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RESEARCH ARTICLE

Debris flow deposits within the Palaeogene lava fields of NW Scotland: evidence for mass wasting of the volcanic landscape during emplacement of the Ardnamurchan Central Complex

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Abstract Coarse fragmental rocks, previously interpreted as primary pyroclastic accumulations infilling flared vents (Richey JE 1938) "The rhythmic eruptions of Ben Hiant, Ardnamurchan, a tertiary volcano. Bull Volcanol" 2(3):1–21), are re-interpreted as predominantly debris flow deposits, with minor hyperconcentrated and stream-flow deposits, temporally and spatially associated with the Palaeogene Ardnamurchan Central Complex (ACC), NW Scotland. These volcaniclastic rocks are conglomerates and breccias, interbedded with siltstones and sandstones, which formed by surface processes on a dissected landscape, developed in response to shallow emplacement of the ACC. Clast-matrix and photo-statistical analyses allow the palaeo-topography and drainage system to be reconstructed and the development of a palaeo-geographic model for the volcanic landscape. Slabs of basalt, dolerite and sandstone were transported as megablocks during catastrophic, gravity-driven events. Lower energy intervals during volcanic hiatuses are marked by lacustrine-fluvial volcaniclastic siltstones and sandstones preserving palynomorph assemblages. We suggest that shallow intrusion is a plausible initiation mechanism for mass wasting in other large igneous provinces. Historically, deposits of the type described here may have been misidentified as vent facies pyroclastic materials.

Keywords Mass wasting · Debris flows · Conglomerates · Volcaniclastic · Palaeogene flood basalts · Ardnamurchan Central Complex · Palaeo-geography

Introduction

In 1938, James Ernest Richey of the British Geological Survey published his novel interpretation of the Ben Hiant district of the Palaeogene Ardnamurchan Central Complex (ACC), western Scotland: *The rhythmic eruptions of Ben Hiant, Ardnamurchan, a Tertiary volcano* in *Bulletin Volcanologique* (precursor of *Bulletin of Volcanology*) (Richey 1938). This study constituted an early attempt to describe an ancient volcanic sequence, interpret the volcanological processes involved in its formation, and to relate this activity to modern systems.

The exhumed Palaeogene volcanoes of NW Scotland, part of the Hebridean Igneous Province (HIP), have, over the last hundred years, been used as a test bed for understanding a wide range of volcanic processes. Interpretations of these rocks, presented by luminaries such as Judd, Geikie, Harker, Bailey and Richey, were fundamental to the early development of volcanology (Judd 1889; Geikie 1897; Harker 1904; Bailey et al. 1924; Richey and Thomas 1930). For many years these interpretations were

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never seriously challenged, and have been cited in a variety of publications on volcanology and igneous petrology (e.g. Walker 1975, 1993a; Williams and McBirney 1979; Hall 1996). Specifically, genetic links were made between coarse fragmental rocks, such as those at Ben Hiant, and shallow intrusive bodies throughout the HIP, including ring dykes and stocks of both silicic and mafic composition.

Many of these fragmental rocks were interpreted as classic examples of pyroclastic accumulations preserved as vent facies materials associated with ring dykes and linked to cauldron subsidence events (Richey 1932). Our contribution proposes a radical new interpretation for the Ardnamurchan deposits, and we conclude that they represent the products of high-energy sediment transport (mass wasting) on a dynamic landscape. The model we develop highlights the role of shallow intrusion to produce localised uplift, resulting in catastrophic sedimentation events yielding conglomerates and breccias of debris flow association. As such, this study represents a fundamental re-assessment of our understanding of the Ardnamurchan rocks, some sixty-nine years since Richey presented his ideas in this journal, and has implications for similar rocks within rift-related volcanic systems and associated flood basalt sequences (cf. Ross et al. 2005).

Regional setting and anatomy of the Ardnamurchan Central Complex

The basaltic flood lava sequences and central volcanoes of the NE Atlantic Margin developed in response to rifting during the early Palaeogene. Within the HIP, three flood lava sequences are recognised: Eigg, Skye and Mull (Fig. 1). Upon this volcanic landscape, a number of central volcanoes developed, including Ardnamurchan, Skye, Rum and Mull. Late Palaeogene and Neogene erosion has removed in excess of 1 km of section from these volcanic superstructures, exposing their root zones (Bell and Williamson 2002).

The superbly exposed central complexes, typically 10 km in diameter, are located on narrow uplifted basement ridges which trend NE–SW, parallel to the rift zone (Bell and Williamson 2002). Between these ridges are long-lived sedimentary basins, within which the flood lava sequences were erupted (Butler and Hutton 1994).

The ACC (Fig. 2) comprises three foci of intrusion: Centre 1, the oldest, dominated by a suite of tholeiitic basalt and dolerite cone sheets; Centre 2, containing similar cone sheets, but with a different, more westerly, focus of intrusion, together with a number of large gabbroic ring intrusions, with lopolith and ring-dyke types; and Centre 3, dominated by gabbroic lopoliths (Bell and Williamson 2002; O'Driscoll et al. 2006).

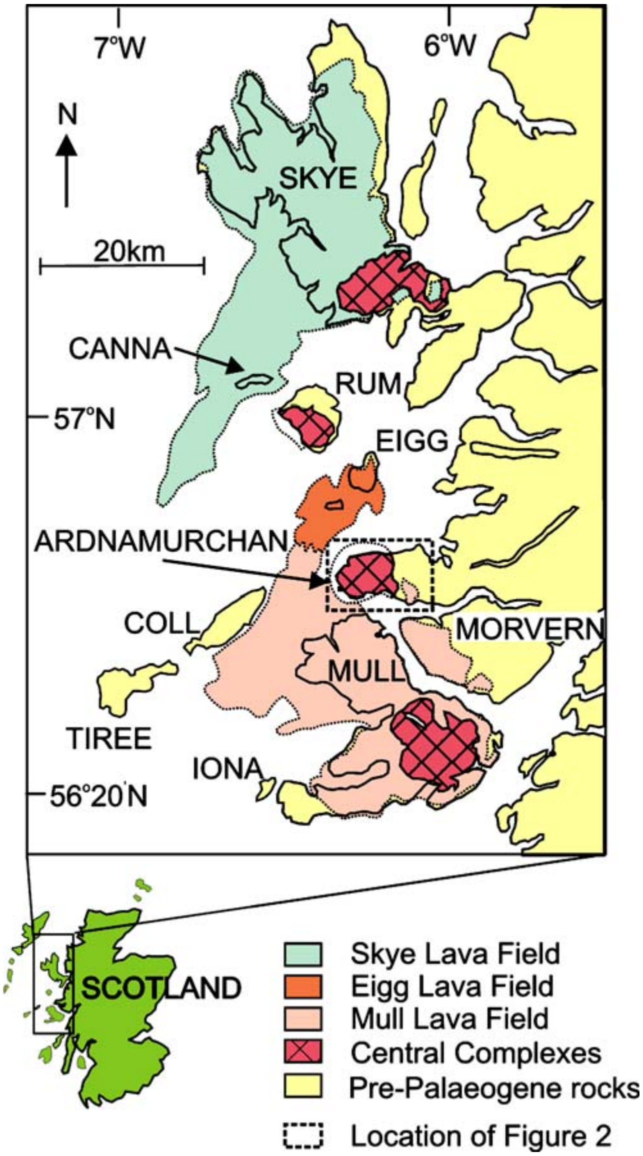


Fig. 1 Regional Palaeogene geology and location map of NW Scotland, indicating the position of the central complexes and lava fields. Key is not stratigraphic

There is still considerable uncertainty as to the nature and amount of regional uplift caused by the flexing of the continental lithospheric plate(s) by a putative proto-Icelandic plume (Thompson and Gibson 1991). However, it is clear that, at least on a localised level, the growth of the HIP central volcanoes and the emplacement of magmas into their root zones, resulted in uplift of several hundreds of metres (cf. Le Bas 1971; Walker 1993b).

Richey's volcano

Steeply-inclined contacts between the fragmental rocks of Ardnamurchan and the older Palaeogene flood lava sequence, an outlier of the Mull Lava Field/Group, and

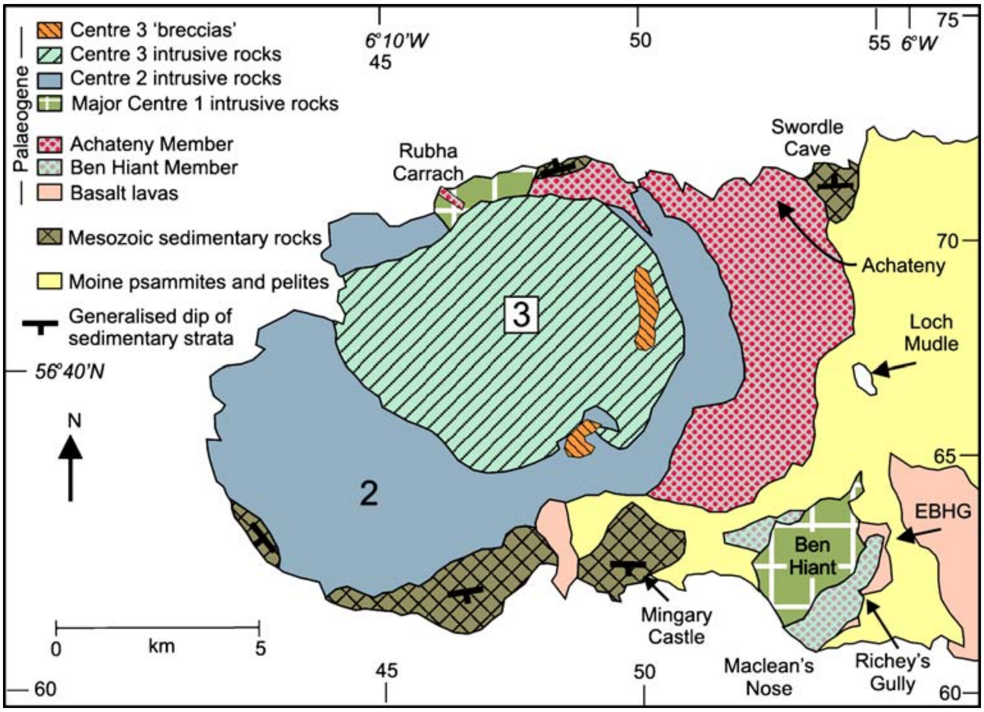


Fig. 2 Simplified geological map of the Ardnamurchan Central Complex, indicating the position of the Ben Hiant and Achateny members. EBHG = East Ben Hiant Gully. Ordnance Survey of Great Britain Grid provided

basement Neoproterozoic (Moine) psammites and pelites, were regarded as vent walls. Richey's interpretation of the Ben Hiant outcrop involved repeated, or rhythmic, explosive eruptions of trachytic magma. The various heterogeneous fragmental, or clastic, rocks were identified as primary stratified infills, comprising interbedded layers of agglomerate and tuff, resulting from the repeated explosive eruption of trachytic magma (Richey and Thomas 1930; Richey 1938). The initial formation of two large craters was attributed to violent vesiculation and explosive disintegration of the magma, shattering the country-rocks and forming 'agglomerates.' The trachytic magma then solidified as a plug within the feeder conduit, causing pressure, with time, to build up. The increased magma pressure would ultimately lead to another eruption, with the 'agglomerates' representing shattered plug material, together with fragments derived from the conduit and vent walls. The interbedded, fine-grained material was regarded as the ash or fines within the eruption column, which accumulated as airfall products. This cycle of 'agglomerate' and 'tuff' accumulation repeated, according to Richey, some 50 or more times.

The Ardnamurchan deposits

General characteristics and definition of members

The 'vents' identified by Richey and Thomas (1930) and Richey (1938) are referred to here, in general *geographic* terms, as the Ben Hiant and Achateny outcrops (Fig. 2). They contrast in that, at Ben Hiant, the rocks are preserved in a near-continuous vertical profile, with a relief in excess of 200 m and a lateral extent of several hundreds of metres, whereas at Achateny, observations are restricted to a coastal area with a relatively small amount of vertical relief, and more discontinuous exposures inland. Thus, complementary datasets (vertical or 'stratigraphic' and plan) have been obtained from the two outcrops.

The rocks which form the two outcrops are, in places, layered, ranging from obviously fine-grained units a few metres thick, underlain and overlain by considerably coarser-grained material, through to indistinct surfaces which can be traced for only a few metres and involving only minor differences in the average fragment sizes. On the basis of their stratified appearance, together with a variety of internal characteristics such as fragment/clast roundness, cross-stratification and grading, to be discussed below, we conclude that these rocks formed by accumulation on the land surface during the early Palaeogene and may be regarded as sedimentary rocks. Furthermore, the presence of abundant non-volcanic fragments and a lack of primary pyroclastic textures, for example shards, bombs, welding fabrics and fiamme, can also be used to infer that we are dealing with sedimentary accumulations. We now redefine these two outcrops as members, the Ben Hiant and Achateny members, of the Plateau Formation of the Mull Lava Group (see below), rather than 'vents.'

