RESEARCH ARTICLE

VOLCANICA

Submitted: 2023-07-14 | Accepted: 2024-07-03 | Published: 2024-09-04

Rapid caldera subsidence and fluctuating eruption dynamics: the lithostratigraphy and structure of the Loch Bà Caldera, Isle of Mull, NW Scotland

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Abstract

Caldera-forming eruptions represent extremely hazardous events. The Loch Bà Caldera on the Isle of Mull, NW Scotland, preserves an ~120 m thick sequence of Palaeogene silicic pyroclastic rocks and collapse breccias. Here we present the first detailed account of the lithostratigraphy and architecture of the caldera-fill. A silicic explosive eruption generated pyroclastic density currents that deposited a range of rhyolitic ignimbrite lithofacies as the caldera collapsed. Abrupt changes in ignimbrite lithofacies and lateral thickness changes are attributed to volcano-tectonic faults and incremental collapse of the caldera. Five eruption phases have been recognised that record rapid switching between sustained high-fountaining and low-fountaining "boil-over" eruptions. The ignimbrites are unconformably overlain by mesobreccias and inward rotated megablocks of basalt lava country rock, which record catastrophic inward collapse of the caldera walls and margins. Our results provide new insights into caldera collapse and intra-caldera-fill that can be applied to other volcanoes worldwide.

Keywords: Caldera; Ignimbrite; Breccia; Pyroclastic density current; Mull.

1 Introduction

Direct observations of caldera-forming eruptions are rare and very hazardous. Caldera-forming processes are thus commonly interpreted from the geological record but often remain unclear with many modern calderas covered by younger volcanic rocks, obscuring intra-caldera deposits and processes, and other ancient calderas obscured by large later intrusions and/or country rock [e.g. Lipman 1976; Branney and Kokelaar 1994; Lipman 1997; Moore and Kokelaar 1997; 1998; Kokelaar and Moore 2006; Smith and Kokelaar 2013; Gooday et al. 2018; Jordan et al. 2018; Drake et al. 2022]. The Loch Bà Caldera, on the Isle of Mull, NW Scotland, is well dissected and allows us to observe proximal intra-caldera products and determine caldera subsidence and associated eruption dynamics. The caldera exhibits remarkable heterogeneity in its ignimbrite lithofacies, which record considerable variation in eruption dynamics. Although there are constraints to this study, our findings can be applied to recent and modern caldera volcanoes worldwide to help inform volcano-tectonic and eruption models.

The area around Loch Bà comprises the eroded remains of a Palaeogene caldera. Loch Bà is renowned for its mixed-magma ring-dyke/ring-fault (the 'Loch Bà Ring-Dyke' or 'Loch Bà Felsite') [Richey 1932; Lewis 1968; Sparks 1988], which surrounds a series of poorly understood 'felsites' and 'agglomerates' that have been linked to explosive eruptions and caldera collapse [e.g. Bailey et al. 1924; Richey 1932; Lewis 1968; Bell and Emeleus 1988; Sparks 1988; Emeleus and Bell 2005; Brown et al. 2009]. When the Loch Bà area was first mapped (~1910–1920), our understanding of caldera collapse and associated volcanic and magmatic processes was still in its infancy, with the account of Clough et al. [1909] of the Glencoe 'cauldron' in western Scotland the only comprehensive description and interpretation of a deeply dissected caldera volcano. At Loch Bà, caldera collapse, or 'cauldron subsidence', was recognised based on the presence of the agglomerates, felsites and exposures of basalt lava interior to the ring-dyke/ring-fault, which was in turn surrounded by older basaltic lavas and intrusions [Bailey et al. 1924; Richey 1932; Lewis 1968]. The felsites were variably interpreted as rhyolite lavas and intrusions, and the agglomerates as pyroclastic deposits associated with vent-forming eruptions of magma rising along the ring-fault, and brecciation and subsidence of country rock [Bailey et al. 1924; Richey 1932; Lewis 1968].

Similar Palaeogene rocks in this part of NW and western Scotland have been re-interpreted as volcaniclastic rocks related to caldera-forming and sector collapse processes [e.g. Bell and Emeleus 1988; Troll et al. 2000; Brown and Bell 2006; 2007; Brown et al. 2009; Holohan et al. 2009; Gooday et al. 2018; Drake et al. 2022]. In this study, the first to give a detailed account of the caldera-fill, we interpret the Loch Bà felsites and agglomerates as ignimbrites, deposited during a caldera-forming eruption, and breccias formed due to the collapse of caldera walls. We use a modern lithofacies approach to characterise the ignimbrites and their architecture, and flow-boundary models to explain their sedimentation from pyroclastic density currents [e.g. Branney and Kokelaar 1992; 1997; 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014]. The interaction of the pyroclastic density currents (PDCs) with the substrate and the relationships of the currents/deposits with caldera faults and margins are also considered. We recognise five distinct phases of eruption in the caldera, followed by a catastrophic collapse event, or events, recorded by thick mesobreccias and brecciated megablocks of basalt lava coun-

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Editor: A. R. L. Kushnir | Typesetter: J. Farquharson

try rock. Locally, rhyodacite domes cut the ignimbrites and may represent a phase of caldera resurgence. We develop facies models outlining the evolution of the Loch Bà Caldera and compare its evolution with other calderas.

2 Regional geology and the Loch Bà Caldera

The Loch Bà Caldera forms part of the Mull Central Complex, which itself is part of the British Palaeogene Igneous Province (BPIP), a sector of the North Atlantic Igneous Province (NAIP). The NAIP developed on thinned continental crust in response to the rifting and eventual seafloor spreading that marked the opening of the North Atlantic Ocean [Thompson and Gibson 1991; Saunders et al. 1997]. Rifting has been attributed to the impingement of the putative proto-Iceland plume on the base of the lithosphere [Saunders et al. 1997], possibly assisted, or triggered by an impact event [Drake et al. 2017]. Volcanic and magmatic activity in the BPIP occurred ~61.5–54.5 Ma, with the first igneous material occurring as a basalt clast within a meteoritic ejecta layer, dated at 61.54 ± 0.42 Ma (Ar-Ar, [Drake et al. 2017]). The earliest volcanism was dominated by three subaerial lava fields (Eigg, Skye, and Mull) Figure 1A erupted predominantly from fissure systems, together with localised central vents. The lava fields were intruded by upwelling magma, which developed into 'central complexes', interpreted as the shallow roots of large Palaeogene volcanoes, up to 10 km in diameter [see reviewsby Bell and Williamson 2002; Emeleus and Bell 2005].

The Mull Lava Field comprises three distinct (lithostratigraphic) formations: 1) the basal Staffa Lava Formation [Williamson and Bell 2012]; 2) the Plateau Lava Formation [Bailey et al. 1924; Kerr 1995; Kerr et al. 1999]; and 3) the Central Mull Lava Formation [Bailey et al. 1924]. The lava field is intruded by the Mull Central Complex, with remnants of the Central Mull Lava Formation preserved only as screens between intrusions of the central complex and in associated, more continuous, outcrops interpreted as subsided caldera-fills [Bailey et al. 1924].

The Mull Central Complex is divided into three loci of igneous activity (Centres 1 to 3; Figure 1B) [Bailey et al. 1924; Skelhorn 1969; Bell and Williamson 2002; Emeleus and Bell 2005]. Centre 1, the 'Early Caldera' or 'Glen More Centre', represents the earliest phase of activity and is characterised by gabbroic and granitic intrusions, 'vent agglomerates' (breccias) and 'felsites', and Central Mull Lava Formation basaltic lavas. Many of these rocks are intruded by cone sheets and dykes. Centre 1 is interpreted as a caldera based on the presence of subsided masses of basalt lavas of the younger Central Mull Lava Formation and their association with arcuate exposures of vent agglomerate [Bailey et al. 1924]. Igneous activity migrated towards the NW, forming Centre 2, the 'Beinn Chaisgidle Centre'. This centre contains numerous, steeply dipping, outward inclined, basic and silicic ring-dykes, and younger, inward inclined basaltic cone sheets [Bailey et al. 1924]. Activity continued to migrate to the NW, forming Centre 3, the 'Late Caldera' or 'Loch Bà Centre' (sometimes, and hereafter, referred to as the Loch Bà Caldera). Centre 3 comprises large granitic intrusions and cone sheets, and the rocks associated with the Loch Bà Caldera [Bailey et al. 1924; Sparks 1988].

The Loch Bà Caldera (Figure 1B, Figure 2) is ~8 km across and its margin is marked by a ring-fault and extensive exposures of the Loch Bà Ring Dyke (also known as the Loch Bà Felsite), which was originally dated at 58.48 ± 0.18 Ma (Ar-Ar [Chambers and Pringle 2001]), but this likely underestimates the true age by several hundred thousand years (pers. comm. R. Mahajan, 2023). The Loch Bà Ring Dyke is a steeply outward-dipping mixed magma ring-dyke. It is a 'banded rhyolitic welded tuff' with inclusions of basic and more evolved material and is thought to have been sourced from a compositionally zoned magma chamber [Sparks 1988]. The rhyolite and inclusions display a range of textures from eutaxitic to parataxitic to flow banded. These textures suggest that the magma exploited a growing ring-fracture above the magma chamber, partially fragmented, and most likely fed pyroclastic eruptions at the surface [Sparks 1988]. Subsidence of country rocks overlying the magma chamber (including basalt lavas of the Central Mull Lava Formation) occurred along the ring-fault, at least partially synchronous with the emplacement of the Loch Bà Ring Dyke. Continued subsidence and eruption of magma resulted in a caldera-forming eruption and the development of the caldera-fill described in this study.

3 Methodology, terminology, and constraints

Field mapping and logging were undertaken in the NW sector of the caldera (Figure 2, Figure 3, Figure 4). We divided the caldera-fill into formations, which were in turn sub-divided into members, based on their stratigraphic position and lithofacies architecture. Lateral lithofacies associations were recognised, where possible, by identifying shared lithofacies characteristics (e.g. colour, grain size, structure) and prominent features (e.g. fiamme, accretionary lapilli) across the region, accounting for displacement by inferred faults. Stratigraphic logs were undertaken on appropriate lithologies and are composite due to non-continuous exposure. Due to an absence of abundant reliable 'bedding' horizons, the thicknesses shown on logs are apparent thicknesses. Petrographical analysis of the ignimbrites was undertaken to assist field interpretation.

