RESEARCH ARTICLE

VOLCANICA

"Hot and sticky" and "cold and damp" pyroclastic eruptions, and their relationship with topography: valley- and lake-filling ignimbrites, Ardnamurchan, NW Scotland

David J. Brown*[α], Ailsa K. Quirie[α,β], Peter Reynolds[α,γ], and Simon M. Drake[δ]

[α]School of Geographical and Earth Sciences, University of Glasgow, Molema Building, Lilybank Gardens, Glasgow, G12 8QQ, UK.
[β]Shell International, Shell Centre, London, SE1 7NA, UK.
[γ]Kendal College, Milnthorpe Road, Kendal, Cumbria, LA9 5AY, UK.
[δ]School of Earth and Planetary Sciences, Birkbeck College, University of London, Malet Street, London, WC1E 7HX, UK.

Abstract

Pyroclastic density currents are complex mixtures of rock, ash and gas and represent significant hazards at many active volcanoes worldwide. Ignimbrites are the deposits of pyroclastic density currents and can be used to record the eruption dynamics and the interaction of the current with the landscape over time and space. The Sròn Mhòr Member in Ardnamurchan, NW Scotland, is a newly documented sequence of silicic Paleocene ignimbrites. Five phases of eruption are recorded by the ignimbrites, which range from non-welded to welded to lava-like. Between each eruption phase, a period of non-deposition occurred, during which rapid erosion and incision took place. The ignimbrites record how pyroclastic density currents of different temperature, grain size, rheology, and composition interacted with the landscape, filling ancient valleys and lakes, before switching to or re-establishing new drainage pathways. Our results provide further insight into ignimbrite deposition that can be applied to volcanoes worldwide.

Keywords: Ignimbrite; Pyroclastic density current; Topography; Magma mixing; Paleocene.

1 Introduction

Ignimbrites are the deposits of pyroclastic density currents (PDCs) and provide vital records of the nature of pyroclastic eruptions, including their explosivity, the nature of the current in terms of its particulate matter and flow dynamics, the interaction of the current with the contemporaneous landscape, and the sedimentation of the resultant deposit. Pyroclastic eruptions at active volcanoes are hazardous events, and due to these dangers they can be difficult to monitor and analyse. Furthermore, at active volcanoes the resultant deposits may be rapidly covered by the deposits of later events, and/or rapidly eroded by subsequent PDCs and/or erosive events. Whilst acknowledging that burial, erosion, alteration, metamorphism, and intrusion may obscure observations at ancient volcanoes, they can provide insight where incised deposits allow us to study the architecture of pyroclastic systems. Therefore, in conjunction with experimental and numerical modelling studies, we must investigate ignimbrites from both ancient and recent volcanic eruptions to help understand the nature of the density currents and their eruptive behaviour, as well as the interaction of currents with the landscape.

PDCs may undergo rapid switching of eruptive styles and flow dynamics [e.g. Branney and Kokelaar 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014; Breard et al. 2016; Breard and Lube 2017; Lube et al. 2020] and so detailed observation of ignimbrite lithofacies, together with experimental and numerical modelling, is required to reconstruct these events. PDCs have a complex relationship with the topography. They typically seek out topographic lows such as valleys or basins where deposition is concentrated [Pittari et al. 2006; Kokelaar et al. 2007; Doronzo et al. 2010; Brown and Branney 2013]; however, the current can be depositing in one area whilst bypassing (i.e. not depositing) others, before potentially switching to new areas [Brown and Branney 2004; Williams et al. 2014]. The resultant deposits provide only a partial record of the density current due to syn- and post-eruptive erosion, and bypassing/non-deposition of the current, and therefore do not truly reflect the total volume of erupted product [e.g. Brown and Branney 2004; 2013]. PDCs may encounter topographic barriers that limit their runout; however, they can potentially overtop these, leading to deposition in new areas [e.g. Bursik et al. 1998]. They may also undergo buoyancy reversal and liftoff into buoyant plumes injecting ash into the atmosphere [Andrews and Manga 2011]. Currents may initially be topographically restricted before advancing in all directions and overtopping topographic barriers [Williams et al. 2014]. As PDCs move over topography they are also capable of eroding substrates. This may influence the lithic content of resultant ignimbrites, but critically promotes self-channelisation of the PDCs, which can lead to continued and substantial erosion of the substrate [Brand et al. 2014].

The nature of ignimbrites is also greatly affected by eruption and density current temperature. Ignimbrites may range from non-welded to welded to lava-like, reflecting progressively lower eruption columns/air entrainment and explosivity, and increased temperature [Ross and Smith 1961; Walker 1983; Branney and Kokelaar 2002; Trolese et al. 2019], although welding is also influenced by factors such as magmatic temperature, particle concentration, PDC runout distance, and deposit thickness/overburden [e.g. Branney and Kokelaar 1992;

* david.brown@glasgow.ac.uk

Submitted: 2024-01-31 | Accepted: 2024-05-21 | Published: 2024-07-25

Editor: P. Rowley | Typesetter: J. Farquharson

Freundt and Schmincke 1995; Freundt 1998; 1999; Branney and Kokelaar 2002; Quane and Russell 2005; Wadsworth et al. 2019]. How these “hot” and “cold” eruptions may differ, especially their relationships with topography, is only partially understood.

This study attempts to unravel some of the complexities of pyroclastic density current behaviour and ignimbrite deposition with a case study of Paleocene ignimbrites from Ardnamurchan, NW Scotland (Figures 1 and 2). This newly documented sequence of pyroclastic rocks preserves a variety of non-welded, welded and lava-like ignimbrites, which we define as the “Sròn Mhòr Member” after their type-locality (“Sròn Mhòr” = Scottish Gaelic for “Big Nose”). We identify five phases of eruption, each with prolonged periods of repose and erosion in between. PDCs in each successive eruptive phase interacted with the palaeo-topography in complex ways, influencing the resultant ignimbrite type and its structure. Our results show that ignimbrites provide excellent palaeo-geographic and palaeo-environmental proxies, and that studies of ancient volcanics can aid in our understanding of eruption dynamics and the development of ignimbrite sheets. This knowledge may be applied to data gathered from active and recent eruptions and used in conjunction with experimental and numerical modelling data.

2 Regional geology

The modern day Ardnamurchan peninsula (Figure 1A) comprises basement regional metamorphic rocks, typically psammites and pelites, of the Neoproterozoic Morar Group of the Wester Ross Supergroup (formerly and widely known as part of the “Moine Supergroup”) [Richey and Thomas 1930; Krabbendam et al. 2021]. The basement rocks are unconformably overlain by thin exposures of Mesozoic sedimentary rocks, typically Lower Jurassic in age. The remainder of the peninsula is dominated by Paleogene igneous rocks [Richey and Thomas 1930] (Figure 1B).

The rocks described in this study make up part of the British Paleogene Igneous Province (BPIP), a sector of the much larger North Atlantic Igneous Province (NAIP), a Large Igneous Province. The NAIP is associated with the opening of the North Atlantic Ocean, where thinned continental crust was rifted and sea-floor spreading occurred [Thompson and Gibson 1991; Saunders et al. 1997]. North Atlantic opening and the development of the NAIP is attributed to the emplacement of the Iceland plume at 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 oldest recorded 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]). Early volcanism was dominated by the eruption of three subaerial lava fields (Eigg, Skye and Mull) in the Hebrides of Scotland (Figure 1A), which were emplaced from fissure systems and central vents. These lava fields were then intruded by upwelling magma, interpreted as the shallow roots of large Paleogene volcanoes, up to 10 km in diameter (see reviews by Bell and Williamson [2002] and Emeleus and Bell [2005]). These intrusive masses and associated volcanic rocks are typically referred to as “central complexes” (Figure 1B). Paleogene pyroclastic rocks associated with the central complexes have typically been interpreted as subsided intra-caldera fills, for example on Mull [Bailey et al. 1924; Sparks 1988], Rum [Troll et al. 2000; Holohan et al. 2009], and Skye [Bell 1985; Drake et al. 2022] as well as Arran, located in south western Scotland (Figure 1A) [Gooday et al. 2018]. Other limited exposures of pyroclastic rocks not associated with caldera fills are located on the Isle of Eigg (the “Sgurr of Eigg Pitchstone” [Emeleus 1997; Brown and Bell 2013]).

The Mull Lava Field (Mull Lava Group [BGS 2009]) comprises three distinct (lithostratigraphic) formations: 1) the oldest 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 youngest Central Mull Lava Formation [Bailey et al. 1924]. The lava field dominates much of the Isle of Mull, but remnants of it are also preserved on the nearby Ardnamurchan and Morvern peninsulas (Figure 1B). These basalt lavas have been assigned to the Plateau Formation of the Mull Lava Group [BGS 2009].

The Ardnamurchan Central Complex is divided into three geographic centres of igneous activity (Centres 1 to 3) (Figure 1B) [Richey and Thomas 1930; Bell and Williamson 2002; Emeleus and Bell 2005]. Centre 1 is the earliest phase of activity and is characterised by various cone sheets/deflected dykes and rarer larger intrusive sheets (e.g. the Ben Hiant Dolerite; Figure 2) of basalt and microgabbro/dolerite [Richey and Thomas 1930; Magee et al. 2012a; b]. Centre 2 is dominated by larger gabbroic intrusions, some of which are layered, and mixed magma ring-intrusions [Richey and Thomas 1930; Day 1989]. Centre 3 is dominated by large gabbroic intrusions [O'Driscoll et al. 2006; O'Driscoll 2007] and minor intermediate to silicic intrusions towards its centre. Radiometric dating of the complex is limited but Centre 3 intrusions have been dated at ~59.05–58.6 Ma [Emeleus and Bell 2005].

A series of clastic rocks are located at the margins of the Ardnamurchan Central Complex. These rocks were originally interpreted as “vent agglomerates,” pyroclastic rocks associated with explosive eruptions and collapse of material into the crater [Richey and Thomas 1930; Richey 1938]. The area around the mountain Ben Hiant and its subsidiary peaks Sròn Mhòr and Stallachan Dubha (Figure 2), which forms the basis of the current study, received particular attention, with Richey [1938] envisaging a series of “rhythmic eruptions” from the vent and accumulation of agglomerate and tuff. Both the rocks at Ben Hiant and in the Achateny area in the east and north-east of the peninsula (Figure 2) were re-interpreted in recent years as debris flow conglomerates and breccias, locally interbedded with fluvial and lacustrine sandstones and siltstones, and were re-classified as the Ben Hiant Member and the Achateny Member of the Plateau Formation of the Mull Lava Group [Brown and Bell 2006; 2007; BGS 2009]. Following the re-interpretation of the “vent agglomerates” as sedimentary rocks [Brown and Bell 2006; 2007], there are no other documented exposures of pyroclastic rocks on the Ardnamurchan peninsula. Within the study area (Figure 2), prominent exposures of a glassy/vitrophyric rock, or “pitchstone,” with a dacitic composition [Preston et al. 1998], were variably interpreted as lavas [Richey and Thomas 1930; Richey 1938] and sills [BGS 2009].

3 Methodology, constraints, and terminology

Field mapping was undertaken in the area around Sròn Mhòr and Ben Hiant (Figure 2). We define the pyroclastic rocks identified in this area as the "Sròn Mhòr Member," which unconformably overlies the Ben Hiant Member [Brown and Bell 2006; 2007]. Together, these members are part of the Plateau Formation of the Mull Lava Group (aka Mull Lava Field) [BGS 2009]. The Sròn Mhòr Member was sub-divided into five distinct phases, defined by their stratigraphic position, including way-up indicators such as cross-stratification, and lithofacies architecture (Figures 2 and 3; Table 1). Stratigraphic logging was undertaken where possible, and palaoecurrents/flow directions measured where appropriate. Petrographical analysis of the ignimbrites was undertaken to assist field interpretation.

Exposure in the study area is relatively limited and the rocks are often heavily weathered and altered. Given these constraints it can be difficult to identify lithofacies and units across wide areas. Logging was only possible at one type locality and so correlations across the study site were impossible. Given the constraints of exposure, determining fragmentation mechanism, transportation process, or depositional setting can be challenging. For ambiguous deposits, the descriptive, non-genetic terminology of Cas and Wright [1987] was used. Where primary pyroclastic textures/features (e.g. pumices, welding fabrics, rheomorphism) were clearly identified, then standard 'primary volcaniclastic' terminology was used [White and Houghton 2006].

