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A proximal record of caldera-forming eruptions: the stratigraphy, eruptive history, and collapse of the Palaeogene Arran caldera, western Scotland

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Abstract:	Caldera-forming volcanic eruptions are among the most dangerous, and can generate extensive pyroclastic deposits and deliver ash into global atmospheric circulation systems. As calderas collapse, the eruptions can deposit thick proximal ignimbrite sequences and thinner ignimbrites more distally. However, the proximal record of caldera collapse is often obscured by later intrusions, volcanism, faults, alteration, water and sediments, which significantly limits our understanding of these eruptions. A Palaeogene caldera system in central Arran, western Scotland, preserves a rare proximal caldera-fill succession, the Arran Volcanic Formation. This caldera largely comprises highly heterogeneous ignimbrites and minor intra-caldera sedimentary rocks. The current level of erosion, and the general absence of faults, intrusions and sediments, allows a complex stratigraphy and collapse history to be determined, which can be linked to changing eruptive styles at a constantly-evolving volcano. The first recorded phase was eruption of a homogeneous rhyolitic lava-like tuff, deposited from high temperature, high mass-flux pyroclastic density currents generated from low fountaining columns that retained heat. A succeeding phase of highly explosive Plinian eruptions, marked by a thick blanket of massive lapilli tuffs, was then followed by piston-like caldera collapse and erosion of steep caldera walls. Volcanism then became generally less explosive, with predominantly lava-like and eutaxitic tuffs and cognate-spatter-rich agglomerates interbedded with non-homogenous lapilli tuffs. 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 rocks and evidence for surface water, which includes a localised basaltic-andesitic phreatomagmatic tuff. The caldera-forming eruptions recorded by the Arran Volcanic Formation provide an important insight into caldera collapse processes and proximal ignimbrite successions. The lack of thick autobreccias and lithic-rich lapilli- and block-layers indicates that subsidence was relatively gradual and incremental in this caldera, and not accompanied by catastrophic wall collapse during eruption. The relatively horizontal nature of the caldera-fill units and paucity of intra-caldera faulting, indicate piston subsidence was the dominant method of collapse, with a relatively coherent caldera floor bounded by a steeply-dipping ring fault. Possible resurgence may have caused later doming of the floor and radial distribution of subsequent ignimbrites and sedimentary rocks. Our work emphasises the continued need for field studies of caldera volcanoes.
Response to Reviewers:	Editor comments

	Keywords: These have been changed to better reflect the specifics of the paper “The necessary addition is a better setting of your work in general context…” Additions have been made to the Abstract (lines 12-18), Introduction (lines 51-96), and the discussion (lines 518-542), with a final sentence at the end of the Conclusions (lines 637-640). References to other studies have been added throughout the discussion, in order to better set this work in the context of modern global studies. “Please, in the figures, also add the numbers to the scale bars and in the caption state how long the hammer is.” These have been done for all figures “Please also add labels to the features named in the photos in the figure captions” This has been done in all relevant figures. “Please also check the referencing” This has been done, largely thanks to your suggestions, and is now consistent throughout.
Author Comments:	Dear Editor, We wish to submit our revised manuscript, now entitled "A proximal record of caldera-forming eruptions: the stratigraphy, eruptive history, and collapse of the Palaeogene Arran caldera, western Scotland". Your comments were helpful, and we all feel the manuscript has been greatly improved. Sincerely Bob Gooday

Table 1

Unit	Locations	Description	Interpretation
Muileann Gaoithe Member [translation: *windmill*]	Muileann Gaoithe in far NE of complex (extra-caldera). Dereneneach in the far W of the complex.	*Lithologies*: Massive rhyolite (77-79 wt.% SiO_2) tuff. Minor mLT and red weathered non-welded tuff. *Crystals and clasts*: Abundant quartz up to 2 mm. K-feldspar, plagioclase, Fe-Ti oxides. Clasts in mLT = sandstone, dolerite, rhyolite *Textures*: cm-scale flow banding in lower and upper parts. Sub-mm fabric defined by <1 mm to near-continuous elongate bands	Rhyolitic parataxitic to lava-like ignimbrite. Very high-grade ignimbrite of 'Snake River type' (Andrews and Branney, 2011). Rapid deposition from a high temperature, (>900˚C) high-mass-flux pyroclastic density current from low fountaining eruption. mLT record pulses of higher explosivity. Red tuff (sT) represents upper surface of ignimbrite sheet in contact with atmosphere.
Allt Ruadh Member [translation: *red stream*]	Western slopes of Ard Bheinn. Lower Glen Craigag.	*Lithologies*: Orange- and grey-weathering mLT. Minor crystal-rich and glassy tuffs. *Crystals and clasts*: pre-Palaeogene schist, sandstone, quartzite. Palaeogene basalt, dolerite, occasional granite. Crystal tuffs contain feldspar and minor quartz *Textures*: mLT massive. Crystal tuffs are eutaxitic to lava-like.	Lithic-lapilli-rich non-welded ignimbrite deposited from a PDC at a flow-boundary zone dominated by fluid-escape, with very little turbulent shear-induced tractional segregation (Branney and Kokelaar, 2002). Highly explosive, caldera-forming eruptive phase. mTcr record phases of lower explosivity.
Creag Shocach Conglomerates [translation: *snout crag*]	Western slope of Ard Bheinn. Creag Shocach above Glenloig.	*Lithologies*: Red conglomerates, breccias, and minor sandstones *Crystals and clasts*: Pre-Palaeogene medium- to coarse-grained red sandstones and quartzite conglomerates. Fine to medium sand matrix. *Textures*: Clast supported and matrix supported in different areas.	Erosion of Devonian and Permo-Triassic lithologies from steep caldera walls left by caldera subsidence related to eruption of the Allt Ruadh Member. Deposition – alluvial/fluvial.
Creag an Fheidh Member [translation: *deer crag*]	Creag an Fheidh. E of Creag Shocach.	*Lithologies*: glassy mT, mTcr, and mLT *Crystals and clasts*: Crystals largely feldspar, with lesser quartz. Clasts in mLT of rhyolite and sedimentary rocks. Upper surface contains rounded pebbles and cobbles of rhyolite and quartzite. *Textures*: Some bedding-parallel flow-fabric in glassy units. Some mTcr are eutaxitic	Heterogeneous ignimbrites recording a range of eruptive styles. mLT and mTcr record variably highly-explosive eruptions and deposition from a PDC at a flow-boundary zone dominated by fluid-escape. Eutaxitic and glassy tuffs record higher emplacement temperatures. Rounded clasts evidence for fluvial reworking on upper surface of ignimbrite.

Allt Beith tuff cone [translation: *birch stream*]	Near the head of the Allt Beith	*Lithologies*: Finely laminated basaltic-andesitic (54.5 wt.% SiO_2) tuff *Crystals and clasts*: None identified *Textures*: Planar bedding and cross-stratification. Some graded bedding.	Localised phreatomagmatic tuff cone – very fine grain size suggests intense fragmentation. Well-developed stratification suggests deposition from a fully dilute pyroclastic density current at a traction dominated flow boundary zone (Branney and Kokelaar 2002, Brown et al 2007).
White Tuff Member	Western slopes of Ard Bheinn. Plateau between Ard Bheinn and Glen Craigag.	*Lithologies*: Massive rhyolite (76-77 wt.% SiO_2) tuff with some autobreccia and conglomerate at top *Crystals and clasts*: Quartz and feldspar up to 2 mm. Upper conglomerate contains clasts of rhyolitic tuff, basalt, quartzite *Textures*: Largely massive with planar and chaotic flow banding in places	Rhyolitic lava-like ignimbrite. Very high-grade ignimbrite of 'Snake River type' (Andrews and Branney, 2011). Rapid deposition from a high temperature, (>900˚C) high-mass-flux pyroclastic density current from low fountaining eruption. Autobreccia may record post-deposition slumping. Upper conglomerate evidence for fluvial reworking on upper surface of ignimbrite.
Pigeon Cave Member	Slopes of Binnein na h-Uaimh. E of Glen Craigag.	*Lithologies*: Turquoise-weathering mLT and mAg with minor glassy mT *Crystals and clasts*: Quartz and less abundant feldspar and Fe-Ti oxides. Clasts of pre-Palaeogene schist and sandstone and Palaeogene basalt and rhyolite. Lava-like cognate spatter clasts. *Textures*: Some bedding-parallel fabric in glassy units. Cognate spatter clasts are elongate ribbons.	Heterogeneous ignimbrites recording highly dynamic and fluctuating deposition history. mT and mLT formed as above. mAg formed from rapid deposition of cognate clasts (with lithic lapilli) from a pyroclastic density current rich in ash and dominated by fluid escape (Branney and Kokelaar, 2002).
Binnein na h-Uaimh conglomerates [translation: *hill of the caves*]	Northern slopes of Binnein na h-Uaimh.	*Lithologies*: Very coarse conglomerate. *Crystals and clasts*: Pebbles to large cobbles of sandstone and schist (resemble local Dalradian units) and smaller pebbles of vein quartz and quartzite. *Textures*: Clast supported. No clast alignment.	Debris flow conglomerate recording mass wasting of surrounding landscape into caldera.
Ard Bheinn Member [translation: *high peak*]	Summits of Ard Bheinn and Binnein na h-Uaimh.	*Lithologies*: Dominated by glassy rhyolitic (77 wt.% SiO_2) mT and mTcr. Minor autobreccias, agglomerates, and lapilli tuff. Purple-grey units near top are dacitic (68-70 wt. % SiO_2)	Mostly lava-like ignimbrites. Lower part of unit (to 440 m) is thought to represent one single eruption event, with hot (>900°C) ash deposited from a pyroclastic density current at

		Crystals and clasts: Crystals in mTcr are primarily plagioclase. Coarse crystal tuff at base contains large resorbed quartz and less abundant feldspars. *Textures*: Largely vitrophyric with platy flow fabric in places. Agglomerates show distinct banding. Lapilli tuff near top is eutaxitic with fiamme of mafic material.	a relatively stable flow-boundary zone. Continuous jointing throughout suggests one single cooling unit. Upper parts of the member (above 440 m) likely formed from a series of small pyroclastic fountaining eruptions of varying temperature, recording deposition at an unstable flow-boundary zone. Agglomerates deposited rapidly from a proximal pyroclastic density current.

Table 2

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 3

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

A proximal record of caldera-forming eruptions: the stratigraphy, eruptive history, and collapse of the Palaeogene Arran caldera, western Scotland

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Abstract: Caldera-forming volcanic eruptions are among the most dangerous, and can generate extensive pyroclastic deposits and deliver ash into global atmospheric circulation systems. As calderas collapse, the eruptions can deposit thick proximal ignimbrite sequences and thinner ignimbrites more distally. However, the proximal record of caldera collapse is often obscured by later intrusions, volcanism, faults, alteration, water and sediments, which significantly limits our understanding of these eruptions.

A Palaeogene caldera system in central Arran, western Scotland, preserves a rare proximal caldera-fill succession, the Arran Volcanic Formation. This caldera largely comprises highly heterogeneous ignimbrites and minor intra-caldera sedimentary rocks. The current level of erosion, and the general absence of faults, intrusions and sediments, allows a complex stratigraphy and collapse history to be determined, which can be linked to changing eruptive styles at a constantly-evolving volcano.

The first recorded phase was eruption of a homogeneous rhyolitic lava-like tuff, deposited from high temperature, high mass-flux pyroclastic density currents generated from low fountaining columns that retained heat. A succeeding phase of highly explosive Plinian eruptions, marked by a thick blanket of massive lapilli tuffs, was then followed by piston-like caldera collapse and erosion of steep caldera walls. Volcanism then became generally less explosive, with predominantly lava-like and eutaxitic tuffs and cognate-spatter-rich agglomerates interbedded with non-homogenous lapilli tuffs. 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 rocks and evidence for surface water, which includes a localised basaltic-andesitic phreatomagmatic tuff.

The caldera-forming eruptions recorded by the Arran Volcanic Formation provide an important insight into caldera collapse processes and proximal ignimbrite successions. The lack of thick autobreccias and lithic-rich lapilli- and block-layers indicates that subsidence was relatively gradual and incremental in this caldera, and not accompanied by catastrophic wall collapse during eruption. The relatively horizontal nature of the caldera-fill units and paucity of intra-caldera faulting, indicate piston subsidence was the dominant method of collapse, with a relatively coherent caldera floor bounded by a steeply-dipping ring fault. Possible resurgence may have caused later doming of the floor and radial distribution of subsequent ignimbrites and sedimentary rocks. Our work emphasises the continued need for field studies of caldera volcanoes.