The caldera-fill is dominated by fragmental rocks containing volcanic debris, and in ancient volcanic settings, determining fragmentation mechanism, transportation process, or depositional setting of these materials can be challenging. The descriptive, non-genetic terminology of Cas and Wright [1987] was initially used to describe deposits, and where primary pyroclastic textures/features (e.g. pumices, welding fabrics, ash aggregates) were clearly identified, which was possible in most cases, then standard 'primary volcaniclastic' terminology was used [White and Houghton 2006].

An ignimbrite is defined as the deposit of a pyroclastic density current, typically rich in pumice and pumiceous ash shards, although scoriaceous and mixed examples also occur. PDC is a general term for a ground-hugging current of pyroclasts and gas (including air) that moves because it is denser than the surrounding atmosphere (or water) and also under the influence of gravity [Branney and Kokelaar 2002]. Ignimbrites are typically deposited incrementally during the sustained passage of a PDC ('progressive aggradation'), and variations in grain size, sorting, and structure within ignimbrites

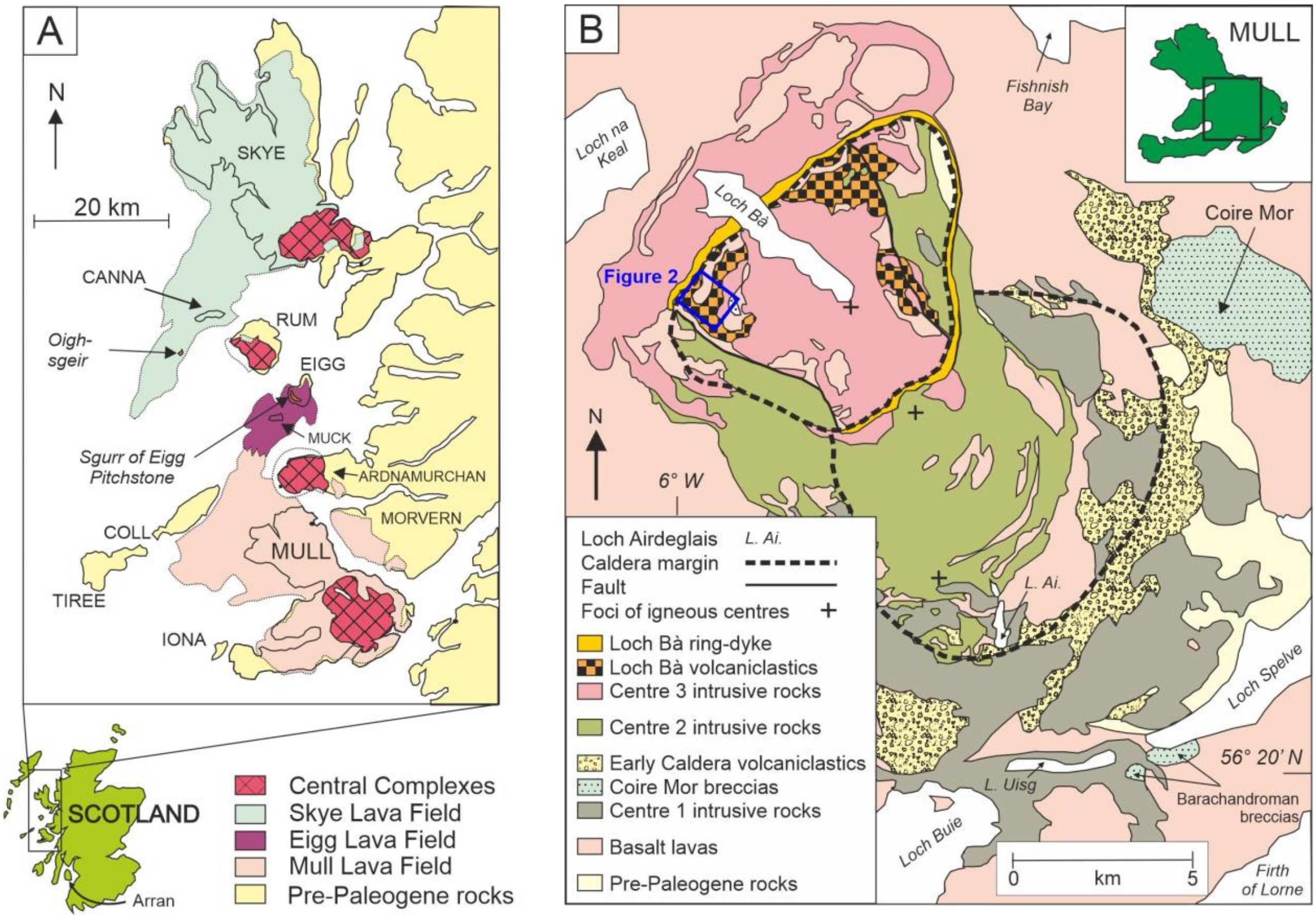

Figure 1: [A] Simplified geological map of the British Paleogene Igneous Province. [B] Simplified geological map of the Mull Central Complex. Inset shows position on Mull. Blue box shows position of Figure 2.

can be explained in terms of spatial and temporal fluctuations in flow competence, velocity, and clast concentration operating within the current [e.g. Branney and Kokelaar 1992; 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014]. Lithofacies in ignimbrites are defined using non-genetic terminology based upon internal sedimentary structure, grain size, sorting, and composition (after Branney and Kokelaar [2002]).

Although a well-dissected example of a caldera, exposure in the Loch Bà area, particularly the ignimbrites of the caldera-fill, is poor, and typically restricted to narrow, moderately incised stream sections. Much of the area is also obscured by forest and/or restricted by access constraints, and therefore, our study is limited to the NW sector of the caldera. Description and interpretation of the rocks is further hindered by intense hydrothermal alteration and weathering. Nonetheless, through detailed and methodical observations it is possible to reconstruct the lithostratigraphy and structure of the caldera.

4 Field relationships

The caldera-fill was sub-divided into two distinct formations: 1) the Loch Bà Ignimbrite Formation; and 2) the Loch Bà Breccia Formation. The Loch Bà Ignimbrite Formation was sub-divided into five distinct members, defined by their stratigraphic position and lithofacies architecture. The Loch Bà Breccia Formation unconformably overlies the Loch Bà Ignimbrite Formation and based on stratigraphic position and lithofacies architecture it may be sub-divided into two distinct members.

4.1 The Loch Bà Ignimbrite Formation

We were unable to recognise convincing unconformities, such as palaeosols/weathered horizons or interbedded sedimentary rocks, between the members in the Loch Bà Ignimbrite Formation, which would provide evidence of eruption hiatuses. Such unconformities may be obscured due to the poor exposure outlined above; however, in the absence of such features, we suggest that the Loch Bà Ignimbrite Formation essentially represents a single eruption and records deposition from the sustained passage of a single, but non-uniform and unsteady, PDC, or more likely, from a series of rapidly emplaced currents that followed with limited time for the settling of ash (e.g. to form extensive fall deposits) suspended in the atmosphere. Although several lithofacies are shared by the various members we have sub-divided them based on their gross overall characteristics and the (dis)appearance of relatively distinctive units, albeit it was difficult to correlate these across the area (Figure 2, 3, 4, and 5). In all the ignimbrites, the juvenile components are challenging to recognise. In the non-welded units, the lapilli/blocks are dominated by lithic

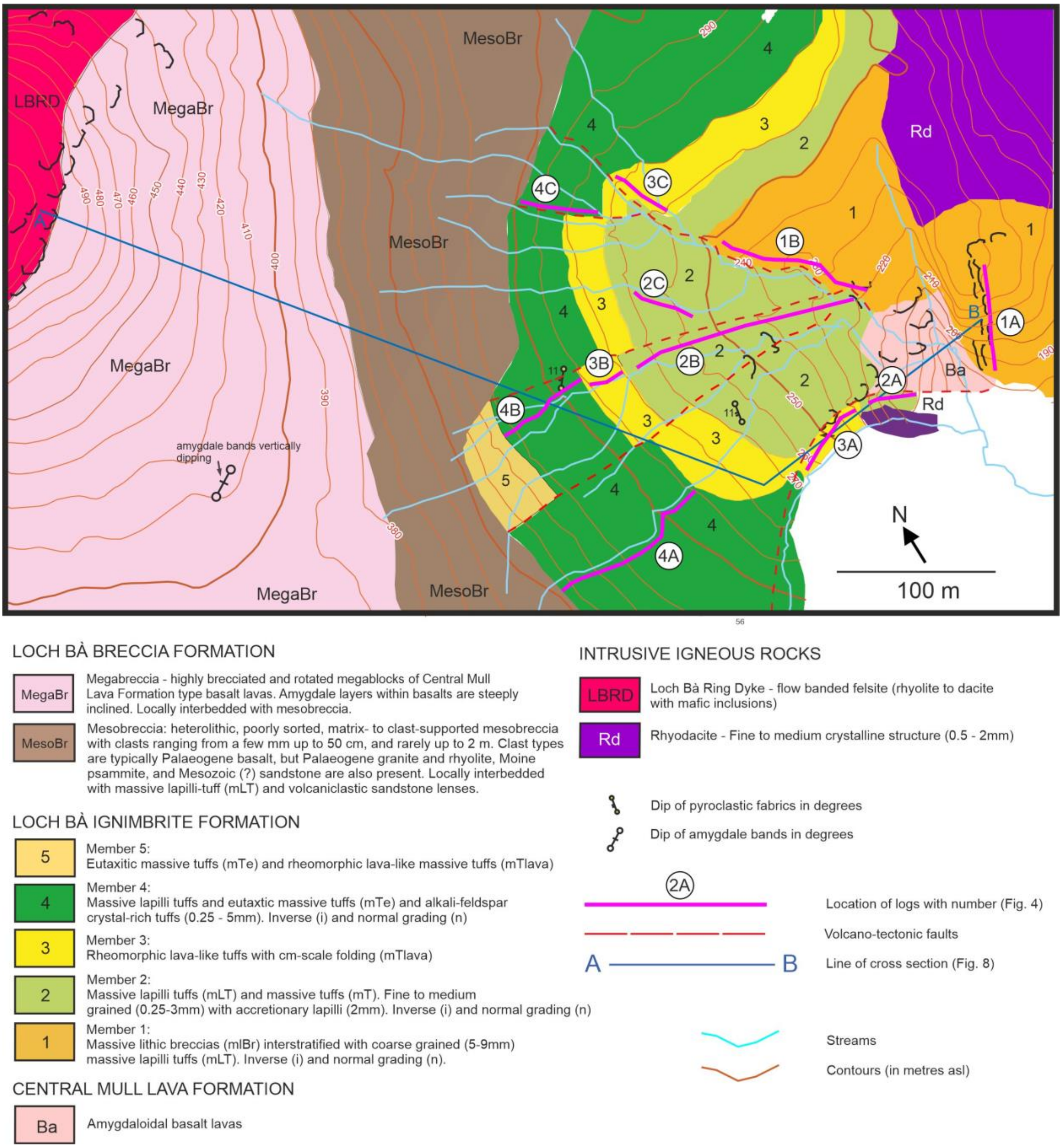

Figure 2: Geological map of the NW sector of the Loch Bà Caldera (see Figure 1B for location).

material. Pumice lapilli/blocks are not observed and are presumably rare and/or have been weathered out or altered such that they are unrecognisable. Juvenile fragments of ash grade are observed in the matrix in the form of altered pumiceous shards, although they are again heavily altered (see Section 5). In welded units, pumice lapilli are preserved as fiamme; these are also heavily altered/chloritised, and in the matrix as above. In lava-like units, juvenile material has coalesced and undergone rheomorphic flow.

