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Ardnamurchan 3D cone-sheet architecture explained by a single elongate magma chamber

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The Palaeogene Ardnamurchan central igneous complex, NW Scotland, was a defining place for the development of the classic concepts of cone-sheet and ring-dyke emplacement and has thus fundamentally influenced our thinking on subvolcanic structures. We have used the available structural information on Ardnamurchan to project the underlying three-dimensional (3D) cone-sheet structure. Here we show that a single elongate magma chamber likely acted as the source of the cone-sheet swarm(s) instead of the traditionally accepted model of three successive centres. This proposal is supported by the ridge-like morphology of the Ardnamurchan volcano and is consistent with the depth and elongation of the gravity anomaly underlying the peninsula. Our model challenges the traditional model of cone-sheet emplacement at Ardnamurchan that involves successive but independent centres in favour of a more dynamical one that involves a single, but elongate and progressively evolving magma chamber system.

The Ardnamurchan central igneous complex occupies an E-W striking peninsula that forms the westernmost part of the Scottish mainland and represents a section through the heart of a Palaeogene (~59 Ma) central volcano (Fig. 1) at approximately 2 km beneath the former land surface¹. It hosts numerous and mostly mafic intrusive bodies, including ring-dykes, lopoliths, and, in particular, swarms of centrally-inclined sheets that are widely regarded as the archetypal examples of “cone-sheets”^{2,3}. The term “cone-sheet” describes a thin, arcuate magmatic intrusion that dips inward towards a central source and thus has the shape of an “inverted cone” (e.g.^{2,4}). Anderson (1936)⁴ based his pioneering conceptual model of the emplacement mechanics of cone-sheets and ring-dykes largely on the Ardnamurchan example. Cone-sheets have recently gained renewed attention for their fundamental role in building the interior of long-lived volcanoes, for feeding surface eruptions, and because cone-sheet swarms may be used to infer depth, size, and shape of underlying magmatic source(s) (cf^{5–7}).

Mapping of the rocks and structures at Ardnamurchan led Richey and Thomas (1930)³ to define three successive centres of activity (Centres 1, 2, and 3) from the focal points of the exposed cone-sheet swarm(s) and their relative age relationships with major intrusions (Fig. 1). This concept implies cyclic magmatic activity with lateral shifts in source locus and is assuming that one centre solidified and cooled before renewed build-up of a successive centre commenced⁸, an interpretation that has also been offered for multiple cone-sheet focal points at the neighbouring Isle of Mull igneous complex². However, data that have become available since Richey and Thomas (1930)³ on absolute ages, compositions of intrusive units, and particularly on their geometry and emplacement styles do not always support the distinction of separate centres at Ardnamurchan (e.g.^{9,10}). We have therefore used the field records and structural data from the available geological maps of the Ardnamurchan central complex and projected all recorded cone-sheet intrusions in 3D to test the traditional concept of three static centres with multiple and successive magmatic sources, as proposed by Richey and Thomas (1930)³.

Results

Dip values between about 30° to 35° are characteristic for distal cone-sheets, whereas dip values of about 60° to 70° are typical in the more central exposures, e.g. south of Sanna Bay^{3,11}. The 3D projections of the 797 suitable cone-sheet traces suggest that most cone-sheets dip towards a focal region ~1.5 to 4 km below the central part of the peninsula (56°44' N; 6°08' W; see animation of the three-dimensional model in the Supplementary Information), i.e. approximately 3.5 to 5 km below the former volcanic edifice. There they delineate a larger