Keywords: caldera collapse, resurgence, pyroclastic, lava-like ignimbrites, eruptive history

Introduction

Calderas are the surface expressions of complex volcano-magmatic systems, with prolonged periods of unrest and eruption (Acocella et al., 2015; Nobile et al., 2017) punctuated by extensive periods of quiescence. Although much debated, caldera collapse is typically caused by the withdrawal of large volumes of magma from shallow magma chambers (Druitt and Sparks, 1984; Lipman, 1997; Cole et al., 2005; Cashman and Giordano, 2014), and subsidence of a coherent block of crust into the underpressurised chamber(s) (Mori and McKee, 1987; Lipman, 1997, Cole et al., 2005; Acocella 2007), although collapse may also be triggered by overpressure within the chamber initiating fractures in the roof rocks (Gudmundsson, 1988; 1998). Caldera-forming eruptions are typically silicic and can deposit extensive sheets of ignimbrite both within and beyond the collapse caldera, together with widespread fall deposits, and even the circulation of ash globally (e.g. Self and Rampino, 1981; Self et al., 1984; Newhall and Dzurisin 1988; Hildreth and Fierstein, 2012).

Understanding caldera-forming eruptions and syn-eruptive collapse mechanisms is notoriously difficult at both modern and ancient calderas. Monitoring unrest at active calderas using seismic and remote sensing methods is essential in forecasting volcanic activity, but understanding these relationships is complex. How much magma withdrawal is required to induce collapse and how does collapse vary (Geshi and Miyabuchi, 2016)? Furthermore, how many collapse events may occur in the lifecycle of a caldera (e.g. due to evacuation of multiple magma reservoirs), and how might the deposits of these different eruption and collapse events vary both temporally and spatially (proximal and distal)? Answering these questions at active calderas is challenging, as only the latest stages in the caldera's deposits and structures are preserved and access may be further obscured by water and sediments (Acocella, 2007).

Therefore, we can look to ancient and more recent but inactive calderas. There are numerous field studies of such calderas (see reviews by Cole et al., 2005; Cashman and Giordano, 2014) that attempt to resolve questions on caldera collapse and evolution, and these have been supported more recently by numerical and analogue modelling studies (e.g. Troll et al., 2002; Acocella, 2007; Geshi et al., 2012). However, ancient calderas can typically be obscured by resurgent intrusions and volcanic deposits, thoroughly disrupted by faults and hydrothermal alteration, and/or obscured by water and later sediments. The level of erosion and preservation of the volcanic deposits and caldera-controlling structures can also represent a particular constraint to study. These constraints are particularly important with respect to the intra-caldera/proximal records of eruption, which are consequently less well studied than more distal, better preserved ignimbrite sheets (Smith and Kokelaar, 2013).

Therefore, it remains a challenge to volcanologists to identify ancient calderas where access and preservation allow for detailed field observations that can be used to elucidate caldera collapse and caldera-forming eruption processes. We argue that, given modern advances in physical volcanology (in particular pyroclastic density currents, the sedimentation of ignimbrites, and better understanding of lava-like ignimbrites; e.g. Branney and Kokelaar, 2002; Branney et al., 2008; Brown and Branney, 2013), it is therefore essential to revisit localities that have not received recent attention. In this paper, we present a field study of a Palaeogene caldera system on the Isle of Arran, western Scotland, as an example of the proximal record of caldera-forming eruptions and the nature of collapse within the caldera.

Why the Isle of Arran?

The Isle of Arran in the Firth of Clyde, western Scotland, hosts some well-preserved remnants of the British Palaeogene Igneous Province (Fig. 1). The British Palaeogene Igneous Province itself is part of the North Atlantic Igneous Province, a predominantly mafic Large Igneous Province 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 North Atlantic Igneous Province comprises the extensive lava fields of Skye, Eigg, Mull-Morvern, and Antrim (Emeleus and Bell, 2005), as well as localised intrusive and volcanic centres (Fig. 1), including Arran. 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 British Palaeogene Igneous Province 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 access, the British Palaeogene Igneous Province has been the source of many developments in the global understanding of volcanological processes.

Pyroclastic rocks in the British Palaeogene Igneous Province 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. Detailed studies of the pyroclastic successions on Skye and Rùm have revealed complex histories of caldera collapse in the British Palaeogene Igneous Province (Troll et al., 2000; Holohan et al., 2009; 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 (Troll et al., 2000; 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, and make comparison with, other lava-like ignimbrite-producing volcanic provinces, for example, the Snake River Plain (Knott et al., 2016), the

Paraná Magmatic Province (Luchetti et al., 2017), and the Canary Islands (Sumner and Branney, 2002).

Despite these advances in the region, the caldera system in central Arran has remained poorly studied. The caldera (approximately 9 km^2) is well exposed in places, and contains a caldera-fill sequence of pyroclastic and minor sedimentary rocks. Critically, it has not been overly disrupted by alteration, faults, later intrusions and volcanic deposits, and the level of erosion is such that a relatively undisturbed sequence of the caldera stratigraphy and its structure is preserved. Therefore, this makes Arran an extremely important area in which to study volcanic and sedimentary processes, how these change through time and, in particular, proximal records of ignimbrite deposition at a caldera volcano, and its collapse mechanisms. Despite all these advantages, central Arran has been the subject of few studies since the work of King (1955).

By way of example, the historically active Öskjuvatn caldera at Askja, North Iceland, is a comparable size (around 12 km^2) to the Arran caldera and occupies a similar tectonic (rift) setting (Trippanera et al., 2018). However, observations of the caldera-fill succession at Askja are impossible due to the presence of a large lake, and the only information on collapse processes during and following the 1875 eruption are from historical sources, which can be unreliable (Hartley and Thordarson, 2012). Given the similarities to such a nearby caldera that is close to significant population centres in Europe, we emphasise the need for detailed field study of localities such as Arran and the lessons that can be learned and applied to active calderas.

In this paper, we present new field and petrographic data from the pyroclastic rocks preserved in central Arran, propose a volcanological model for the formation, evolution, and collapse of the caldera, and discuss the nature of eruptions and proximal record of caldera-forming eruptions. We include discussion on what our analysis of this ancient centre shows in terms of large caldera-forming eruptions, their deposits, and resulting structures in general.

Geological setting

The pre-Palaeogene rocks in the northern part of Arran (Fig. 1) comprise the Neoproterozoic to Lower Cambrian schists, phyllites, and grits of the Southern Highland Group (BGS, 1987), this being 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. 1). 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, is known to cross Arran (Fig. 1), but its exact trace is uncertain (Young and Caldwell, 2012).

The Palaeogene igneous rocks on Arran (Fig. 1) comprise the North Arran Granite, a caldera system in the centre of the island, and a suite of sills and minor intrusions in the south of the island, which vary in composition from dolerite to rhyolite. 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 (BGS, 1987). These dykes intrude the Dalradian meta-sedimentary rocks, the Palaeozoic and Mesozoic sandstones, and the Palaeogene intrusions (Tyrell, 1928; BGS, 1987). 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 evolved cores, are common across much of southern Arran (Tyrell, 1928; BGS, 1987). The most well-known of these forms cliffs and coastal outcrops at Drumadoon Point (Fig. 1), and this intrusion, and adjacent dykes, have been dated at 59.04±0.13 Ma and 59.16±0.17 Ma (Meade et al., 2009). In this contribution, the Palaeogene caldera system in central Arran is named the Central Arran Igneous Complex, while the pyroclastic and sedimentary intra-caldera succession is termed the Arran Volcanic Formation.

The Central Arran Igneous Complex includes a series of pyroclastic rocks and coarse grained intrusions, and is approximately 4 km $\times$ 5 km in area. It was first mapped by 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. 2). King (1955) mapped the western part of the Central Arran Igneous Complex in detail and suggested that it was younger than the North Arran Granite, due to the fact that it appears to have been emplaced into sedimentary rocks that were previously domed during emplacement of the North Arran Granite, around 2 km to the north.

The 'vent agglomerates' (Tyrell, 1928) of the 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 volcanic edifices 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) also 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’).

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 manganese-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 (UK). Major element analyses were carried out using inductively coupled plasma optical emission spectrometry (ICP-OES). Accuracy was constrained by subjecting the international reference materials BIR-1 (basalt) and JG-3 (granodiorite) to the same process. Precision was constrained by duplicates of unknown samples – duplicates generally provided uncertainties of <5% for elements with concentrations >2 wt%.

The Central Arran Igneous Complex

As part of the present study, the western half of the Central Arran Igneous Complex has been re-mapped (Fig. 2). 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, should not be described as a 'ring complex'. Although exposure of the caldera-fill rocks on the slopes of Ard Bheinn and Binnein na h-Uaimh (Figs 2, 3) is good, exposure in the majority of the rest of the complex is limited 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 downfaulting of the complex.

Intrusive rocks of the Central Arran Igneous Complex

The north and east of the complex (Figs. 1, 2), are dominated by the pre-caldera Glenloig Hybrids, named after the most accessible exposure under the bridge at Glenloig. They include texturally 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. In some stream sections, isolated exposures of quartz-bearing gabbro are found, 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 2, 3).

Several granitic bodies are found within the Central Arran Igneous Complex. The largest of these is the Glen Craigag Granite, which is mostly exposed in the upper parts of Glen Craigag and Ballymichael Glen, in the centre of the complex (Fig. 2). 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.

Several smaller granitic bodies crop out around the margins of the Central Arran Igneous Complex (Fig. 2). These are here 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' (Tyrell, 1928), but our mapping shows that they are isolated from one another at this level of erosion. Relationships to the other units of the Central Arran Igneous Complex 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 rocks of the Arran Volcanic Formation. This suggests that the granites intruded the lower pyroclastic units of the Arran Volcanic Formation. 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 rock on the western slopes of Ard Bheinn and Binnein na h-Uaimh (Figs 2, 3) 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, and patches of iddingsite show alteration of primary olivine. This unit displays a clear intrusive relationship with several of the pyroclastic units of the Arran Volcanic Formation, with small fingers of dolerite intruding into the overlying unit (White Tuff Member). In many places, especially near the contacts, the dolerite is heavily brecciated, with peperitic textures visible in several exposures. There is also one small outcrop of the underlying unit (Allt Ruadh Member) preserved above it. Other than this, it is largely concordant with stratigraphy (Figs. 2, 3), so we interpret the unit as a sill.

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) (Fig. 2). No mafic dykes are observed intruding the Satellite Granites or the caldera-fill succession of the Arran Volcanic Formation. The only dyke seen intruding an intra-caldera ignimbrite is a pitchstone (i.e., silicic and vitrophyric) dyke in a tributary to the Glen Craigag stream.

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.

The Arran Volcanic Formation comprises a number of different mappable pyroclastic units which we interpret as ignimbrites (i.e., the deposits of pyroclastic density currents) (Fig. 2), separated by erosional unconformities and sedimentary horizons. They are best exposed in the western third of the complex (i.e., west of Glen Craigag; Fig. 2), with good exposure on the high ground around Ard Bheinn and Binnein na h-Uaimh (Fig. 3). This is the area that King (1955) described in detail. Exposures of these rocks are found over an elevation change of more than 400 m (Fig. 3), giving the best estimate of total preserved thickness. Dips of units and other structural data are impossible to measure due to the lack of bedding seen at the scale of individual exposures. Where a sense of dip can be gleaned from following contacts, beds appear approximately horizontal. Away from a small number of outcrops showing a possible caldera basement, it is impossible to estimate how far the Arran Volcanic Formation extends below the level of exposure. An unknown thickness of the Arran Volcanic Formation above the current level of exposure has been lost to erosion.

The general volcanic stratigraphy of the area is shown in Fig. 4, with stratigraphic and lithological information displayed in Table 1. We assign the mappable pyroclastic units as individual members within the Arran Volcanic Formation, based on lithological variations between units, and the presence of mappable palaeotopographic surfaces. The general characteristics of each member (weathering colour, lithology, clast composition, *etc*.) are generally distinct enough to allow isolated exposures to be assigned to the appropriate unit. However, the upper surfaces of all members show evidence for fluvial reworking, erosion, deposition of sedimentary units, and/or prolonged contact with the atmosphere (Fig. 4), which all suggest volcanic hiatuses. Reddened units are tentatively used to identify either distinct members or inter-member eruptive/flow units whose surfaces have undergone prolonged exposure to the atmosphere (no features of true palaeosols such as rootlets or bioturbation were identified). Within members, deposition is assumed to be sustained with lithological differences reflecting variations in mass-flux and temperature during progressive aggradation of the ignimbrite (Branney and Kokelaar 2002). Within certain members, cooling joints are used to identify distinct cooling units. The terminology used to describe the different lithofacies mapped here is given in Table 2 and follows the lithofacies code approach of Branney and Kokelaar (2002).