An "ignimbrite" is defined as the deposit of a PDC, typically rich in pumice and pumiceous ash shards [Branney and Kokelaar 2002]. "Pyroclastic density current" 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 may contain gradations from "fully dilute" to "granular fluid-based" [Branney and Kokelaar 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014] (Table 1). Ignimbrites are typically deposited by "progressive aggradation," with incremental growth during the sustained passage of a PDC, although aggradation can also be "stepwise". Variations in grain size, sorting, and structure within ignimbrites are due to spatial and temporal fluctuations in flow competence, velocity, and clast concentration operating within the current, and the nature of the "flow boundary zone" between current and deposit [Branney and Kokelaar 1992; 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014] (Table 1). Massive and diffuse-stratified deposits have been associated with granular fluid-based currents, with "fluid-escape dominated" and "granular flow dominated" flow boundary zones respectively, and stratified deposits have been associated with fully dilute currents, with "traction dominated" flow boundary zones [Branney and Kokelaar 1992; 2002; Sulpizio and Dellino 2008; Sulpizio et al. 2014] (Table 1). However, PDC dynamics are incredibly complex and there is a vast body of recent literature based on experimental and modelling studies on these topics, which are beyond the scope of this study [e.g. Rowley et al. 2014; Sulpizio et al. 2014; Lube et al. 2015; Breard et al. 2016; Dufek 2016; Breard and Lube 2017; Dellino et al. 2019; 2020; Jones et al. 2023].

Ignimbrites are defined as "non-welded" (non-defomed pyroclasts) to "welded" (flattened and aligned pyroclasts, displaying fiamme/eutaxitic texture) to "lava-like" (agglutinated/coalesced pyroclasts displaying flow banding/fabric and rheomorphic structures), reflecting changes in temperature, explosivity, eruption column height, deposit thickness etc., as outlined above [e.g. Walker 1983; Branney and Kokelaar 1992; Freundt and Schmincke 1995; Freundt 1998; 1999; Branney and Kokelaar 2002; Quane and Russell 2005; Andrews and Manga 2011; Wadsworth et al. 2019].

Lithofacies in the ignimbrites (Table 1) were defined using non-genetic terminology based upon features such as internal sedimentary structure, grain size, sorting, and composition [after Branney and Kokelaar 2002]. Full lithofacies terms are used in the text and Table 1 and any abbreviations summarised in the figures. We use the term "valley-fill" or "valley filling" to describe parts of ignimbrite sheets deposited within valleys, and the term "veneer" to describe, in a non-genetic sense, topography-draping, thinner ignimbrites deposited on topographic highs [Brown and Branney 2013].

4 Field relationships and petrography

We have sub-divided the Sròn Mhòr Member into five phases (Figure 3) based on our field mapping (Figure 2) and these are also summarised in Table 1. These phases represent distinct eruptive periods with significant hiatuses between each, as recorded by the presence of erosional unconformities ("palaeo-valleys") and/or interbedded sedimentary rocks. Field relationships between the five phases are complex, and nowhere in the study area are all exposed in stratigraphic continuity, indicating that deposition was highly localised and/or preservation potential of the deposits was poor. Within some phases various sub-units can be identified. Given the absence of weathering horizons/palaeosols or interbedded sedimentary rocks between sub-units, this indicates that each phase likely represents a single eruptive period 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 [Branney and Kokelaar 2002; Sulpizio and Dellino 2008]. The Sròn Mhòr Member in the study area is cut by microgabbro and porphyritic microgabbro Centre 1 intrusions of the Ardnamurchan Central Complex [Richey and Thomas 1930] (Figure 2) and so the ignimbrites must pre-date these. Later Centre 3 intrusions of the central complex provide the only available radiometric ages, and these are dated from ~59.05–58.6 Ma [Emeleus and Bell 2005]. Due to the constraints of exposure, we cannot preclude the existence of earlier or later eruptive phases in the sequence.

4.1 Phase 1

Phase 1 ignimbrites are only preserved in two isolated localities to the NW of Ben Hiant and comprise pumiceous (heavily altered and locally chloritised), locally welded, massive breccia (Figures 2 and 3). The breccia is clast- to matrix-supported and clasts are sub-angular pumice, ranging from lapilli typically 2–5 cm across, to blocks 8–10 cm across and locally up

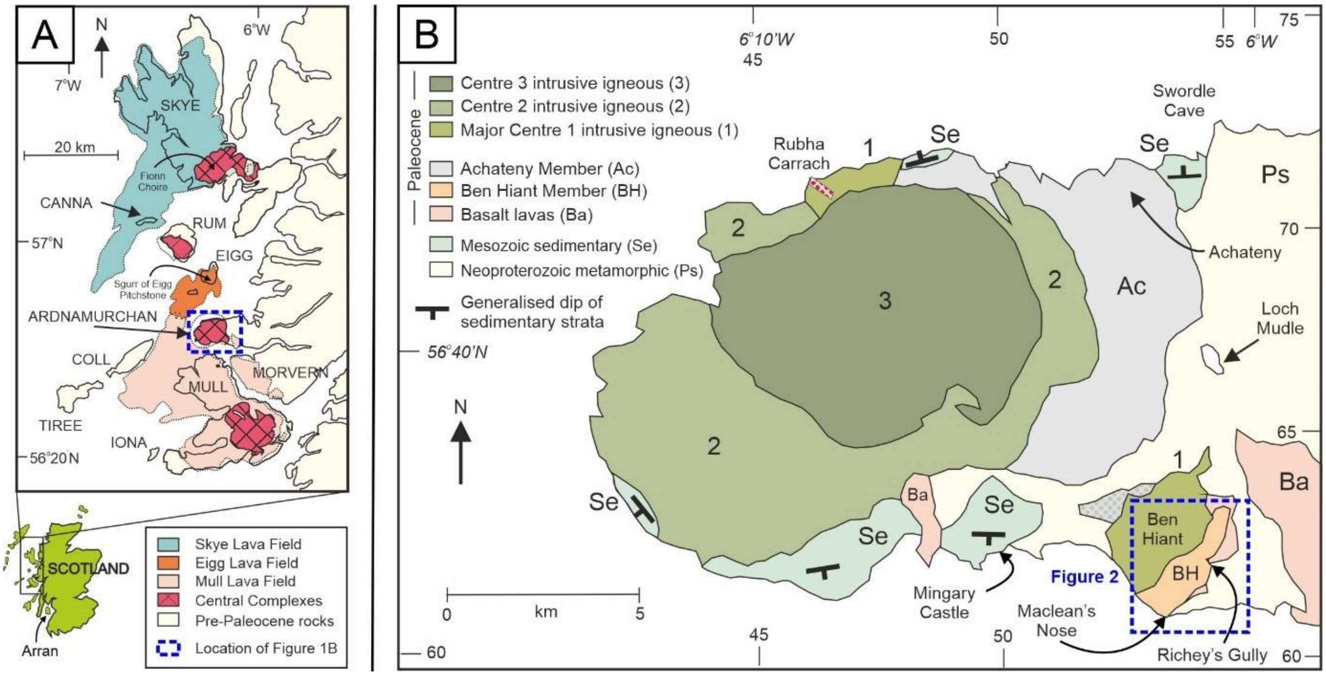

Figure 1: [A] Simplified geological map of the British Paleogene Igneous Province. Blue box shows position of Figure 1B. [B] Simplified geological map of the Ardnamurchan Central Complex. Blue box shows position of Figure 2. Ordnance Survey of Great Britain National Grid provided.

to 20 cm (Figure 4A). The matrix is fine ash and comprises incipiently welded, altered pumiceous fragments, which are flattened and partially aligned, and quartz and feldspar crystals (Figure 4B).

4.1.1 *Interpretation*

The Phase 1 massive breccia records deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based PDC [Branney and Kokelaar 2002; Sulpizio and Dellino 2008]. The massive breccias represent a high-energy phase of an eruption, possibly an initial vent clearing or vent collapse event [Smith and Kokelaar 2013; Jordan et al. 2018; Drake et al. 2022]. The presence of moderately flattened and elongate pumice fragments in the matrix (Figure 4B) indicates sufficient heat was retained for incipient welding of the deposit, both as it aggraded and following deposition.

4.2 Phase 2

Phase 2 comprises a series of reasonably well-preserved tuffs, which have been sub-divided into five separate units (i–v) (Figures 2 and 3). They are well exposed south of Ben Hiant (Figure 2) where they form five distinct sheets up to 25 m thick in total (Figure 5A). These sheets define the five units, which are ~5–10 m thick with well-developed columnar jointing (Figure 5B). An outlier of Phase 2 material is also locally preserved in Richey's Gully (Figure 2), where it forms an exposure with spectacular fan-shaped or radiating jointing pattern (Figure 5C). The units are fine-grained, typically weather grey, range from vitreous to lithoidal, and contain crystals of plagioclase and alkali feldspar, 1–2 mm across, forming <5 % of the rock, as well as rarer crystals of orthopyroxene and clinopyroxene. All units preserve a subtle, but pervasive, base-parallel flow fabric/flow banding (Figure 5D, E). The flow bands are typically 2–3 mm thick, but locally up to 1 cm, and weather dark grey to black. A variety of folds and deformational features are preserved in the flow fabric/flow banding, such as recumbent isoclinal folds (Figure 5F), sheath folds (Figure 5G), and a variety of contorted, tight, "buckle-style" folds (Figure 5H, I), typically towards the top of units. In thin section, the flow fabric records dark and light bands of quartz and feldspar mosaics, with fabric deflected around crystals, indicating flow (Figure 6A). Small mafic inclusions with cauliform margins are preserved throughout and are often concentrated and/or aligned within flow bands (Figure 6A, B). In all units, rare lithic lapilli of basalt, typically 2–3 cm across, are preserved. Throughout all units, various prolate and aligned amygdales, typically 1–2 cm across, and comprising smoky-blue chalcedony are preserved (Figure 5J). The amygdales are aligned towards the SW (Figure 2). Locally, lithophysae up to 5 cm across and partially filled with chalcedony are preserved (Figure 5K). Units iii and v record thin upper autobreccias (Figures 3 and 5A) comprising clasts of the tuff ranging in size from 2–10 cm, set in a glassy matrix (Figure 6B).