The coarse-grained materials are dominated by sub-rounded fragments (clasts) and are therefore best described as volcaniclastic conglomerates, although breccia facies are also present. The finer-grained layers are typically of silt to

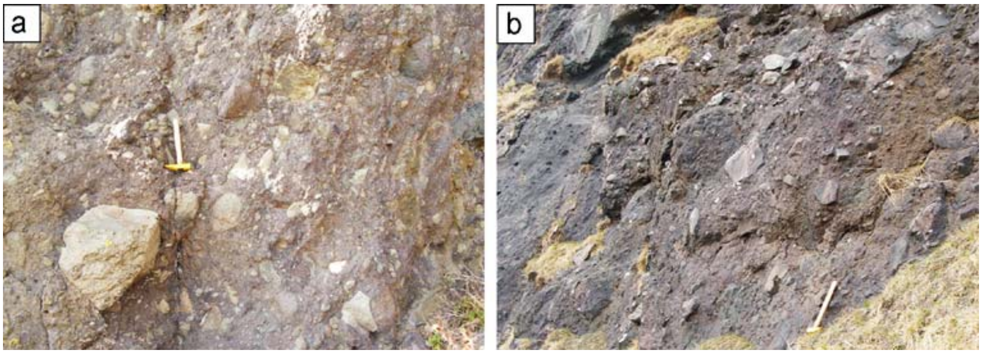


Fig. 3 Field photographs showing general characteristics of the conglomerates of the Ben Hiant and Achateny members. Hammer is 30 cm long. **a** Massive, poorly sorted, matrix- to clast-supported conglomerate set in a matrix of sand-grade basaltic material. Clasts are sub-rounded to sub-angular and are up to 50 cm across. **b** Massive, poorly sorted, matrix-supported conglomerate set in a matrix of sand-grade basaltic material. Clasts are sub-angular to sub-rounded and are up to 80 cm across

sand grade material and therefore will be referred to as volcaniclastic siltstones and sandstones.

The (volcaniclastic) conglomerates are typically clast supported, with sub-rounded to sub-angular cobbles and boulders set in a fine-grained sand to silt grade matrix of comminuted material (Figs. 3 and 4a, b). Clast types include: aphyric basalt, plagioclase- and olivine-porphyritic basalts, plagioclase-megacrystic basalt, scoriaceous and amygdaloidal basalts, dolerite, trachyte, microgranite, ignimbrite (welded tuff), Moine psammite and pelite, Moine (?) quartzite, and various sandstones, including distinctive calcareous sandstone, siltstone and shale of Jurassic age.

The various basalts match with flows from the subjacent Mull Lava Field, where all types are represented. Dolerite clasts are mid grey to black with rare microphenocrysts of plagioclase, and resemble Centre 1 cone sheet intrusive rocks. Trachyte clasts are typically pale grey, although rare examples are black and mottled, and some contain white-weathering amygdales. The spherulitic-textured microgranite clasts can have a pink to dirty brown weathered appearance, but are typically pale grey, with orthoclase phenocrysts up to 5 mm across (Fig. 4c). Spectacular clasts of ignimbrite weather pink–brown to grey, with purple to grey flow banding and fiamme up to 5 cm in length (Fig. 4d). Basement psammite clasts are typically medium-

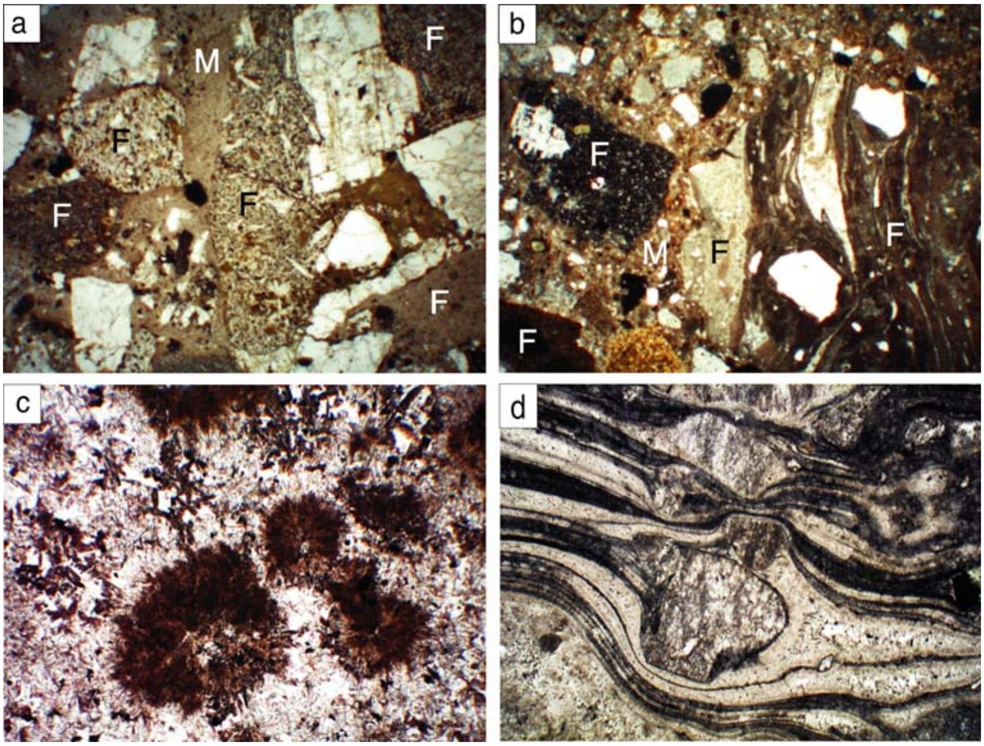


Fig. 4 Photomicrographs. All fields of view are 5 mm from top to bottom. ppl = plane polarised light, xpl = cross polarised light. **a** Comminuted intra-clast material, comprising sub-rounded to sub-angular fragments (F) in a matrix (M) dominated by sand-grade and finer material (ppl). **b** Fragments (F) within comminuted matrix material (M); the large clast filling the right hand part of this view is of ignimbrite (ppl). **c** Spherulitic texture micro-granite clast with skeletal quartz and feldspar crystals (xpl). **d** Ignimbrite clast displaying well-developed eutaxitic texture and feldspar phenocrysts (xpl)

to coarse-grained, pink–grey, layered rocks, in contrast to the finer-grained, mica-rich, dark grey pelites. Quartzite (Moine) clasts range between white and grey. Various types of sandstone (Jurassic) are recognised, ranging from grey to buff to light brown, and are typically quartz arenites or arkoses. Rare clasts include friable dark grey to black siltstone (Jurassic), some laminated and others with discontinuous light grey carbonaceous layers, and black shale (Jurassic).

It is important to note that all but the microgranite and ignimbrite lithologies (Fig. 4c, d) are recognised from outcrops within the Ardnamurchan district (Fig. 2). Ignimbrites occur within the Mull Lava Field (Brown, unpublished observations), tens of kilometres distant, and microgranites crop out within the *younger* ACC. However, no nearby outcrops are documented and, therefore, their presence as clasts within the conglomerates indicates that such rocks were locally available at the time of conglomerate development, but are either no longer present, or have a subcrop below the conglomerates.

Ben Hiant Member

General field relationships

The Ben Hiant Member overlies basement rocks, a thin sequence of Mesozoic sedimentary rocks and the flood lava sequence (Figs. 2, 5 and 6). This unconformity with overstep rises from sea level at Maclean's Nose to ~240 m above ordnance datum (AOD) over a distance of 2.5 km to the north, implying that at least this amount of topography existed on the volcanic landscape prior to the accumulation of the fragmental rocks. The basal contact varies from horizontal to gently inclined. At Maclean's Nose, this junction can only be seen at low tide, where the conglomerates overlie psammites and pelites at a low angle. To the north, below the crags of Sròn Mhór, lavas form a low line of cliffs on the SE flank of Ben Hiant and are up to 30 m thick. Here, the upper surface of the lava sequence is uneven and has been filled by conglomerate (Fig. 7a), indicating an irregular palaeo-topography.

Figure 6 comprises photographic and schematic panoramas of the main Ben Hiant cliff section, together with two detailed graphic logs through the main outcrop. The sequence consists of five conglomerates, A to E, two siltstones, i and ii, and one sandstone, α (Table 1, Fig. 7). Certain of these units are laterally discontinuous. Within the cliff section the conglomerate clasts are predominantly of various basalts, ignimbrite, trachyte and several types of sandstone.

The conglomerates have many gross features in common, including clast types, size distributions and shapes, together with textural relationships with the matrix. The intervening siltstones and sandstone allow us to differentiate the sequence into at least five high-energy depositional units, each separated (except Conglomerates A and B) by lower energy conditions during which the finer-grained lithologies accumulated (Table 1).

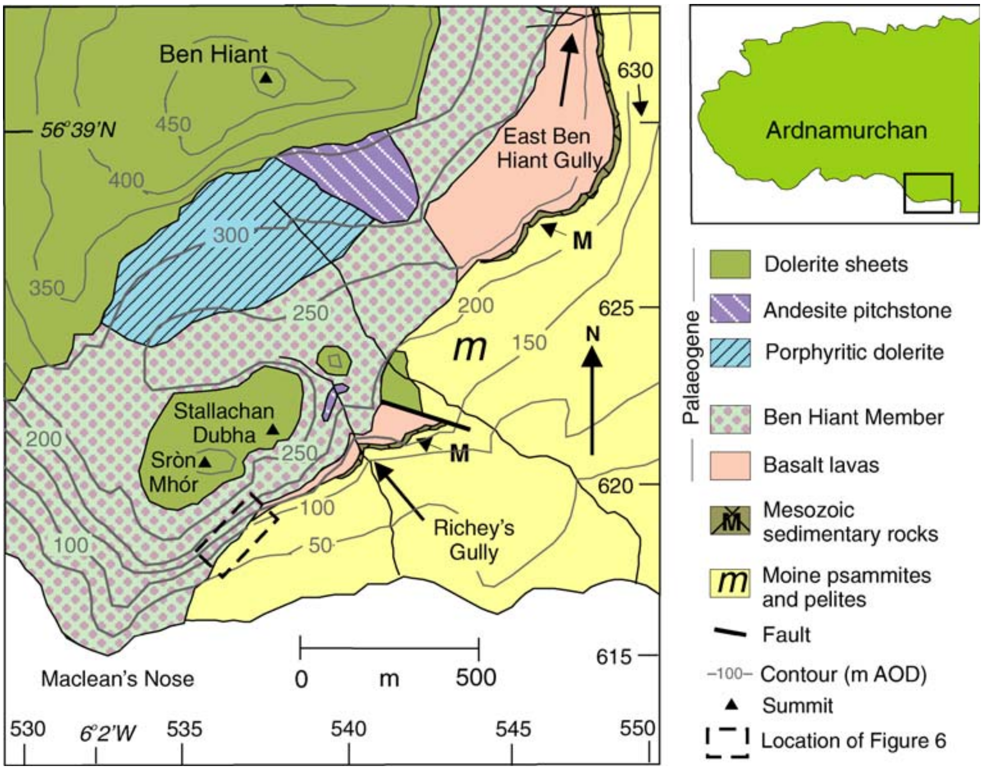
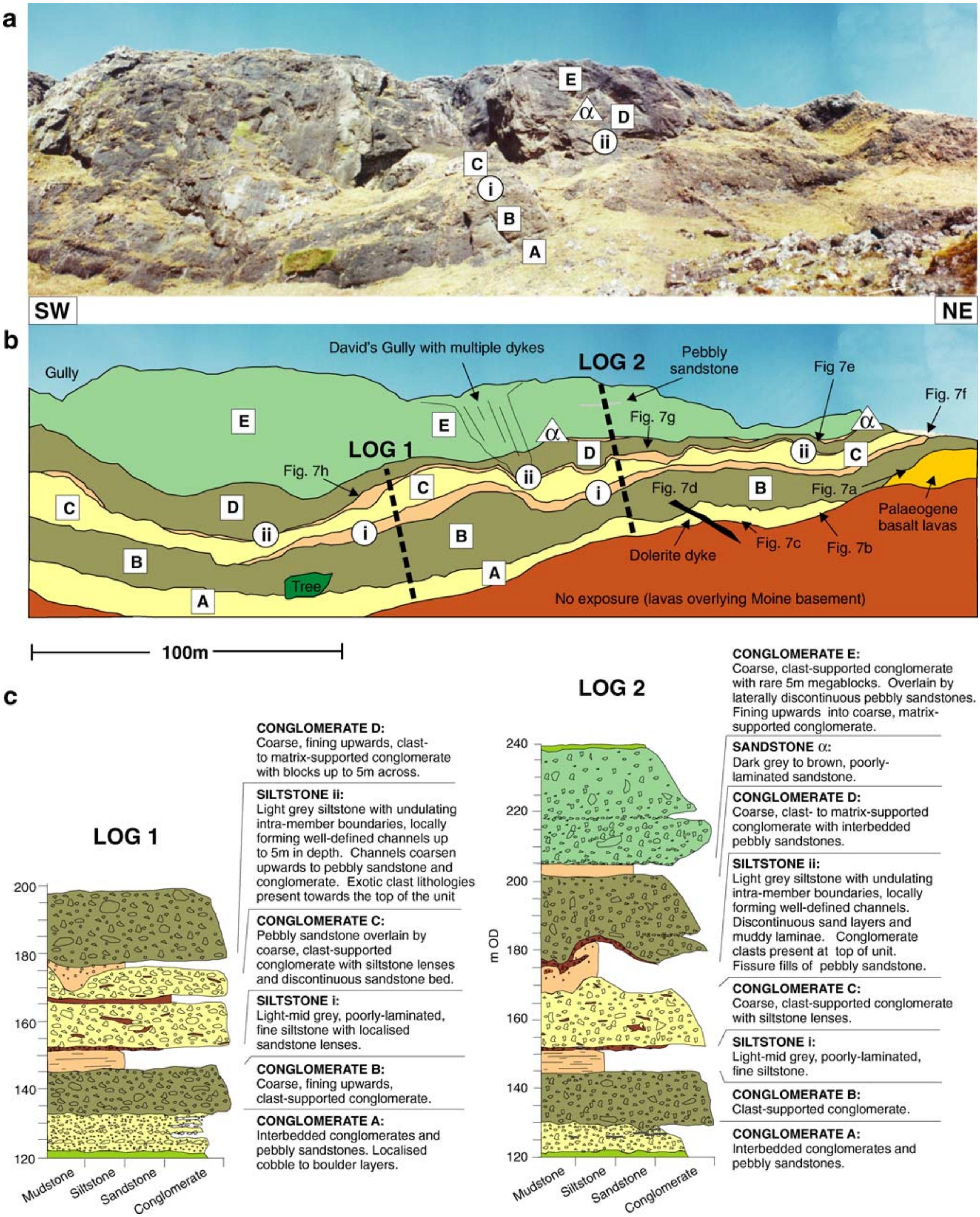


Fig. 5 Simplified geological map of the Ben Hiant and Maclean's Nose area with place names used in the text



LOG 1

CONGLOMERATE D:
Coarse, fining upwards, clast- to matrix-supported conglomerate with blocks up to 5m across.