The Muileann Gaoithe Member

This is the lowest exposed unit within the caldera (Fig. 4), and is the only volcanic unit exposed outside the caldera. A stratigraphic log up the extra-caldera Muileann Gaoithe section is shown in Fig. 5a. It largely comprises a white-weathering flow-banded rhyolite tuff (77-79 wt.% SiO_2, Table 3) with some layers of massive lapilli tuff (mLT) and thinly bedded red tuff (sT). In places near the base the flow banding displays metre-scale folding (Fig. 5b). Abundant smoky quartz crystals up to 2 mm are characteristic of this unit. The glassy groundmass shows sub-mm (Fig. 5c) to continuous (Fig. 5d) compositionally distinct bands.

We interpret the Muileann Gaoithe Member as a rhyolitic parataxitic to lava-like ignimbrite. The layers of lapilli tuff may represent changes in flow-boundary conditions within the aggrading ignimbrite, which could reflect increased explosivity at the vent. The red tuff is thought to represent ash which capped the underlying eruptive unit and was exposed to the atmosphere before deposition of the overlying unit. This would separate the Muileann Gaoithe section into two eruptive units, each capped by a thin red tuff. At Dereneneach, red tuff is only observed at the top of the unit, suggesting only one eruptive unit is exposed here.

The Allt Ruadh Member

The stratigraphy of the Allt Ruadh Member along the Allt Ruadh section is shown in Fig. 6a. It is dominated by orange- and grey-weathering massive lithic-lapilli tuffs (mLT; Fig. 6b), containing clasts of pre-Palaeogene schist, sandstone, and quartzite, and presumably Palaeogene basalt, dolerite, and occasional granite (Fig. 6c). Thin layers of high-grade crystal tuffs (Fig. 6d) are exposed in the lower part of the Allt Ruadh section. Elsewhere in the complex where exposure is not as good, only the mLT are seen.

We interpret this unit as a series of non-welded ignimbrites representing a prolonged period of highly explosive volcanism, in which a large volume of magma was erupted. The vitrophyric and eutaxitic layers are interpreted as phases of lower explosivity in which the pyroclastic density current retained more heat. The purple glassy tuffs near the top of the section (Fig. 6a) may be basal vitrophyres to the overlying packages of mLT.

Creag Shocach conglomerates

The Creag Shocach conglomerates are a series of sandstones, gritstones, and conglomerates which overlie the Allt Ruadh Member (Fig. 4). They are 'mesobreccias' in the classification of Lipman (1976). The clasts (pebbles and cobbles) comprise pre-Palaeogene country rock lithologies, i.e., red sandstones and quartzite conglomerates. The matrix largely comprises fine- to medium-grained quartz sand. We interpret this unit as representing erosion of Devonian and Permo-Triassic lithologies into the caldera from steep caldera walls left by subsidence related to the eruption of the Allt Ruadh Member.

Creag an Fheidh Member

The Creag an Fheidh Member is only exposed in the east of the complex, and appears to be cut off by the same fault that truncates the intra-caldera outcrop of Glenloig Hybrids (Fig. 2). 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) with some massive lapilli tuffs towards the top of the unit (Fig. 7a, b). Some of the crystal tuffs have a characteristically dark glass groundmass (Fig. 7c). In thin section, the eutaxitic tuffs show flattened wispy features interpreted as fiamme (Fig. 7d). The massive lapilli tuff at the top of the unit contains abundant clasts of rhyolite which resemble the Muileann Gaoithe lava-like tuffs. The upper surface contains rounded pebbles and cobbles of rhyolite and quartzite.

The unit is interpreted as a series of localised heterogeneous ignimbrites that were only deposited in the eastern part of the complex. The increasing lithic lapilli content suggests the eruptions became more explosive with time. The rounded pebbles and cobbles and presence of exotic clasts at the top of the unit suggest fluvial reworking of the upper surface of the ignimbrite in a 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 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. 8). Unlike all other erupted products within the CAIC, it is basaltic-andesitic in composition (54.5 wt.% SiO_2; Table 3). The surrounding exposures are dominated by the conglomerates that make up the upper surface of the Creag an Fheidh ignimbrite. We interpret these exposures as the remnants of a small basaltic phreatomagmatic tuff cone or ring. This interpretation is based on four main features: 1) the deposit is very fine grained, suggesting intense fragmentation, 2) phreatomagmatism can explain explosive mafic activity and the production of fine basaltic-andesitic ash, 3) it is surrounded by other deposits of fluvial facies, and 4) it is very localised, being seen nowhere else in the complex.

White Tuff Member

The White Tuff is a very homogeneous, white-weathering rhyolitic tuff. Most exposures of this tuff appear structureless, although in places a distinct planar fabric can be seen (Fig. 9a). 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. 9b). The White Tuff Member is petrologically and geochemically homogeneous. It is rhyolitic throughout (76-77 wt. % SiO_2; Table 3), containing abundant plagioclase, K-feldspar, and smoky quartz crystals 1-5 mm in size (Fig. 12c,d). The top of the unit comprises a localised conglomerate with rounded clasts of rhyolite, basalt, and quartzite. The White Tuff Member is interpreted as a voluminous rhyolitic lava-like ignimbrite. The conglomerate at its upper surface, which contains exotic clasts as well as cobbles of rhyolitic tuff, suggests fluvial working on the exposed surface of the unit after deposition.

Pigeon Cave Member

The Pigeon Cave Member comprises glassy tuffs, massive lapilli tuffs, and massive lapilli agglomerates (Fig. 10a,b). The agglomerates are characterised by weathering to a turquoise colour, and containing elongate ribbons of lava-like rhyolite (Fig. 10c), interpreted as deformed cognate spatter clasts. Many of the crystal tuffs have a distinct black glassy groundmass (Fig. 10d). Small spatter clasts can be recognised in thin section as wispy glassy features (Fig. 10e). The Pigeon Cave Member is interpreted as a series of heterogenous ignimbrites, with the massive lapilli tuffs recording highly explosive eruptions, and the agglomerates recording slightly less explosive spatter eruptions.

The outcrop of 'Cretaceous chalk' at Pigeon Cave on Binnein na h-Uaimh (discussed by Tyrell, 1928) is overlain by the Pigeon Cave Member and 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, as well as in Antrim. It is unclear whether these sedimentary units are part of the caldera floor, subsided megablocks, or have a Palaeogene intra-caldera origin.

Binnein na h-Uaimh conglomerates

The Binnein na h-Uaimh conglomerates comprise a number of exposures of very coarse clast-supported conglomerates (Fig. 4). The contact with the underlying Pigeon Cave Member can be traced for tens of metres down the northern side of Binnein na h-Uaimh, suggesting that flow was towards the north. In places this contact is steep, and is interpreted as the side of a canyon eroded into the underlying ignimbrites. The larger clasts are predominantly schist, which resembles the Dalradian schists exposed several kilometres to the north, on the other side of the Highland Boundary Fault.

Ard Bheinn Member

The Ard Bheinn Member is the youngest exposed volcanic unit in the Central Arran Igneous Complex (Fig. 4). It makes up the summit of Ard Bheinn, so anything above this level has been lost to erosion. Its lower parts are dominated by clast-poor glassy and crystal-rich tuffs (Fig. 11a) with some lithophysae and planar flow fabric. The upper section is less homogenous, with autobreccia, agglomerates (Fig. 11b), crystal tuffs (Fig. 11c; the '*plagioclase porphyry'* of King, 1955), and eutaxitic lapilli tuffs (Fig. 11d). The lowest exposures of this member comprise stratified, lava-like, coarse crystal tuffs (Fig. 11b) which appear to fill a valley eroded into the underlying units (Fig. 2). This valley can be traced towards the south, away from Ard Bheinn, suggesting that flow here was to the south.

The Ard Bheinn Member is interpreted as a series of high-grade ignimbrites – most being 'lava-like' on the basis of completely agglutinated pyroclasts (Fig. 11c, e). The lower part of the Ard Bheinn section (360 m to 440 m on Fig. 11a) displays consistent columnar jointing, suggesting that this section acted as a single cooling unit. The upper parts of the member were likely formed from a series of small pyroclastic fountaining eruptions of varying explosivity and emplacement temperature.

Bedded Tuffs

Some isolated exposures around the upper parts of Ballymichael Glen comprise ignimbrites that display stratification and flow banding on a variety of scales. These are shown in Fig. 2. 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 cannot determine their position within the stratigraphy of the Arran Volcanic Formation.

Discussion

This work demonstrates that the Central Arran Igneous Complex represents a well-preserved caldera system filled by a pyroclastic succession at least 400 m thick, the Arran Volcanic Formation. A number of sequential mappable units have been recognised, most of which are preserved within a broadly circular area, interpreted as a caldera. We discuss the collapse of the caldera and the nature of proximal ignimbrites before presenting an eruption history.

Collapse (and resurgence?) of the caldera

Given that the Arran Volcanic Formation comprises Palaeogene surface-deposited rocks juxtaposed against Devonian and Permo-Triassic rocks, it must occupy a caldera which has experienced at least some degree of downfaulting and must therefore possess at least one ring fault. Although this fault is not exposed, the complex meets the other criteria of Brown *et al*., (2009) for recognising a caldera in the British Palaeogene Igneous Province: (1) a collapse succession of breccias; and (2) evidence of subsidence (i.e., displacement relative to country rocks).

A transect from the western edge of the caldera to the summit of Binnein na h-Uaimh is relatively well exposed, and no significant breaks or duplications in stratigraphy are seen. This suggests that there is only one ring fault, i.e.*,* at the contact between the Arran Volcanic Formation and the pre-Palaeogene sedimentary country rocks. Experimental studies and their comparison to real examples suggest that a caldera that displays one outward-dipping reverse ring fault is likely to have experienced subsidence in the range of 100 m to 1 km (Acocella, 2007).

One fault is identifiable *within* the caldera (Fig. 2), but there are doubtless others. The change in stratigraphy across this fault suggests the sense of movement was ‘down to the east', but there is no way to determine the magnitude of displacement. This fault is radial to the caldera.

Given the presence of at least one radial fault, an element of piecemeal subsidence can be assumed (Moore and Kokelaar, 1998; Troll et al., 2002). However, there are no other places where the stratigraphy is noticeably disrupted at the scale of the available exposure, so this was clearly not a dominant collapse mechanism. There may also be an element of trapdoor subsidence (Lipman, 1997), as massive lapilli tuffs of the Allt Ruadh Member are exposed in the east of the complex at the same elevation as the summit of Ard Bheinn. This could suggest greater subsidence of the caldera to the west, but could also be explained by lateral changes in deposit thicknesses (Brown and Branney, 2013) or amount of erosion. There is no evidence of consistently inward-dipping beds, or significant evidence of slumping, so funnel-like subsidence has not occurred (e.g. Miyakejima, Japan – Geshi et al., 2012). Given the broadly horizontal nature of the caldera-fill units and the lack of significant intra-caldera faulting, the closest-approximated end-member subsidence style (by the classification of Lipman, 1997; Acocella, 2007) is piston subsidence, in which a coherent caldera floor is bounded by one or more steeply-dipping ring faults. It is uncertain whether the Arran caldera ring fault is a simple outward-dipping reverse fault (Stage 2, Acocella, 2007) or an inward dipping normal fault with volcanic deposits masking the internal earlier ring fault (Stage 4, Acocella, 2007). However, the relatively simple stratigraphy and lack of disruption likely indicate an outward-dipping reverse fault, supporting rare field and seismic evidence from calderas such as Rabaul, Papua New Guinea (Mori and McKee, 1987; Saunders, 2001).

The upper two units described here – i.e*.,* the Binnein na h-Uaimh conglomerates and the Ard Bheinn Member – show some evidence of flow-directions towards the edges of the caldera. This suggests that at this stage in the caldera's history, there was a palaeotopographic high roughly in the location of the current Ard Bheinn summit. We tentatively suggest that this could be evidence for resurgent doming in the period following the main Allt Ruadh-related collapse event. Following Troll et al. (2002), doming may also explain the presence of the radial fault described above, and the northerly transport of Dalradian clasts within the caldera. Uplift associated with caldera resurgence has been linked to shallow magmatic intrusion of sills/dykes and laccoliths. This process has been identified through magnetotelluric imaging on the island of Ischia (Bay of Naples, Italy), where some 800 m of uplift, accompanied by volcanic activity, has occurred (Di Giuseppe et al., 2017).