4.2.1 *Interpretation*

These units were previously described as "pitchstones" and variably interpreted as lavas [Richey and Thomas 1930; Richey 1938] and sills [BGS 2009], but here, we interpret them as pyroclastic tuffs. The pervasive base-parallel flow banding (e.g. Figure 3, 5D, 5E, 6A), the absence of thick autobreccias generally, and the complete absence of basal autobreccias are typical of lava-like ignimbrites rather than lavas [e.g. Branney et al. 1992; Henry and Wolff 1992; Branney et al. 2008; Andrews and Manga 2011], and this is further supported by the pres-

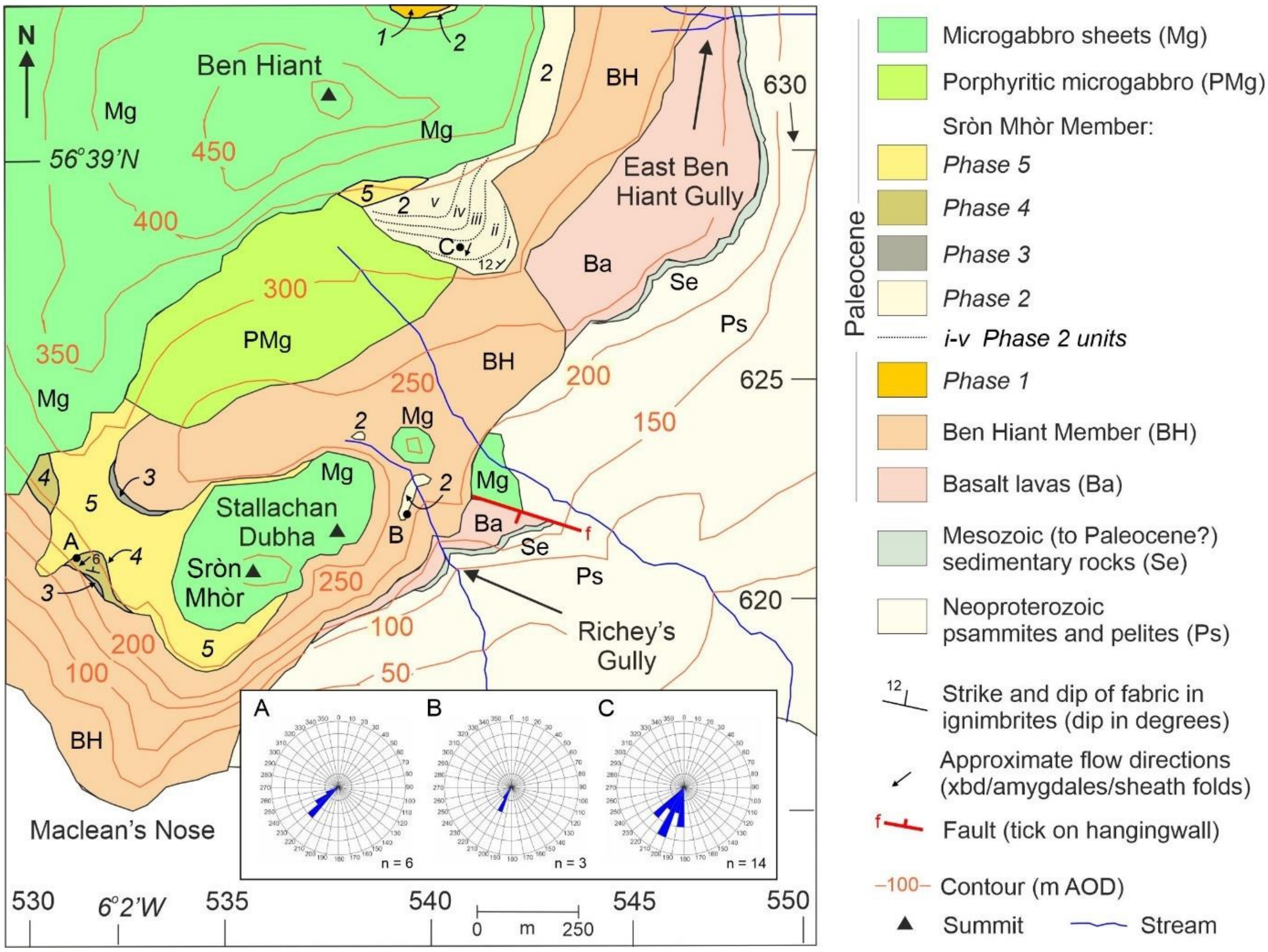

Figure 2: New geological map of the area around Ben Hiant, Ardnamurchan, showing the distribution of the Sròn Mhòr Member. Inset shows position on Ardnamurchan. Ordnance Survey of Great Britain National Grid provided. Rose diagrams showing palaeocurrent/flow directions ([A] – cross bedding, [B] and [C] – aligned amygdales/sheath folds).

ence of rare lithic lapilli. The outlier of Phase 2 material in Richey's Gully, is interpreted as a valley-filling deposit, with the currently preserved exposure with the radiating jointing recording where the ignimbrite was deposited against a steep valley wall [e.g. Jutzeler et al. 2010; Brown and Bell 2013], precluding an intrusive origin. The absence of any country rock between all Phase 2 units further supports this interpretation. We interpret the flow banding as rheomorphic flow structures (i.e. flow fabric and folds). Rheomorphism is caused by syn- and post-depositional hot-state shearing and slumping of the semi-molten pyroclastic deposit [Branney and Kokelaar 1992; Branney et al. 1992; Sumner and Branney 2002; Branney et al. 2008; Andrews and Manga 2011]. These structures indicate that the ignimbrites were formed by a "hot" PDC, generated from a sustained, low-fountaining "boil-over" type eruption, where admixing of air is insufficient to form a buoyant, convecting Plinian-type plume [Branney and Kokelaar 2002], and pyroclasts underwent hot-state agglutination and coalescence. Deposition was likely from a fluid escape-dominated flow boundary zone in a granular fluid-based PDC [Branney and Kokelaar 2002; Sulpizio and Dellino 2008]. Both syn- and post-depositional textures of rheomorphism can be identified. The pervasive base-parallel flow bands (Figure 5D, E), recumbent isoclinal folds (Figure 5F), and sheath folds (Figure 5G) indicate syn-depositional rheomorphism, together with the prolate and aligned amygdales (Figure 5J), which record a stretching lineation imposed by shear on the aggrading deposit by the over-riding PDC [Andrews and Manga 2011; Brown and Bell 2013]. The prolate aligned amygdales and sheath folds provide evidence of flow towards the south and SW. The buckle folds towards the top of units (Figure 5H, I) indicate that as the current passed/dissipated the deposits underwent hot-state slumping and sliding, refolding the earlier formed syn-depositional rheomorphic fabrics, with this deformation being concentrated in the upper (and outer) parts of units [Andrews and Manga 2011]. The localised autobreccias at the top of units iii and v (Figures 3 and 6B) formed as the deposits cooled and fractured [Sumner and Branney 2002; Andrews and Manga 2011; Brown and Bell 2013]. The presence of these post-depositional rheomorphic textures and autobreccias, indicates there was a sufficient pause between emplacement units to develop these features [Andrews et al. 2008].

Table 1: Summary of phases (shown in stratigraphical order) and associated lithofacies in the Sròn Mhòr Member.

Phase and lithofacies	Description	Interpretation
Phase 5: Crystal rich massive lapilli-tuff, (mLTcr)	Dark brown lapilli-tuff with up to 50 vol. % of plagioclase crystals, 1 mm–5 cm, typically 1–2 cm. Crystals crudely inverse graded. Lithic lapilli of typically basalt 1–2 cm across, up to 30 cm. Fine ash matrix.	Progressive aggradation from a high concentration fluid escape-dominated flow boundary zone in a granular fluid-based PDC. Eruption tapped a crystal-rich part of a magma reservoir. Reverse grading of crystals indicates increased mass flux, and/or changes in depth of tapping in magma reservoir.
Phase 4: Massive lapilli-tuff (mLT) and massive breccia (mBr)	Variably matrix- to clast-supported, lithic-rich (typically 5–10 cm, up to 20 cm). Normally and reverse graded.	Entry of a pyroclastic density current into a lake and transition into turbidity current. Granular fluid-based PDCs underwent flow stripping/decoupling. Density stratified underflow deposited breccia and lapilli-tuff. Fines from intraflow underwent suspension settling and/or flow depositing massive to stratified tuffs. Multiple PDCs produce repeating coarse-fine cycles. Slumping, soft-sediment deformation and syn-sedimentary faulting took place.
Massive tuff (mT), parallel-stratified tuff (//s) and cross-stratified tuff (xsT)	Massive to parallel-stratified to planar cross-stratified, with asymmetrical ripples, convolute laminae, and scours. Laminae are normally graded. Syn-sedimentary faults locally present.	
Phase 3: Lava-like massive tuff (mTlava-like) and eutaxitic massive tuff (mTe)	Dark grey tuffs with quartz and feldspar, pumiceous fiamme, thin flow bands.	Deposition from a PDC. The presence of eutaxitic texture and flow banding (Fig. 6C), suggests hot state emplacement, and possible fluctuations in eruption column height from fountaining columns, to lower, sustained, "boil-over" eruptions.
Phase 2: Lava-like massive tuff (mT)	Locally, five units preserved. Well-developed columnar jointing. Dark grey to black. Vitreous to lithoidal, with <5% crystals of typically feldspar. Pervasive base-parallel mm-thick flow banding with recumbent isoclinal, sheath, and buckle folds. Rare lithic lapilli. Aligned chalcedony amygdales and lithophysae. Thin upper autobreccias locally preserved.	Progressive to stepwise aggradation from a "hot" PDC, generated from a sustained, low-fountaining "boil-over" type eruption, pyroclasts agglutinated and coalesced. Deposition was likely from a fluid escape-dominated flow boundary zone in a granular fluid-based PDC. Syn-depositional rheomorphism producing recumbent isoclinal and sheath folds, post-depositional rheomorphism producing buckle folds and autobreccias.
Phase 1: Pumice-rich massive breccia (mBrp)	Clast- to matrix-supported, altered sub-angular pumice clasts, 2–20 cm across, locally welded. Fine ash matrix, incipiently welded pumice.	Progressive aggradation from a high concentration fluid escape-dominated flow boundary zone in a granular fluid-based PDC.

4.3 Phase 3

Phase 3 ignimbrites are preserved only extremely sporadically as thin, highly weathered, small exposures (Figures 2 and 3), and are a maximum of 2 m thick. They are dark grey extremely fine tuffs with 1–2 mm crystals of quartz and feldspar, and vary from eutaxitic, as recorded by aligned altered pumiceous fiamme (Figure 6C), to lava-like, as recorded by thin flow bands.

4.3.1 *Interpretation*

Due to the limited exposure, it is difficult to interpret this sequence, but it likely records deposition from a PDC. The presence of eutaxitic texture and flow banding (Figure 6C), suggests hot state emplacement, and possible fluctuations in eruption column height from fountaining columns, to lower, sustained, "boil-over" eruptions. The resultant PDC certainly retained sufficient heat to cause welding and/or agglutina-

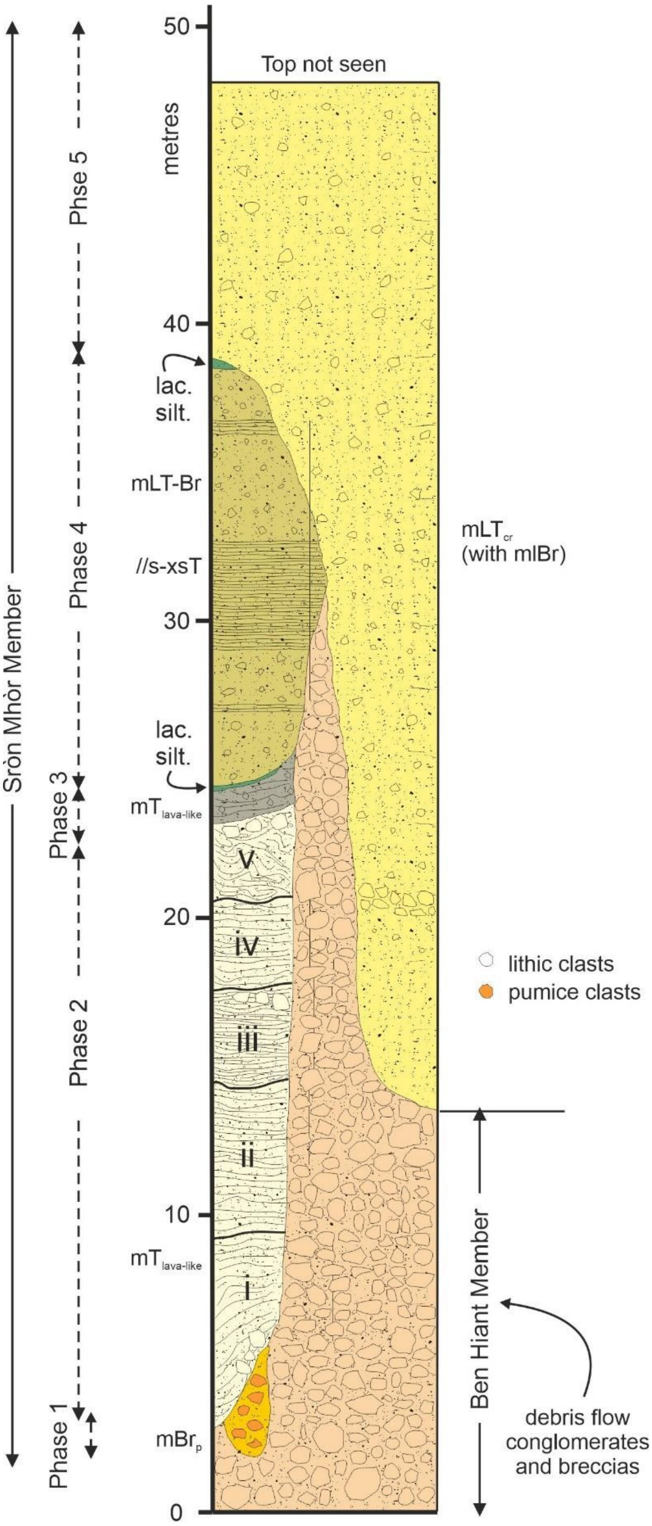

Figure 3: Generalised vertical section of the Sròn Mhòr Member showing complex topography-filling relationships. Colours used are schematic and not representative of actual lithologies. T – tuff; LT – lapilli-tuff; Br – breccia; m – massive; //s – planar-stratified; xs – cross-stratified; l – lithic-rich; cr – crystal-rich; p – pumice-rich; lac. silt – lacustrine (volcaniclastic?) siltstone.

tion/coalescence and rheomorphism [Branney and Kokelaar 1992; 2002].