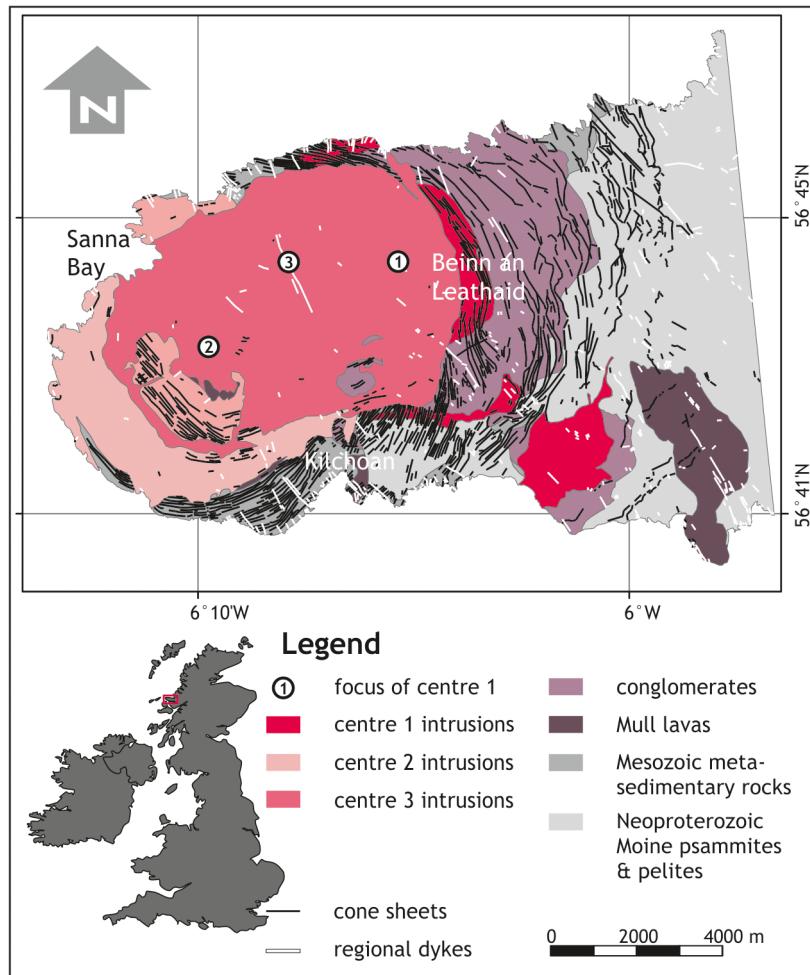


Figure 1 | Simplified geological map of Ardnamurchan peninsula. Based upon Emeleus (2009)¹¹ by permission of the British Geological Survey (CP13/091 British Geological Survey © NERC. All rights reserved.). The map shows the focal points of the three centres and associated intrusions as proposed by Richey and Thomas (1930)³.

single, roughly saucer-shaped focal volume (ca. 6 km × 5 km) that strikes ENE. This single volume (i.e. magma reservoir) can account as source for the majority of the cone-sheets projected (Fig. 3).

No distinction between individual focal points of the cone-sheets (the previously recognised three foci³) can be resolved in the 3D model. Furthermore, the mapping of cone-sheet intersections using 2D cross sections through the 3D model also failed to show distinct focal regions or points that could reproduce the results of Richey and Thomas³ (see Supplementary Information 2).

Discussion

The subsurface region defined as the source volume (see workflow in Supplementary Information 2) is illustrated as a single, ENE-striking, roughly saucer-shaped magma reservoir with two protrusions, one pointing E, the other one pointing S (Fig. 3). The main body is flat-topped, extending from 2 to 4 km depth below the present-day land surface (see Supplementary Information 2 for discussion of errors). The protrusions are at slightly shallower depths, the eastern one reaches from 1.5 to 3.5 km, and the southern one at 1.5 to 3 km. The centre of this source volume is located at approximately 56° 44' N and 6° 7' W ca. 1.3 km S of the Centre 3 focal point of Richey and Thomas' (1930)³ (Figs. 1, 3). The focal points of Centres 1 and 3 are likely located within this source volume, whereas the focal point of Centre 2, to which most cone-sheets were previously assigned³, lies below the western part of the inferred magma reservoir (Fig. 3b).

We interpret this source volume to represent the approximate location, shape, and volume of the magmatic source that fed the majority of the cone-sheets, as well as the larger intrusions, over the lifetime of the Ardnamurchan central complex. This magma reservoir most probably consists of a plexus of intrusions that together occupy the focal region of most of the cone-sheets (cf³). The results of the 3D projection consequently indicate that Ardnamurchan cone-sheets were more likely fed by a single source reservoir instead of several distinct point sources or centres as originally proposed³. Although the exact volume of the estimated source region may not be fully accurate, its overall shape and elongation notably coincide with (i) the elongation direction of the Ardnamurchan peninsula¹¹, (ii) the elongation of the lopolithic intrusions, such as the Great Eucrie (Fig. 4a), (iii) the depositional direction of eroded material from the Ardnamurchan volcano that indicates an E-W aligned ridge-like volcanic edifice¹⁴, (iv) with the elongation direction of the Bouguer gravity anomaly underlying Ardnamurchan^{11,15}, and (v) the deformation outlined by the dips in the Mesozoic sedimentary host rocks that record NE-SW doming¹¹.