The nature of proximal ignimbrites

The majority of ignimbrites in the Arran Volcanic Formation are high grade (lava-like to welded) with rarer low grade, non-welded examples. These ignimbrites are indicative of high temperature, high mass-flux pyroclastic density currents generated from low fountaining columns that retained heat (Braney and Kokelaar, 2002). The lava-like ignimbrites typically display pervasive base-parallel flow banding, indicative of syn-depositional rheomorphism (Andrews and Branney, 2011). There are relatively few examples of post-depositional rheomorphism such as extensive domains of contorted flow banding and refolded folds (Andrews and Branney, 2011), and a general absence of autobreccia. Together, this indicates there was little slumping, sliding, and ultimately brittle deformation of the cool(ing) ignimbrites (e.g. Moore and Kokelaar, 1998; Andrews and Branney, 2011).

Perhaps most noticeable is the general lack of lithic-rich lapilli- and block-layers in the ignimbrites. These types of breccias/lapilli-tuffs are commonly found in intra-caldera proximal ignimbrites and are typically linked to climactic subsidence events and associated caldera wall/floor destabilisation. Modern examples of such units include Ischia (75 ka, Brown et al., 2008) and Pantelleria (46 ka, Jordan et al., 2018) in Italy, and

Tenerife in Spain (273 ka, Smith and Kokelaar, 2013). The absence of these units on Arran indicates that whilst subsidence clearly occurred, it was not always catastrophic and that explosive caldera-forming eruptions can occur without such 'tracers' of caldera collapse.

Overall, the general absence of slumping/sliding ignimbrites and the paucity of collapse-related lithic breccias, support a gradual piston-like collapse of the caldera, with only minimal disruption by faulting and/or later resurgence. In many respects, the Arran caldera is remarkable for its incremental but consistent collapse and the relative stability of the caldera floor.

Eruptive History

We now present an overall model for the eruptive history and caldera evolution of the Central Arran Igneous Complex which is consistent with the observations described in this paper (Fig. 12).

1- The lava-like ignimbrites of the Muileann Gaoithe Member are preserved *in situ* and as clasts within the later ignimbrite units. As the base 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.

2- A period of highly explosive eruptions formed the Allt Ruadh Member (Fig. 12a). This blanket of mLT covers the entire area of the caldera (Fig. 2).

3- This evacuation of magma caused underpressure in the underlying magma chamber and caused the caldera to collapse. Collapse at this stage was piston-like, with a coherent caldera floor moving along a single ring fault, although an element of trapdoor subsidence with thickening to the west *may* have occurred (see Acocella, 2007). The steep caldera walls left by the outward-dipping reverse ring fault collapsed, forming the

Creag Shocach conglomerates (Fig. 12a).

4- The Creag an Fheidh Member was erupted in the eastern part of the caldera (Fig. 2) and ponded against a radial fault (Fig. 12b). The presence of this fault could be due to some degree of resurgent doming (Troll *et al.,* 2002).

5- The upper part of the Creag an Fheidh Member was fluvially reworked in a period of volcanic quiescence. A small pulse of mafic magmatism interacted with this surface water and/or groundwater, and the resulting phreatomagmatic eruption built the Allt Beith tuff cone (Fig. 12b).

6- The rhyolitic lava-like ignimbrites of the White Tuff Member were erupted (Fig. 12c). These ignimbrites are lithologically and petrographically almost identical to the Muileann Gaoithe Member ignimbrites, but were erupted after a significant period of non-homogeneous lower-grade volcanism. This stratigraphy, of variable pyroclastic rocks stratigraphically 'sandwiched' between two thick rhyolite units is very similar to that observed at Sabaloka, Sudan (Almond, 1971). This eruption was followed by a period of volcanic quiescence in which the upper surface was reworked.

7- The Pigeon Cave Member was erupted (Fig. 12c), and intruded by a dolerite sill (Figs 4, 10a). The nature of the pre-Palaeogene sedimentary rocks (Cretaceous chalk and possibly Cretaceous sandstone) is unclear as contacts are not exposed, but work on Rùm suggests that supposed intra-caldera 'megablocks' may in fact be broadly coherent pieces of caldera floor (Holohan *et al*., 2009; see also Lipman, 1976). If this is the case on Arran, these caldera floor segments may have been exposed by subsidence-related faulting and/or resurgent doming (see below).

8- The intrusion of a dolerite sill, or overpressure from the underlying magma chamber, or both, caused resurgent doming to form a palaeo-topographic high (Fig. 12d) in the vicinity of the modern Ard Bheinn summit.

9- Debris flows comprising material from outside the caldera flowed away from this palaeo-high and were deposited as the Binnein na h-Uaimh conglomerates in steep-sided canyons eroded into the upper surface of the Pigeon Cave Member (Fig. 12d).

10- The heterogeneous high-grade ignimbrites of the Ard Bheinn Member were erupted (Fig. 12d). The lowest of these – coarse crystal tuffs – flowed away from the palaeo-high and were deposited in valleys eroded into the underlying members (Fig. 2).

11- An unknown thickness of the Ard Bheinn Member and any overlying units were lost to erosion.

Conclusions

The Central Arran Igneous Complex is a good example of a well-preserved caldera volcano, as previously established by King (1955), and provides an excellent opportunity to investigate an intra-caldera sequence. Its caldera-fill succession, the Arran Volcanic Formation, was eroded to a relatively shallow level, and generally escaped modification by later intrusions/volcanism 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 interpret the caldera-fill rocks in terms of a stratigraphic sequence of successive eruptive units, which had not previously been attempted. This stratigraphy allows us to propose a chronological model for the formation of the complex and infer the processes which occur as small predominantly silicic calderas collapse. 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, found beyond the caldera. The general absence of extra-caldera ignimbrites elsewhere on Arran is presumably due to erosion.

The ignimbrites of the Arran Volcanic Formation are dominated by high grade lava-like and welded ignimbrites. The Allt Ruadh Member is the only surviving product of a highly explosive phase of eruptions and period of caldera collapse. The other members typically record rapid deposition from high temperature (>900˚C), high-mass-flux pyroclastic density currents generated from low-fountaining columns that do not entrain much atmospheric air, and therefore retain large amounts of heat (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 pyroclastic density currents 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) high-grade ignimbrite units occurred during pauses in deposition (e.g. Moore and Kokelaar, 1998). 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 (e.g. Smith and Kokelaar, 2013). Together, these data suggest that although deposition occurred rapidly, caldera subsidence was relatively incremental and piston-like, and that eruption of high grade ignimbrites can occur without catastrophic collapse (see also Lavallée et al., 2006). In eruption hiatuses, however, subsidence continued and exotic material was introduced from outside the caldera by sedimentary processes. Possible resurgent doming events contributed to these processes and influenced deposition of later pyroclastic density currents.

The Arran Volcanic Formation shows that a relatively small caldera can be active through a large number of eruptive periods, separated by significant time gaps, yet can escape large-scale intra-caldera faulting and formation of nested caldera structures, while accommodating significant, but not catastrophic, collapse. We argue that further detailed field investigation of similar calderas (including previously mapped examples), using modern physical volcanology methods and terminology, is essential to elucidate observations from active calderas and modelling experiments.

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Fig. 1 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. Inset shows the onshore locations of magmatic rocks that make up the British Palaeogene Igneous Province in western Scotland and Northern Ireland. 1 – Skye, 2 – Rùm and Eigg, 3 – Ardnamurchan, 4 – Mull, 5 – Arran, 6 – Antrim, 7 – The Mourne Mountains, 8 – Slieve Gullion and Carlingford.

Fig. 2 Geological map of the western half of the Central Arran Igneous Complex. Approximate locations of stratigraphic logs presented in this paper are shown in red. 1 – Ard Bheinn Member, 2 – Creag an Fheidh Member, 3 – White Tuff Member, 4 – Pigeon Cave Member, 5 – Ard Bheinn Member. The grid shows the 1 km eastings and northings of the British National Grid. Inset shows the location of the Central Arran Igneous Complex (CAIC) on Arran in relation to the North Arran Granite (NAG).

Fig. 3 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 Arran Volcanic Formation. The uncoloured parts show areas underlain by the pre-caldera country rock. The summits of Ard Bheinn and Binnein na h-Uaimh are 670 m apart.

Fig. 4 Generalised stratigraphic log of the Arran Volcanic Formation, showing the relationships between the pyroclastic and sedimentary units and major hiatus events. Vertical thicknesses are not to scale. Map symbols are consistent with those in Fig 3.

Fig. 5 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 top of the Muileann Gaoithe Member. Viewed in plane-polarised light. Q – quartz, F – feldspar. The micro-scale flow fabric is defined by texturally/compositionally distinct (different colours) sub-mm and near-continuous bands and prolate rods. d) Photomicrograph of the rhyolitic lava-like ignimbrite from the base of the Muileann Gaoithe Member. Viewed in plane-polarised light. Q – quartz, F – feldspar. The flow fabric is defined by continuous bands.

Fig. 6 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 showing clasts of schist (left), dolerite (right), and altered rhyolite (bottom). Viewed in plane-polarised light. d) Photomicrograph of a glassy eutaxitic- to lava-like tuff containing crystals of quartz (Q), K-feldspar (F), and Fe-Ti oxides (ox). Viewed in plane-polarised light.

Fig. 7 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 massive lapilli tuff from the upper part of the member. Viewed in plane-polarised light. d) Photomicrograph of a eutaxitic tuff from the lower part of the unit, showing flattened clasts (fc) as well as quartz (Q), K-feldspar (F), and Fe-Ti oxide (ox) crystals. Viewed in plane-polarised light.

Fig. 8 Finely laminated and cross laminated basaltic-andesitic tuff that makes up the Allt Beith tuff cone. Hammer for scale is 400 mm long.

Fig. 9 a) Stratigraphic log of the White Tuff Member up the western slopes of Ard Bheinn. b) The thinly banded unit shown at around 415 m 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 massive lava-like ignimbrite from the base of the member, showing the euhedral quartz crystals (Q) that are so characteristic of this ignimbrite, as well as K-feldspar (F) and Fe-Ti oxides (ox). Viewed in plane-polarised light. d) Photomicrograph of banded lava-like ignimbrite from the middle of the member, showing the flow fabric deformed around a large K-feldspar crystal (F). Viewed in plane-polarised light.

Fig. 10 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. It contains elongate streaks and bands of rhyolitic material (rh). d) Photomicrograph of a crystal-rich lapilli tuff with a dark glassy groundmass, lithic lapilli (L), and quartz crystals (Q). Viewed in plane-polarised light. e) Photomicrograph of a crystal-rich agglomerate. The sickle-shaped wispy features are interpreted as small glassy cognate spatter clasts (sc). Viewed in plane-polarised light.

Fig. 11 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 (L) and elongate bands of rhyolite (rh). c) Photomicrograph of the feldspar (F) rich mTcr (‘plagioclase porphyry’ of King, 1955) from the summit of Ard Bheinn. Viewed between crossed polars. d) Eutaxitic massive lapilli tuff at 490 m elevation on the Ard Bheinn log, containing stretched out mafic clasts (mc). Pencil for scale is 150 mm long. e) Photomicrograph of the coarse crystal-rich tuff at the base of the Ard Bheinn Member, showing large quartz (Q) crystals and smaller K-feldspar crystals (F). Viewed in plane-polarised light.

Fig. 12 A series of generalised cross sections through the Arran Volcanic Formation showing the history of eruption and caldera collapse. Lithologies other than the caldera-fill succession have been omitted for clarity.

Table 1 Descriptions and interpretations for the volcanic and sedimentary units that make up the Arran Volcanic Formation.

Table 2 Explanation of ignimbrite lithofacies codes used in this paper, following the terminology of Branney and Kokelaar (2002).

Table 3 Anhydrous whole-rock geochemical data for various ignimbrite samples.