SILTSTONE ii:
Light grey siltstone with undulating intra-member boundaries, locally forming well-defined channels up to 5m in depth. Channels coarsen upwards to pebbly sandstone and conglomerate. Exotic clast lithologies present towards the top of the unit

CONGLOMERATE C:
Pebbly sandstone overlain by coarse, clast-supported conglomerate with siltstone lenses and discontinuous sandstone bed.

SILTSTONE i:
Light-mid grey, poorly-laminated, fine siltstone with localised sandstone lenses.

CONGLOMERATE B:
Coarse, fining upwards, clast-supported conglomerate.

CONGLOMERATE A:
Interbedded conglomerates and pebbly sandstones. Localised cobble to boulder layers.

LOG 2

CONGLOMERATE E:
Coarse, clast-supported conglomerate with rare 5m megablocks. Overlain by laterally discontinuous pebbly sandstones. Fining upwards into coarse, matrix-supported conglomerate.

SANDSTONE α:
Dark grey to brown, poorly-laminated sandstone.

CONGLOMERATE D:
Coarse, clast- to matrix-supported conglomerate with interbedded pebbly sandstones.

SILTSTONE ii:
Light grey siltstone with undulating intra-member boundaries, locally forming well-defined channels. Discontinuous sand layers and muddy laminae. Conglomerate clasts present at top of unit. Fissure fills of pebbly sandstone.

CONGLOMERATE C:
Coarse, clast-supported conglomerate with siltstone lenses.

SILTSTONE i:
Light-mid grey, poorly-laminated, fine siltstone.

CONGLOMERATE B:
Clast-supported conglomerate.

CONGLOMERATE A:
Interbedded conglomerates and pebbly sandstones.

Fig. 6 Photographic (**a**) and schematic (**b**) panoramas of the main Ben Hiant cliff section, together with two stratigraphic logs (**c**). The positions of Conglomerates A–E (*in white squares*), Siltstones i and ii (*in white circles*), Sandstone α (*in white triangle*), and the logs are superimposed on the panoramas. Bedding relationships have been slightly distorted during the digital stitching process. The locations of field photographs in Fig. 7 are indicated

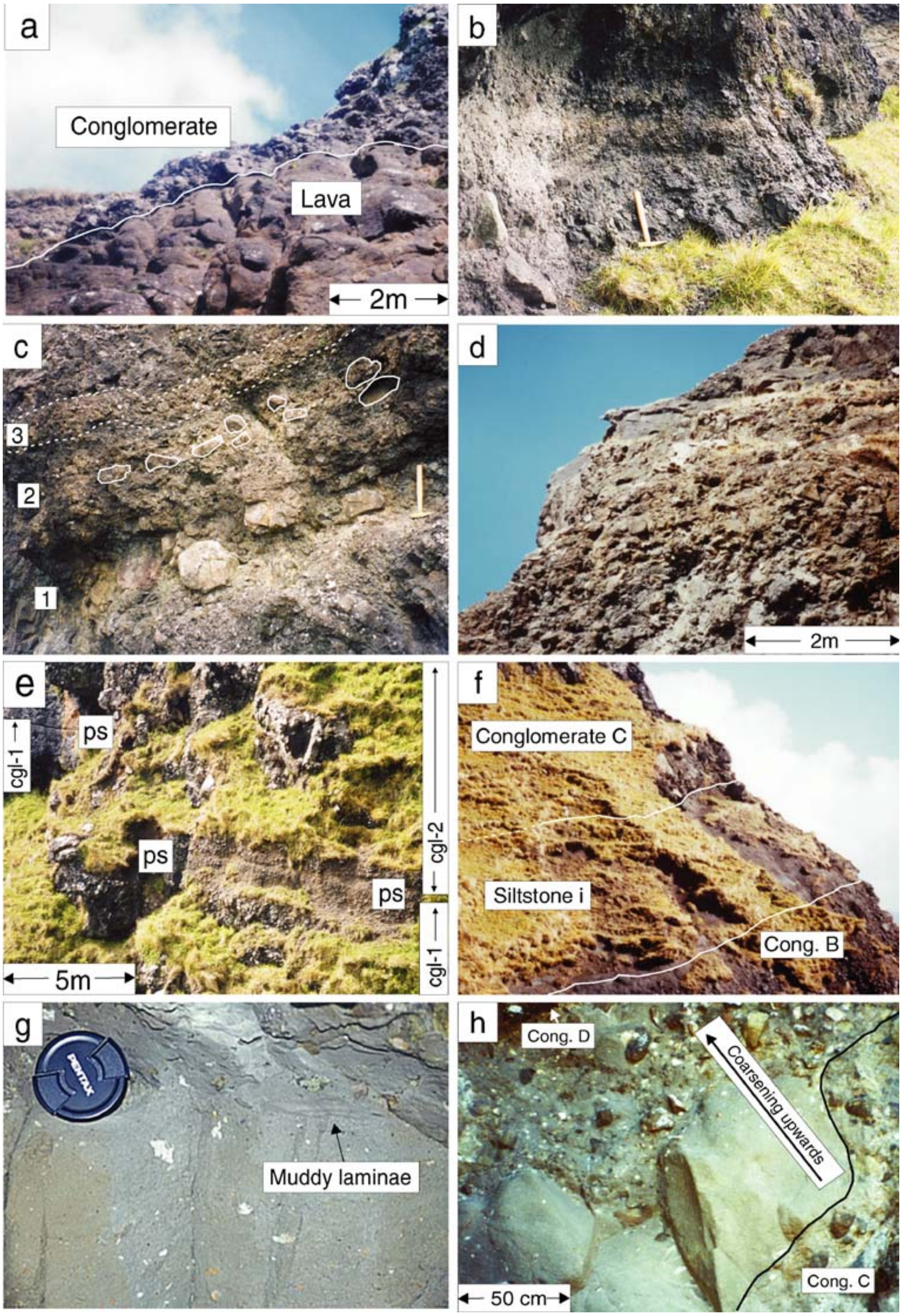


Fig. 7 Field photographs from the Ben Hiant Member (BHM). Hammer is 30 cm long. **a** Basal contact of BHM, unconformably overlying Palaeogene flood basalts [Ordnance Survey of Great Britain Grid Reference NM 5380 6193]. **b** Interbedded conglomerates and pebbly sandstones from Conglomerate A [NM 5370 6194]. **c** Clast-supported layers (1, 2, 3) within Conglomerate A, comprising sub-angular clasts up to 15 cm across, set in a coarse, sandy matrix [NM 5361 6191]. **d** Conglomerate B, an ~15 m thick coarse-grained, clast-supported, dark brown to black, poorly sorted unit [NM 5370 6195]. **e** Conglomerate D, a normally-graded 2.5 m thick conglomerate (cgl-1) fining upwards to a pebbly sandstone (ps) and overlain by a 22.5 m thick, normally graded conglomerate (cgl-2). Position of unit 'cgl-1' appears to change due to perspective [NM 5370 6198]. **f** Light-mid grey, poorly laminated Siltstone i, between Conglomerates B and C [NM 5370 6196]. **g** Siltstone ii, a light grey, 1–10 m thick unit with irregular lower and upper surfaces. Muddy laminae with small-scale cross-bedding and pebbles of friable, fine-grained, white sandstone are present throughout the unit. [NM 5370 6197] Lens cap is 8 cm across. **h** Base of channel structure in Siltstone ii, coarsening upwards and passing into Conglomerate D [NM 5361 6191]

The conglomerates are 10–35 m thick and have relatively sharp basal contacts. Upper contacts are less well defined and thin transitional intervals occur, grading up into either a siltstone or a sandstone. The conglomerates vary from massive (or structureless) sequences, through to beds defined by minor differences in the clast size distribution or matrix abundance. Individual units within the conglomerates vary between planar beds and channel-filling lenses. Loading structures, and fissure fills with fine-grained detritus are common. The intervening argillaceous and arenaceous units have more easily defined internal structure, including planar bedding surfaces, interbedded thin sand- and silt-dominated layers, loading structures, and trains of sub-rounded pebbles defining a crude bedding.

Table 1 Summary of rock types from the Ben Hiant Member

Description of rock types
CONGLOMERATES
A: Laterally variable, ~10 m thick, mid grey, fine-grained, clast-supported (i.e. framework-supported) conglomerates and pebbly sandstones, (Fig. 7a, b). Near horizontally bedded, beds 10 cm to 2 m thick, locally loaded and deformed by overlying Conglomerate B (Fig. 7b, c). Clasts highly weathered, sub-rounded to sub-angular, 2–15 cm across. Matrix of comminuted sand grade basaltic material. Locally, coarse, clast-supported layers contain sub-angular blocks up to 15 cm across (Fig. 7c).
B: ~15 m thick, dark brown to black, coarse-grained, poorly sorted, clast-supported conglomerate (Fig. 7d). Massive to very poorly bedded, weakly normally graded. Matrix of comminuted sand-grade basaltic material. Clasts chaotically organised, commonly oriented vertically with long axes orthogonal to base of unit. Clasts sub-rounded to sub-angular, 2–75 cm across, rarer scattered clasts of 1–2 m. Largest clasts commonly of shattered or fractured basalt. Localised irregular base fills channel-like depressions, up to 1 m deep, causing loading and deformation in the bedding of the underlying Conglomerate A. Large clasts concentrated towards bases of channel structures, channels oriented N–S and NW–SE (probable flow direction to the south and SE).
C: 15–25 m thick, dark brown to black, coarse-grained, poorly-sorted, clast-supported conglomerate. Normally-graded. Matrix of comminuted sand-grade basaltic material. Clasts sub-rounded to sub-angular, 2–7 cm across, rare larger clasts, commonly fractured, 1–2 m. Upper surface of conglomerate is irregular, with a relief of up to 10 m. Locally, lenses of mid-dark grey sandstone and siltstone, from 10 to 50 cm in length (in section), up to 20 cm thick.
D: ~20 m thick, brown-weathering, coarse-grained, poorly-sorted, clast-supported conglomerate (Fig. 7e). Massive to very poorly bedded. Matrix of comminuted sand-grade basaltic material. Heterogeneous, sub-rounded to sub-angular clasts, 2–75 cm across, rare larger clasts, 1–2 m, typically shattered, locally blocks up to 5 m. Top of unit is finer-grained, particularly towards the eastern end of the section. Localised ~5 m thick section near base of unit comprises two discrete normally-graded conglomerates with an intervening pebbly sandstone (Fig. 7e).
E: Minimum 35 m thick, reddish–brown to grey, coarse-grained, poorly sorted, matrix-supported conglomerate. Matrix of light to dark brown comminuted sand-grade basaltic material. Clasts sub-rounded to sub-angular, 2–50 cm across, a few up to 1 m, and rarely 5 m. Locally, along the base of the unit, there is a reverse-graded pebbly sandstone.
SILTSTONES
i: ~8 m thick, light-mid grey. Generally massive, with vague traces of bedding (Fig. 7f). Heavily fractured, easily eroded (contrasts with the commonly near-vertical faces of the conglomerates). Upper and lower surfaces relatively planar. Locally, at top, ~50 cm thick sandstone with pebbles and cobbles up to 20 cm across. Dominant silt grade grains are sub-rounded to sub-angular, of quartz, lithic fragments (typically basalt) and rare (altered) plagioclase. Discontinuous lenses of mudstone and finer-grained patches.
ii: 1–10 m thick, light grey. Bedding defines a series of channels, the bases of which form the thickest part of the unit. Forms a distinct recess and overhang. Lower and upper surfaces are irregular, soft-sediment deformation structures. Channels oriented NW–SE and clast imbrication indicates palaeoflow towards SE. Localised lenses of conglomerate and pebbly sandstone, rare sandy layers up to 2 cm thick, muddy laminae with small-scale cross-bedding (Fig. 7g). Pebbles, typically 1–2 cm across, of friable, fine-grained, white sandstone throughout the unit (not recorded elsewhere). West of prominent David's Gully, unit fills NNW–SSE oriented, channel-like depression in underlying Conglomerate C. Siltstone locally tapers to less than 1 m thick, where base is inclined at a steep angle, typically nearly vertical. Clasts of white sandstone and other lithologies within channel, increase in abundance towards top, producing a gradational boundary with overlying Conglomerate D (Fig. 7h). Locally, fine-grained conglomerate/pebbly sandstone overlies Siltstone ii, in places highly deformed and inter-fingering with siltstone. Dominant silt grade grains are sub-rounded to sub-angular, of quartz, lithic fragments (typically basalt) and rare (altered) plagioclase.
SANDSTONE
α: 50 cm to 2.5 m thick, dark brown. Massive.