The concept of successive magmatic centres was first established for the Mull central complex² and later applied to Ardnamurchan, based on the observed cone-sheet patterns, their relative age relationships with major intrusions, and the occurrence of ring-dykes³, which imply an underlying magma reservoir. However, the three successive centres of Ardnamurchan show unsystematic lateral jumps, contrasting the clear N-ward progression of centres on

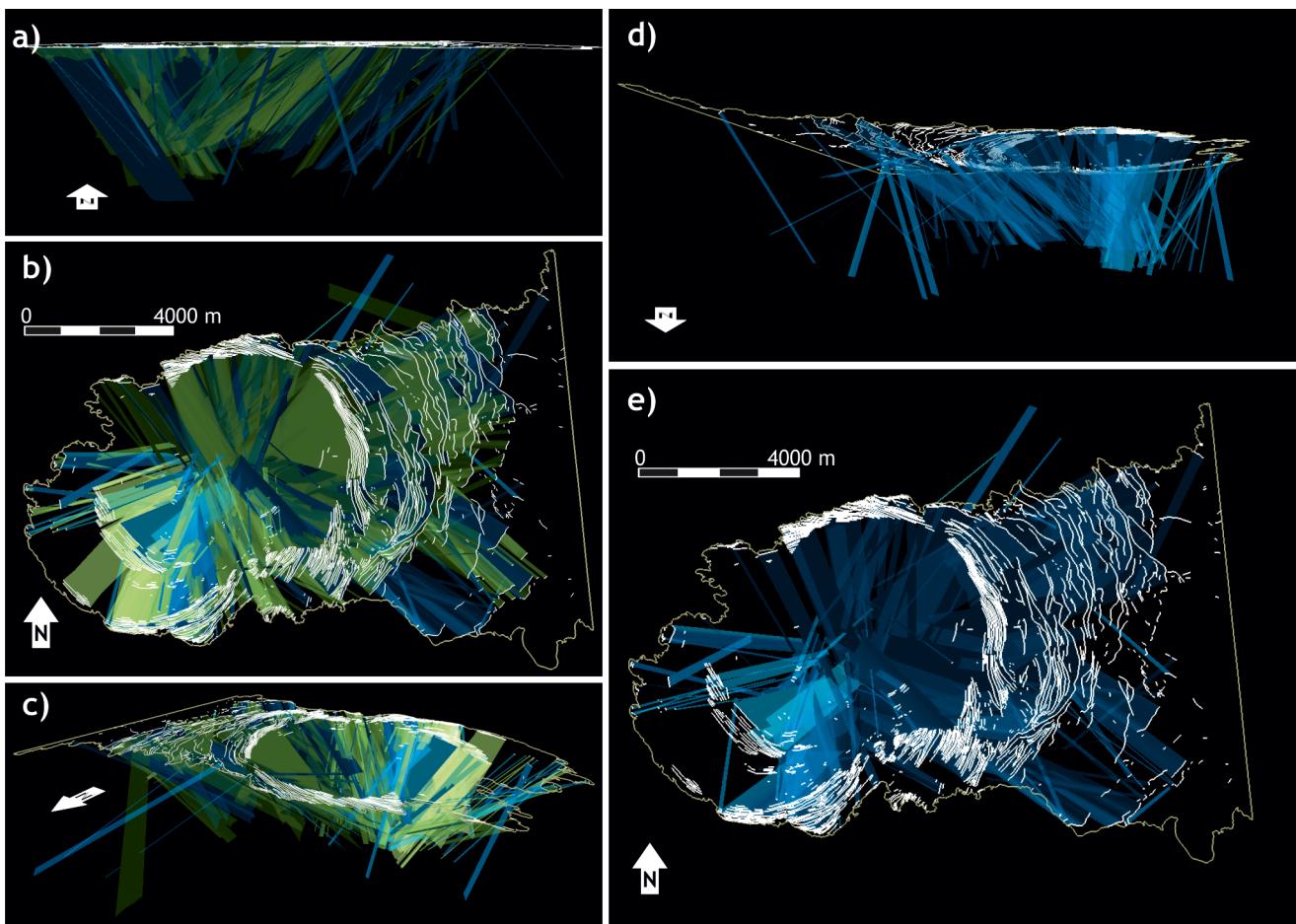


Figure 2 | Three-dimensional model of projected cone-sheets of the Ardnamurchan igneous complex. Projections are based on maps by Richey and Thomas (1930)³ and Emeleus (2009)¹¹ by permission of the British Geological Survey (CP13/091 British Geological Survey © NERC. All rights reserved.). Yellow line = coast line, white lines = map traces of cone-sheets, blue surfaces = projected cone sheets with dip measurements ($n = 145$), green = projected cone-sheets with dips extrapolated ($n = 652$). Scale varies with perspective; see Fig. 1 for location and approximate scale. a) E-W cross-section view. d) Map view. e) Oblique view from NW. c) W-E perspective view from below the Earth's surface. e) Map view. A movie of the model can be found in the supplementary material.

Mull (cf²). Moreover, the Hypersthene Gabbro, one of the “ring-dykes” of Ardnamurchan’s Centre 2, and the Great Eucriite, the main “ring-dyke” of Centre 3, have more recently been suggested to consist of stacks of shallow inward-dipping intrusions. In the latter case, O’Driscoll et al. (2006)⁹ proposed an overall lopolithic shape for the Great Eucriite, while Day (1990)¹⁶ proposed a laccolithic shape for the Hyperstene Gabbro of Centre 2. As a consequence, the occurrence of ring-dykes as a criterion for the identification of separate centres of activity is no longer fulfilled⁹.

Furthermore, the simplification in the traditional approach of cone-sheet projection commonly involves a considerable error, which is for example created by transposition of cone-sheet attitudes from their actual locations onto cross sections (e.g.