4.1.1 *Member 1*

Description

Member 1 is laterally discontinuous, typically occupying the NE sector of the mapped area and at its southern margin it has been offset against Member 2 (Figure 2). It overlies heavily fractured, hydrothermally altered, and weathered basalt lavas, which form part of the subsided Central Mull Lava Formation (Figure 2). Member 1 is characterised by massive lithic-rich breccias, interbedded with massive lapilli-tuffs, not seen elsewhere in the formation (Figure 3, 4, and 5).

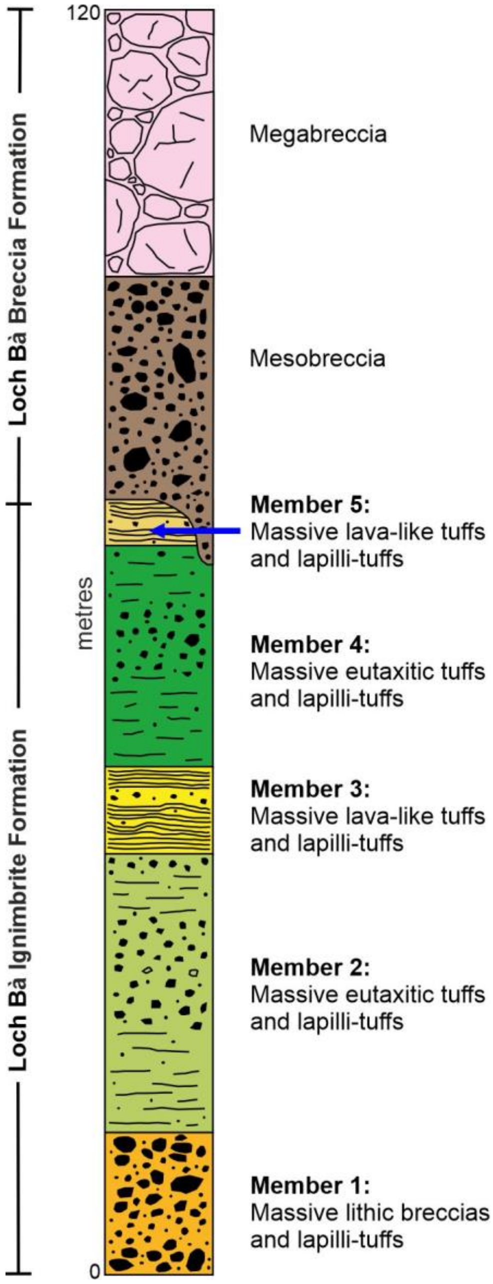

Figure 3: Generalised vertical section through the Loch Bà Ignimbrite Formation and the Loch Bà Breccia Formation.

The basal part of the member is characterised by grey massive lapilli-tuffs (mLT), which comprise grey to black subangular lithic lapilli, typically of basalt lava, ranging from 2–4 mm across, in a fine tuff matrix. The mLT is overlain by a matrix- to clast-supported massive lithic-rich breccia (mlBr), with angular to sub-angular lithic clasts, 10–30 cm across and rare metre-scale blocks (Figure 4, Log 1A; Figure 5A). Clast types include rhyolite, banded tuff, and amygdaloidal basalt lava of both Mull Plateau and Central Mull formation types. The mlBr is overlain by a very fine-grained and relatively featureless massive tuff (mT). Following a long section of no exposure, the next unit comprises grey massive lapilli-tuff with grey sub-angular lithic lapilli, typically of basalt lava, ranging from 2–5 mm across, in a fine tuff matrix (Figure 5B). This mLT is interbedded with massive lapilli-tuffs/breccias, with matrix-supported brecciated fragments ranging from 6–10 cm across (Figure 4, Log 1B). These units are overlain by a grey incipiently welded massive lapilli-tuff (mLTi) with basaltic lithic lapilli, typically 2–3 mm across. This is overlain by a 15 cm thick cross-stratified lapilli-tuff (xsLT), with low angle cross bedding, and a normally graded finer massive lapilli-tuff. The final unit is a clast-supported massive lithic breccia, with grey angular to sub-rounded lithic clasts, up to 15 cm across, of basalt lava and rhyolite resembling Member 1 ignimbrite from lower in the sequence (Figure 2, Log 1B).

Interpretation

Member 1 is dominated by massive breccias and lapilli-tuffs, which record deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based pyroclastic density current. The massive lithic breccias represent the highest energy phase of the eruption, possibly an initial catastrophic collapse and/or vent opening or vent collapse event [Branney and Kokelaar 2002]. Lithic clasts may also have been eroded/entrained from vent walls and/or the substrate. The presence of clasts of tuff not recognised elsewhere in the caldera attest to an earlier explosive eruptive phase whose deposits were incorporated into Member 1. The massive lapilli-tuffs interbedded with the breccias indicate discrete phases of waxing and waning energy during the eruption and record either unsteadiness within the aggrading pyroclastic density current or a change in particle supply at the vent source [Branney and Kokelaar 2002]. The breccias pass up into a massive tuff (mT), which may record deposition by fallout from lofted plumes (e.g. co-ignimbrite clouds) during quiescent intervals between successive currents, or from periodic weak fully dilute pyroclastic density currents with low shear rates [Branney and Kokelaar 2002; Brown and Bell 2007]. The thin bed of cross-stratified lapilli-tuff indicates a transition to deposition from a traction-dominated flow boundary zone in a fully dilute pyroclastic density current [Branney and Kokelaar 2002]. The uppermost breccias in Member 1 are dominated by clasts of earlier Member 1 ignimbrite and appear proximal to faults, and so, their formation could record avalanching/slumping of the aggrading ignimbrite as fault scarps developed during the eruption, a common feature at calderas such as Scafell (Lake District, NW England) and Glencoe (western Scotland) [Branney and Kokelaar 1994; Moore and Kokelaar 1997; 1998; Kokelaar and Moore 2006].

4.1.2 *Member 2*

Description

Member 2 is laterally discontinuous and offset by faults at a number of localities (Figure 2). It varies in thickness due to fault offsets and lateral thickness variations. It overlies basalt lavas of the Central Mull Lava Formation, is intruded by rhyodacite in the southern section of the mapped area and overlies Member 1 in the northern part. Member 2 is characterised by a distinctive basal sequence of green eutaxitic massive tuffs and lapilli-tuffs and a thick overlying sequence of green massive lapilli-tuffs (Figure 3, 4, and 5).

The base of the member comprises green eutaxitic massive tuffs (mTe), with well-developed eutaxitic textures and euhe-