4.4 Phase 4

Phase 4 comprises a spectacular series of enigmatic deposits with a complex depositional history. Exposure is limited to sporadic examples in the west of the study area (Figures 2 and 3). The base of the sequence comprises a thin (<10 cm) dark brown, blocky siltstone. This is overlain by ~12 m of various tuffs, lapilli-tuffs, and breccias, ranging from massive to diffuse-stratified to planar- and cross-stratified (Figure 7). The breccias are massive, variably matrix- to clast-supported, lithic-rich, and comprise blocks and lapilli of basalt and rarer local country rocks, typically 5–10 cm across and up to 20 cm (Figure 8A). Lapilli-tuffs are similar to the breccias and typically massive, although some diffuse stratified variants are present (Figure 8A). The lapilli-tuffs and breccias are normally and inverse graded. The tuffs range from massive to stratified, with the stratified units preserving a variety of spectacular structures, including planar cross-stratification (Figure 8B), asymmetrical ripples (Figure 8C, D), convolute laminae (Figure 8C, D), and scours (Figure 8E). Palaeocurrent directions from cross-bedding are typically towards the SW–WSW (Figure 2). Syn-sedimentary faults, with very thin bands of fine ash plastered along the fault plane are locally present (Figure 8E). In thin section, some laminae in the tuffs are normally graded (Figure 8F). Small mafic inclusions with cauliform margins are preserved in the tuffs and are often concentrated and/or aligned within laminae (Figure 8F). The very top of the sequence is topped by another thin dark brown, blocky siltstone, which is unconformably overlain by Phase 5 deposits (Figures 7 and 9A, B).

4.4.1 *Interpretation*

We interpret Phase 4 as the deposits of a PDC (or series of rapidly emplaced currents) that entered a body of water such as a lake, and which may have started to behave more like a turbidity current [e.g. Kokelaar et al. 2007; Gihm 2023; Martin-Merino et al. 2023]. It is possible to interpret the sequence as wholly pyroclastic; however, the presence of the basal and upper siltstones (Figures 7 and 9B), indicates the presence of a body of water at the beginning and end of eruption. Although the (volcaniclastic?) siltstone is only thin and poorly preserved, and has no diagnostic fossils or structures, we interpret it as a low-energy lacustrine deposit, formed in the hiatus between phases 3 and 4. There is no evidence of any marine incursions in this area during the Paleogene, and lacustrine deposits with supporting palynological evidence have been identified interbedded with debris flow conglomerates and breccias in the underlying Ben Hiant Member (beneath the Sròn Mhòr Member) [Brown and Bell 2006; 2007]. It seems reasonable for low-energy background sedimentation to have taken place during eruption hiatuses, as topographic depressions became filled with water. Furthermore, the presence of convolute lamination structures (Figure 8C, D) supports the occurrence of soft sediment deformation during (and after?) deposition, with possible fluid-escape during loading [Owen et al. 2011], and/or seismic shaking of sediment/tephra [Bran-

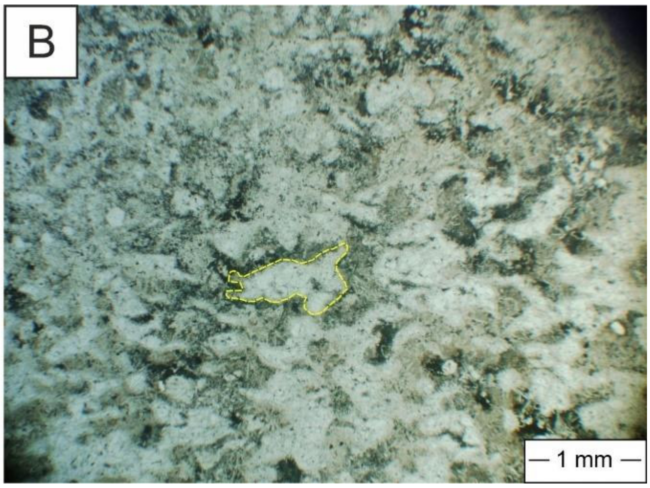

Figure 4: [A] Massive pumice-rich breccia of Phase 1. Knife is 2 cm across. [B] Photomicrograph (PPL) of matrix of Phase 1 altered pumice-rich breccia, with incipiently welded altered pumiceous fragments throughout (example highlighted in yellow). Scale bar is 1 mm across.

ney and Kokelaar 1994; Kokelaar et al. 2007]. These structures are typical of fine-grained sediments and are common in turbidites [Owen et al. 2011; Tinterri et al. 2016] in lacustrine and marine environments, as well as being recognised in pyroclastic deposits [e.g. Douillet et al. 2015].

We suggest that a granular fluid-based PDC entered the proposed lake and underwent flow stripping/decoupling, with a density stratified underflow penetrating down into the lake and depositing the coarse breccias and lapilli-tuffs (e.g. Figure 8A), whilst a stripped fully dilute current travelled along the lake surface [Carey et al. 1996; Kokelaar et al. 2007; Trofimovs et al. 2008; 2013; Gihm 2023]. In the upper parts of the lake, granular intraflows developed from vigorous mixing with lake water [Kokelaar et al. 2007; Gihm 2023]. We suggest that following initial pulses of deposition of coarser material from the underflow (Figure 8A), finer material from the underflow began to settle out, together with fines from the intraflow, and/or settling from the fully dilute current at the surface, or perhaps even fines from lofting plumes above the current [Kokelaar et al. 2007; Gihm 2023; Martin-Merino et al. 2023]. These fines underwent suspension settling and/or flow, with tractional sedimentary structures (i.e. cross-stratification, ripple cross-lamination) forming at higher flow velocity and planar lamination at lower flow velocity (e.g. Figure 8B–D) [Kokelaar et al. 2007; Gihm 2023; Martin-Merino et al. 2023]. There were likely multiple pulses of PDCs into the lake, explaining the repeating coarse–fine cycles preserved (Figure 7). As tephra was deposited within the lake, slumping and syn-sedimentary faulting took place, together with soft-sediment deformation/loading of the sediment, as discussed above (Figure 8C, E) [Owen et al. 2011; Douillet et al. 2015; Tinterri et al. 2016; Martin-Merino et al. 2023]. Given the absence of obvious primary pyroclastic features it seems that lake water was not displaced such that sub-aerial deposition of PDCs took place here. Rather, PDCs were unsteady and short-lived and transformed into turbidity currents as the front of the PDC disintegrated [Gihm 2023]. Due to the limited exposure/preservation it is challenging to interpret the size and depth of the postulated lake and how proximal or distal these deposits are from the shoreline. However, the mixture of breccias, lapilli-tuffs and tuffs (Figure 7) suggest a more proximal-medial location rather than a distal location where tuff and/or mud would be dominant [Di Capua and Scasso 2020; Zhou et al. 2020; Martin-Merino et al. 2023]. Following the cessation of eruptive activity, background lacustrine sedimentation resumed.

4.5 Phase 5

Phase 5 deposits are concentrated in one large exposure in the west of the study area and limited sporadic exposures elsewhere (Figures 2 and 3). The sequence comprises a spectacular, crystal-rich lapilli-tuff, with a valley-filling geometry (Figure 9A), unconformably overlying the uppermost siltstone of Phase 4 (Figure 9B). Deposits are massive lapilli-tuff, weathering dark brown with prominent crystals of plagioclase feldspar. The crystals range in size from 1 mm up to spectacular examples 5 cm across (~5% of deposit), but are typically 1–2 cm. The crystals form up to 50 vol. % of the rock, although it varies from ~25–50 % (Figure 9C). The unit is inverse graded, indicated by an increase in crystal size.

Sporadic lithic lapilli, typically of basalt and local country rock, 1–2 cm across, are present throughout, and locally, blocks of basalt up to 30 cm across are preserved (Figure 9D, E). These lapilli are not obviously graded but given their scarcity it is difficult to determine. The matrix comprises fine ash, and in thin section rare vitroclastic fragments are deflected around crystals, which are highly fragmented throughout (Figure 9F). Some crystals show resorbed margins and small mafic inclusions with cauliform margins are preserved (Figure 9F).

4.5.1 *Interpretation*

Previously interpreted as a "porphyritic dolerite" [Richey and Thomas 1930], we interpret the Phase 5 massive lapilli-tuff as an ignimbrite due to its valley-filling nature (Figure 9A), the presence of lithic lapilli and blocks (Figure 9D, E), the extensive crystal fragmentation (Figure 9F), and the presence

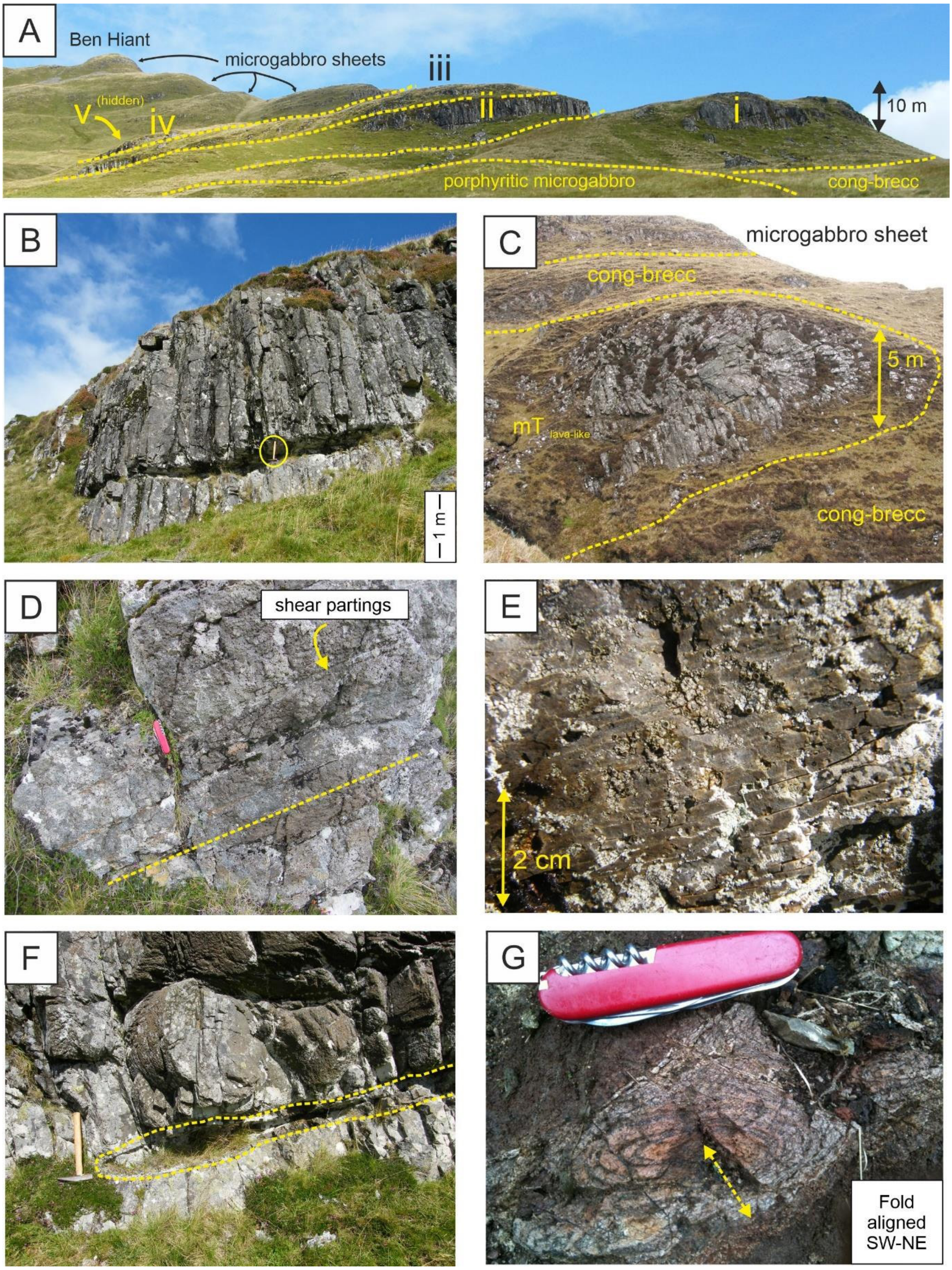

Figure 5: Phase 2 lava-like ignimbrites of the Sròn Mhòr Member. [A] Field relationships of Units i–v in Phase 2. Cong-brecc = conglomerates/breccias of the Ben Hiant Member. [B] Columnar jointing in Unit ii. Hammer (highlighted) is 30 cm in length. [C] Outlier of Phase 2 in Richey's Gulley (Figure 2) with radiating jointing. Cong-brecc = conglomerates/breccias of the Ben Hiant Member. [D] Pervasive base-parallel flow banding in Unit i. Knife is 10 cm in length. [E] Pervasive base-parallel flow banding in Unit iii. [F] Recumbent isoclinal fold in Unit iii. Hammer is 30 cm in length. [G] Sheath fold in Unit iv. Aligned NE–SW. Knife is 10 cm in length.

