the base of the Muileann Gaoithe ridge. In this sample, the micro-fabric is dominated by sub-mm in length wispy bands (1), with some more continuous bands, forming parataxitic texture. The crystal cargo contains quartz (dark blue), plagioclase (turquoise), and K-feldspar (purple)

Fig. 7 Total alkali against silica (TAS) diagram for selected clast-free ignimbrites

Fig. 8 a) Stratigraphic log of the Allt Ruadh Member along the Allt Ruadh section. b) A typical exposure of orange-weathering massive lapilli tuff (mLT) found in the Allt Ruadh Member. c) Photomicrograph of typical mLT. The large object on the right (1) is a heavily altered clast of Muileann Gaoithe-like lava-like ignimbrite. This view also shows smaller clasts of basalt (2) and quartz and feldspar crystals (3). Scale bar = 500 µm, viewed in plane-polarised light. d) Major-element map of the white eutaxitic tuff (mTe) exposed at around 240 m elevation in the Allt Ruadh section. The texture is defined by elongate but discontinuous bands of compositionally distinct glass (black, grey, and purple). Crystals are quartz (dark blue) and plagioclase (turquoise)

Fig. 9 The Creag Shocach conglomerates. a) The conglomerates exposed in the cliffs of Creag Shocach, showing a coarse red sandy matrix and clasts dominated by white vein quartz. b) A rounded clast of coarse sandstone with layers of pebbly conglomerate on Creag Shocach. c) Similar conglomerates exposed on the western slopes of Ard Bheinn, showing some layers of coarse sandstone

Fig. 10 a) Stratigraphic log of the Creag an Fheidh Member along the Creag an Fheidh section. b) A massive lapilli tuff in the upper part of the unit. c) Photomicrograph of a crystal-rich tuff from the lower part of the unit. The crystals are largely quartz (1) and heavily altered feldspar (2). Scale bar = 500 µm, viewed in plane-polarised light. d) Photomicrograph of a eutaxitic tuff from the lower part of the unit, showing flattened clasts (3) as well as occasional quartz crystals (1). Scale bar = 500 µm, viewed in plane-polarised light

Fig. 11 Finely laminated and cross laminated basaltic-andesitic tuff that makes up the Allt Beith tuff cone

Fig. 12 a) Stratigraphic log of the White Tuff Member up the western slopes of Ard Bheinn. b) The thinly banded unit shown at around 415m in the log. The meso-scale flow-fabric is clearly visible as bands of different colours, in this case yellow and grey. c) Photomicrograph of typical lava-like ignimbrite within the member, showing the euhedral quartz crystals (1) that are so characteristic of this ignimbrite, as well as K-feldspar (2) and Fe-Ti oxides (3). Scale bar = 500 µm, viewed in plane-polarised light. d) Major element map of a flow-banded portion of the lava-like ignimbrite. The lava-like microfabric is shown by the continuous bands of compositionally distinct (black and purple) material. Crystal content includes quartz (dark blue), K-feldspar (purple), and less-abundant plagioclase (green) and Fe-Ti oxides (red)

Fig. 13 a) Stratigraphic log of the Pigeon Cave Member up the northern side of Binnein na h-Uaimh, where it is intruded by brecciated fingers of the basalt/dolerite sill. b) Stratigraphic log of the Pigeon Cave Member up the western side of Binnein na h-Uaimh, where it is not intruded by the sill. Dashed lines from a) show possible lateral bed correlations. c) Photograph showing a typical green-weathering massive lapilli agglomerate from the lower part of the Pigeon Cave Member west of Binnein na h-Uaimh. It contains elongate streaks and bands of rhyolitic material (1). d) Photomicrograph of a crystal-rich lapilli tuff with a dark glassy groundmass, lithic lapilli (2), and quartz crystals (3). Scale bar = 500 µm, viewed in plane-polarised light. e) Photomicrograph of a typical lapilli tuff showing clasts of glassy rhyolite (2) and abundant quartz and feldspar crystals (3). Scale bar = 500 µm, viewed in plane-polarised light

Fig. 14 a) The contact between the underlying Pigeon Cave mLT and the Binnein na h-Uaimh conglomerates (dashed line). The steep contact here is interpreted as the side of a palaeocanyon. b) Examples of some of the clasts in the conglomerate, including a crenulated schist (1) and vein quartz (2). c) The coarsest part of the Binnein na h-Uaimh conglomerates

Fig. 15 a) Stratigraphic log of the Ard Bheinn Member up the southern side of Ard Bheinn. b) Massive lapilli agglomerate near the summit on Binnein na h-Uaimh, looking north showing lithic lapilli (1) and elongate bands of lava-like material (2). c) Photomicrograph of the feldspar

(3) rich mTcr ('plagioclase porphyry' of King, 1955) from the summit of Ard Bheinn. Scale bar = 500 µm, viewed between crossed polars. d) Eutaxitic massive lapilli tuff at 490 m elevation on the Ard Bheinn log, containing stretched out mafic clasts (4). e) Photomicrograph of the coarse crystal-rich tuff at the base of the Ard Bheinn Member, showing large quartz crystals (5) and smaller K-feldspar crystals (3). Scale bar = 500 µm, viewed in plane-polarised light

Fig. 16 A series of generalised cross sections through the AVF showing the history of eruption and caldera collapse. Lithologies other than the caldera-fill succession have been omitted for clarity. Annotations in italics show the locations where certain features are exposed

Table 1 Explanation of ignimbrite lithofacies codes used in this paper, following the terminology of Branney and Kokelaar (2002)

Table 2 Anhydrous whole-rock geochemical data for the ignimbrites shown in Fig 7