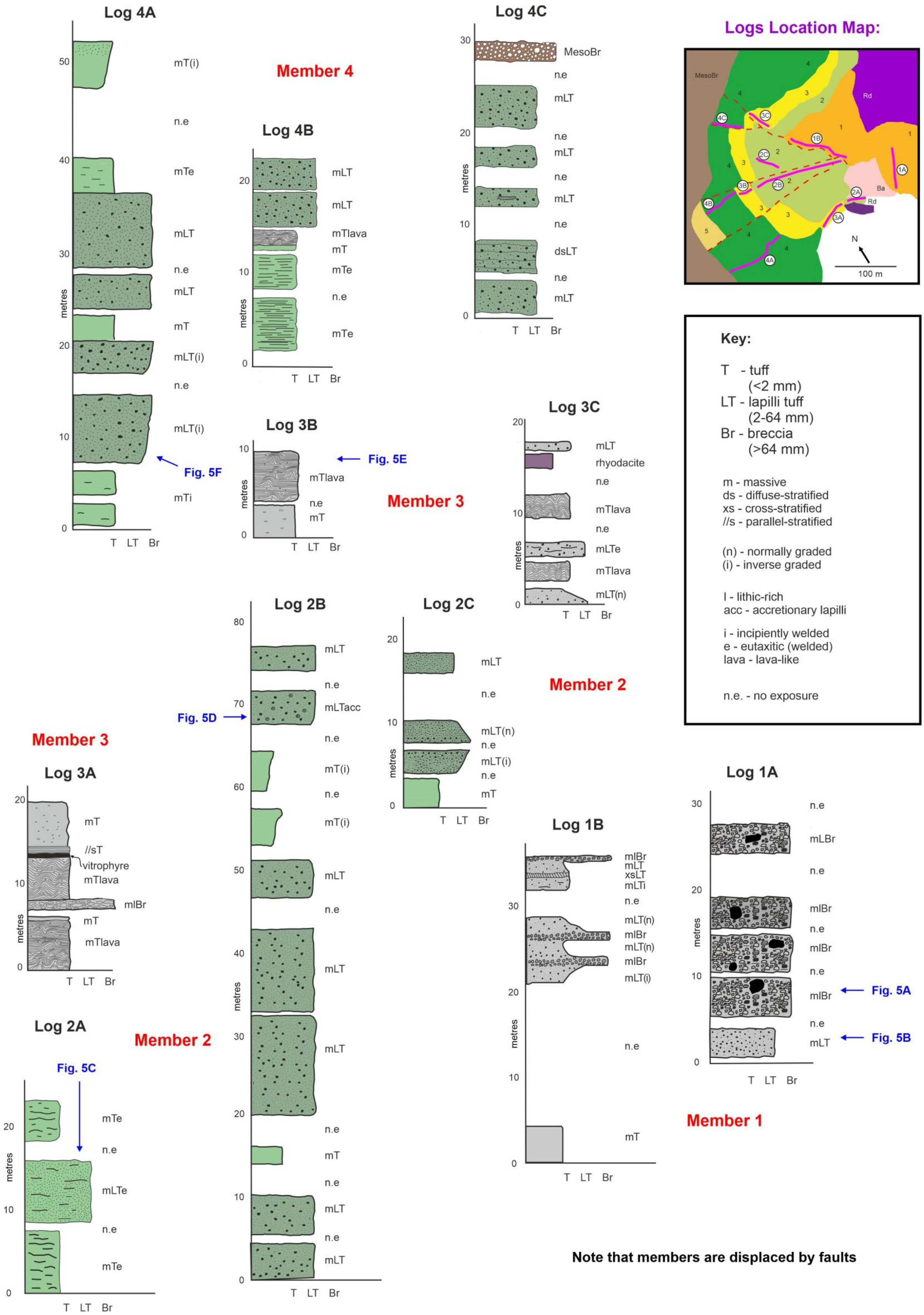

Figure 4: Lithostratigraphic logs of members 1–4 in the Loch Bà Ignimbrite Formation. Logs are tied to approximate topographic height (Figure 2). Location of logs shown in top right (see also Figure 2). Position of distinctive features/units in Figure 5 indicated in blue. Standard grain size terminology is used for primary volcaniclastic rocks (T – tuff = <2 mm; LT – lapilli-tuff = 2-64 mm; Br – breccia = >64 mm) [White and Houghton 2006]. Colours on log highlight distinctive colours/features in members.

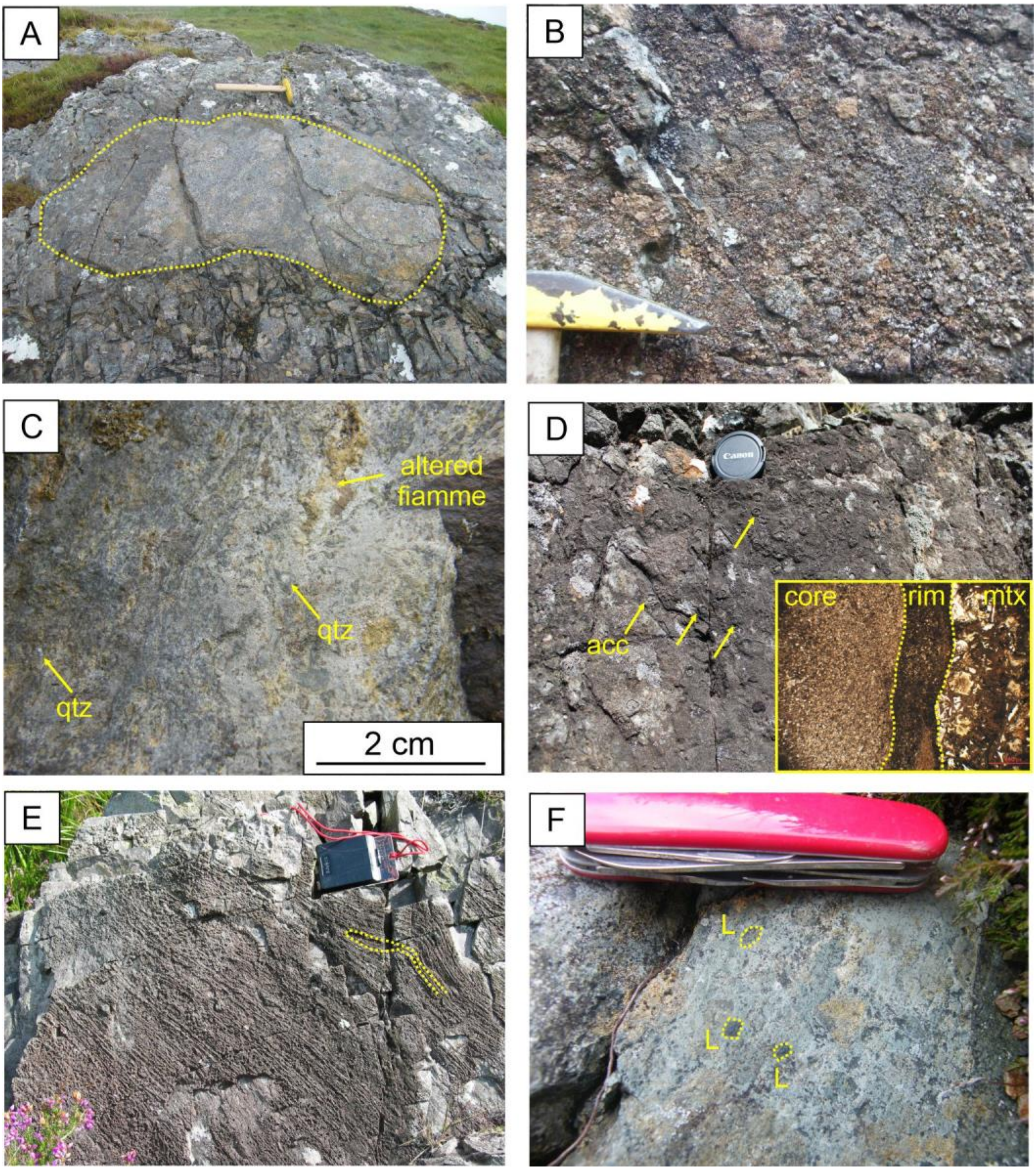

Figure 5: The Loch Bà Ignimbrite Formation, highlighting examples of characteristic features and distinctive units. [A] Member 1 massive lithic breccia with metre-scale basalt block. Hammer is 30 cm in length. [B] Typical massive lapilli-tuff of members 1 and 2. [C] Massive eutaxitic lapilli-tuff of Member 2. Note altered fiamme and quartz (qtz) crystals. [D] Accretionary lapilli (acc) bearing massive lapilli tuff of Member 2. Camera lens cap is 8 cm across. Inset is a photomicrograph through an accretionary lapillus, showing core and rim. View is plane polarised light and 1 mm across. [E] Lava-like tuff of Member 3, showing pervasive flow banding and rheomorphic folds (highlighted). Compass is 10 cm across. [F] Incipiently welded massive lapilli-tuffs, with rare lithic lapilli (L), of Member 4. Knife is 10 cm in length.

dral to subhedral alkali feldspars up to 0.5 mm across, which form ~10 % of the unit (Figure 5C). The mTe is overlain by a green eutaxitic massive lapilli-tuff with black sub-angular lithic lapilli of basalt, typically 2 mm across, and a further alkali feldspar-rich eutaxitic massive tuff (Figure 4, Log 2A). The eutaxitic tuffs are overlain by a thick sequence of massive lapilli-tuffs with black sub-angular lithic lapilli of basalt, typically 2 mm across. The massive lapilli-tuffs are interbedded with green massive tuffs, similar to the units lower in the member, and locally they display inverse grading (Figure 4, Log 2B). Towards the top of the massive lapilli-tuffs an accretionary lapilli-bearing unit is preserved (mLTacc) (Figure 5D). The accretionary lapilli comprise medium- to coarse-ash unstructured cores, surrounded by fine- to medium-ash laminae, which are locally normally graded (Figure 5D inset). The accretionary lapilli are sub-spherical, 0.5-1 mm across, form discontinuous lenses, and comprise~10 % of the unit. The mLTacc is overlain by further green massive tuffs and lapilli-tuffs, which locally display inverse and normal grading (Figure 4, Log 2C).

Interpretation

Member 2 is dominated by massive lapilli-tuffs, which record deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based pyroclastic density current. The lithofacies in Member 2 record relatively subtle changes in grain size, indicative of limited waxing and waning energy during this phase of the eruption and *relative* steadiness within the pyroclastic density current [Branney and Kokelaar 2002]. The source vent may have been more firmly established during this phase of the eruption. The eutaxitic lapilli-tuffs record hot-state syn- and post-depositional welding. The presence of accretionary lapilli indicates that ash pellets were formed in a lofting co-ignimbrite or "phoenix" plume before they dropped through the pyroclastic density current where they accreted finer grained rims [Brown et al. 2010].

4.1.3 *Member 3*

Description

Member 3 is laterally discontinuous with offset of up to 20 m by faults at a number of localities. It varies in thickness due to fault offsets and lateral thickness variations, and conformably overlies Member 2. Member 3 is characterised by massive grey rhyolitic lava-like ignimbrite (mTlava) (Figure 3, 4, and 5).

The lava-like tuffs are grey, vitric, and crystal-rich, with subhedral alkali feldspars and rare quartz, typically 0.5 to 1 mm across, comprising ~10 % of the rock (Figure 5E). Rare lithic lapilli of basalt lava and rhyolite, typically ~2–5 mm across, are also present. The tuffs typically display a flow fabric/banding with dark and light attenuated bands, locally deformed around crystals and lithic lapilli. The fabric is typically planar to undulose, but cm-scale open, isoclinal and sheath folds are present. The fabrics are typically steeply dipping (ca. 60–70°), particularly in the vicinity of faults. Locally,

interbedded clast-supported massive lithic breccias are present, typically near faults. These breccias comprise subangular clasts, typically 5–10 cm across, of the lava-like tuff (Figure 4, Log 3A). Locally, the mT lava is overlain by a thin upper vitrophyre, which is in turn overlain by a planar-stratified tuff (//sT) and a crystal-rich massive tuff (alkali feldspars, 0.5–1 mm across) (Figure 4, Log 3A). The lava-like tuffs are also interbedded with poorly sorted massive lapilli-tuffs containing black lithic lapilli of basalt lava, typically 2–3 mm across (Figure 4, Log 3C).