Palynology

The palynomorph content of the silt to sand grade-dominated beds (Siltstones 1 and 2, Sandstone α, and siltstone lenses within Conglomerate C) provides important data concerning both the deposition of these units, as well as the overall range of botanical environments in the Ardnamurchan district (Fig. 2) during formation of the Ben Hiant Member. In all cases, the analysed samples were of fine-grained material from the siltstones and sandstone; similar rocks of known Jurassic age and represented by clasts from the interbedded conglomerates were not sampled. The citations of the taxa discussed in the text are those presented by Jolley (1996, 1997).

Abundant diagnostic Palaeogene palynomorphs were recovered from all samples, and these are devoid of fusain or charred material. The presence of pollen and the absence of scorched/burnt material argue against a pyroclastic origin for these deposits. The variety of palynomorphs allows the palaeoecology and palaeogeography of the Palaeogene land surface of the Ardnamurchan district to be reconstructed. The samples are dominated by pine-type grains, *Pityosporites*, which are typical of upland areas, ~1,000 m a.s.l., similar to present-day montane conifer forests. Large amounts of *Inaperturopollenites hiatus* are also present and indicate input from a source area rich in Taxodiaceae trees, most likely *Metasequoia* or *Glyptostrobus*. These trees formed upland forests, typically with an understorey of ferns, at elevations of ~500 m and are related to extant species such as the Dawn Redwood. During development of the Palaeogene lava fields of NW Scotland *Metasequoia*-type pollen represented the most common flow-top vegetation (Jolley 1997).

The remaining pollen preserves evidence of a more diverse, lowland palynoflora. *Nyssa* and *Castanea* type pollens (e.g *Nyssapollenites kruschi subsp. analepticus* and *Cupuliferoidaepollenites liblarensis*) and small tree fern materials are also identified. These palynomorphs are typical of lowland swampy areas and mixed mesophytic forests found at elevations of less than 500 m. These areas were, most likely, rapidly colonised by ferns, present in all samples, such as *Laevigatosporites haardti*, and *Deltoidospora adriennis,* a Cyathaceae tree fern, both typical early swamp colonists; together with *Corrusporis, Stereisporites* and *Lycopodiumsporites rotundoides,* all low frequency ferns. Swamp-dwelling angiosperms of the Juglandaceae (i.e. Walnuts, Hickories, Pecans) are represented by minor amounts of *Momipites* and *Caryapollenites* species. Static freshwater (most likely lacustrine) conditions are indicated by the presence of *Botryococcus braunii*, a chlorophycean algae. Palynomorphs derived from marine and/or estuarine environments are absent.

Achateny member

General field relationships

Within the outcrop area of the Achateny Member, the present-day topography is relatively subdued and there are few long and continuous sections through the conglomerates. A number of exposures are present along the northern coastal section from Fascadale to Swordle Cave and at other inland localities (Fig. 8, Table 2), and further west at Rubha Carrach (Fig. 2), that allow critical compositional, shape and size trends to be identified. Deposit characteristics are summarised in Tables 2 and 3 and illustrated in Figs. 9 and 10.

Achateny Member deposits are best exposed inland in the U-shaped valley of the Achateny Water. Here, they are bound to the east by basement psammites and pelites and, locally, Mesozoic sedimentary rocks, whereas to the west they are invaded by intrusive rocks of centres 2 and 3. The conglomerates are cut by Centre 1 cone sheets. The basement rocks east of the valley form a series of upland areas, including the ridge of Beinn Bhreac, now topographically above the Palaeogene rocks of the Achateny Water, and most likely also during the Palaeogene. The uncon-

Fig. 8 Simplified geological map of the Achateny area with place names used in the text

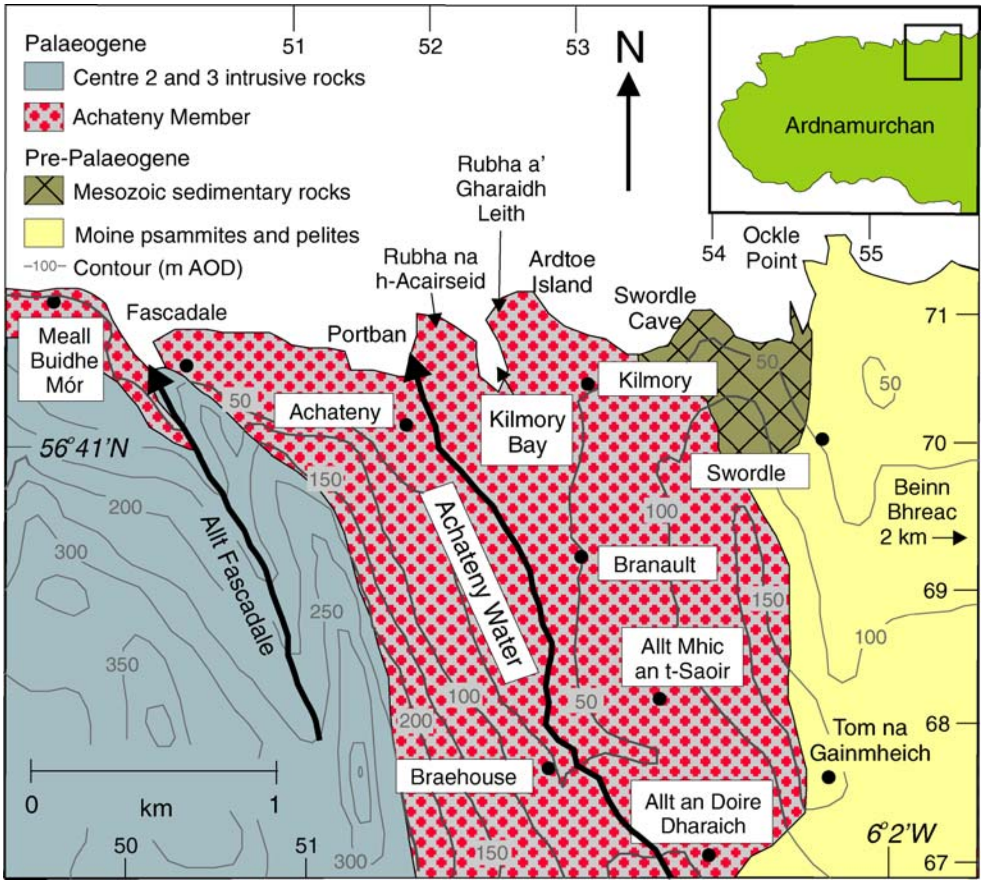


Table 2 Summary of rock types from the Achateny Member

Description of rock types
SOUTHERN EXPOSURES
Allt an Doire Dharaich [NM 536 672] (Fig. 8): Dark brown to black, fine-grained, matrix-supported conglomerates, locally grading into poorly-sorted pebbly sandstones. Clasts typically sub-angular, less commonly sub-rounded, 2–10 cm across, rare clasts up to 30 cm. Matrix of dark brown basaltic sand grade material. Clasts of various basalts, psammite, quartzite, and rare sandstone.
Allt Mhic an t-Saoir [NM 5343 6833]: 10 m thick section comprises two discrete units of dark brown to black, fine-grained, matrix-supported conglomerate. Upper slightly coarser, forming a gently inclined channel oriented N–S and NNW–SSE, indicating northerly transport direction.
NORTHERN EXPOSURES (Fascadale to Swordle Cave)
General characteristics: coarse-grained, clast-supported conglomerates (Fig. 9). Massive and graded units, with sub-rounded clasts of Mesozoic sedimentary rocks and Palaeogene silicic igneous rocks. Distribution of the former strongly linked to the underlying geology, whereas silicic clasts, although locally concentrated, cannot be linked to any present-day outcrop. Considerable variation in clast lithology, size, and shape.
Meall Buidhe Mór and Fascadale: pink and green clast-supported conglomerates dominated by sub-rounded to rounded clasts (2–20 cm; rarely up to 1 m) of scoriaceous and plagioclase-phyric basalts. Massive.
Rubha na h-Acairseid: reddish-brown, clast-supported conglomerates with sub-rounded clasts of calcareous sandstone, typically 20–50 cm across; rare sandstone blocks are much larger, with one example 30 m by 25 m (Fig. 9c, Table 3). Smaller clasts and larger blocks, up to 5 m across, of identical material, surround this megablock. Smaller clasts have bedding planes and bedding structures with internally coherent orientations, but differing from that of adjacent megablock. No comparable sandstone found in situ within Mesozoic sequence east of Achateny Member. Scattered clasts of fossiliferous sandy limestone (of Lower Jurassic Broadford Beds), typically sub-rounded to sub-angular, 10–20 cm across. Locally, sub-angular clasts (2–10 cm) of yellow, green and grey, thermally-altered shale form distinctive clast-supported units. Overall nature of these tightly packed and chaotically arranged shale-dominated conglomerates (Fig. 9d) suggests derivation by shattering of a larger pre-existing outcrop. Similar shales crop out at Mingary Castle (Fig. 2) on the south coast of the peninsula.
Three discrete units, each with distinctive clast assemblage (Conglomerates P, Q and R; Fig. 10a). Conformable relationships and presence of normal grading and channel structures, suggest flow processes were responsible for deposition. Each unit comprises more than one flow or 'lobe.' Conglomerate P is at least 10 m thick, matrix-supported, with approximately equal proportions of sub-rounded clasts (2–20 cm; rarely up to 1 m) of microgranite, aphyric and scoriaceous basalts, together with rare sandstone. Top surface is defined by overlying ~8 m thick, clast-supported, sandstone-clast -dominated unit, Conglomerate Q, with rare clasts >2 m. Approximately two-thirds of total clasts in Conglomerate Q are sandstone, with one third of calcareous sandstone, mainly as megablocks. At top of sequence is a siltstone-clast –dominated, clast-supported Conglomerate R, ~5 m thick, composed of sub-angular, typically laminated siltstone and thermally altered shale clasts (~50 vol.%), and less common sub-rounded sandstone clasts. Undulating boundary between conglomerates Q and R has a relief of 10–20 cm. Conglomerate R contains channel-like surfaces, with up to ~1 m relief (Fig. 9e), indicating breaks in sedimentation and multiple depositional events. Channels between and within Conglomerates P, Q and R are cross-cutting and overlapping, with palaeoflow directions inferred from channel axis, ranging between NW to ENE, although generally towards the north.
Kilmory Bay: two ~15 m high sea-stacks of conglomerate with gently undulating beds, 2–5 m thick, each a discrete debris flow unit. Dark brown to black, clast-supported conglomerates (30 vol.% matrix) with large (2–40 cm; rarely up to 1 m), sub-rounded to sub-angular clasts of aphyric basalt, together with less common scoriaceous basalt. An ~50 cm thick palaeosol occurs between two of these units, confirming subaerial environment of deposition (Fig. 9f). Tree mould within easternmost sea-stack indicates surface accumulation. Numerous other exposures might be interpreted as basaltic lava flows, with pitted, rubbly tops, but presence of rounded clasts of microgranite and basalt, most obvious on prepared, slabbed surfaces, in these apparent 'lavas,' confirms they are conglomerates.
Rubha a' Gharaidh Leith: ~5 m thick sequence of light to dark brown, matrix-supported, normally-graded conglomerates and pebbly sandstones, interbedded with ~5 cm thick, pebble-rich layers (Fig. 9g). Sub-rounded clasts 2–5 cm across.
RUBHA CARRACH
Separated from main Achateny Member outcrops by gabbroic intrusions of centres 2 and 3, and a large Centre 1 dolerite cone sheet (Fig. 2). Forms a prominent and spectacular ~60 m high cliff, ~500 m in length, tapering to a point at its seaward end. Cut by multiple minor intrusions.
Grey to yellow–brown, (Fig. 9h), clast-supported conglomerates, approximately equal proportions of sub-rounded and sub-angular clasts, 2–30 cm across, rarer clasts up to 60 cm. Clast lithologies include: aphyric basalt, porphyritic andesite, quartzite, sandstone, calcareous sandstone, limestone, microgranite, ignimbrite and rhyolite. Sub-angular quartzite and sub-rounded aphyric basalt clasts typically dominate the unit. The matrix is a highly resistant quartz-rich sand.
Three units (Fig. 10b). Lowest, Conglomerate Y, ~15 m thick, clast-supported, clasts 10–20 cm across, rarer clasts of quartzite and porphyritic andesite up to 50 cm. Overlying is a ~70 cm thick unit of grey, carbonate-cemented, quartz-rich, bedded pebbly sandstone. This unit extends laterally for only 15 m. Small sediment drapes over large clasts in underlying Conglomerate Y. Clasts from overlying Conglomerate Z protrude down into the sandstone, as a result of loading. ~45 m thick matrix-supported Conglomerate Z overlies the sandstone and contains a high proportion of aphyric basalt clasts. These clasts are sub-rounded to sub-angular, 10–25 cm across, but scattered clasts up to 1 m are also common. Towards base of Conglomerate Z, are ~40 cm thick lenses of sandstone, ~70 cm to 1 m across, composed of material identical to that in subjacent sandstone.

formable contact(s) of the conglomerate with the basement is rarely exposed, but can be seen at Tom na Gainmheich [NM 5445 6774] (Fig. 9a). At a small roadside quarry, NE of Kilmory [NM 5370 7051], conglomerate overlies heavily fractured Mesozoic shale (Pabay Shale Formation) and contains approximately 50 vol.% angular shale clasts.