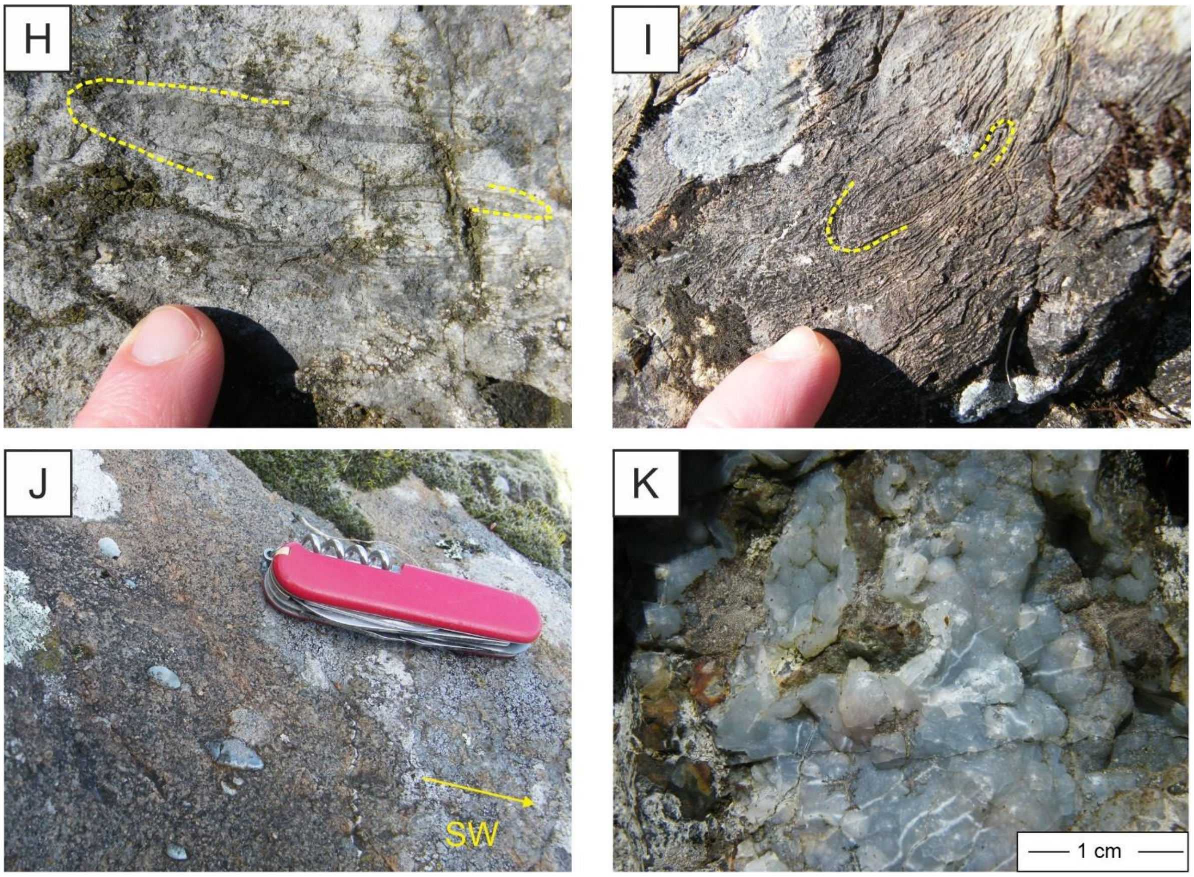

Figure 5 (cont.): Phase 2 lava-like ignimbrites of the Sròn Mhòr Member. [H] and [I] Buckle style folding in Unit ii, with some fold hinges partially highlighted. [J] Aligned prolate amygdales of chalcedony in Unit ii. Oriented SW (arrow). [K] Lithophysae filled with chalcedony.

of vitroclastic material in the matrix (Figure 9F). The lapilli-tuff likely records deposition from a fluid escape–dominated flow boundary zone in a granular fluid-based PDC [Branney and Kokelaar 2002; Sulpizio and Dellino 2008]. The rock is remarkable for the high volume and size of its crystals. Crystal-rich ignimbrites are relatively common, such as the "monotonous intermediates" of, for example, North America [e.g. Hildreth 1981; Lipman 2007], the P1 ignimbrite of Gran Canaria [Freundt and Schmincke 1995], and the Permian Ora Ignimbrite of Italy [Willcock et al. 2013], all of which can have up to ~50 vol.% crystals. However, we are not aware of any other published accounts of crystal-rich ignimbrites with such large crystals (i.e. the 5 cm examples). We suggest that the eruption tapped a crystal-rich part of a magma reservoir, possibly remobilising a crystal mush/cumulate, where large "earlier" formed crystals had grown or were growing (see Section 6). The inverse grading observed in crystal size could reflect variable mass flux during the eruption and/or changes in depth of tapping in the magma reservoir.

5 Eruption Model

We envisage a protracted eruption model (Figure 10) for the Sròn Mhòr Member with periods of erosion and background sedimentation, punctuated by relatively rapid eruptions. The sequence preserves a remarkable variety of lithofacies in a small area and records a wide range of eruption column and density current types and temperatures. As exposure is limited, we cannot preclude earlier and later eruptive events. Phase 1 commenced with highly explosive pumice-rich eruptions, with deposition concentrated in localised palaeo-valleys (Figure 10A). A period of non-deposition of unknown length followed, with palaeo-valleys and depressions developing across the landscape. High temperature, low-fountaining "boil-over" eruptions occurred, depositing the Phase 2 lava-like ignimbrites, which filled the topography and ponded in palaeo-valleys. The aggrading ignimbrite was subject to syn-depositional rheomorphism, and then when the eruption ceased underwent slumping and sliding, forming post-depositional rheomorphic structures (Figure 10A). Similar eruptions formed Phase 3 ignimbrites, although possible fluctuations in eruption column height and temperature resulted in variable welded to lava-like textures. During another period of repose of unknown length, small lakes developed in topographic lows, with background suspension settling sedimentation (Figure 10B). In Phase 4, explosive eruptions generated PDCs, some of which entered the lake, where they underwent flow stripping/decoupling. Coarse material formed underflows and was deposited forming lapilli-tuffs and breccias, whereas fine material was deposited from mixed intraflows or from fully dilute currents at the surface of the lake. The

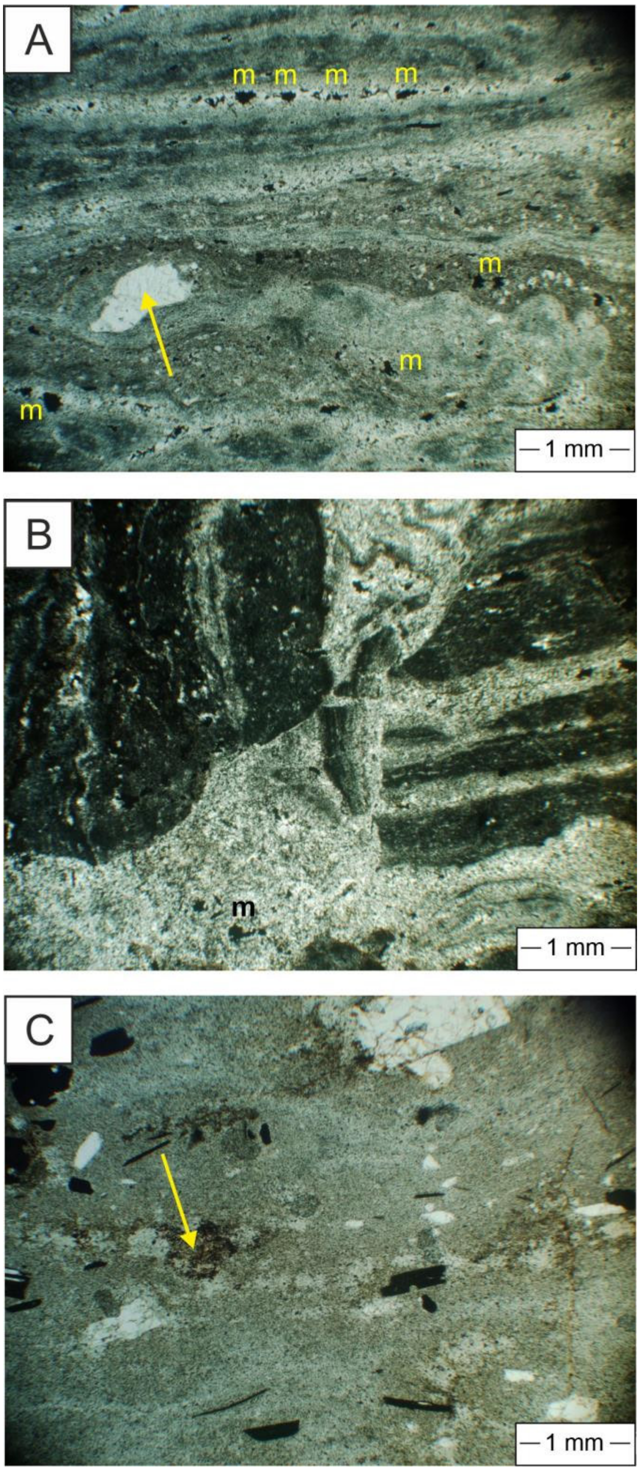

Figure 6: Photomicrographs of Phase 2 and 3 ignimbrites. All images PPL and scale bars 1 mm across. [A] Flow banding/flow fabric in Phase 2 Unit i lava-like ignimbrite. Note banding deflected around resorbed feldspar crystal (arrow). Mafic inclusions (m) with cauliform margins are preserved. [B] Brecciated upper part of Phase 2 Unit iii lava-like ignimbrite, showing clasts of rotated lava-like tuff in glassy matrix. Mafic inclusions (m) with cauliform margins are preserved. [C] Phase 3 welded ignimbrite: eutaxitic tuff showing highly altered pumiceous fiamme (arrow).

fines formed tuffs with tractional sedimentary structures such as cross-stratification and ripples (Figure 10B). The growing deposits were subject to soft-sediment deformation, shaking and faulting. As eruptions ceased, background lacustrine sedimentation re-commenced. Another prolonged period of repose occurred, during which time significant palaeo-valleys developed. A final PDC was erupted, depositing the Phase 5 crystal-rich massive lapilli-tuffs, filling the palaeo-valleys (Figure 10C).