Interpretation

Member 3 is dominated by lava-like ignimbrites. High-grade (rheomorphic, lava-like) ignimbrites can be very difficult to distinguish from rhyolite lavas [cf. Branney and Kokelaar 1992; Henry and Wolff 1992; Branney and Kokelaar 2002; Sumner and Branney 2002; Branney et al. 2008]; however, we interpret these units as ignimbrites due to: 1) the presence of internal breccia horizons; 2) the presence of eutaxitic horizons; and 3) the interbedded massive lapilli-tuffs. The lava-like tuffs record deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based pyroclastic density current. However, their deposition and rheomorphism is controlled by the nature of the eruption and the temperature of the current. Lava-like ignimbrites are typically associated with sustained, low-fountaining "boil-over" type eruptions, where admixing of air is insufficient enough to form a buoyant, convecting Plinian-type plume. Consequently, enough heat is retained in the density currents to facilitate hot-state agglutination and coalescence of pyroclasts at the lower flow boundary zone. Rheomorphism is caused by syn- and post-depositional hot-state shearing and slumping of the semi-molten deposit [Branney and Kokelaar 1992; 2002; Sumner and Branney 2002; Branney et al. 2008; Andrews and Branney 2011]. The interbedded massive lapilli-tuffs in Member 2 indicate that, periodically, more typical buoyant plumes developed, and eruption energy waxed and waned.

The vitrophyre and the planar stratified tuff could be related. The vitrophyre could represent the chilled upper part of one of the lava-like tuffs, and the planar-stratified tuff an ignimbrite deposited from a traction-dominated flow boundary zone in a fully dilute pyroclastic density current. Alternatively, the thinness of the tuff and the planar nature of its bedding could be used to interpret the unit as a fall deposit, whose base has been fused to vitrophyre [Branney et al. 2008], although there is no evidence of a sustained Plinian-type plume (e.g. widespread pumice), or interpreted as ash associated with a lofting co-ignimbrite or "phoenix" cloud. Due to the poor discontinuous exposure, it is challenging to determine the extent and nature of this deposit.

The presence of steeply dipping rheomorphic fabrics adjacent to faults within the caldera succession indicates that the rheomorphism was, in part, coeval with active faulting during eruption and deposition of the tuffs. As the semi-molten deposit formed, it ponded against the developing fault scarp, with continuing subsidence along the fault resulting in the development and accentuation of the sub-vertical fabric [Branney and Kokelaar 1992; 1994]. The breccias within the lava-like tuffs could be a result of hot-state brecciation during faulting and/or slumping of the aggrading deposit [Branney and Kokelaar 1994]. The PDCs could have been fed from fissures exploiting the volcano-tectonic faults in the caldera. These faults could also have acted as eruptive fissures to insulate the ascending magma and maintain its high temperature.

4.1.4 Member 4

Description

Member 4 is laterally discontinuous and varies in thickness due to fault offsets and lateral thickness variations. It overlies Member 3 and is offset against it by faults. Member 4 is characterised by green massive lapilli-tuffs interbedded with eutaxitic massive lapilli-tuffs (Figure 3, 4, and 5).

The base of the member (at Log 4A, Figure 4) comprises green fine-grained (0.25–1 mm) incipiently welded to eutaxitic massive tuffs (mTi/mTe). The massive tuffs coarsen upwards into green massive lapilli-tuffs with black lithic lapilli of basalt lava, typically 2–3 mm across, in an ashy matrix (Figure 5F). Macroscopic spherulites, ranging from 0.5–1 mm across, and subhedral pink alkali feldspars 1–2 mm across, are locally present across all units (Figure 4, Logs 4A–C). Although the massive lapilli-tuffs are relatively homogeneous, weakly developed inverse grading, diffuse bedded lenses, and lenses of tuff are locally present (Figure 4, Log 4C). A single sub-angular clast (20 cm across) of distinctive Loch Bà Ring-Dyke material was observed in one of the lapilli-tuffs.

Interpretation

Member 4 is dominated by massive tuffs and lapilli-tuffs, which record deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based PDC. The member coarsens up-section and indicates an increase in mass flux, which could have been caused by either increasing eruptive energy or a change in particle supply at the vent. The eutaxitic tuffs record hot-state syn- and post-depositional welding. The occurrence of diffuse bedded lenses within the massive lapilli-tuffs indicates periodic deposition from a granular flow-dominated flow boundary zone in a granular fluid-based PDC [Branney and Kokelaar 2002]. The tuff lenses may represent further periodic fluctuations in mass flux (e.g. decreasing energy, change in particle supply at the vent) [Branney and Kokelaar 2002]. The occurrence of a clast of Loch Bà Ring-Dyke material indicates that the conduit(s) which fed the ignimbrite-forming eruption passed through the ring-dyke and therefore, the intrusion predates at least this part of the eruption.

4.1.5 Member 5

Member 5 is very poorly exposed and is only observed at a few localities. It comprises lava-like tuffs very similar to those of Member 3 and is interpreted as representing a return to a "boil-over" type eruption.

4.2 Loch Bà Breccia Formation

Description

The Loch Bà Breccia Formation unconformably overlies the various members of the Loch Bà Ignimbrite Formation. We have identified two distinct lithofacies that may be regarded as separate members: 1) volcaniclastic 'mesobreccias'; and 2) volcaniclastic 'megabreccias' (Figure 2 and Figure 6).

The mesobreccias fill an erosional unconformity on the ignimbrites. The mesobreccias are grey to reddish brown, massive, heterolithic, poorly sorted, and matrix- to clast-supported (Figure 6A, 6B) with clasts typically a few mm up to 50 cm, with some up to 2 m, and further rarer examples up to 10 m across. The clasts are set in a basaltic sand-grade comminuted matrix. The majority of the clasts are sub-angular to sub-rounded, and many of the larger more angular clasts, show 'jigsaw-fit' textures, locally with evidence of clast rotation. Clast types are typically Palaeogene basalt (Central Mull Lava and Plateau Lava formation types), but Palaeogene granite and rhyolite (Loch Bà Ring-Dyke material), Mesozoic (?) sandstone, and Neoproterozoic psammite are also present. The breccias are locally interbedded with lenses of volcaniclastic sandstone, typically 1 m thick and up to 10 m across. Locally, thin beds of green-brown massive lapilli-tuff, typically <50 cm thick and laterally discontinuous over a few metres, are present.

The mesobreccias are overlain by a sequence of volcaniclastic megabreccia. The megabreccia comprises megablocks, typically 10–20 m but commonly up to 50 m across, of Central Mull Lava Formation basalt (Figure 6C). The megablocks are reddish brown to grey, highly fractured and thoroughly hydrothermally altered, displaying extensive chloritisation and zeolitisation. The lava is amygdaloidal with amygdales, typically of calcite and quartz, up to 1 cm across. The amygdales form distinct bands, a few cm thick and metres across, which typically dip steeply towards the centre of the caldera (Figure 6D). However, despite this general disposition the dip and strike of the bands are highly variable. Although the majority of megablock margins cannot be distinguished due to limited exposure, they are identified as clasts based on their internal disaggregation and the disposition of the amygdale bands. The matrix of the megabreccia essentially comprises clast- to matrix-supported breccia similar to the underlying mesobreccias. Rare mesobreccia lenses are also found amongst the megabreccia.

Interpretation

We interpret the mesobreccias and megabreccias as mass wasting deposits, associated with caldera subsidence, collapse of caldera walls and/or break up of caldera floor. They are similar to the classic caldera collapse breccias described by Lipman [1976]. We re-emphasise that these materials were deposited within the growing caldera depression (i.e. surrounded by caldera-bounding ring-dyke, and intact country rock material) and their presence provides evidence for its formation.

We interpret the mesobreccias as high-energy mass flow deposits due to: 1) the dominance of poorly sorted, massive units; 2) the dominance of matrix-supported depositional units; 3) the general absence of grading within discrete depositional units; 4) the absence of directional grain fabrics; and (5) the abundance of large boulders, including blocks several metres across. Such textures are indicative characteristics of high-energy debris flow deposits [e.g. Johnson and Rodine 1984; Pierson and Scott 1985; Smith 1986; Pierson and Costa 1987; Smith and Lowe 1991; Manville et al. 2009]. These debris flow events were most likely initiated by gravitational collapse and slumping of topographically elevated caldera walls, although contemporaneous explosive volcanism, faulting, seismicity, intrusion, and rainfall may also have been triggering mechanisms. Loose debris, including recently collapsed material, scree-slope talus, and alluvial detritus on the caldera floor is then mobilised in debris flows [Miura and Tamai 1998; Moore and Kokelaar 1998; Bacon et al. 2002]. During quiescent periods after the earlier eruption, background fluvio-lacustrine sedimentation may resume, and the interbedded volcaniclastic sandstones may represent reworking of material from the debris flow fans [Brown et al. 2009; Manville et al. 2009; Gooday et al. 2018]. The lensoid geometries of the sandstones are indicative of fluvial sedimentation. The presence of clasts of Loch Bà Ring-Dyke material within the mesobreccias indicates that at least part of the ring-dyke had been emplaced, and possibly exhumed, at this point in the caldera's history.

We interpret the megabreccias as similar mass wasting deposits; however, they appear to represent a more significant, catastrophic collapse event. The variably oriented megablocks are indicative of oversteepening of caldera walls and collapse into the caldera depression, together with landsliding from unstable volcano-tectonic fault scarps [Branney and Kokelaar 1994; Moore and Kokelaar 1997; 1998]. As caldera walls and fault scarps collapse, large blocks of country rock become detached and rock/debris slides/avalanches may be initiated. These blocks become heavily fractured and may locally grade into clast-supported breccias [Glicken 1991; Yarnold 1993; Kessler and Bédard 2000; Reubi and Hernandez 2000; Geshi et al. 2002; Bernard et al. 2009], although some of the megablocks could be pieces of subsided/segmented caldera floor [Miura and Tamai 1998]. The presence of mesobreccia lenses may indicate downslope transitions to debris flow [Schneider and Fisher 1998] and/or reworking of earlier collapsed material.

4.3 Rhyodacite

Description

The Loch Bà Ignimbrite Formation is locally cut by masses of rhyodacite. These units are grey to purple, fine- to medium-grained, with a groundmass of alkali feldspar, plagioclase feldspar, quartz and biotite, and rare microphenocrysts of alkali feldspar. Locally, the rhyodacite is brecciated at its margins.

Interpretation

We interpret the rhyodacite as small, shallow intrusions into the caldera-fill, some of which may have breached the surface and built domes and cones above the caldera floor. They most likely represent a period of resurgence following the caldera-forming eruption and subsidence.

5 Petrography of the ignimbrites

The ignimbrites display evidence for very strong post-depositional alteration: much of the original glass has been turned into clay and chlorite and in some places very fine epidote is present. Despite this alteration, two distinct mineralogical and textural assemblages are recognised (Figure 7).