The published map of the area suggests that the conglomerates have a complex relationship with the Palaeogene flood

Table 3 Summary of megablocks from the Achateny Member

LOCATION	DESCRIPTION	SIZE AND SHAPE (m)
Numerous, poorly exposed examples in the valley of the Achateny Water. Five better-exposed examples at Kilmory (Fig. 8, NM 532 698)	Fractured and shattered, brown to grey weathered, aphyric, vesicular basalt blocks (Mull Lava Field types), surrounded by basalt-dominated conglomerate. Locally, basalt is weakly blocky to prismatically jointed. Rare examples of amygdaloidal basalt (amygdales 1–2 cm across). Fragmentation: closely spaced (5–20 cm), blocky discontinuities to weakly fractured.	Typically 5–15 m across, locally up to 30 m across; generally tabular
Rubha na h-Acairseid (Fig. 8, NM 5206 7085, Table 2)	Reddish–brown, planar to cross bedded (1–3 cm) calcareous sandstone (Lower Jurassic, Bearreraig Sandstone Formation), surrounded by calcareous sandstone-dominated conglomerate. Bedding oriented vertically in block. Not fragmented.	30 m by 25 m, surrounded by ~5 m by 5 m examples; equant

basalt lavas (British Geological Survey 1969). The ‘lavas’ of this area, however, differ from those on and east of Ben Hiant, which are characterised by typical ‘stepped’ plateau lava topography. Inter-lava lithologies such as shale, and reddened palaeosol surfaces are present and, at the base of the sequence there is a red mudstone. However, at Achateny, there is no evidence of a stepped topography and the ‘lavas’ form low hummocks, locally surrounded by basalt-dominated conglomerate within the valley floor of the Achateny Water. ‘Lava’ can be seen lying both above and below the conglomerates and there is no regular outcrop pattern. Furthermore, the ‘lavas’ are intensely fractured and shattered, with no evidence of features such as prismatic or columnar jointing (Fig. 9b), and distinct flows cannot be identified. Together, these features suggest that the ‘lavas’ are, in fact, large clasts or ‘megablocks’ of basalt and dolerite enclosed by the conglomerates, and were derived from the local lava field (Table 3).

Palynology

Palynological analysis was not carried out on the Achateny Member due to an absence of appropriate argillaceous sedimentary units.

Clast type, roundness and size data

Methodology

Traverses through the Ben Hiant and Achateny members provide a three-dimensional network of data concerning the nature of the clasts and the proportion of matrix. These traverses comprise four trending approximately N–S and two trending approximately E–W (Figs. 11 and 12). One vertical traverse was undertaken in the Ben Hiant cliff section. Data were collected at points along traverses and the most complete data acquisition was on coastal and high relief areas. At each sample point, a linear transect of 10 m was measured and data were collected concerning clast type and degree of rounding at a 10 cm spacing. For this purpose, a clast was described as >2 cm (Fisher 1960) and clast roundness was described as one of: rounded, sub-rounded, sub-angular or angular. If no clast was present at the sample point, the point was recorded as ‘matrix.’ Thus, over each 10 m transect, 100 data points were recorded, giving detailed information on clast lithology (and hence clast population heterogeneity), the amount of rounding, and the proportion of clasts to matrix (or large-clast ‘abundance’). Clast size was measured at 25 cm intervals in order to provide an indication of the mean value. Where the 25 cm points coincided with matrix, then the ‘clast size’ was recorded as a notional 4.5 mm. This ‘field matrix’ typically comprises ~75% sand (1 mm median, thin section measured) and ~25% coarser fragments (2 mm–2 cm, 15 mm median, visual estimation), thus giving an overall median of ~4.5 mm for the sub-2 cm fraction. At each sample site, the average (mean) of the five largest clasts (except megablocks) was also measured to provide information on flow competence. In total, 40 transects were conducted and are included in the traverses described, below.

Traverse data and interpretation

The data presented in Fig. 12 indicate:

(1) The traverse through the Ben Hiant Member (A–B) indicates an increase in clast population heterogeneity towards the south, with a transition from typically aphyric basalt clasts in the north, to deposits rich in clasts of various Mesozoic sedimentary rocks in the south (Fig. 12a). The clast abundance, roundness and mean size all increase towards the south (Fig. 12b, c and d). At the northern limit of the Ben Hiant Member, the

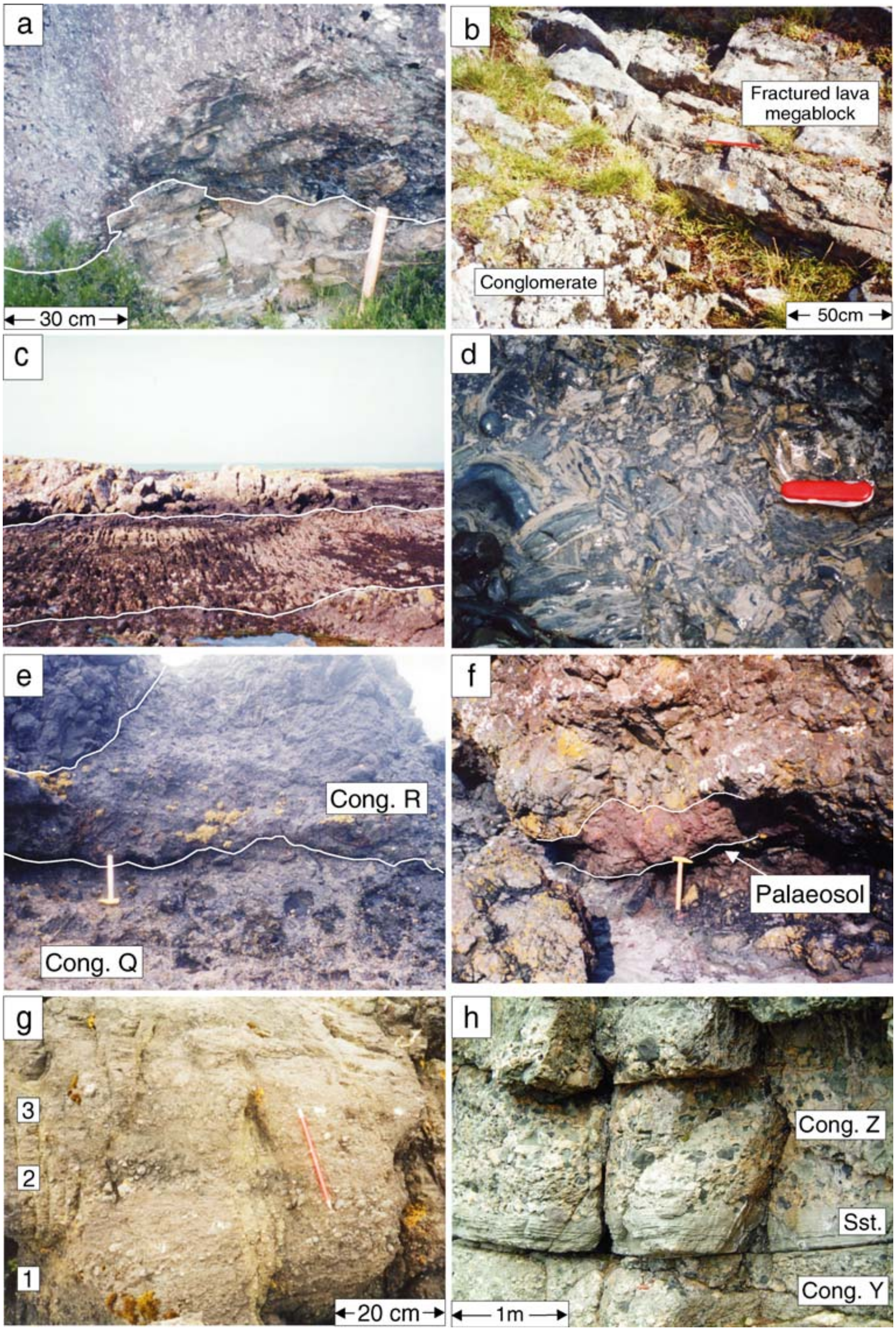


Fig. 9 Field photographs from the Achateny Member (AcM). Hammer is 30 cm long. **a** Basal contact of AcM, unconformably overlying Moine psammites and pelites [NM 5445 6774]. The conglomerates are dominated by Moine clasts. **b** Fractured basaltic lava megablock embedded in Moine quartzite-dominated conglomerate. Megablocks form hummocky topography in this area [NM 5313 6804]. **c** Bedded calcareous sandstone megablock at Rubha na h-Acairseid, measuring 30 m by 25 m [NM 5206 7085]. **d** Sub-angular clasts of shale forming a tightly packed and chaotically arranged conglomerate [NM 5215 7088]. **e** Undulating boundary between conglomerates Q and R with a relief of 10–20 cm. A channel-like structure with up to ~1 m relief in Conglomerate R is defined (*top left hand corner*) [NM 5229 7075]. **f** 0.5 m thick reddened palaeosol between two conglomerate units [NM 5247 7057]. **g** Normally-graded, matrix-supported beds of light to dark brown conglomerate and pebbly sandstone form a ~5 m thick sequence interbedded with ~5 cm thick, pebble-rich layers (1, 2, 3) [NM 5241 7099]. Pencil is 15 cm long. **h** Interbedded conglomerates (Y, Z) and sandstone (Sst.) from the Rubha Carrach area [NM 4617 7053]

conglomerates are typically homogeneous and matrix-supported, dominated by relatively angular, small clasts (2–20 cm across), whereas to the south they are typically more heterogeneous and clast supported, with large (10–50 cm; but up to 3 m across) sub-rounded clasts.

(2) A mirror image of the trends described in (1), above, is noted from the traverses through the Achateny Member (A–B north, C–D, E–F). In the south, aphyric basalt and psammite clasts are dominant. The clast population heterogeneity increases towards the north, to deposits rich in clasts of various Mesozoic sedimentary lithologies (Fig. 12a). The abundance of large clasts, degree of clast roundness and mean size also all increase towards the north (Fig. 12b, c and d). A relatively homogeneous clast population, comprising dominant small (2–20 cm), angular clasts, typically matrix-supported, occurs at the

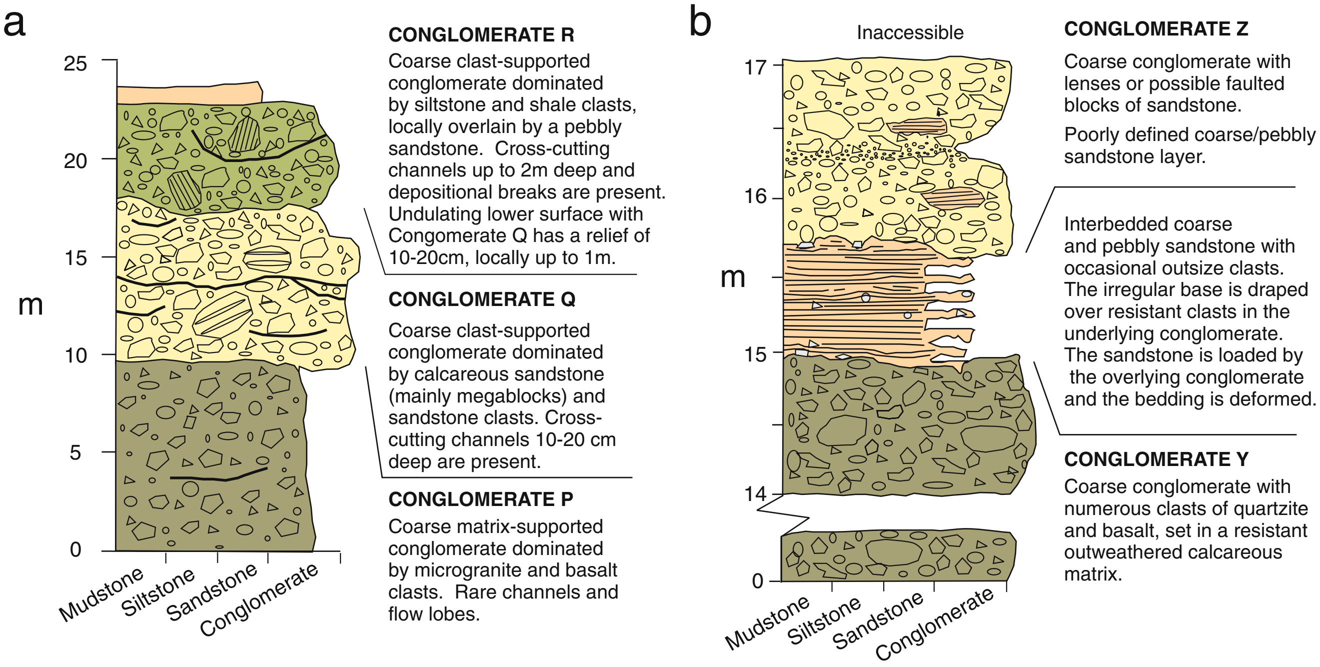


Fig. 10 Stratigraphic logs from **a** the Rubha na h-Acairseid [NM 5229 7075] and **b** Rubha Carrach [NM 4617 7053] areas of the Achateny Member. The lower part of Conglomerate **P** is only visible at extremely low tides

southern end of the outcrop, whereas to the north the clast population is more heterogeneous. These clast-supported deposits are dominated by large (10–50 cm, but up to 3 m across), sub-rounded clasts.

(3) The E–W traverses (G–H, I–J) reveal no specific spatial trends for the various parameters, but record localised concentrations of clasts of microgranite and scoriaceous basalt that may indicate restricted sources for these lithologies (Fig. 12a). This implies that the dispersal system may have been compartmentalised.

(4) A vertical traverse of the Ben Hiant cliff section (X–Y) reveals an up-section increase in the percentage of matrix (Fig. 12b) and a decrease in mean clast size (Fig. 12d).