6 Discussion

6.1 Relationships of pyroclastic density currents with topography, and the nature of the palaeo-landscape

PDCs have a complex relationship with topography. PDCs are typically sustained and highly variable in flux, and their deposits record the evolving density current with time and space [e.g. Branney and Kokelaar 2002; Sulpizio et al. 2014; Williams et al. 2014], albeit the vertical record does not reflect the complete eruption sequence. As PDCs move downslope, they may be depositing in some areas, typically in palaeo-valleys or breaks-in-slope at the base of volcanoes, due to depletive flow, whilst completely or partially bypassing other areas [Brown and Branney 2004; 2013; Williams et al. 2014]. These locations may change during an eruption as topography is filled, and/or the current begins to erode its own deposits, and/or later PDCs further adjust the landscape [Brand et al. 2014]. There are extensive studies on the sedimentation of ignimbrites from well exposed modern volcanoes such as Tenerife where thick, extensive ignimbrite sheets are preserved [e.g. Brown et al. 2003; Brown and Branney 2013; Dávila-Harris et al. 2023]. While the level of exposure severely limits such detailed study of the Sròn Mhòr Member, repeated evidence of topography-filling (e.g. valleys, lakes) behaviour is recorded, regardless of the nature of the ignimbrite (non-welded to lava-like). The PDCs preferentially exploited topographic lows, before potentially forming thin veneers on topographic highs [Pittari et al. 2006; Williams et al. 2014]. In hiatuses between eruptions new topographic lows were established. In some cases, lows may have been only partially filled, or exploited multiple times. This appears to have been the case in phases 4 and 5, where the palaeo-valley filled by Phase 5 cuts the site of the lake filled in Phase 4. Based on ignimbrite morphologies and palaeocurrent indicators (Figure 2), we propose a generalised depositional axis running from NE to SW (Figure 11). Our model highlights the main likely topographic lows and postulated thin veneer deposits beyond these. Phase 2 appears to record more southerly transport, before this valley is filled and new lows are carved towards the SW in phases 4 and 5 (Figure 11). Phases 1 and 3 are too localised to include in the model. We note that regionally, the Paleocene lavas filled NNE to SSW trending extensional basins [Emeleus and Bell 2005], and it appears as though this remained the major depositional trend during these pyroclastic eruptions.

Dating of eruptions is beyond the scope of this study, and so determining the durations of repose between eruptions and calculating erosion rates is not possible. Nonetheless, erosion must have been relatively rapid to create such topography.

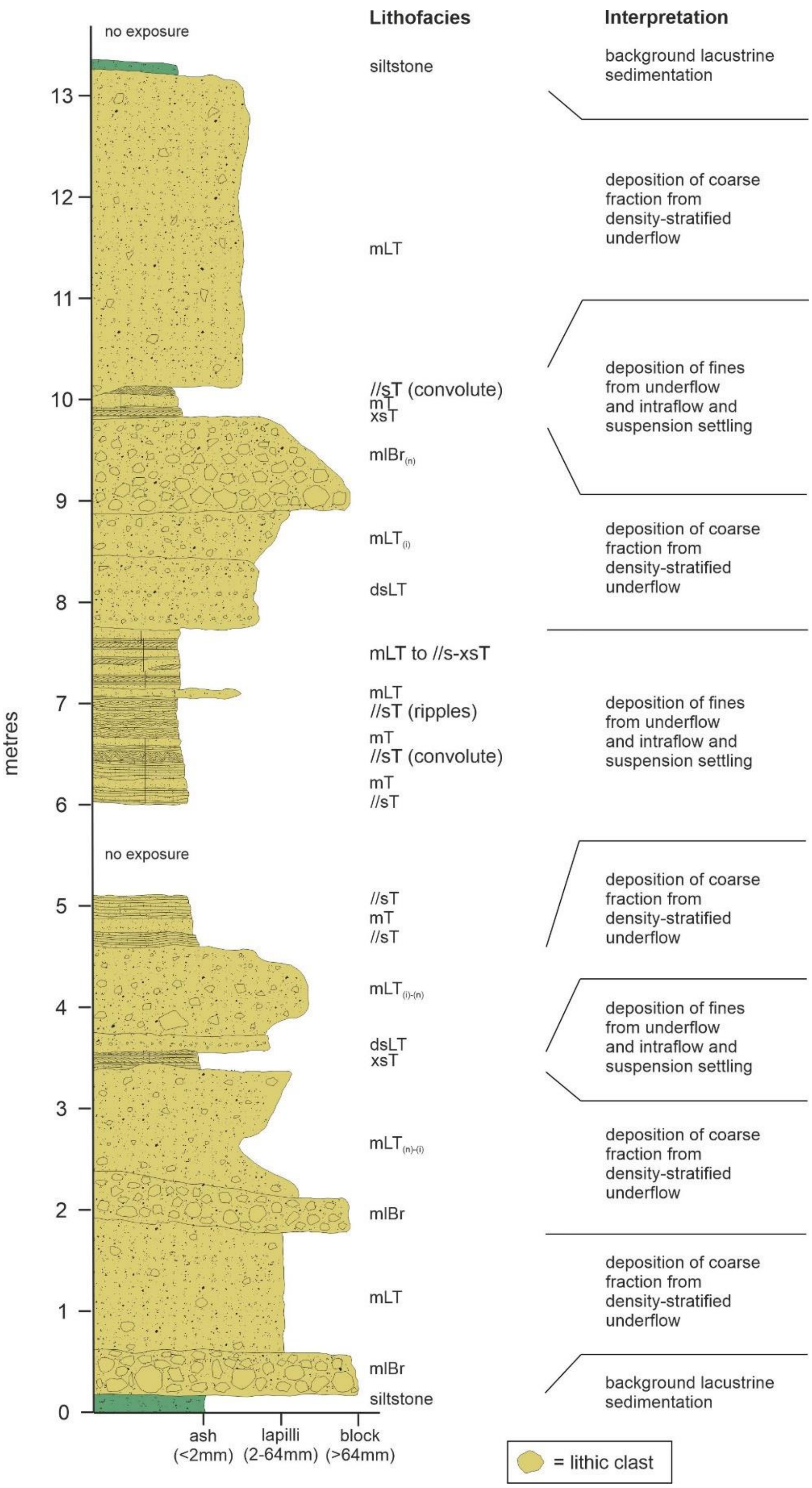

Figure 7: (Left) Stratigraphic log of Phase 4 ignimbrites of the Sròn Mhòr Member. Colours used are schematic and not representative of actual lithologies. T – tuff; LT – lapilli-tuff; Br – breccia; m – massive; ds- diffuse-stratified; //s – planar-stratified; xs – cross-stratified; l – lithic-rich; cr – crystal-rich; p – pumice- rich; (n) – normally graded; (i) – inverse

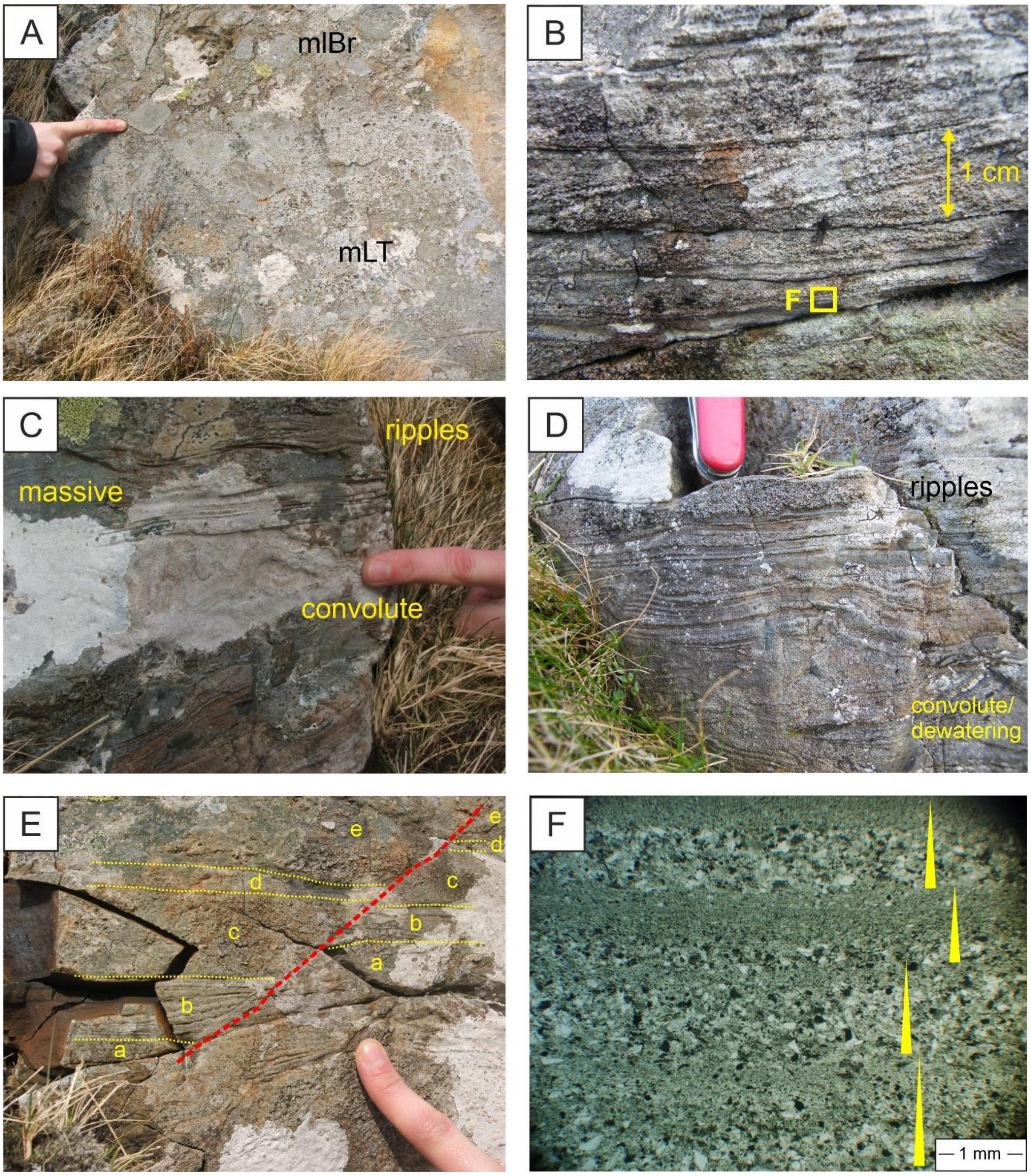

Figure 8: Phase 4 ignimbrites of the Sròn Mhòr Member. [A] Interbedded massive lapilli-tuffs (mLT) and massive lithic breccias (mlBr) showing normal and inverse grading. [B] Cross-stratified tuffs. Palaeocurrent direction is towards the SW. Box shows location of [F]. [C] Stratified tuffs interbedded with thin massive tuffs. Ripples and convolute laminae are present. [D] Stratified tuffs with ripples and convolute laminae. Knife is 2 cm across. [E] Syn-sedimentary fault (highlighted in red) in massive and stratified tuffs. Marker horizons are shown—note thickening of beds on downthrown side. [F] Photomicrograph (PPL, scale bar is 1 mm across) of stratified tuffs showing normally graded laminae (yellow triangles – coarse at base, fine at top). Position of sample noted indicated in [B]. Small black grains comprise mafic inclusions with cauliform margins and other unresolvable fines.