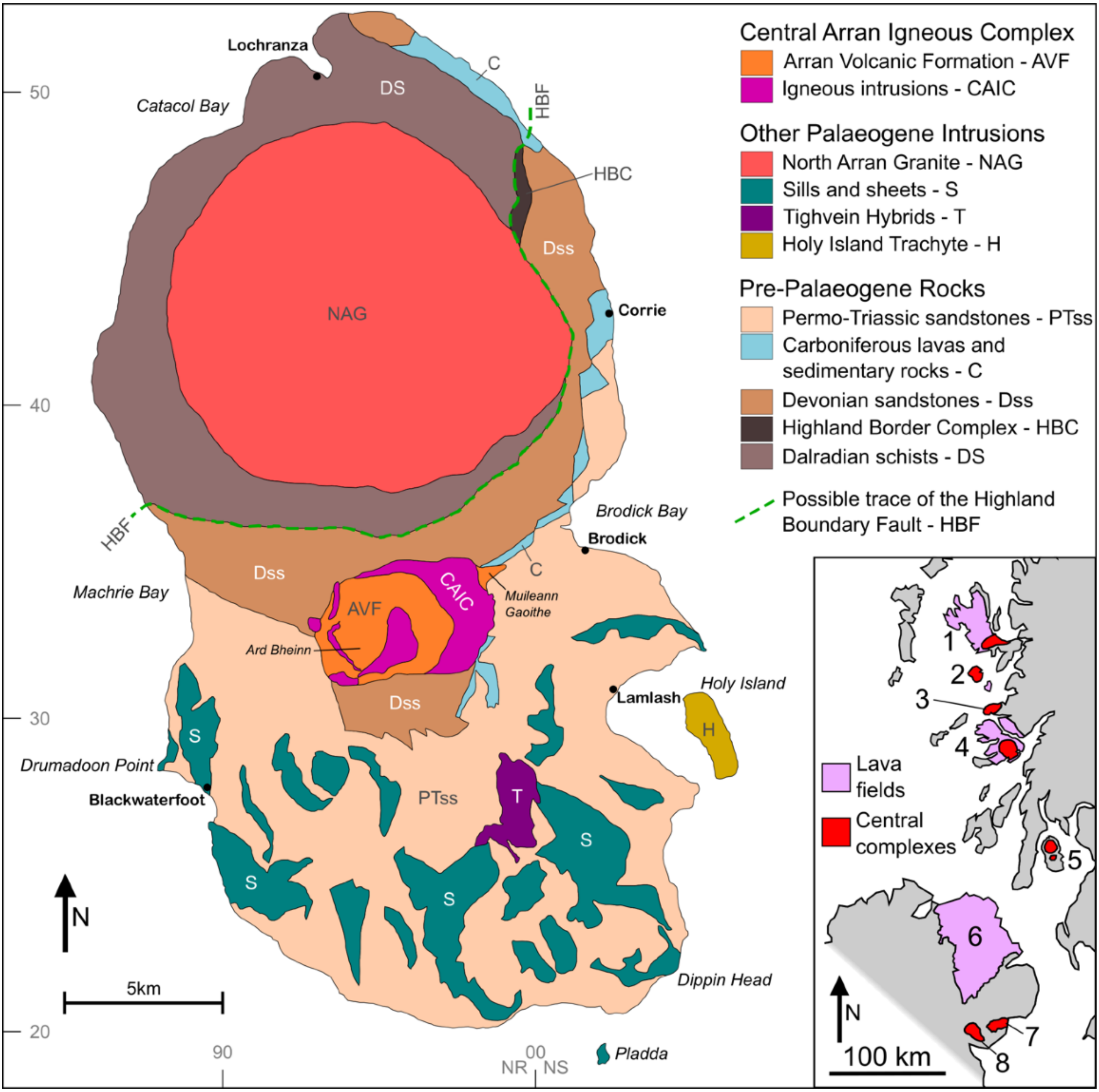
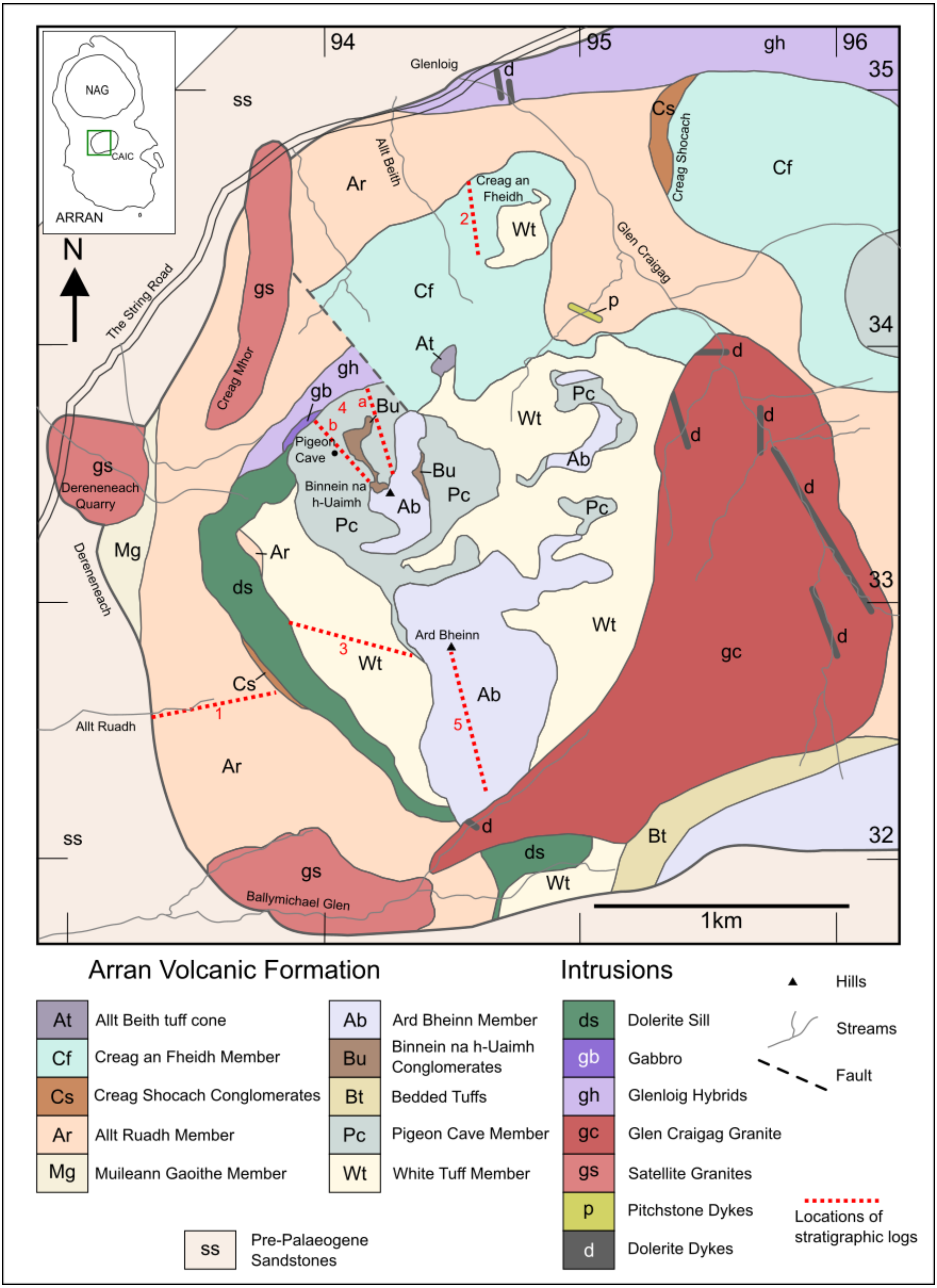

Central Arran Igneous Complex
Arran Volcanic Formation - AVF
Igneous intrusions - CAIC
Other Palaeogene Intrusions
North Arran Granite - NAG
Sills and sheets - S
Tighvein Hybrids - T
Holy Island Trachyte - H
Pre-Palaeogene Rocks
Permo-Triassic sandstones - PTss
Carboniferous lavas and sedimentary rocks - C
Devonian sandstones - Dss
Highland Border Complex - HBC
Dalradian schists - DS
Possible trace of the Highland Boundary Fault - HBF
Lochranza
Catacol Bay
DS
C
HBF
HBC
Dss
NAG
Corrie
Brodick Bay
Brodick
HBF
Machrie Bay
Dss
CAIC
AVF
C
Muileann Gaoithe
Ard Bheinn
Dss
Lamlash
Holy Island
H
Drumadoon Point
Blackwaterfoot
S
PTss
T
S
S
S
N
5km
Dippin Head
Pladda
50
40
30
20
90
00
NR
NS
Lava fields
Central complexes
1
2
3
4
5
6
7
8
N
100 km

Figure 1



NAG
CAIC
ARRAN
N
94
95
96
35
34
33
32
Glenloig
ss
gh
d
Cs
Creag Shocach
Cf
Allt Beith
Ar
Creag an Fheidh
2
Wt
Glen Craigag
gs
The String Road
p
At
Creag Mhor
gh
gb
4
a
b
Bu
Pigeon Cave
Binnein na h-Uaimh
Ab
Pc
gs
Dereneneach Quarry
Mg
Dereneneach
ds
Ard Bheinn
3
5
gc
Allt Ruadh
1
Bt
Ballymichael Glen
1km
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 Bedded Tuffs
Pc Pigeon Cave Member
Wt White Tuff Member
ss Pre-Palaeogene Sandstones
Intrusions
ds Dolerite Sill
gb Gabbro
gh Glenloig Hybrids
gc Glen Craigag Granite
gs Satellite Granites
p Pitchstone Dykes
d Dolerite Dykes
Hills
Streams
Fault
Locations of stratigraphic logs

Figure 2

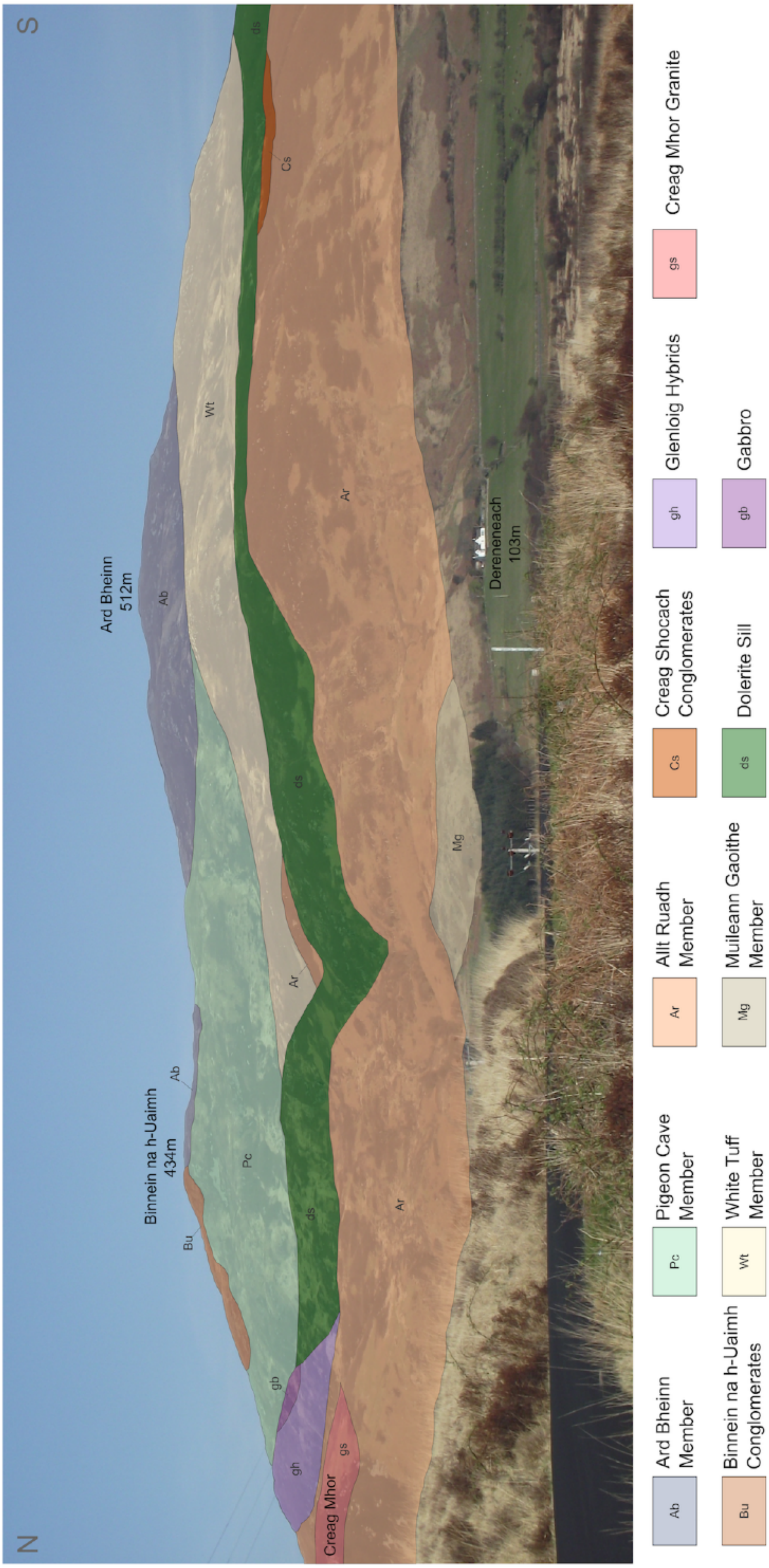

N
S
Ard Bheinn
512m
Binnein na h-Uaimh
434m
Dereneneach
103m
Creag Mhor
Ab
Bu
Pc
gb
gh
gs
ds
Ar
Mg
Wt
Cs
Ab Ard Bheinn Member
Bu Binnein na h-Uaimh Conglomerates
Pc Pigeon Cave Member
Wt White Tuff Member
Ar Allt Ruadh Member
Mg Muileann Gaoithe Member
Cs Creag Shocach Conglomerates
ds Dolerite Sill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