The conglomerate units of the Ben Hiant and Achateny members display channelised and lobate geometries, which act as crude palaeo-flow direction indicators and point towards the conglomerates having been sourced from an area south of Loch Mudle (Fig. 11), where they achieve their minimum thicknesses. This area may have acted as a relatively upstanding ‘sedimentary watershed,’ or ‘drainage divide,’ from which the conglomerates were derived. From this upland area, coarse clastic materials were dispersed towards the south and the north, resulting in the compositional trends described above.

Photo-statistical analysis

Statistical methods of photo-analysis have been developed to quantify the strength of clast orientation, or directional clast fabric, in various types of volcaniclastic mass flow deposits (Karatson et al. 2002). This fabric strength (*R*) is defined as ‘the resultant vector length of clast alignment computed from clast angles visible on a vertical outcrop face’ and can be obtained from image analysis and statistical assessment of photographs of outcrops. Karatson et al. (2002) derived *R* values of 28% for near-vent breccias characterised by relatively weak fabrics and 46% for volcaniclastic mass flow deposits, which display a stronger fabric. Mass flow fabric analysis is discussed in detail by Davies and Walker (1974), Smith (1986), Major and Voight (1986), Cappaccioni and Sarrochi (1996) and Bertran et al. (1997).

We have applied the methodology of Karatson et al. to the Ardnamurchan deposits and the resultant data are summarised in Table 4. Our interpretation of these photo-statistical analyses is also confirmed where 3D exposures of the outcrop are available. Six sites in the Ben Hiant Member and two sites in the Achateny Member were selected for analysis. Data for two localities are presented in the form of rose diagrams (Fig. 11). A 3-D view of an idealised block of a mass flow unit, displaying bedding/palaeoflow parallel, vertically stacked and imbricated clasts (discussed below) is provided (Fig. 11).

R-values from the Ben Hiant Member range between 44% and 64%, on average 56.2%, and so can be characterised as having a strong preferred fabric (Bertran et al. 1997). The *R*-values appear to increase in a southerly direction, indicating a greater degree of clast alignment in the interpreted direction of palaeoflow. There are, however,

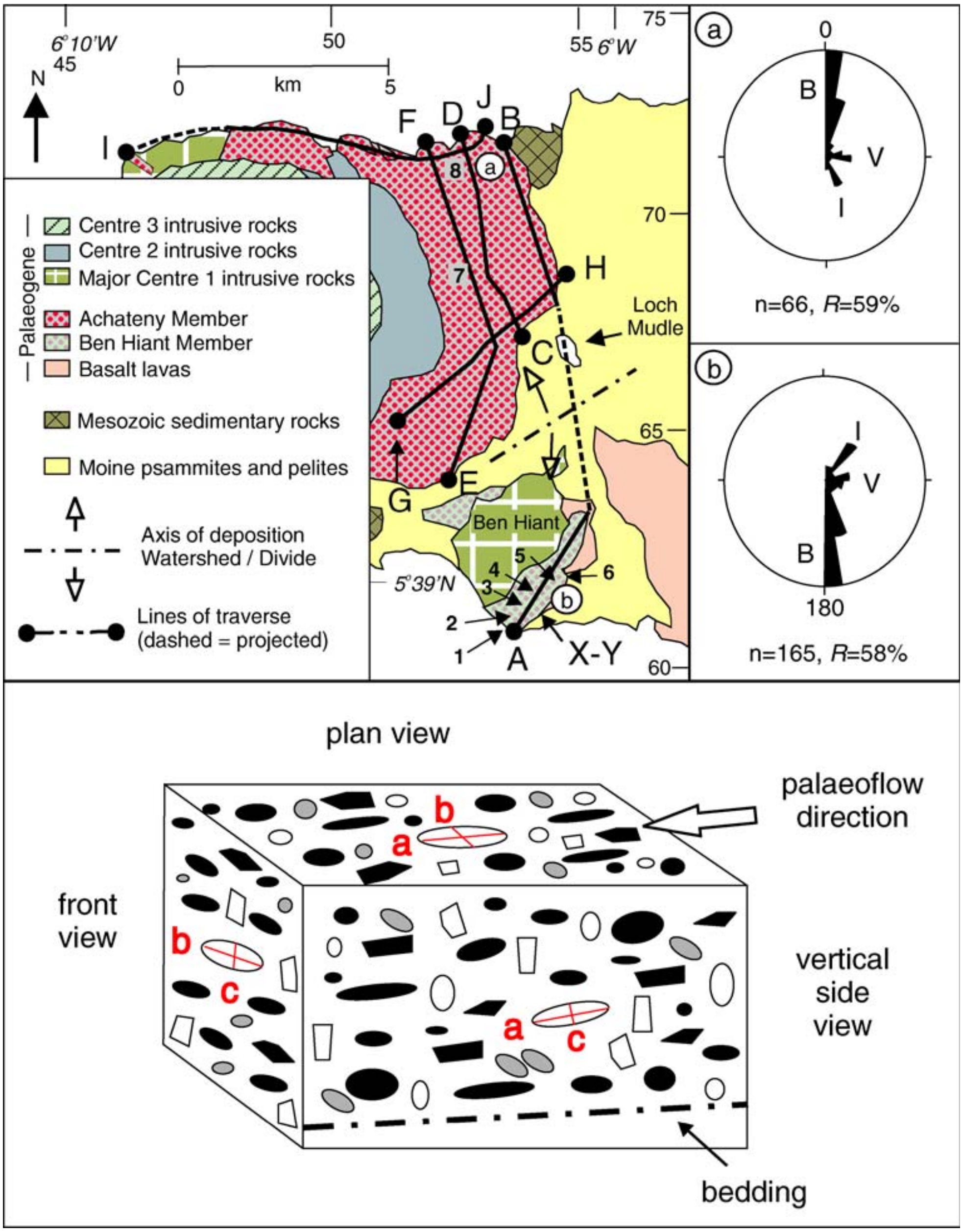


Fig. 11 Map showing location of sedimentary watershed, clast-matrix analysis traverses (A–J, X–Y), and rose diagrams (**a**, **b**) depicting preferred orientations of clasts at representative data points, 8 and 4, respectively. *Traverses*: A–B Maclean's Nose to Swordle Cave, C–D Allt an Doire Dharaich to Ardtoe Island, E–F Camphouse to Portban, G–H Allt na Mi Chomhdhail to Tom na Gainmheich, I–J Rubha Carrach to Swordle Cave, X–Y Ben Hiant Vertical Section. *Rose diagrams*: *B* = Bedding/palaeoflow parallel clasts, *V* = Vertically stacked clasts, *I* = Imbricated clasts. *Photo-statistical analysis*: 1–8 Data points (see Table 4). *Block diagram*: 3-D view of an idealised block of a mass flow unit. Bedding/palaeoflow parallel clasts (*black*), vertically stacked clasts (*white*), imbricated clasts (*grey*), clast axes (*a*, *b*, *c*)

inconsistent results at sites 2 and 6. Site 2 has an *R*-value of 44.7% and, although still considered high, is lower than the others. This may be because of a smaller sample population at this site, thus reducing its validity, as Karatson et al. (2002) recommend a sample population of 150, although geographical heterogeneity may also be responsible. Sites 1–5 are located at or near the base of the sequence (Conglomerate A or B) and, therefore, are at a similar stratigraphic level. Site 6, however, is located at a much higher stratigraphic level, within a fine-grained, matrix-supported unit and, therefore, cannot be expected to follow the observations at sites 1–5. For the Achateny Member, sites 7 and 8 have *R*-values of 47.1% and 59.1%, respectively, in agreement with their proximal and distal locations, as deduced from other palaeo-flow direction indicators, discussed above. Rose diagrams with *R* and *n* values for sites 4 and 8 are presented in Fig. 11. All sample sites produce similar rose diagrams, with an abundance of clasts with near-horizontal orientations, and with *a*-axes parallel to bedding and the interpreted palaeoflow direction (determined from channel axes). A smaller group of imbricated clasts can also be identified. Together, these reflect a bimodal distribution of clasts, typically observed at the front of debris flows (Major and Voight 1986) and caused by the commonly developed imbrication and/or remobilisation and mixing of deposits (Karatson et al. 2002). The appearance of 'vertical' clasts, orthogonal to the palaeoflow direction, is typical of deposition *en masse*

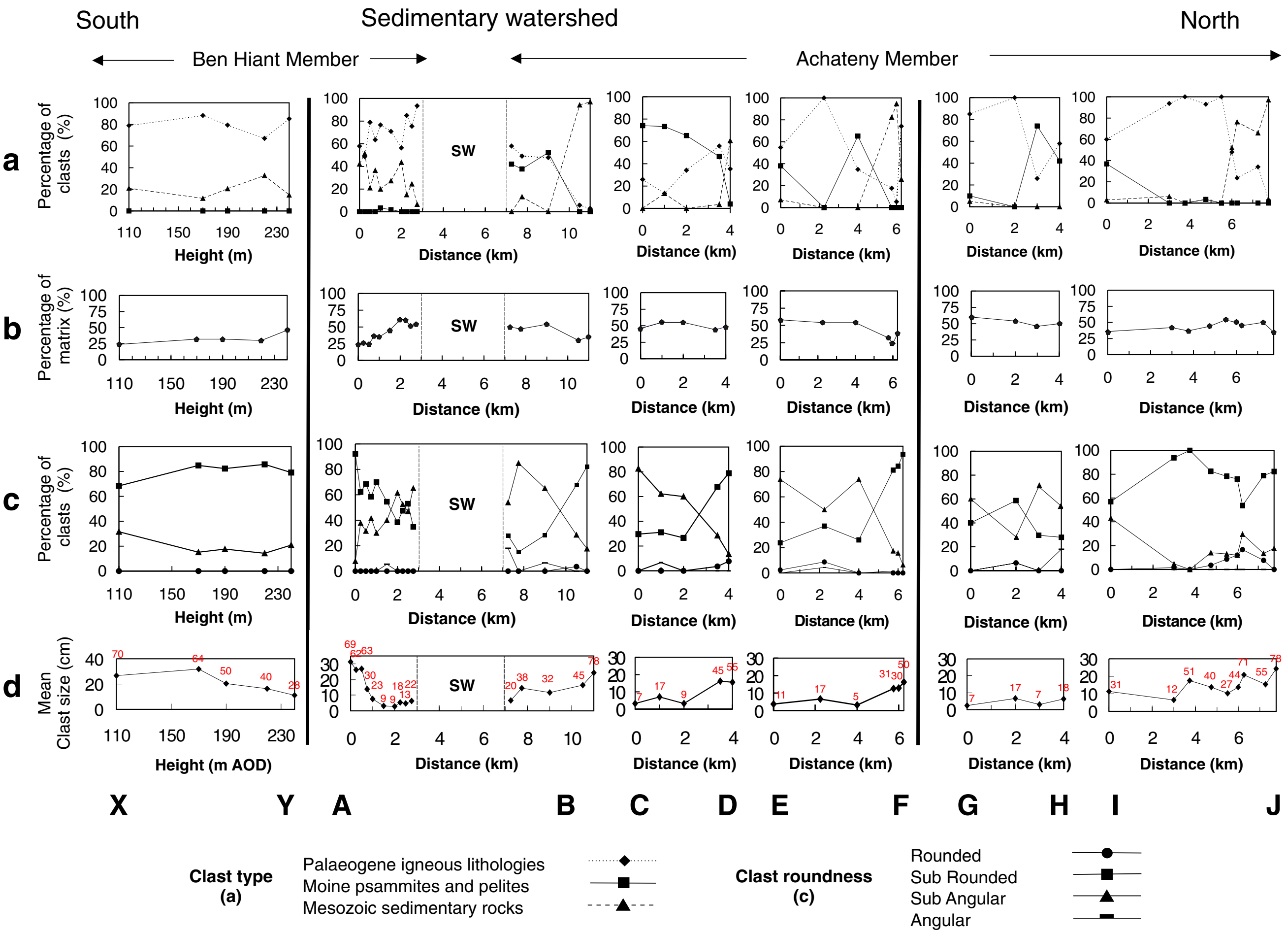


Fig. 12 Clast type, roundness and size data. **a** Clast type versus distance. **b** Proportion of matrix versus distance. **c** Clast roundness versus distance. **d** Mean clast size versus distance. *Small figures* are mean (in cm) of five largest clasts at sample site (not to scale). *SW* = Sedimentary watershed. Location and nomenclature of traverses is given in Fig. 11. North and south are indicated. *AOD* = above ordnance datum

within a debris flow, rather than through accumulation by rolling of clasts on the surface (see below) (Cas and Wright 1987; Orton 1996).

Table 4 Fabric data for the Ben Hiant and Achateny members

Site No.	Distance from 'source' (km)	Recorded values (n)	R value
Ben Hiant Member (BHM)			
1	4	215	63.3
2	3.75	102	44.7
3	3.6	137	58.1
4	3.25	165	58.4
5	3.15	155	50.9
6	3	160	61.8
Achateny Member (AcM)			
7	2	67	47.1
8	5	66	59.1

Sedimentation processes

Richey's (1938) model of rhythmic eruptions of trachytic magma from vents to produce the fragmental rocks associated with the ACC does not fit with our observations. The typically large clast size and internal architecture of the stratified Ben Hiant and Achateny outcrops (Fig. 3), together with clast-matrix relationships and photo-statistical analysis, indicate that they are high-energy surface deposits. Megablocks, up to 30 m across, attest to catastrophic mass wasting processes on the contemporaneous land surface. Furthermore, a sedimentary watershed is identified, from which debris was sourced (Fig. 11). Interbedded fine-grained units, predominantly volcaniclastic siltstones with muddy laminae, represent periods of low-energy sedimentation, possibly in inter-channel areas. Three viable transport mechanisms for such high-energy surface deposits are: debris avalanche; debris flow and stream-flow. Below we discuss the relative merits and involvement of each mechanism.