The Sròn Mhòr ignimbrites are cut by intrusions of Centre 1 of the Ardnamurchan Central Complex. This was a period of intense uplift and erosion due to shallow magma emplacement, resulting in the triggering of large debris flows and instability of the landscape forming the Ben Hiant and Achateny members (Figure 2; Brown and Bell [2006, 2007]). The conglomerates and breccias of these units, given their clastic nature and likely limited consolidation, would be prone to rapid erosion promoting the formation of topography and valley incision, to then be exploited by the later PDCs. Although not di-

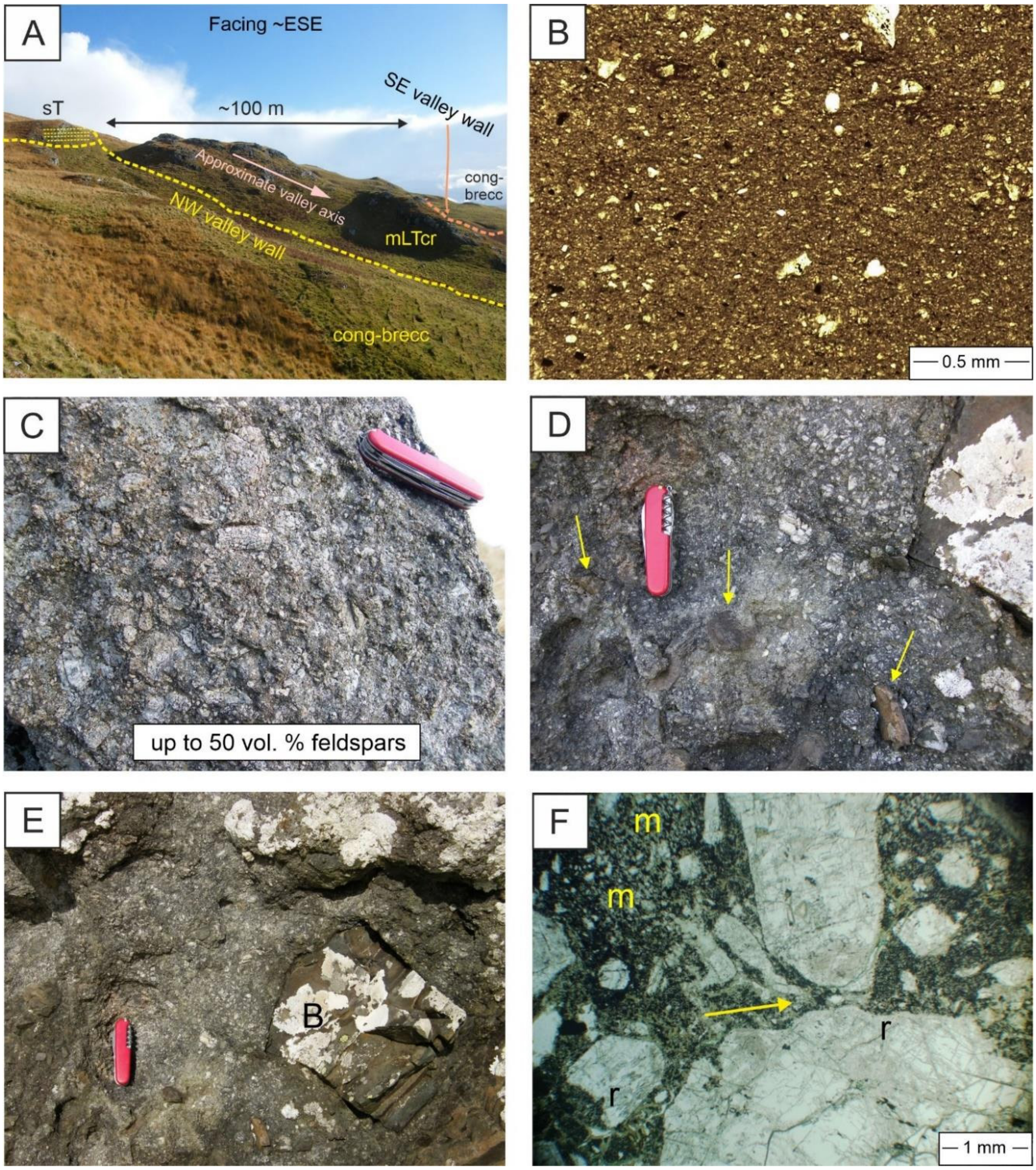

Figure 9: Phase 5 ignimbrites of the Sròn Mhòr Member. Knife in [B]–[E] is 10 cm in length. [A] Field relationships of Phase 5 ignimbrites (mLTcr – crystal-rich massive lapilli-tuff) showing valley-filling nature with underlying conglomerates and breccias of the Ben Hiant Member (cong-brecc) and Phase 4 ignimbrites (sT – stratified tuffs). [B] Photomicrograph of lacustrine (volcaniclastic?) siltstone of Phase 4 sequence. Image is PPL and scale bar is 0.5 mm across. [C] Crystal-rich massive lapilli-tuff of Phase 5, showing ~50% vol. % of plagioclase feldspar crystals. [D] Lithic lapilli (arrows) of basalt in crystal-rich massive lapilli-tuff. [E] Lithic block of basalt (B) in crystal-rich massive lapilli-tuff. [F] Photomicrograph of Phase 5 crystal-rich massive lapilli-tuff showing fractured crystals, fine glassy matrix, and deformed fragments around crystals (arrow). Image is PPL and scale bar is 1 mm across. Some crystals show resorbed margins (r), and small mafic inclusions (m) are present in the matrix.

rectly analogous, for comparison, in the Bandas del Sur Group of Tenerife, seven ignimbrite-dominated formations with significant erosion surfaces and palaeotopography between each formation, were erupted over ~500 kyr [Brown et al. 2003]. In the Sròn Mhòr Member, syn-eruptive erosion by the PDCs may have played a role in developing palaeotopography, both in older underlying deposits, and syn-eruptive aggrading deposits, due to self-channelisation of the PDCs [Brand et al. 2014]; however, no direct evidence of this (e.g. gutter casts, tool marks, the presence of clasts of older phases in younger units) is present [Pittari et al. 2006; Brown and Branney 2013]. Although the nature or proximity of the source volcanic ed-

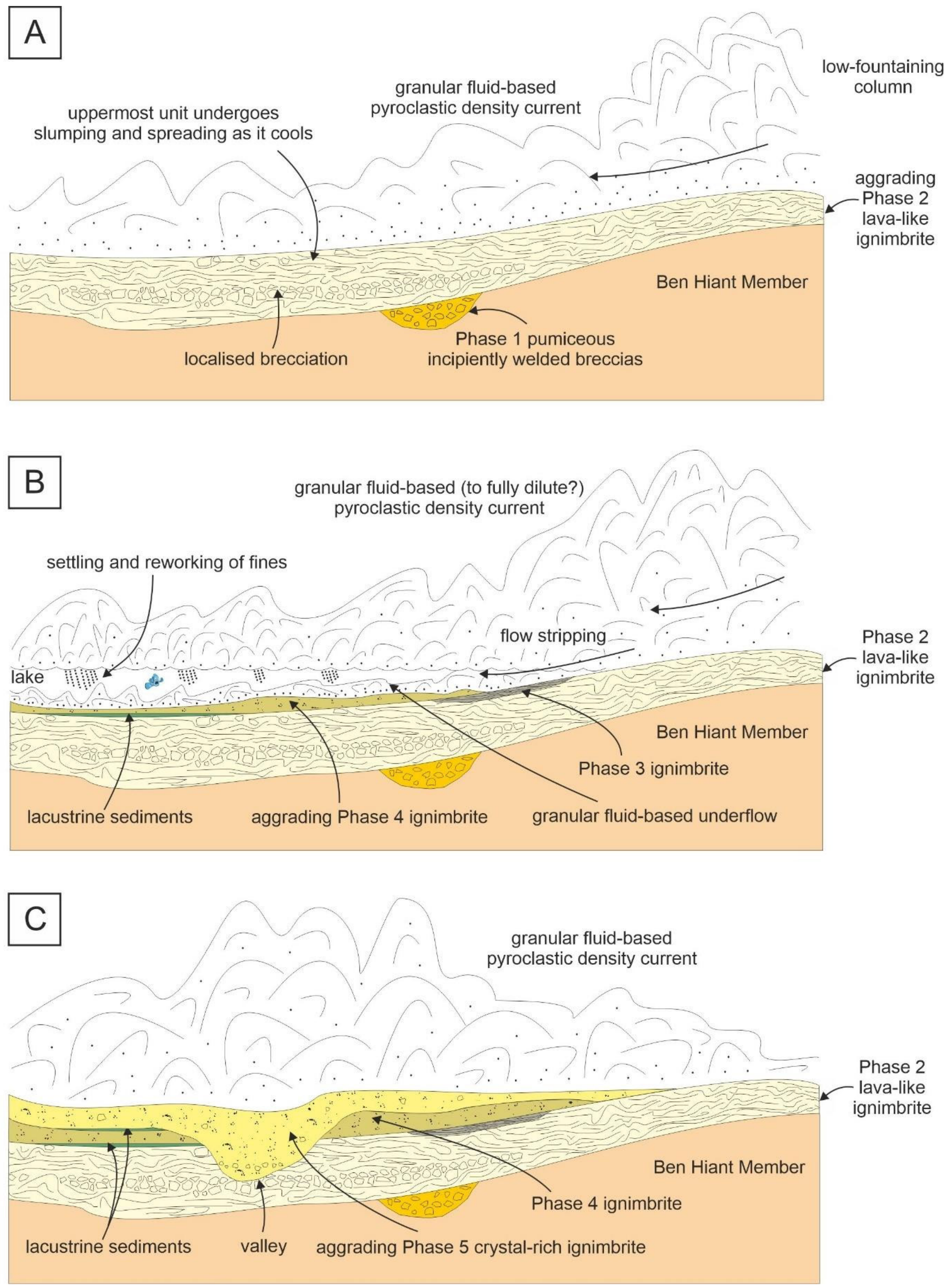

Figure 10: Schematic eruption model of the Sròn Mhòr Member. No scale or geographic orientations are implied. [A] Existing substrate of Ben Hiant Member conglomerates and breccias, with localised palaeo-valleys and depressions. Phase 1 ignimbrites deposited and fill valleys. Period of repose where thin veneers are likely eroded. Phase 2 eruptions begin with a high-temperature low fountaining column collapsing and depositing lava-like ignimbrites, which undergo syn- and post-depositional rheomorphism. The ignimbrites again fill palaeo-topography. Period of non-eruption and erosion. [B] Phase 3 ignimbrites deposited and locally preserved. A lake develops in a larger palaeo-depression and lacustrine suspension settling sedimentation begins. Phase 4 eruptions commence and granular fluid-based pyroclastic density currents enter lake. Flow stripping occurs generating dense underflows depositing coarse lapilli-tuffs and breccias, and fines settling out from intraflows and dilute currents at the lake surface. Eruption ceases, lake-bed eventually dries out and further erosion of valleys occurs. [C] Phase 5 eruptions commence from highly explosive eruptions and deposit crystal-rich lapilli-tuffs which fill palaeo-valleys.

ifice is not known for the Sròn Mhòr Member ignimbrites, the study emphasises the importance of erosional and depositional relationships with topography. Albino et al. [2020] studied pyroclastic eruptions from the 3rd June 2018 eruption of Fuego, Guatemala, using remote sensing data, which demonstrated rapid erosional events and topographic changes in upper volcanic regions and bulking of deposits in valleys and lower slopes, and the processes recorded in this study may be broadly analogous.

6.2 Nature of eruptions and pre-eruptive magmatic conditions

The ignimbrites of the Sròn Mhòr Member record a diverse variety of lithofacies and welding facies (non-welded to welded and lava-like), reflecting highly variable eruption column heights, density current conditions and temperatures. Although erosion and preservation potential are a constraint to this study, ignimbrite sheets elsewhere tend to comprise much thicker units, with stratigraphy dominated by specific styles of ignimbrite. For example, the ignimbrites of the Bandas del Sur Group in Tenerife are dominated by thick pumice-rich non-welded to welded ignimbrites and related fall deposits, associated with Plinian eruptions [Brown et al. 2003; Dávila-Harris et al. 2023]. Conversely, the ignimbrites of the Snake River Plain are dominated by thick lava-like ignimbrite sequences, from low fountaining "boil-over" eruptions, with relatively minor amounts of non-welded ignimbrites [Andrews et al. 2008; Branney et al. 2008; Knott et al. 2016]. Whilst these examples are of course not representative of all ignimbrite sheets, the Sròn Mhòr Member is notable for its rapid switching between end-member eruption types during its (relatively) short emplacement. Similar observations have been noted from other volcanic centres in the BPIP (e.g. Arran [Gooday et al. 2018]; Skye [Drake et al. 2022]), and suggest this is a feature of this igneous province. In all the Sròn Mhòr ignimbrites, associated fall deposits are absent. These may have been removed due to erosion, but it may also suggest that eruptions did not develop *sustained* high Plinian columns.