Figure 3

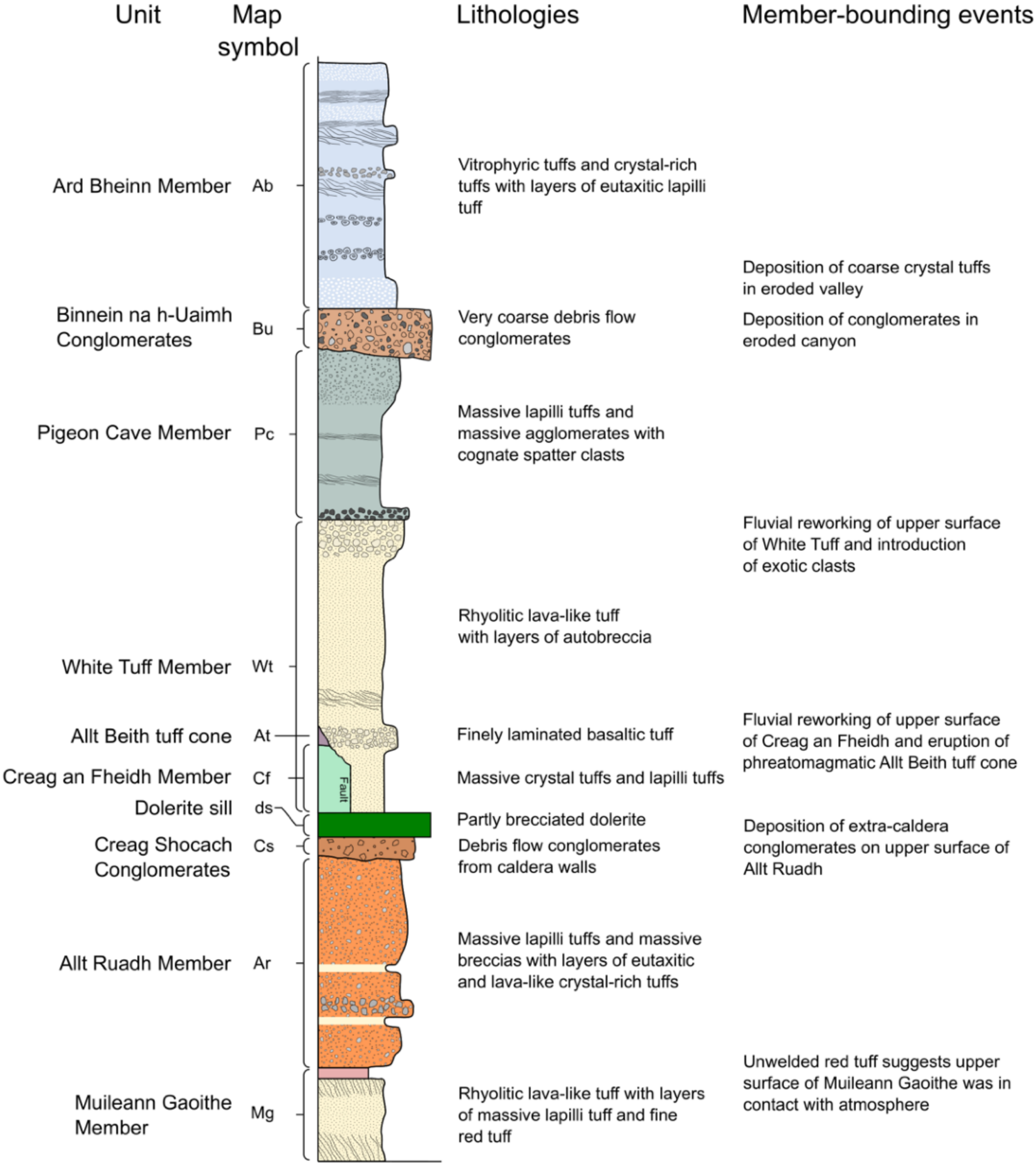

Unit
Map symbol
Lithologies
Member-bounding events
Ard Bheinn Member
Ab
Vitrophyric tuffs and crystal-rich tuffs with layers of eutaxitic lapilli tuff
Deposition of coarse crystal tuffs in eroded valley
Binnein na h-Uaimh Conglomerates
Bu
Very coarse debris flow conglomerates
Deposition of conglomerates in eroded canyon
Pigeon Cave Member
Pc
Massive lapilli tuffs and massive agglomerates with cognate spatter clasts
Fluvial reworking of upper surface of White Tuff and introduction of exotic clasts
White Tuff Member
Wt
Rhyolitic lava-like tuff with layers of autobreccia
Allt Beith tuff cone
At
Finely laminated basaltic tuff
Fluvial reworking of upper surface of Creag an Fheidh and eruption of phreatomagmatic Allt Beith tuff cone
Creag an Fheidh Member
Cf
Fault
Massive crystal tuffs and lapilli tuffs
Dolerite sill
ds
Partly brecciated dolerite
Creag Shocach Conglomerates
Cs
Debris flow conglomerates from caldera walls
Deposition of extra-caldera conglomerates on upper surface of Allt Ruadh
Allt Ruadh Member
Ar
Massive lapilli tuffs and massive breccias with layers of eutaxitic and lava-like crystal-rich tuffs
Unwelded red tuff suggests upper surface of Muileann Gaoithe was in contact with atmosphere
Muileann Gaoithe Member
Mg
Rhyolitic lava-like tuff with layers of massive lapilli tuff and fine red tuff

Figure 4

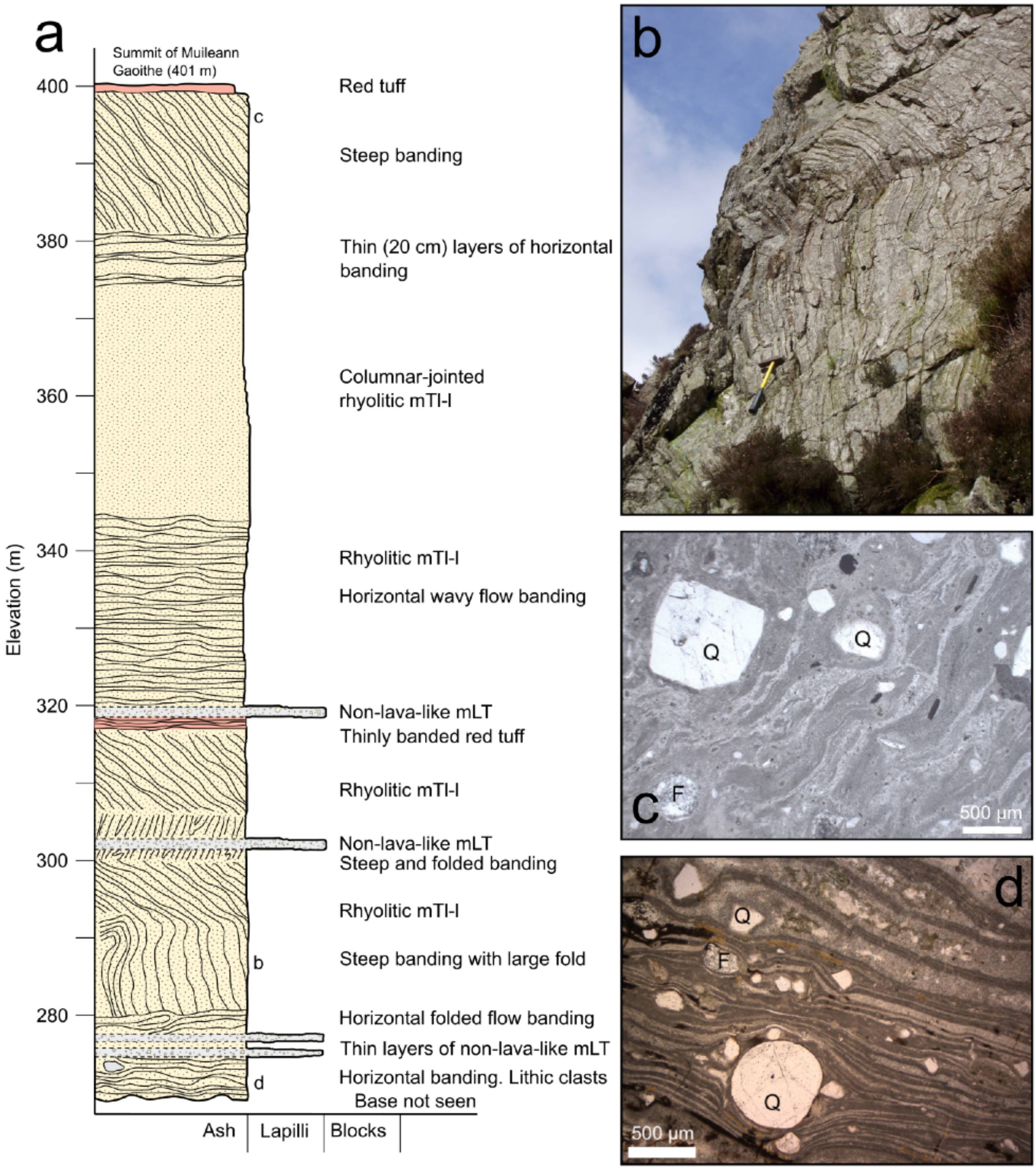
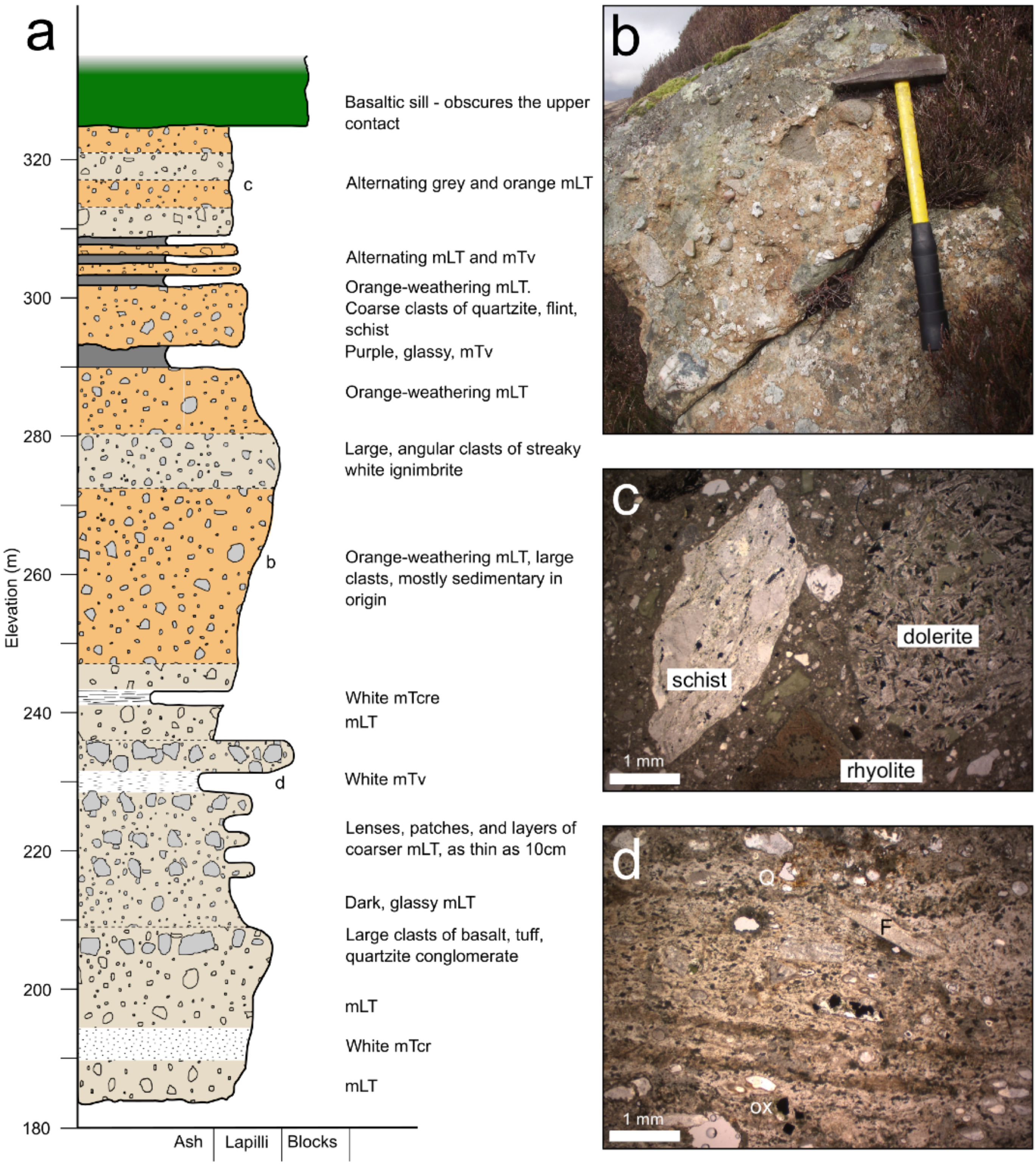