Debris avalanche

Debris avalanche deposits result from large-volume collapses of steep slopes, initiating rapidly moving material as landslides and, ultimately, developing into granular flows (Glicken 1991; Reubi et al. 2006). The resultant deposits can be several tens of kilometres across, and are essentially structureless, commonly with megablocks up to hundreds of metres across (Smith and Lowe 1991; Glicken 1991; Yarnold 1993).

On Ardnamurchan, to the north of, but proximal to the watershed (Fig. 11), the conglomerates and breccias of the Achateny Member are composed primarily of angular and sub-angular aphyric basalt and basement psammite and pelite clasts. Rarer rounded clasts may have developed in response to prior fluvial transport and/or weathering events, for example spheroidal or doleritic weathering, common in flood basalt provinces. Megablocks of basalt up to 30 m across are recognised, forming a present-day hummocky topography. These megablocks are heavily fractured, and are enclosed by the conglomerates. These relationships suggest that they may have been transported within a semi-rigid mass of debris (now conglomerate/breccia), where blocks are delimited due to faulting and begin to slide, with shear pressures fragmenting the moving mass. This material then transforms to a semi-rigid flow with brecciated and fractured upper and middle zones (Reubi and Hernandez 2000).

Debris avalanches typically have a basal friction layer, composed of homogeneous, cataclastic, comminuted material formed by grinding and abrasion of the ‘overriding’ megablocks and clasts (Schneider and Fisher 1998). No such cataclastic layer is identified for the Achateny Member. Pebbly volcaniclastic sandstone occurs locally beneath some of the megablocks, but is composed of sub-rounded pebbles and coarse sand, not angular, cataclastically-derived material.

Debris avalanche deposits are also typically highly clast supported. However, proximal to the watershed, the conglomerates are matrix-supported, with matrix forming approximately 50 vol.% of the rock. The Ardnamurchan deposits show significant clast population heterogeneity, characterised by large, rounded clasts or blocks of locally derived country rock material. A degree of mixing may occur within debris avalanches when the basal layer develops a turbulent character and picks up clasts from the source edifice (Reubi and Hernandez 2000). This characteristic is uncommon, however, and certainly not developed to the degree observed in the Ardnamurchan deposits. Finally, towards the north coast, normally graded units and poorly developed cross-cutting channels are observed, which are not recognised in debris avalanches.

Thus, the Achateny Member conglomerates share some characteristics with debris avalanche deposits, such as megablocks and the development of a hummocky topography. However, the presence of numerous, sub-rounded, locally-derived clasts, together with the absence of jigsaw-fit textures or a basal cataclastic layer, and their common matrix-support, suggests that they are not debris avalanche deposits. The shattered megablocks may, however, indicate the influence of catastrophic slides, possibly due to faulting.

There is no evidence of debris avalanche deposits south of the watershed in the Ben Hiant Member. Clast size is typically <1 m, no more than 5 m, and they are not always shattered. Neither jigsaw-fit textures nor basal cataclastic layers are present and sub-rounded, locally-derived clasts are abundant. The Ben Hiant conglomerates are interbedded with volcaniclastic siltstones and sandstones, indicating a series of cyclic, high- and low-energy environments and styles of deposition that are not generally recognised in debris avalanche deposits.

Debris flow

Debris flows comprise poorly sorted assemblages of large clasts, set in a fine-grained matrix. They are typically small-scale deposits (tens of metres to a few km), which display features such as cross-cutting channels or lobes and may be weakly graded (Blair and McPherson 1998). Debris flows are typically initiated in mountainous areas from failures of soil, regolith and/or weathered bedrock, commonly triggered by heavy rainfall, resulting in water-debris slurries (Johnson 1984; Smith 1986; Smith and Lowe 1991).

The regional distribution of clasts within the Ardnamurchan conglomerates is strongly allied to the geology of the pre-conglomerate land surface. This land surface would have been mantled with regolith and/or talus, and the debris flows initiated when water mobilised these loose sediment/rock mixtures (Innes 1983). Prior weathering, erosion and limited transport of debris from surface exposures yielded the dominant clast lithologies. The sub-rounded to rounded clast population may, most easily, be attributed to prior fluvial transport and/or weathering events. Within the Ardnamurchan depositional system, aphyric basalt and basement psammite typify the bedrock in areas proximal to the watershed, resulting in relatively homogeneous clast populations (Fig. 12). In more distal areas, where the pre-conglomerate land surface comprised Mesozoic shale, this lithology contributed significantly to the clast population. These clasts remained sub-angular, reflecting their overall fabric. Only on the northern coastline, where the most distal part of the Achateny Member crops out, are nearby in situ exposures of Jurassic limestone and sandstone. Here, these rock types occur as clasts in the conglomerates. Significantly, the sub-rounded nature of a proportion of these clasts suggests that they are not first cycle components of the conglomerates, having already been through a previous weathering and transport cycle. Debris flows are typically bulked up by the entrainment of surface materials as they move downslope (Fisher 1983; Smith and Lowe 1991), possibly explaining the strong correlation between bedrock geology and the conglomerate clast population. The clast populations may also reflect variations in sediment supply, changes in downslope gradient (larger clasts deposited more easily) and progradation of the depositional systems (Lirer et al. 2001).

The link between bedrock geology and overlying clast type population is further emphasised by discrete concentrations of certain lithologies in the conglomerates. Between Rubha Carrach and Swordle Cave (I–J, Fig. 11) there are localised concentrations of microgranite and scoriaceous basalt clasts. Microgranite of this type is not present in situ in the Ardnamurchan district and scoriaceous basalt is highly localised. Their presence in the conglomerates indicates that the debris flows entrained these materials from localised sources (now buried?) of such lithologies on the pre-conglomerate land surface. Similar examples of single-lithology-dominated deposits are recognised throughout the Achateny Member (e.g. Figs. 9e, 10). Criteria for debris flow recognition, such as clast mixing, can be ambiguous where flows are dominated by coarse, blocky talus (Yarnold 1993) and perhaps these concentrations indicate localised talus (or scree) and/or regolith accumulations, which have not been widely dispersed or mixed by the overriding debris flow. The chaotically arranged, shale-dominated, angular-clast deposits depicted in Fig. 9d may have been formed in a similar manner, although their extremely tightly packed nature is more indicative of derivation by shattering of a larger, pre-existing block.

Increasingly rounded and compositionally heterogeneous clast assemblages occur relatively distal to the watershed. In debris flows, the detritus that forms the original clast population is typically bulked up and mixed with other surface materials as it moves downslope (Fisher 1983; Smith and Lowe 1991). These processes explain not only the presence of a more heterogeneous and rounded clast population (from previously eroded and weathered debris), but also the increase in the degree of clast support in distal areas (Fig. 12). As material was entrained, the coarsest materials were pushed to the front of individual debris flows (Takahashi 1978, 1980, 1981). Basal contacts indicate the irregular pre-conglomerate topography of the district, confirmed by the evidence for upland and lowland areas identified in the palynological analysis.

Photo-statistical clast analysis of the Ben Hiant Member indicates a local imbrication of clasts (Fig. 11). These features imply a bimodal distribution of clasts typical of debris flows, and may be linked to the dilution of flow fronts (Major and Voight 1986; Pierson and Costa 1987). Debris flows are commonly impounded within drainage channels (‘valley-confined flows,’ Innes 1983), their flow paths being essentially controlled by local topographic relief (Sohn et al. 2002). However, they may overtop these features, producing localised, finger-like, overlapping lobes (Yarnold 1993). Within the Achateny Member we recognise such small-scale channels and their associated depositional surfaces, for example at Rubha na h-Acairseid (Figs. 9e and 10). Measurement of clast orientation within debris flow channel deposits can reveal variable palaeoflow patterns, commonly with clasts oriented at ‘high’ angles to the overall trend of the channel (Sohn et al. 2002), as identified from the Ardnamurchan photo-statistical analyses.

The Ben Hiant Member, comprising stacked conglomerates interbedded with fine-grained lacustrine and fluvial sedimentary units, is also typical of a debris flow association (Blair and McPherson 1998). Such strata fill small gullies and channels and, during the waning phase of debris flow deposition, or hiatuses, revert to lower energy hyperconcentrated flow or fluviatile deposition, with water-washing and recycling of the debris flow surfaces (Pierson and Costa 1987; Smith and Lowe 1991). During the most quiescent periods, lacustrine deposition may occur. Siltstone ii of the Ben Hiant Member displays such channel structures. Poorly sorted, clast- to matrix-supported, pebbly gravel beds are also recognised in such associations (Blair and McPherson 1998) and have been identified from Conglomerate A of the Ben Hiant Member (Fig. 7a, b).

Examples of hyperconcentrated flow deposits (Smith 1986) may be recognised in Conglomerates A and D of the Ben Hiant Member (Fig. 7b, c, e) and in certain units of the Achateny Member (Fig. 9g), which are dominated by sand- to gravel-grade material with a well-defined stratification, similar to deposits from the Ellensburg Formation, Washington, NW USA, as described by Smith and Lowe (1991). Conglomerate A may represent initial hyperconcentrated flow, followed by debris flow deposition, south of the watershed. The subsequent four conglomerates are interpreted as high-energy debris flow deposits, although Conglomerate D locally displays hyperconcentrated flow characteristics. Locally, siltstones and sandstones form channel-fill deposits that cut into the top surfaces of the conglomerates. Sandy layers, cross-bedding and muddy laminae within these siltstones indicate inputs of different sediment and demonstrate weak current (lacustrine) activity.

Stream-flow

Certain characteristics of the Ben Hiant and Achateny members are consistent with high-energy stream-flow, specifically the rounding of a proportion of clasts. However, such rounded clasts are commonly in close association with distinctly angular examples, in heterogeneous mixtures of sediment (Fig. 3). True *rounded* clasts are relatively rare (Fig. 12), with sub-rounded clasts only dominant in localised areas. Furthermore, a number of these rounded to sub-rounded clasts are composed of basalt, a rock prone to spheroidal weathering. Given the elevated nature of the contemporaneous landscape (Fig. 13 and palynology data), a drainage system undoubtedly developed, and would have generated a significant fluvial system. Such fluvial accumulations occur interbedded with the flows of the Mull and Skye lava fields (Emeleus 1985; Williamson and Bell 1994) and are characterised by the association of *well* rounded and graded conglomerates, with numerous cross bedded sandstone units, laminated mudstones and thin coals. In the south–west part of the Mull Lava Field, the sequence can be sub-divided into six sedimentary-volcanic couplets (Bell and Williamson 2002), and invariably the associated conglomerates preserve evidence of cross-stratification and grading. The most famous of these units is the sequence at Ardtun, part of which comprises siltstones containing perfectly preserved leaf assemblages (Bailey et al. 1924). A similar sequence is preserved in the Skye Lava Field at the Allt Mor locality (Williamson and Bell 1994). The contrasting appearance of the Ardnamurchan deposits, part of the Mull Lava Field, indicates a different *overall* mode of deposition. The *general* lack of sorting, graded units, cross stratification and cross lamination is in stark contrast to the clear-cut examples of fluvial sedimentation outlined above. Undoubtedly, fluvial systems would have contributed significantly to the Ardnamurchan deposits. However, we interpret their final mode of transportation and deposition as being of debris flow association. Coarse, clastic conglomerates may be produced in fluvial megafan and braidplain settings, and form units with lenticular to tabular geometries, typically metres thick (Collinson 1996; Browne and Naish 2003). However, such a wholly fluvial interpretation is unlikely for the following reasons: (1) a general lack of organised clast segregation, either into beds or cross beds (n.b. Conglomerates A–E represent separate depositional units); (2) the dominant clasts are sub-rounded to sub-angular; and (3) the regular occurrence of extremely poorly sorted, massive units (e.g. Conglomerate E is ~35 m thick). Slope profile migration with time, would lead to the superposition of dominant debris flow deposition and minor distal fluvial deposition.