The first assemblage is characteristic of the tuffs and lapilli-tuffs of members 1, 2, and 4. These units contain crystals, typically 0.1 to 0.5 mm, of subhedral alkali feldspar and subordinate microcline, some of which are heavily fragmented, and clasts of lithic material (Figure 7A, 7B). Fine-grained altered pumice lapilli, which have been deformed and stretched, are locally preserved. The 'original' glassy matrix has locally been preserved and displays rare cuspate shards of glass in a finer mosaic of quartz and feldspar microlite (Figure 7C, 7D). There are also abundant spherulites, which are typically undeformed and comprise microlites of quartz. In Member 2, rare examples of accretionary lapilli, displaying characteristic core and rim morphology, are present (Figure 5D inset).

The second assemblage is characteristic of the lava-like tuffs of members 3 and 5. These tuffs comprise abundant crystals, typically 0.1 to 0.5 mm, of alkali feldspar, many of which are resorbed and display sieve-like textures, and are often sintered together. Rare examples also display perthitic textures. Rare crystals of plagioclase display oscillatory zoning. The matrix is typically altered to clay, but it does retain much of its original structures in the form of small-scale rheomorphic flow laminations and folds (parataxitic texture), which comprise recrystallised mosaics of quartz and feldspar (Figure 7E). There are numerous spherulites in the matrix, which are deformed and comprise microlites of quartz (Figure 7F).

The presence of spherulites throughout the ignimbrites indicates that vapor-phase crystallisation played an important part in their formation. Voluminous dissolved volatiles in the ignimbrite are responsible for spherulitic textures and microlites, with the latter crystallising from the escaping gases. Indeed, the high volatile content of the ignimbrite may have enabled low viscosity to be maintained, thus enabling agglutination and coalescence of particles, and consequently welding of the deposit [Branney and Kokelaar 2002]. The deformed spherulites within members 3 and 5 indicate that they formed during deposition of the ignimbrite, with the agglutinating flow distorting them, whereas non-deformed spherulites (members 1, 2, and 4) would have been produced by vesiculation in the post-depositional unit [Branney and Kokelaar 1992].

Many intra-caldera ignimbrites are subject to oxidation and high temperature metamorphism due to the existence of hydrothermal systems within the caldera [Donoghue et al. 2008]. The abundant chlorite, epidote, and clay are thought to result from similar processes at Loch Bà and indicate that the caldera played host to a vigorous hydrothermal system after the ignimbrite-forming eruption.

6 Discussion

6.1 Caldera collapse

The documented field relationships allow us to construct a model of the nature and timing of subsidence at the Loch Bà Caldera (Figure 8 and Figure 9). The (inferred) faults which displace the Loch Bà Ignimbrite Formation are interpreted to be volcano-tectonic in nature and reveal a complex subsidence history within the caldera (Figure 2, 8, and 9). The existence of steeply dipping rheomorphic fabrics and breccias in some of the tuffs close to the faults suggests that fault formation and subsidence was contemporaneous with ignimbrite deposition in members 3 and 5; however, we cannot exclude the possibility of: 1) differential welding of an ignimbrite ponded across an existing fault scarp; 2) an ignimbrite draping over, or accreting to, an existing scarp; or 3) some combination of

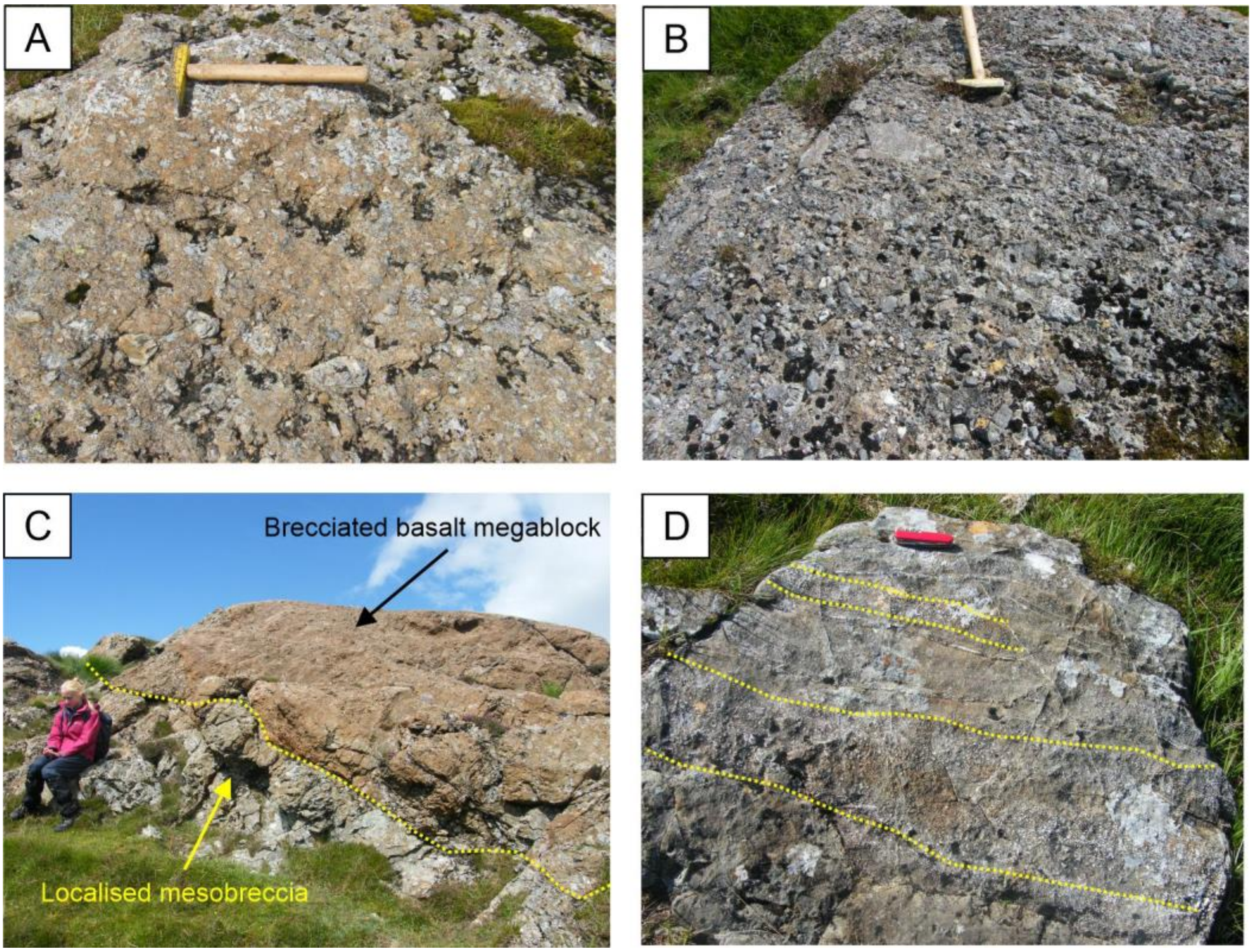

Figure 6: The Loch Bà Breccia Formation. [A] Matrix-supported mesobreccia. Hammer is 30 cm in length. [B] Variably matrix- to clast-supported mesobreccia. Hammer is 30 cm in length. [C] Brecciated basalt megablock in megabreccia with localised mesobreccia matrix. Person in image is approximately 1 m in seated position. [D] Rotated basalt block in megabreccia showing amygdale bands. Knife is 10 cm in length.

these mechanisms [Branney and Kokelaar 1994]. The thickness variations in the ignimbrites and the chaotic nature of the offset units also provide further evidence for differential fault-controlled subsidence in the caldera [Branney and Kokelaar 1994]. The various fault blocks most likely subsided at different times during the eruption, such that the ignimbrites exhibit topographically controlled deposition and ponding within the caldera. The field relationships and structures strongly resemble piecemeal collapse observed at various calderas worldwide, including the type locality piecemeal calderas of Scafell and Glencoe [e.g. Branney and Kokelaar 1994; Lipman 1997; Moore and Kokelaar 1997; 1998; Cole et al. 2005; Kokelaar and Moore 2006; Acocella 2007; Drake et al. 2022]. Following these events, the caldera then appears to have undergone further catastrophic collapse events related to oversteepening and collapse of caldera margins and fault scarps, to produce the mesobreccias and megabreccias of the Loch Bà Breccia Formation.

From a review of existing field and modelling data on calderas, Acocella [2007] developed a four-stage model of caldera collapse. The four stages reflect progressively increasing subsidence and include: 1) downsag; 2) reverse ring fault subsidence; 3) peripheral downsag; and 4) peripheral normal ring fault subsidence. Geshi et al. [2002] suggest that subsidence evolves from being controlled by the activity of the caldera ring-fault systems ('structure-controlled'), to being controlled by erosion of the caldera wall and sedimentation at the floor ('erosion-controlled'). The Loch Bà Ignimbrite Formation appears to record the transition through the four stages of Acocella [2007]. Members 1 and 2 record an initial, perhaps rapid, subsidence phase (stages 1 and 2) before more peripheral subsidence and the development of volcano-tectonic faults within the caldera and its margins (stages 3 and 4). This contemporaneous subsidence is particularly well demonstrated by members 3 and 5. At this point, peripheral normal ring fault subsidence continued with the inward rotation and collapse of caldera walls to form the breccias of the Loch Bà Breccia Formation, recording the transition from structure-controlled subsidence to erosion-controlled subsidence [Geshi et al. 2002].