a
Summit of Muileann Gaoithe (401 m)
Elevation (m)
400
380
360
340
320
300
280
Red tuff
Steep banding
Thin (20 cm) layers of horizontal banding
Columnar-jointed rhyolitic mTl-l
Rhyolitic mTl-l
Horizontal wavy flow banding
Non-lava-like mLT
Thinly banded red tuff
Rhyolitic mTl-l
Non-lava-like mLT
Steep and folded banding
Rhyolitic mTl-l
Steep banding with large fold
Horizontal folded flow banding
Thin layers of non-lava-like mLT
Horizontal banding. Lithic clasts
Base not seen
Ash
Lapilli
Blocks
c
b
d
Q
Q
F
500 µm
Q
F
Q
500 µm

Figure 5



a
Elevation (m)
320
300
280
260
240
220
200
180
Ash
Lapilli
Blocks
c
b
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, tuff, quartzite conglomerate
mLT
White mTcr
mLT
b
c
schist
dolerite
rhyolite
1 mm
d
Q
F
ox
1 mm

Figure 6

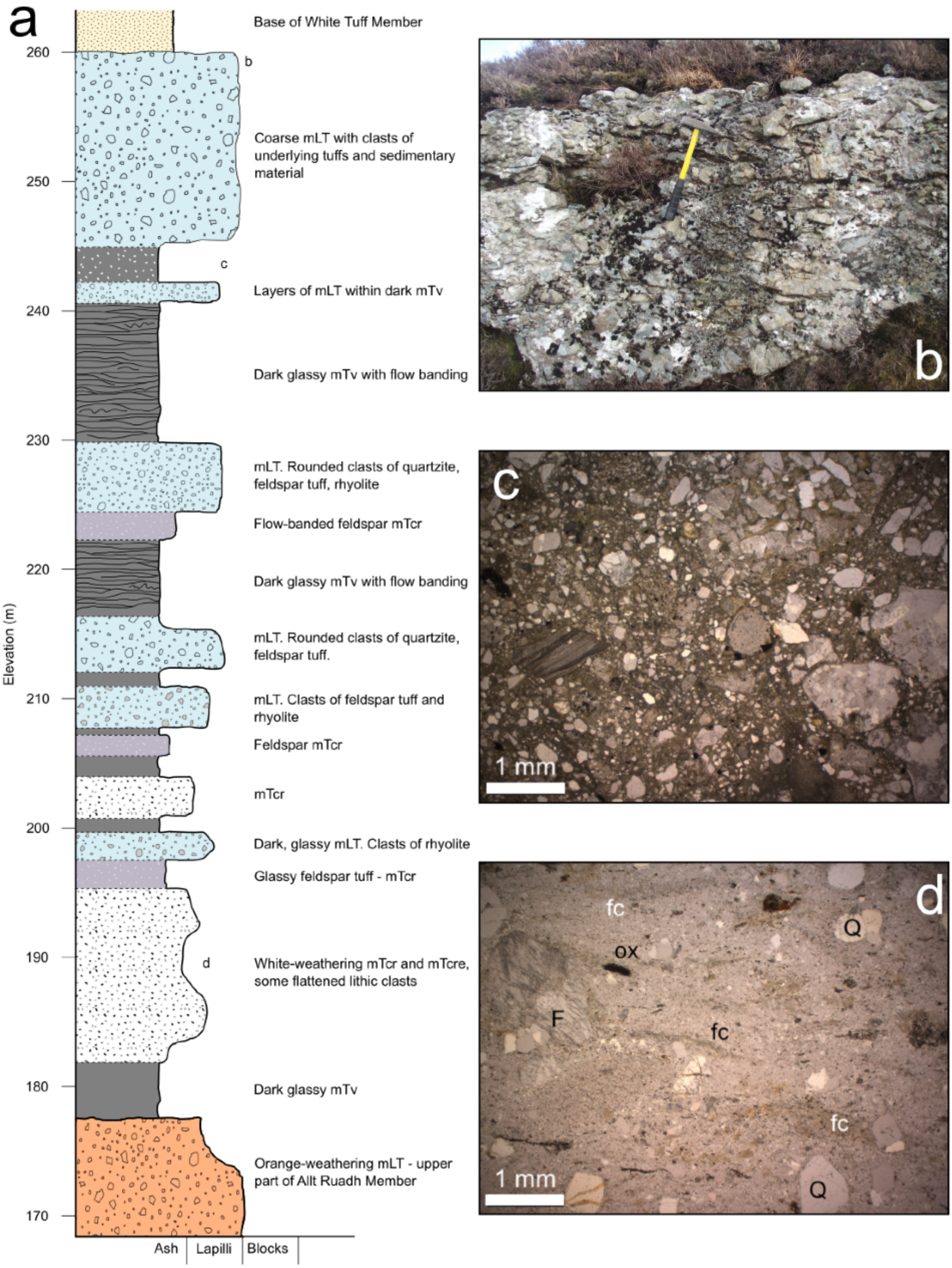

a
Base of White Tuff Member
260
b
Coarse mLT with clasts of underlying tuffs and sedimentary material
250
c
Layers of mLT within dark mTv
240
Dark glassy mTv with flow banding
230
mLT. Rounded clasts of quartzite, feldspar tuff, rhyolite
Flow-banded feldspar mTcr
220
Dark glassy mTv with flow banding
Elevation (m)
mLT. Rounded clasts of quartzite, feldspar tuff.
210
mLT. Clasts of feldspar tuff and rhyolite
Feldspar mTcr
mTcr
200
Dark, glassy mLT. Clasts of rhyolite
Glassy feldspar tuff - mTcr
190
d
White-weathering mTcr and mTcre, some flattened lithic clasts
180
Dark glassy mTv
Orange-weathering mLT - upper part of Allt Ruadh Member
170
Ash
Lapilli
Blocks
b
c
1 mm
d
fc
Q
ox
F
fc
fc
1 mm
Q

Figure 7

Figure 8

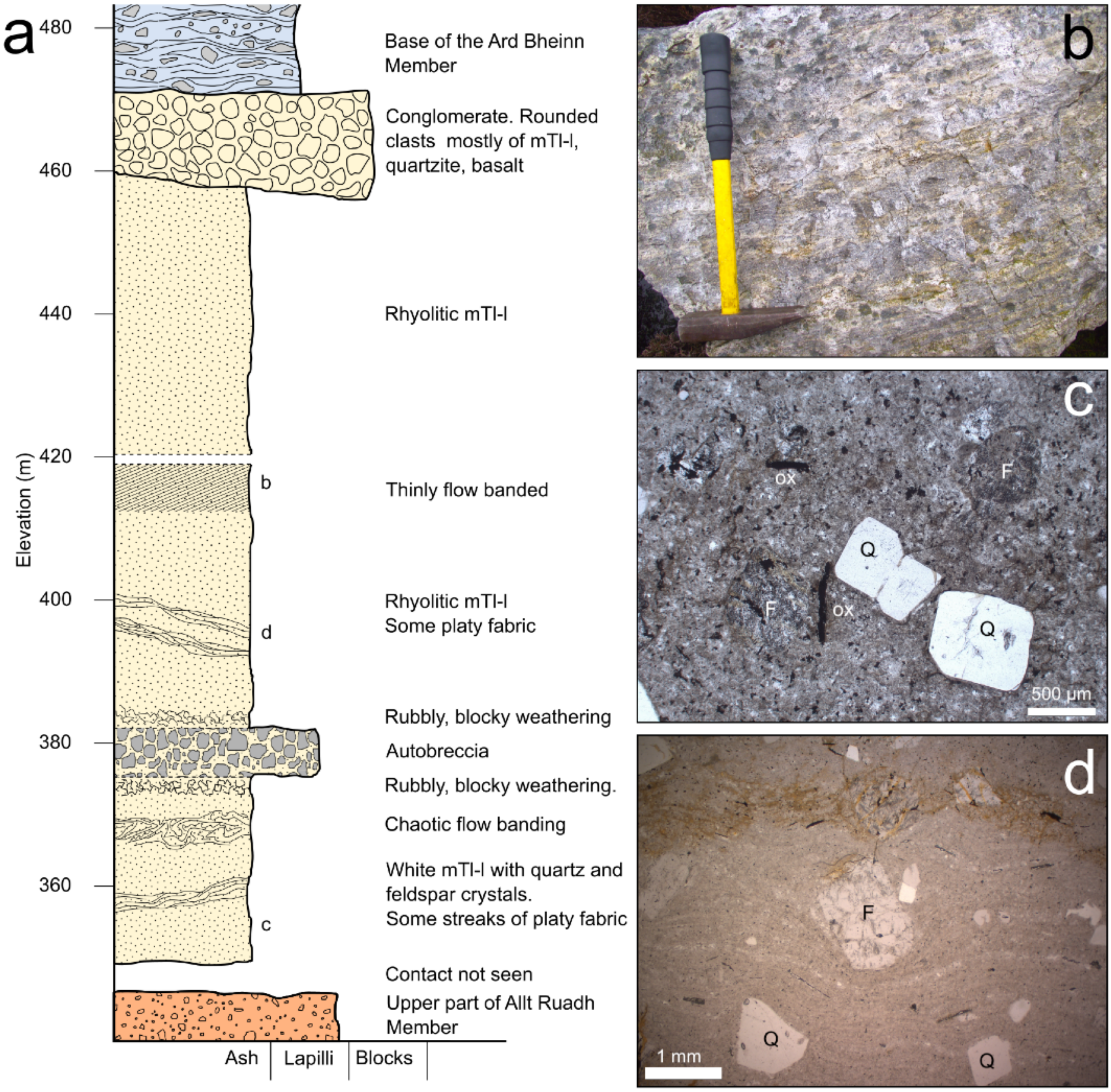

a
480
460
440
420
400
380
360
Elevation (m)
b
d
c
Base of the Ard Bheinn Member
Conglomerate. Rounded clasts mostly of mTl-l, quartzite, basalt
Rhyolitic mTl-l
Thinly flow banded
Rhyolitic mTl-l
Some platy fabric
Rubbly, blocky weathering
Autobreccia
Rubbly, blocky weathering.
Chaotic flow banding
White 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
ox
F
Q
F
ox
Q
500 µm
d
F
Q
1 mm
Q