Phase 1 ignimbrites are pumice-rich, but pumice is rare in other units. Given the age, weathering, and alteration of the deposits, pumice in other units may have been eroded, weathered to clay, diagenetically altered/compacted, and/or rendered unidentifiable due to lava-like textures. Phases 2 and 3 record higher-grade lava-like, and locally welded/eutaxitic ignimbrites, indicative of higher-temperature, low-fountaining eruptions. The Phase 2 lava-like ignimbrites have a bulk dacitic composition but contain glomerocrysts of pyroxene, titanomagnetite, and ilmenite, along with the main assemblage of plagioclase crystals [Preston et al. 1998]. Many of the crystals show evidence of resorption and we have also observed a variety of mafic inclusions with cauliform margins in all units. Together, these features suggest magma mixing [Troll et al. 2004]. Phase 4 ignimbrites are lithic-rich and at least partially involved the entry of a density current, or currents, into a lake. The presence of abundant coarse lithic lapilli and blocks indicates a high explosivity eruption, although pumice is again noticeably absent. It is unclear whether phreatomagmatism played a role in this eruption phase. The tuffs and matrix of the lapilli-tuffs and breccias comprise very fine ash, much of which is glassy and unresolvable in thin section. Given the likely localised nature of the lake, it seems probable that fragmentation was magmatic, creating variably granular fluid-based and fully dilute density currents. Nonetheless, we cannot rule out further phreatic fragmentation on entry of the density current into the lake and/or interaction of magma with groundwater in the shallow sub-surface, resulting in phreatomagmatism [De Rita et al. 2002]. Mafic inclusions are present in the Phase 4 tuffs, again indicative of magma mixing [Troll et al. 2004; Liszewska et al. 2018], although their extremely fine nature and the associated fine ash and lithic material is indicative of rapid, efficient fragmentation and heat loss. Finally, Phase 5 ignimbrites record a remarkable, coarse, crystal-rich eruption (up to 50 vol.%). This was likely a highly explosive eruption given the energy required to expel so many and such large crystals. Magma may have exploited a volcano-tectonic fault with rapid depressurisation and cracking of country rocks allowing expulsion of a viscous crystal-rich column and subsequent PDC [e.g. Willcock et al. 2013]. As previously suggested, this ignimbrite indicates the tapping of a crystal mush/cumulate in the magma reservoir, although it is unknown whether these are from the roof, wall, or base of the chamber. Mafic inclusions and resorbed crystals are present throughout, and together this suggests the reservoir was fractionating, possibly zoned, and subject to magma mixing [Troll et al. 2004; Liszewska et al. 2018].

In phases 2, 4, and 5, evidence of magma mingling (e.g. mafic inclusions, mafic crystals/glomerocrysts, resorbed crystals) is preserved, and cannot be ruled out in the poorly exposed Phase 1 and 3 ignimbrites. These features indicate the repeated influx of hotter basaltic magma into more silicic reservoirs, and this likely acted as an eruption trigger. The basaltic magma may have provided the significantly increased temperature required for the types of "boil-over" eruptions recorded in Phases 2 and 3 [Troll et al. 2004; Liszewska et al. 2018], the expulsion of highly viscous crystal-rich magma in Phase 5, and for the rapid vesiculation and fragmentation of magma preserved in Phase 4. In summary, the Sròn Mhòr Member records a diverse assemblage of frequently switching eruptions, sometimes "hot and sticky" and sometimes "cold and damp" (where water was involved), sourced from a compositionally diverse magma reservoir, or reservoirs, with mixing of multiple magma batches from different sources.

6.3 Volcanism in Ardnamurchan and the wider British Paleogene Igneous Province

Volcanic rocks on Ardnamurchan are restricted to the basalt lavas of the Mull Lava Field. The conglomerates and breccias of the Ben Hiant and Achateny members were previously interpreted as "vent-filling agglomerates" related to explosive eruptions but are now interpreted as debris flow deposits [Brown and Bell 2006; 2007]. The ignimbrites of the Sròn Mhòr Member therefore represent the first true explosive eruption products on Ardnamurchan. This is likely primarily due to the level of erosion on the present-day Ardnamurchan peninsula, which is dominated by the intrusive igneous rocks of the Ardnamurchan Central Complex; however, ignimbrites

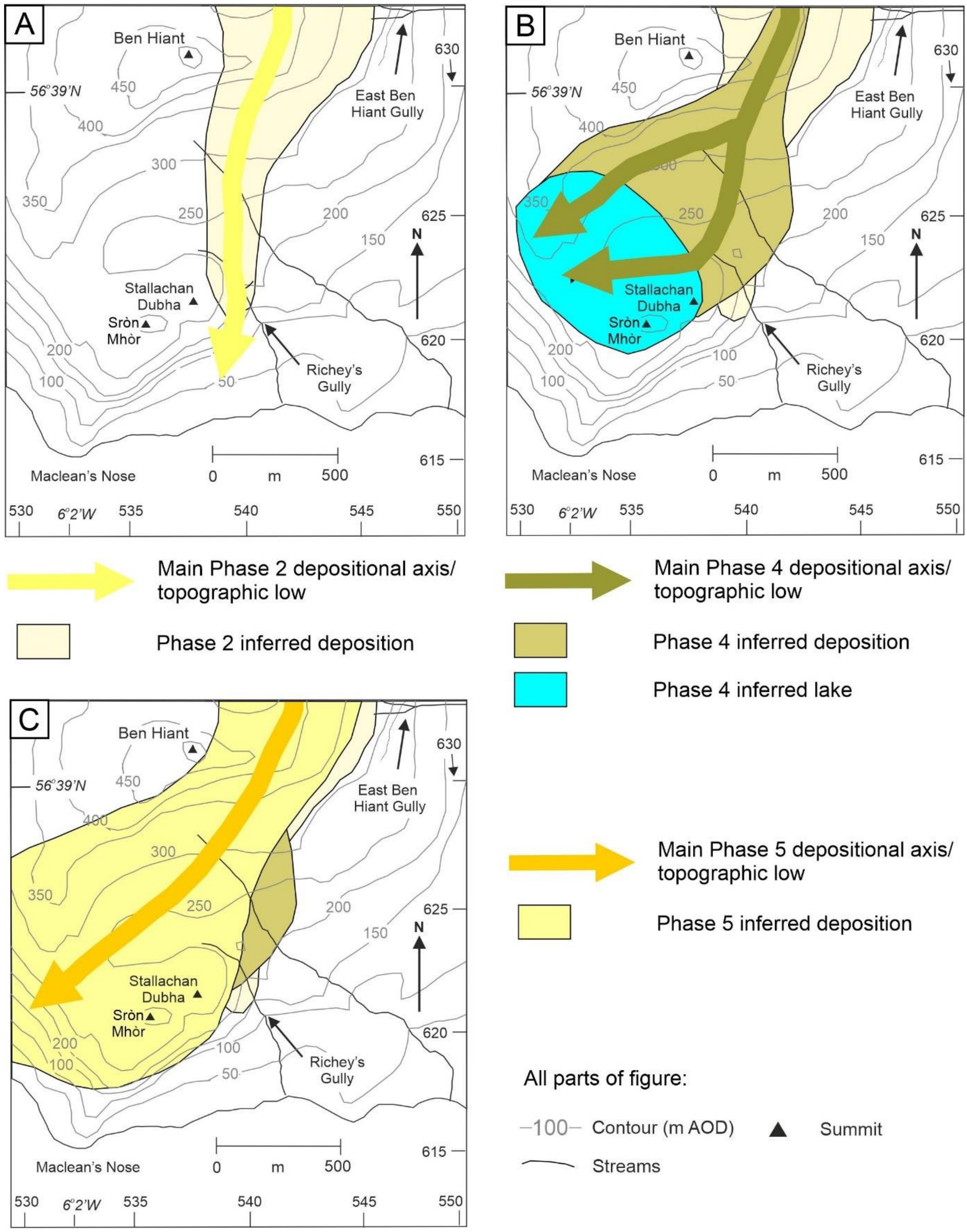

Figure 11: Schematic maps of potential run-out and deposition of the Sròn Mhòr Member pyroclastic density currents/ignimbrites. Present day topography of the area is depicted for geographical reference but bears no relation to Paleocene deposition and topography.

are preserved in other volcanic centres of the BPIP (e.g. Arran [Gooday et al. 2018]; Rum [Holohan et al. 2009]; Skye [Drake et al. 2022]). These examples are associated with caldera collapse, but there is no evidence preserved of such a structure on Ardnamurchan. A source vent or caldera may have existed on Ardnamurchan but is no longer preserved. Alternatively, it is possible that the Sròn Mhòr ignimbrites were erupted from a more distant source. The Sgurr of Eigg Pitchstone on the Isle of Eigg (Figure 1) is a valley-filling lava-like ignimbrite [Brown and Bell 2013], and it has been suggested that it was erupted from the Skye Central Complex ~50 km away [Brown and Bell 2013; Troll et al. 2019]. Ignimbrites may be deposited 10s of km from source and this suggestion is certainly feasible, although the coarse breccias and lapilli-tuffs preserved perhaps indicate a relatively more "local" source for the Sròn Mhòr ignimbrites. Numerous large clasts (10s of cm, up to 2 m) of purple to grey flow-banded lava-like ignimbrite are found within the underlying Ben Hiant Member [Brown and Bell 2006; 2007], and although no *in situ* exposures of this ignimbrite have been found either, it again hints at a relatively proximal volcanic source. A crystal-rich lapilli-tuff [Drake 2015], remarkably similar in appearance to the Phase 5 ignimbrite, is located ~65 km away at Fionn Choire on Skye (Figure 1A), but no conclusive links can be made to this unit.

7 Conclusions

The Sròn Mhòr Member records a diverse series of silicic ignimbrite lithofacies. It has been sub-divided into five eruptive phases, with periods of non-deposition and erosion between each. In Phase 1, coarse pumice-rich breccias from an explosive eruption were deposited. In Phase 2, massive lava-like ignimbrites, which underwent both syn-depositional and post-depositional rheomorphism, were deposited. These ignimbrites were deposited from hot pyroclastic density currents generated by low fountaining, "boil-over" eruptions. Similar ignimbrites were deposited in Phase 3, but local welding indicates fluctuating eruption conditions and perhaps occasional lofting of the eruption column. Phase 4 recorded a highly explosive eruption that deposited lithic-rich massive and stratified tuffs, lapilli-tuffs and breccias, involving the entry of a pyroclastic density current, or currents, which underwent flow stripping, into a lake. In Phase 5, crystal-rich tuffs were deposited during a highly explosive eruption, indicating the tapping of a crystal-rich mush zone in the magma chamber. All ignimbrites in the sequence filled topographic lows in the landscape such as palaeo-valleys and palaeo-lakes. These depressions were filled or partially filled during eruption, before periods of repose and the resumption of background sedimentation, and/or erosion and rapid incision. The main depositional axis was from ~NE to ~SW, with drainage pathways seemingly exploited multiple times. Eruptions were likely triggered by magma mixing in compositionally zoned magma reservoirs. These ignimbrites represent the first documented pyroclastic sequence on Ardnamurchan and reveal complex, rapidly switching, and highly variable eruption dynamics and interactions with topography in the British Paleogene Igneous Province.

Author Contributions

DB undertook fieldwork, created figures, and wrote the manuscript. AQ, PR, and SD undertook fieldwork and edited the manuscript.

Acknowledgements

This paper is dedicated to the memory of Professor Roderick Brown. Rod became a stalwart of University of Glasgow undergraduate field classes to Ardnamurchan, mapping the area around Ben Hiant. DB has many beautiful memories of spending time with Rod in the field area, discussing wild theories (Rod humouring his "daft ignimbrite stories"), and enjoying his fantastic field class barbeques. Rod was a true friend and is greatly missed.

Brian Bell, Jeff Harris, Iain Allison and the late Henry Emeleus are thanked for introducing DB to the area, teaching him so much, and for years of endless, excellent debate on the geology of Ardnamurchan. Charlotte McLean, John Buchanan, Kate Dobson, Peter Nicholls, Ross Dymock, Duncan Hay, and Thomas Taylor are thanked for field jollity. Rebecca Williams and an anonymous reviewer are thanked for their helpful comments that greatly improved the manuscript. Pete Rowley is thanked for editorial support.

Data Availability

All data are available on request from the corresponding author.

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