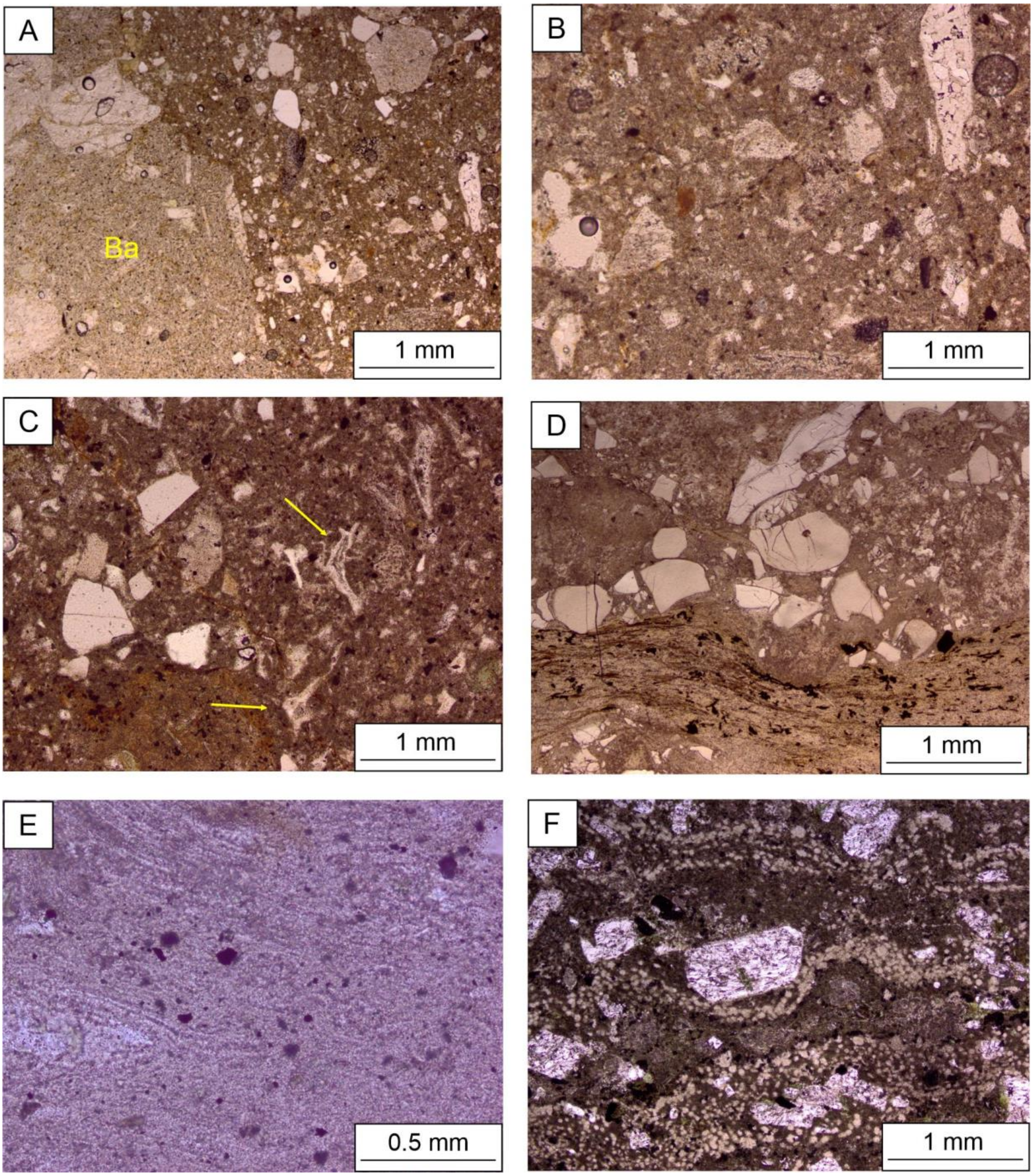

Figure 7: Petrography of the Loch Bà Ignimbrite Formation. [A] Typical massive lapilli-tuff of Member 1. Note basalt (Ba) lava lapilli. [B] Typical massive lapilli-tuff of Member 2. [C] Cuspate shards (arrows) in massive lapilli-tuff of Member 2. [D] Glassy shards (black) in massive lapilli-tuff of Member 2. [E] Parataxitic texture in massive lava-like tuff of Member 3. [F] Flow fabric with spherulites in massive lava-like tuff of Member 3. All images are in plane polarised light.

6.2 Eruption chronology

Five main eruption phases have been recognised in the Loch Bà Caldera and are summarised in Figure 9. Phase 1 commenced with a significant high-energy, catastrophic event, which may be linked to significant subsidence in the early formation of the caldera and/or vent-opening. An explosive, fountaining column developed and collapsed generating a granular fluid-based pyroclastic density current(s) that deposited vent proximal lithic breccias interbedded with lapilli-

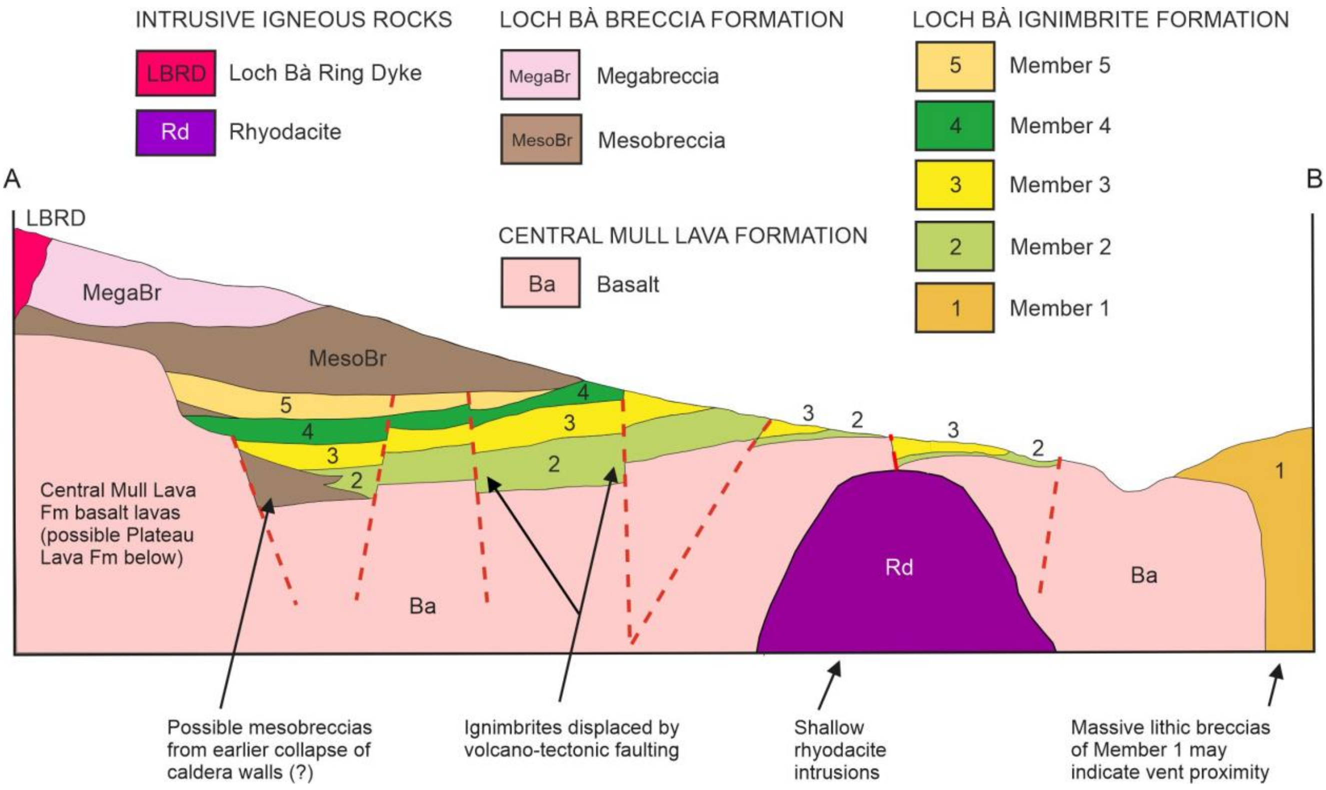

Figure 8: Schematic cross section of the Loch Bà Caldera (see Figure 2 for location).

tuffs (Member 1), indicating variable mass flux, unsteadiness in the current, and changes in particle supply at the vent. Periodically the density current(s) became fully dilute and deposited stratified tuffs. The coarse lapilli-tuffs and breccias present are similar to intra-caldera proximal breccias interpreted as records of catastrophic caldera collapse elsewhere in the BPIP [e.g. Gooday et al. 2018; Drake et al. 2022]. They also resemble coarse lithic breccias at other calderas worldwide (e.g. Tenerife [Smith and Kokelaar 2013]; Pantelleria [Jordan et al. 2018]), where these units are interpreted as representing climactic collapse of the edifice. Given the limited exposure at Loch Bà it is unclear whether the Phase 1 deposits represent the initial collapse or a climactic phase, although tuff clasts in Member 1 suggest earlier activity. Phase 2 saw sustained passage of the density current(s) and deposition of lapilli-tuffs and tuffs (Member 2). Mass flux was more stable and relatively minor waxing and waning cycles are recorded, together with some hot-state deformation and welding, perhaps indicating fluctuations in column height and air entrainment [Ross and Smith 1961; Walker 1983; Branney and Kokelaar 2002; Trolese et al. 2019], although variations in magmatic temperature, particle concentration, PDC runout distance, and deposit thickness/overburden [e.g. Branney and Kokelaar 1992; Freundt and Schmincke 1995; Freundt 1998; 1999; Branney and Kokelaar 2002; Quane and Russell 2005; Wadsworth et al. 2019] could also be involved. The presence of accretionary lapilli attests to the formation of buoyant co-ignimbrite plumes, where ash pellets formed in the presence of moisture, before falling through the density current and accreting ash rims. It is possible that these plumes where present throughout much of the eruption, but relatively fragile ash aggregates were not preserved in coarse lithic-rich and/or welded facies. Phase 3 saw the nature of the eruption change to a low-fountaining "boil-over" type event. This change may be linked to a significant influx of higher-temperature magma, perhaps from a thermally and/or compositionally zoned magma reservoir [e.g. Troll et al. 2004; Liszewska et al. 2018; Pimentel et al. 2021], and/or widening of the vent to reduce column height [e.g. Suzuki and Koyaguchi 2012]. Heat retention (linked to factors such as compositional and thermal zoning in the magma reservoir, low fountaining columns, PDC particle concentration and runout, and deposit thickness, as discussed above) resulted in hot-state agglutination and coalescence of pyroclasts at the lower flow boundary zone. The aggrading semi-molten deposit underwent syn- and post-depositional rheomorphism (hot-state shearing and slumping [Andrews and Branney 2011]), forming lava-like tuffs and breccias (Member 3). Deposition was influenced by developing fault scarps, against which the tuffs ponded. Interbedded lapilli-tuffs indicate that occasionally the PDCs entrained more air and lofted. In Phase 4 a sustained high-fountaining column developed and the density current deposited lapilli-tuffs and tuffs (Member 4). Mass flux generally increased throughout this period of the eruption, reflecting increasing energy and particle supply from the vent. Phase 5 saw a return to a low-fountaining "boil-over" type event, and the deposition of lava-like tuffs (Member 5), likely for the reasons outlined above. Members 1, 2, and 4 are more lithic-rich and this may also have contributed to inhibiting welding [e.g. Eichelberger and Koch 1979]. At this point the main eruptive activity ends, although the pres-