Figure 9

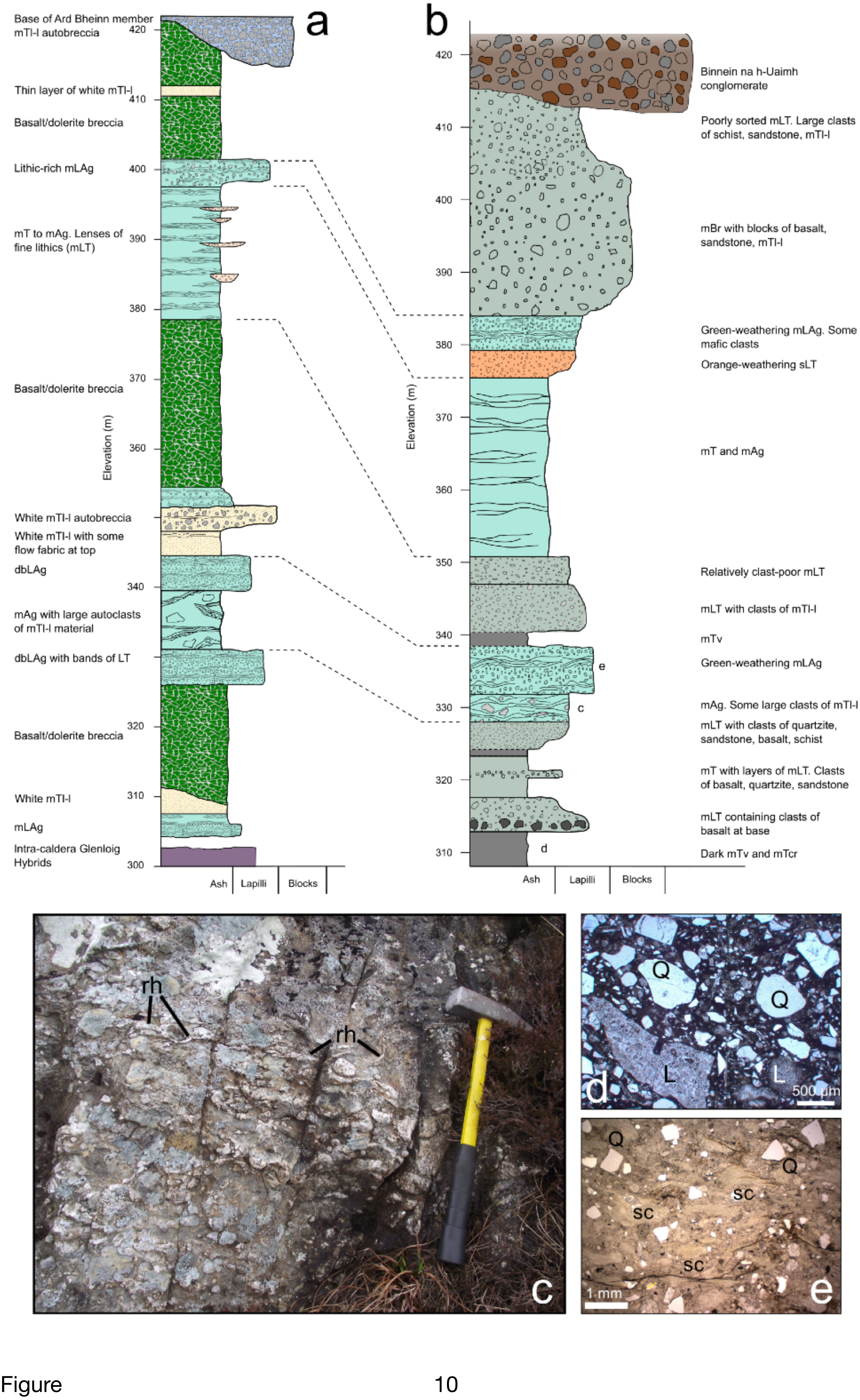

a
b
Base of Ard Bheinn member
mTl-l autobreccia
Thin layer of white mTl-l
Basalt/dolerite breccia
Lithic-rich mLAg
mT to mAg. Lenses of fine lithics (mLT)
Basalt/dolerite breccia
White mTl-l autobreccia
White mTl-l with some flow fabric at top
dbLAg
mAg with large autoclasts of mTl-l material
dbLAg with bands of LT
Basalt/dolerite breccia
White mTl-l
mLAg
Intra-caldera Glenloig Hybrids
Elevation (m)
Ash
Lapilli
Blocks
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 and mTcr
rh
c
Q
L
500 μm
d
sc
1 mm
e

Figure 10

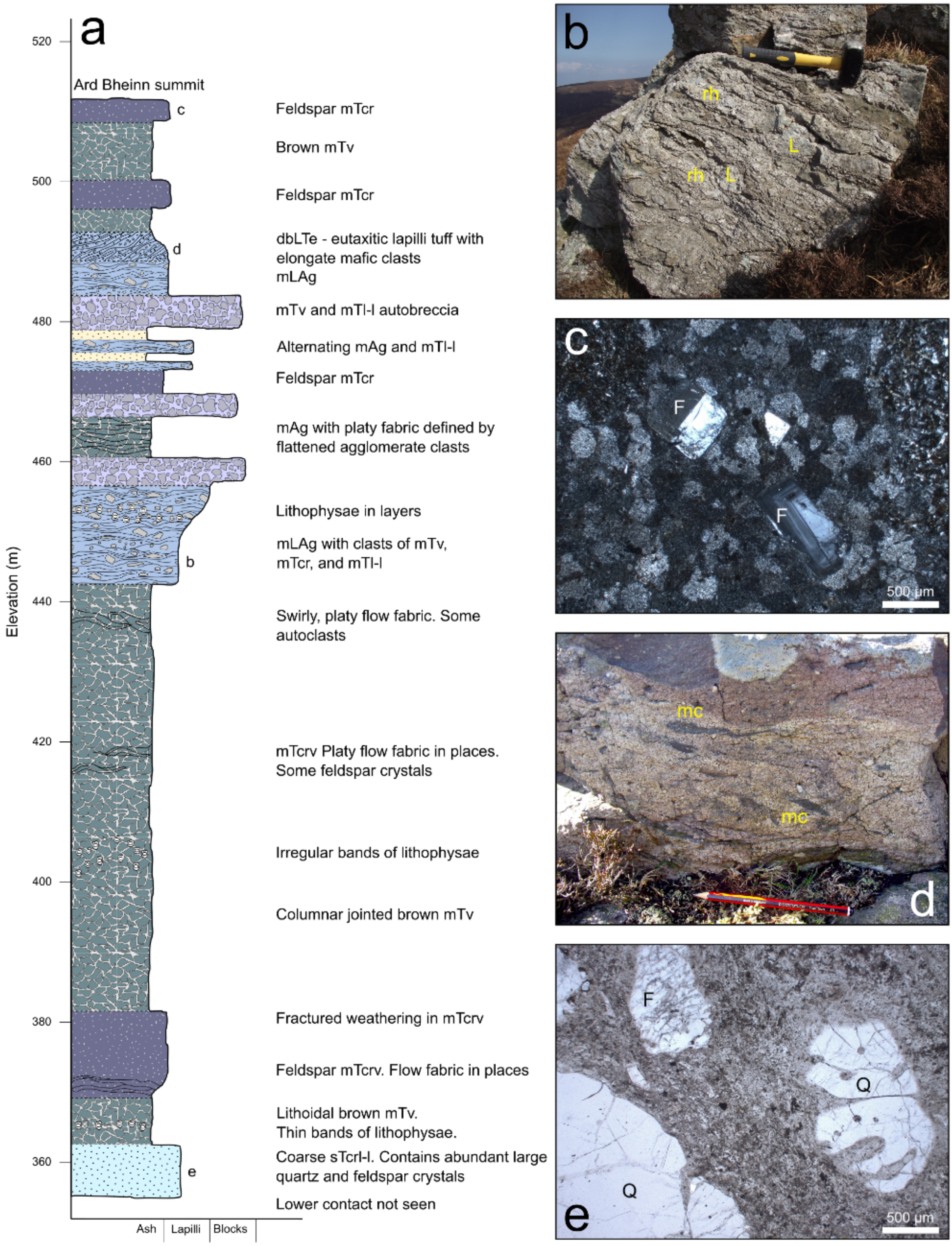
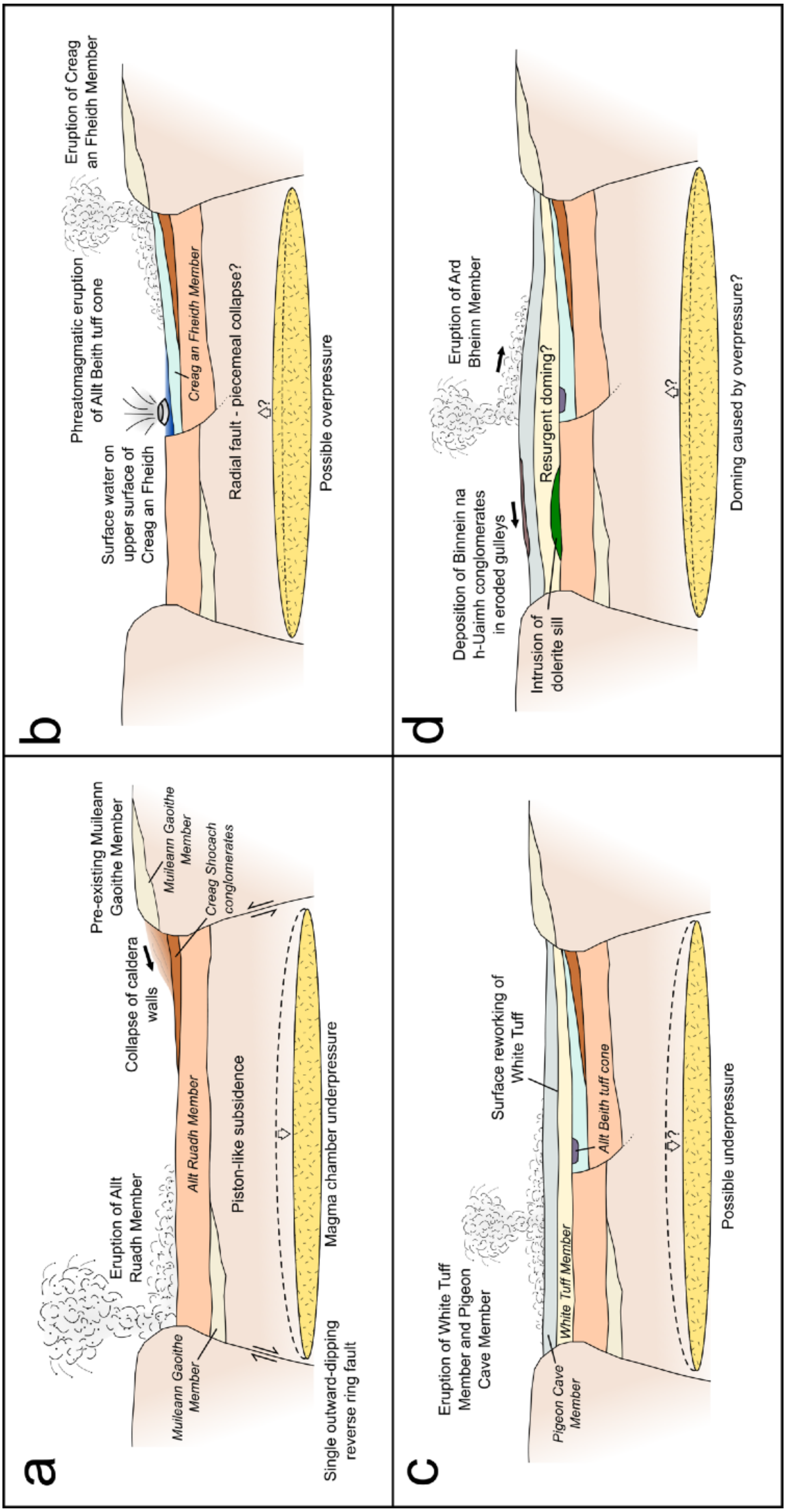

a
Elevation (m)
520
500
480
460
440
420
400
380
360
Ard Bheinn summit
c
d
b
e
Feldspar mTcr
Brown mTv
Feldspar mTcr
dbLTe - eutaxitic lapilli tuff with elongate mafic clasts
mLAg
mTv and mTl-l autobreccia
Alternating mAg and mTl-l
Feldspar mTcr
mAg with platy fabric defined by flattened agglomerate clasts
Lithophysae in layers
mLAg with clasts of mTv, mTcr, and mTl-l
Swirly, platy flow fabric. Some autoclasts
mTcrv Platy flow fabric in places. Some feldspar crystals
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
rh
L
rh
L
c
F
F
500 µm
mc
mc
d
F
Q
Q
e
500 µm

Figure 11



a
Eruption of Allt Ruadh Member
Collapse of caldera walls
Pre-existing Muileann Gaoithe Member
Muileann Gaoithe Member
Allt Ruadh Member
Creag Shocach conglomerates
Piston-like subsidence
Magma chamber underpressure
Single outward-dipping reverse ring fault
b
Surface water on upper surface of Creag an Fheidh
Phreatomagmatic eruption of Allt Beith tuff cone
Eruption of Creag an Fheidh Member
Creag an Fheidh Member
Radial fault - piecemeal collapse?
Possible overpressure
c
Eruption of White Tuff Member and Pigeon Cave Member
Surface reworking of White Tuff
Pigeon Cave Member
White Tuff Member
Allt Beith tuff cone
Possible underpressure
d
Deposition of Binnein na h-Uaimh conglomerates in eroded gulleys
Eruption of Ard Bheinn Member
Intrusion of dolerite sill
Resurgent doming?
Doming caused by overpressure?

Figure 12