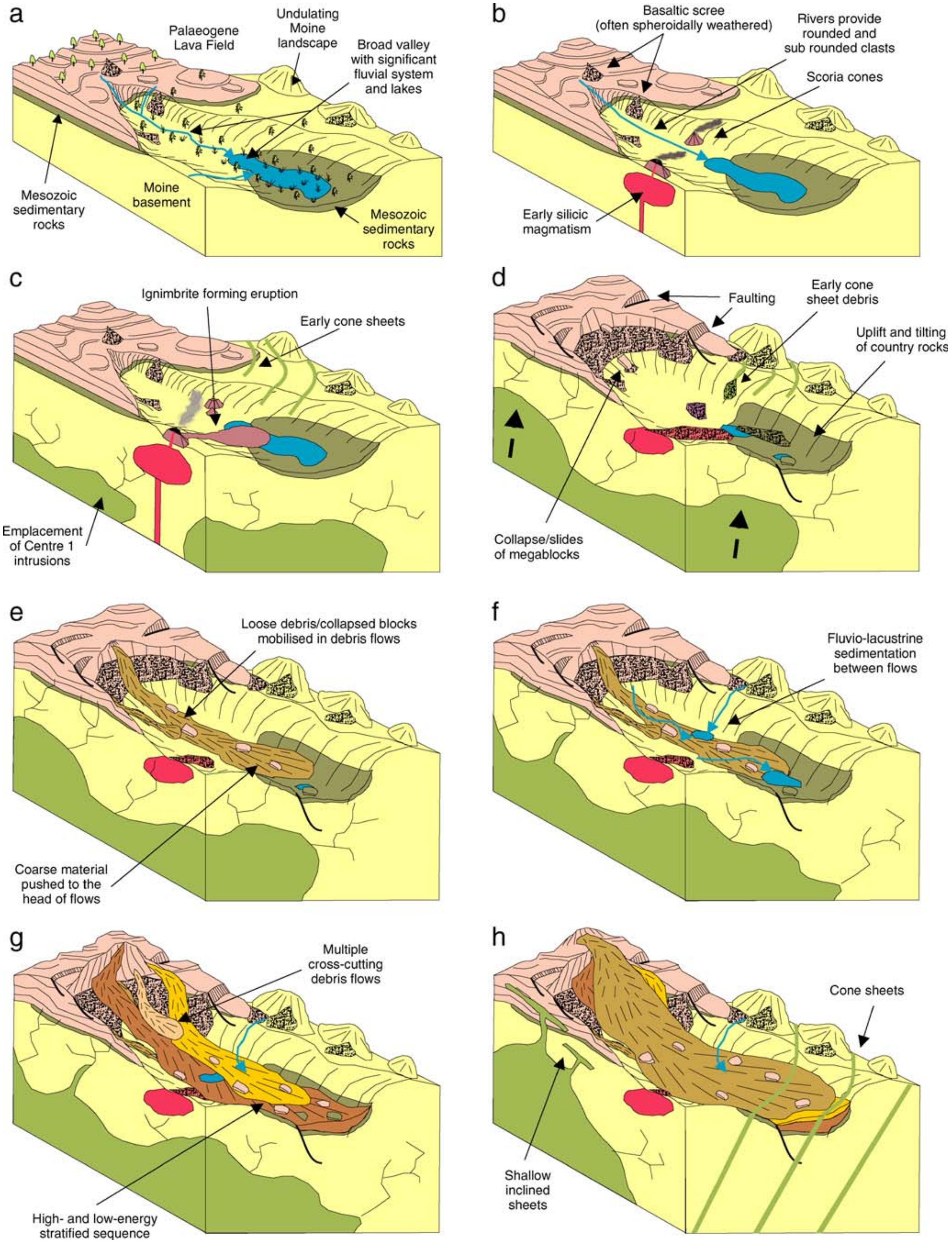
Uplift mechanisms, rate of uplift and palaeogeographical reconstruction of the volcanic landscape

The sedimentary watershed we have identified represents a relatively elevated area from which the Ardnamurchan conglomerate depositional system originated. The presence of large clasts and megablocks clearly points towards episodes of substantial mass movement, suggesting that the palaeo-topography during conglomerate deposition must have had considerable relief. The localised removal of tens of metres of the lava sequence from below the southern part of the Ben Hiant Member and from the majority of the outcrop of the Achateny Member, indicates that a relatively mature landscape had already developed in the vicinity of the ACC, prior to conglomerate deposition. To the east, the then still relatively elevated hills of basement psammites and pelites may have controlled the palaeo-topography and overall palaeo-geography during the Palaeogene, restricting or stopping dispersal of sediment towards the east.

Nearby upland areas, with elevations of ~1,000 m, may be inferred from the palynological data. Pine-type grains, *Pityosporites,* indicate input from upland sources. Stratigraphic and mineralogical studies indicate that at least 1 km of material has been eroded from the Mull Lava Field, suggesting considerable relief may have developed during the Palaeogene (cf. Walker 1971; Emeleus 1985; Williamson and Bell 1994; Holness 1999; Bell and Williamson 2002).

Recent work by Chambers et al. (2005) on the ages of the Eigg and Skye lava fields, together with the timing of formation of the Rum Central Complex, has provided a much-reduced estimate of the period of volcanic activity within this district. Chambers et al. (2005) suggested that within 0.92 m.y., the Eigg Lava Field was erupted, the Rum central volcano developed and was unroofed, and the Canna Lava Formation (of the Skye Lava Field) was

Fig. 13 Schematic reconstruction of the uplift, erosion and sedimentation history of the Ardnamurchan conglomerates. This reconstruction is a generalised interpretation of events in the Ardnamurchan district and depicts an amalgamation of features observed in the Ben Hiant and Achateny members. One flank of the postulated sedimentary watershed is illustrated, but similar events would have occurred on the opposing side. **a** Early Palaeogene landscape with upland forested areas, draining into lowland areas characterised by heavily vegetated swamps and lake environments. Erosion locally exposed Mesozoic sedimentary rocks and Neoproterozoic (Moine) basement, producing scree/talus deposits. **b** Early silicic and basic magmatism of the Ardnamurchan Central Complex (ACC) produced minor intrusions, locally forming small vents and cones. Fluvial systems deposited sub-rounded and rounded clasts on valley floor and slopes. **c** Ignimbrite-forming eruptions occurred. Basaltic magma of the ACC was emplaced into the country rocks and some intrusions reached shallow crustal levels. **d** Early silicic intrusions were unroofed and eroded. Continued emplacement of the ACC caused uplift and doming of the Ardnamurchan district. Faulting detached megablocks from the land surface, which collapsed/slid downslope. **e** Detritus was mobilised in debris flows, which entrained weathered and eroded material from the land surface. The largest clasts were pushed to the front of flows. **f** Flows began to wane, forming hyperconcentrated and streamflow deposits. Small rivers and lakes formed during the more quiescent periods. **g** Further uplift of the ACC continued, initiating multiphase debris flow deposition, and preserving a high- and low-energy stratified sequence. **h** Debris flow conglomerates were cut by later intrusions of the ACC ▶


a
Palaeogene Lava Field
Undulating Moine landscape
Broad valley with significant fluvial system and lakes
Mesozoic sedimentary rocks
Moine basement
Mesozoic sedimentary rocks
b
Basaltic scree (often spheroidally weathered)
Rivers provide rounded and sub rounded clasts
Scoria cones
Early silicic magmatism
c
Ignimbrite forming eruption
Early cone sheets
Emplacement of Centre 1 intrusions
d
Faulting
Early cone sheet debris
Uplift and tilting of country rocks
Collapse/slides of megablocks
e
Loose debris/collapsed blocks mobilised in debris flows
Coarse material pushed to the head of flows
f
Fluvio-lacustrine sedimentation between flows
g
Multiple cross-cutting debris flows
High- and low-energy stratified sequence
h
Cone sheets
Shallow inclined sheets

erupted. Approximately 1 km is thought to have been lost from the top of the Rum central volcano (Emeleus 1983) during an interval of 0.53 m.y., the age difference between the formation of the layered peridotites of the Rum volcano (60.53±0.04 Ma; Hamilton et al. 1998) and lavas of the Skye Lava Field (60.00±0.23 Ma; Chambers et al. 2005) and, therefore, an erosion rate of 1.89 mm per year can be calculated. Chambers et al. (2005) noted that this figure is comparable with erosion rates in the Himalayas, involving fluvial incision and catastrophic landslides, with the latter contributing significantly to the erosion rate. Together with the Ardnamurchan conglomerates, this suggests that mass wasting processes were important episodes in the rapid unroofing of the Palaeogene central complexes of NW Scotland.

Concentrations of ignimbrite clasts within the Ardnamurchan conglomerates indicate prior, localised pyroclastic activity, with accumulation of material on the contemporaneous land surface. Clasts of microgranite imply the unroofing of earlier silicic intrusions. Thus, the Ardnamurchan area was magmatically and tectonically active prior to the deposition of the Ben Hiant and Achateny members. The radially diverging dips of the Jurassic strata around the ACC provide clear evidence for the genetic link between doming and intrusion (Fig. 2). Although *some* Centre 1 cone sheets cut the conglomerates, the related uplift must have commenced earlier. Evidence for cone sheets pre-dating conglomerate deposition (and causing uplift) is provided by the presence of Centre 1 cone sheet rock types as clasts within the conglomerates (Richey and Thomas 1930 and this study). Doming due to upwelling magma (silicic diapirs) and the formation of localised vents is also widely recognised in central complexes of the Province (Walker 1975) and the ignimbrite and microgranite clasts may be remnants of such processes. Thus, the diverging sediment transport directions towards the north and south, and the relationship of the conglomerates with the Centre 1 cone sheets, imply synchronous sedimentation and doming (i.e. periods of uplift interspersed by sedimentation).

Consequently, a topographic ‘high’ must have developed over the ACC, even if there were no eruptive products contributing towards a volcanic superstructure. From this elevated region, the megablocks and enclosing conglomerates were transported by mass movement. The watershed may not represent the highest point or the focus of intrusion and uplift, as there is little evidence to suggest that there was a point source of intrusion. Nonetheless, the area above the ACC must have provided a source region with significant relief, possibly as much as 1,000 m, based upon the aggregate vertical thickness of the suites of cone sheets (Richey and Thomas 1930; British Geological Survey 1969, 1976). This link between cause and effect provides compelling evidence for shallow emplacement of magma having a direct and, indeed, near-synchronous effect on landscape development and sedimentation processes.

Mass wasting in other volcanic systems

Identification of volcaniclastic rocks in Large Igneous Provinces (LIP), worldwide, is typically restricted to basal hyaloclastites, and pyroclastic units (e.g. Ross et al. 2005). The only other detailed account of a *similar* deposit to those described here, is from the Jurassic Mawson Formation, Allan Hills, Antarctica (Reubi et al. 2006). This heterogeneous sequence, interpreted as a debris avalanche deposit, comprises both volcanic and non-volcanic debris, with megablocks up to 80 m across, and fills a pre-existing topography. Emplacement of large intrusions is suggested as the initiation mechanism. One significant difference between this deposit and the Ardnamurchan rocks is the absence of rounded clasts (JDL White personal communication). Nonetheless, no other detailed descriptions of either debris flow or debris avalanche deposits from continental flood lava sequences have been published (cf. Reubi et al. 2006). However, it is our opinion that such deposits are unlikely to be rare, given the many common features shared by LIPs, in particular the emplacement of shallow intrusions and the development of topographic relief.

Within the ocean basins, many active volcanoes, for example the Canary Islands and the Hawaiian archipelago, provide abundant evidence for slope failure, landslide activity and the development of debris deposits on their flanks (Lipman et al. 1988; Thouret 1999; Masson et al. 2002). These coarse clastic units give way to distal volcaniclastic turbidites. There is a close spatial association between landslide development and the active volcanic rift zones: failure is primarily initiated by one or more of shallow intrusion, pore fluid pressure change, seismicity, gravitational spreading or sea level change. Caldera collapse is not considered to be a viable mechanism for these collapse events, indicating that landslides should not be unexpected in large igneous provinces (Masson et al. 2002).

Synthesis

Palaeogene clastic rocks of the Ardnamurchan district, NW Scotland, have previously been interpreted as classic examples of vent-filling agglomerates (Richey 1938). We re-interpret these rocks as the products of debris flow deposition on a landscape undergoing dynamic uplift due to the emplacement of shallow intrusions of the Ardnamurchan Central Complex (ACC). Below, we summarise the complex sequence of events that occurred on this landscape (Fig. 13).

During the early Palaeogene, the landscape comprised upland areas, with a mature pine forest vegetation, and rivers and streams draining into lowland areas within broad valleys. Locally, small rivers fed swamps and lakes, which supported a dense vegetation of ferns and flowering plants. Erosion of the Palaeogene Mull Lava Field, enhanced by the typical warm and wet environments of the time, locally exposed Mesozoic sedimentary rocks and Neoproterozoic basement psammites and pelites, littering the landscape with scree/talus deposits and regolith. Sub-rounded to rounded clasts would have been contributed by the background fluvial system.

Magmatic activity associated with the ACC was in its infancy, with minor silicic intrusions and basic magma locally piercing the contemporaneous land surface, in the form of small vents and scoria cones. Ignimbrites were sporadically deposited, although the locations of the source vents are unknown. The large body of basic magma associated with Centre 1 of the ACC was emplaced into the country rocks of the district and, locally, cone sheets and dykes penetrated to shallow levels, possibly even venting to the surface. These early cone sheets, together with silicic intrusions, already crystallised, were unroofed and eroded onto the Palaeogene land surface. The ACC was emplaced into increasingly shallower levels of the country rocks, causing uplift and doming of the Ardnamurchan district.

Faulting occurred in response to the uplift and, locally, megablocks of the lava field and underlying Mesozoic lithologies were detached, collapsing or sliding downslope, within masses of scree and previously transported fluvial material. Loose debris and collapsed blocks (including early cone sheets) were mobilised in debris flows, most likely initiated by continuing uplift, tectonism and heavy rainfall. Locally, debris flows were confined to valleys and small channels, but may have overtopped these features, producing large lobate geometries. The flows moved downslope and were bulked up as they entrained material from the land surface, with the largest clasts being pushed to the heads of flows. As weathered, eroded debris was incorporated into the flows, the deposits became more clast-supported, with increasingly heterogeneous and rounded clast populations, in distal areas. Flows began to wane and were diluted with water, producing hyperconcentrated flow, and ultimately stream-flow, deposits, akin to the 1982 “lahar run-out events” at Mount St. Helens (Smith and Lowe 1991). Subsequently, small rivers drained the debris flow fans and, locally, lakes and swamps, colonised by ferns, angiosperms and small trees, developed.

Uplift associated with emplacement of the ACC continued, and further debris flows were initiated. Debris flow deposition was multiphase, with cross-cutting flows locally forming channels in underlying deposits, and sampling discrete talus and regolith accumulations. The cycle of high-energy debris flow, occasional hyperconcentrated flow, and low-energy fluvio-lacustrine sedimentation continued, producing a complex, stratified sequence. The debris flow conglomerates and associated deposits were cut by later cone sheets of Centre 1 of the ACC. This was followed by emplacement of intrusive rocks of centres 2 and 3 of the ACC and significant erosion.

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