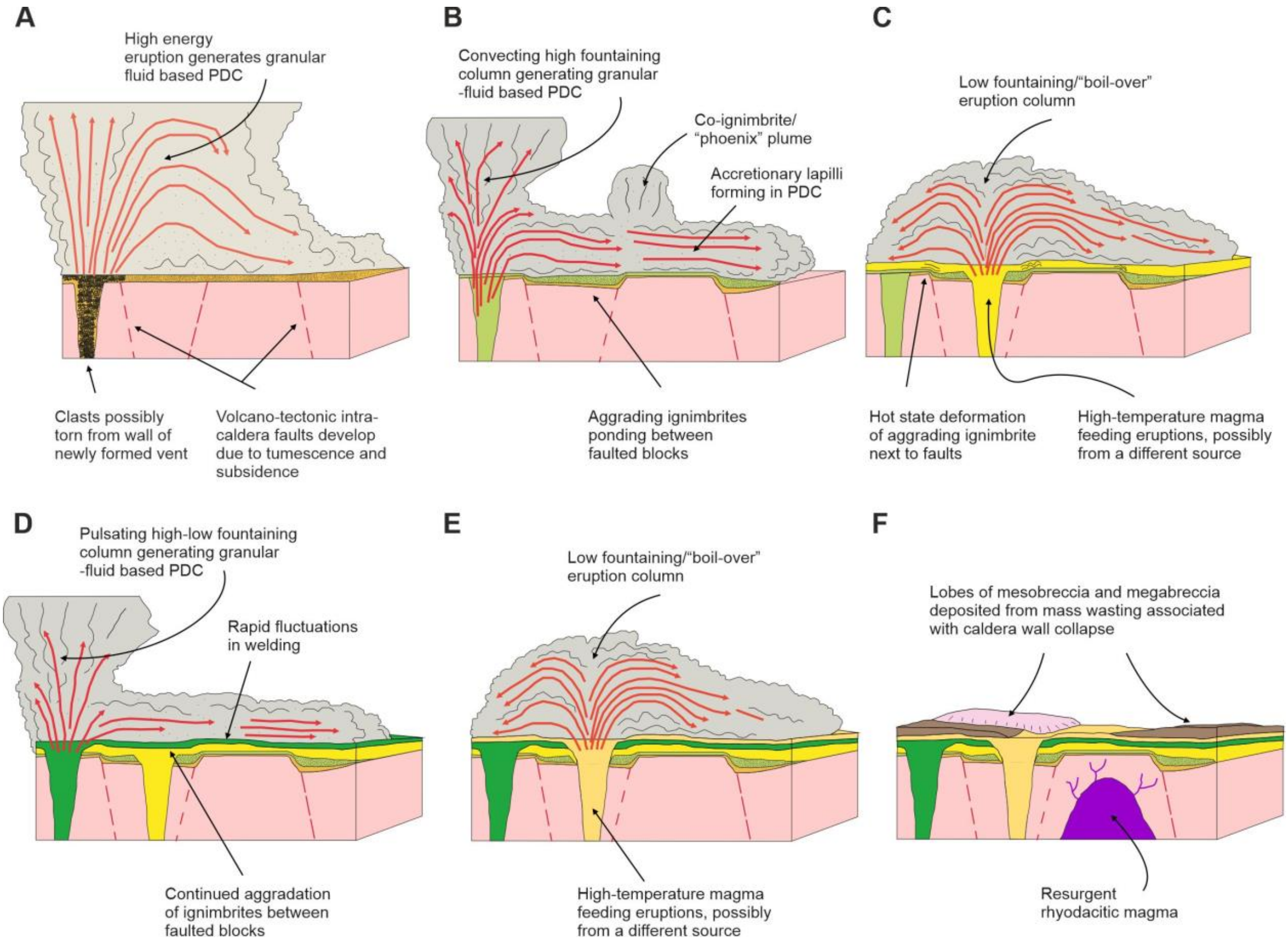

Figure 9: Schematic block diagrams showing the development of the Loch Bà Caldera. No scale is implied, or any geographic part of the caldera inferred. [A] Phase 1: Initial high-energy event forming lithic breccias of Member 1. [B] Phase 2: Sustained high fountaining eruption forming tuffs and lapilli-tuffs of Member 2. [C] Phase 3: Low fountaining "boil-over" type eruption forming lava-like ignimbrites of Member 3. [D] Phase 4: Sustained but pulsating high-low fountaining eruption forming tuffs and lapilli-tuffs of Member 4. [E] Phase 5: Low fountaining "boil-over" type eruption forming lava-like ignimbrites of Member 5. [F] Post-eruption collapse of caldera walls depositing mesobreccia and megabreccia.

ence of minor lapilli-tuffs in the mesobreccias indicates that small-volume PDCs were still being generated. It is possible however, that part of the eruptive record is missing due to erosion and subsequent mass wasting/collapse. Following further caldera collapse and deposition of the mesobreccias and megabreccias, the caldera-fill was intruded by rhyodacitic magma. This magma may have breached the surface, forming resurgent domes and cones.

6.3 Coeval rheomorphic and non-rheomorphic ignimbrites

Although gross lithofacies characteristics have been used to identify members in the Loch Bà Caldera, the ignimbrites are remarkable for their abundant lithofacies variations, particularly within the lava-like tuffs. High-grade (rheomorphic, lava-like) ignimbrites, both intra- and extra-caldera, typically comprise thick, voluminous sheets of rhyolite associated with extensive ashfall deposits, and widespread evidence of emplacement in lacustrine-alluvial environments (e.g. intercalated lake sediments, phreatomagmatic tuffs, peperites) (see review, Snake River Plain, NW USA [Branney et al. 2008]). Further instances are seen at, for example: 1) Glencoe Caldera, where 100–150 m thick lava-like rheomorphic ignimbrites are interbedded with ash aggregate-bearing phreatomagmatic tuffs and fluvio-lacustrine sedimentary rocks, and overlain by more typical eutaxitic ignimbrites [Moore and Kokelaar 1997; 1998; Kokelaar and Moore 2006]; and at 2) Scafell Caldera, where hundreds of metres thick rheomorphic ignimbrites are associated with extensive fall deposits, and phreatomagmatic units linked with intermittent explosive interaction with ground and lake water [Branney and Kokelaar 1992; 1994; Brown and Bell 2007; Kokelaar et al. 2007]. At Loch Bà, there is little to no evidence of interbedded fall deposits, phreatomagmatic units, and caldera lake sedimentary rocks, although we do acknowledge the limitations of exposure. Rather, the lava-like tuffs are typically associated with thicker non-welded massive ignimbrites, and are themselves, interbedded with similar thin, non-welded ignimbrites. While lava-like tuffs commonly display internal lithofacies variations, these typically include eutaxitic zones, breccias and vitrophyres, rather than non-welded units [e.g. Branney and Kokelaar 1994; Andrews and Branney 2011]. The relationships in Loch Bà indicate relatively rapid switching of eruption types, and/or PDC dynamics including considerable variations in mass flux and current unsteadiness, and/or degrees of welding within the caldera, comparable with recently reported calderas elsewhere in the Palaeogene of NW and western Scotland (Arran [Gooday et al. 2018]; Skye [Drake et al. 2022]) (Figure 1A). Alternatively, these rapid fluctuations could perhaps suggest eruption, possibly coeval, from different vents, to produce the rheomorphic and non-rheomorphic units, although we have been unable to determine the location(s) of any such structures. Together, the coarse breccias, absence of fall deposits, and development of features such as caldera lakes, indicates that caldera collapse was relatively rapid and catastrophic.

7 Conclusions

The Loch Bà Caldera comprises a thick sequence of ignimbrites and breccias that have been sub-divided into lithostratigraphic units based on lithology and stratigraphic position. The ignimbrites comprise the Loch Bà Ignimbrite Formation, which has been sub-divided into five distinct members that broadly correspond to five phases of eruption in the caldera. The ignimbrites were deposited rapidly during the sustained passage of a non-uniform and unsteady pyroclastic density current, or a series of rapidly emplaced currents. Lithofacies include: 1) non-welded to eutaxitic massive tuffs, lapilli-tuffs and breccias and rarer planar- and cross-stratified tuffs and lapilli-tuffs; and 2) lava-like tuffs and breccias. The preserved eruption sequence began with a high-energy phase (catastrophic collapse and/or vent-opening) and continued with alternating relatively high- and low-fountaining "boil-over" type eruptions. Caldera collapse occurred along a series of piecemeal fault blocks, and the presence of steeply dipping rheomorphic fabrics and breccias in some of the tuffs close to the faults indicates that fault formation and subsidence was contemporaneous with ignimbrite deposition. Subsidence in the caldera continued and resulted in deposition of the mesobreccias and megabreccias of the Loch Bà Breccia Formation during high-energy mass wasting events.

This study provides important insight to the mechanisms of caldera collapse and evidence for the transition from structure-controlled subsidence to erosion-controlled subsidence. The early part of caldera subsidence was dominated by thick, coarse ignimbrites indicating catastrophic collapse during the eruption, followed by piecemeal collapse, and then mass wasting as explosive volcanism ended. The caldera also records evidence for coeval eruption of rheomorphic and non-rheomorphic ignimbrites and the rapid switching between more typical high fountaining to low fountaining "boil-over" type eruptions. Such relationships are not typically recognised in other high-grade ignimbrite sequences/calderas and provide further insight to these relatively poorly understood eruptions.

Author Contributions

PN and DB undertook fieldwork, wrote the manuscript, and prepared figures. RD undertook fieldwork and edited the manuscript.

Acknowledgements

Peter Reynolds is thanked for field assistance and logistical support in Loch Bà. Brian Bell and John Faithfull are thanked for introducing DB to the area and for helpful discussion. Adriano Pimental and Natasha Dowey are thanked for helpful, constructive reviews that greatly improved the manuscript. Alexandra Kushnir is thanked for editorial support.

Data Availability

All data are available on request from the corresponding author.

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