³; cf¹⁰; see also Supplementary Information 2), which may explain how Richey and Thomas (1930)³ reached the conclusion that Ardnamurchan cone-sheets converged towards three different focal points. In fact, an attempt to reproduce the three focal points of Richey and Thomas (1930)³ within our 3D model did not produce any systematic intersections of projected cone-sheets (see Supplementary Information 2). In addition, our current understanding of the formation, shape, and evolution of actual crustal magma chambers (e.g.¹⁷ and references therein) suggests that the concept of focal points, i.e. source locations that lack shape and volume, is probably dramatically oversimplified. Moreover, field evidence and the results of analogue, theoretical, and numerical modelling (e.g.^{12,18,19}) suggest that

cone-sheets most likely nucleate at the upper lateral ends (i.e. the sides) of flat-roofed, sill-like magma chambers, as opposed to the centre of a reservoir, as implied in the traditional focal-point approach. Our new approach, which takes the above-mentioned points into consideration and which is based on the same input data as used by Richey and Thomas (1930)³ produces a solution that defines a single, elongate source of such a geometry.

A test for the existence of multiple centres would be to analyse systematic cross-cutting relationships between cone-sheets of the different centres (cf²). Ardnamurchan cone-sheets assigned to different centres generally occur in geographically distinct areas³, but where cone-sheets of Centres 1 and 2 should be adjacent, exposure is poor and no intersection has been observed. The absence of distinct petrographic and compositional trends between cone-sheets^{20,21} is in fact more consistent with a single reservoir as temporally distinct centres might be expected to produce a distinguishable range of compositions, e.g. as a result of variable degrees of differentiation and/or crustal contamination (e.g.^{22,23}). Thus, no systematic age succession has been established based on field evidence³ or composition²¹. Geochronological data for the cone-sheets and their host rocks would help to unravel potential age differences of cone-sheets. However, detailed age data of the cone-sheets and other intrusions do not exist. The available ages of Ardnamurchan intrusive rocks, K-Ar of considerable vintage, indicate a rapid emplacement within 1 to 2 Ma²⁴. Thus, radiogenic dating provides little prospect for resolving

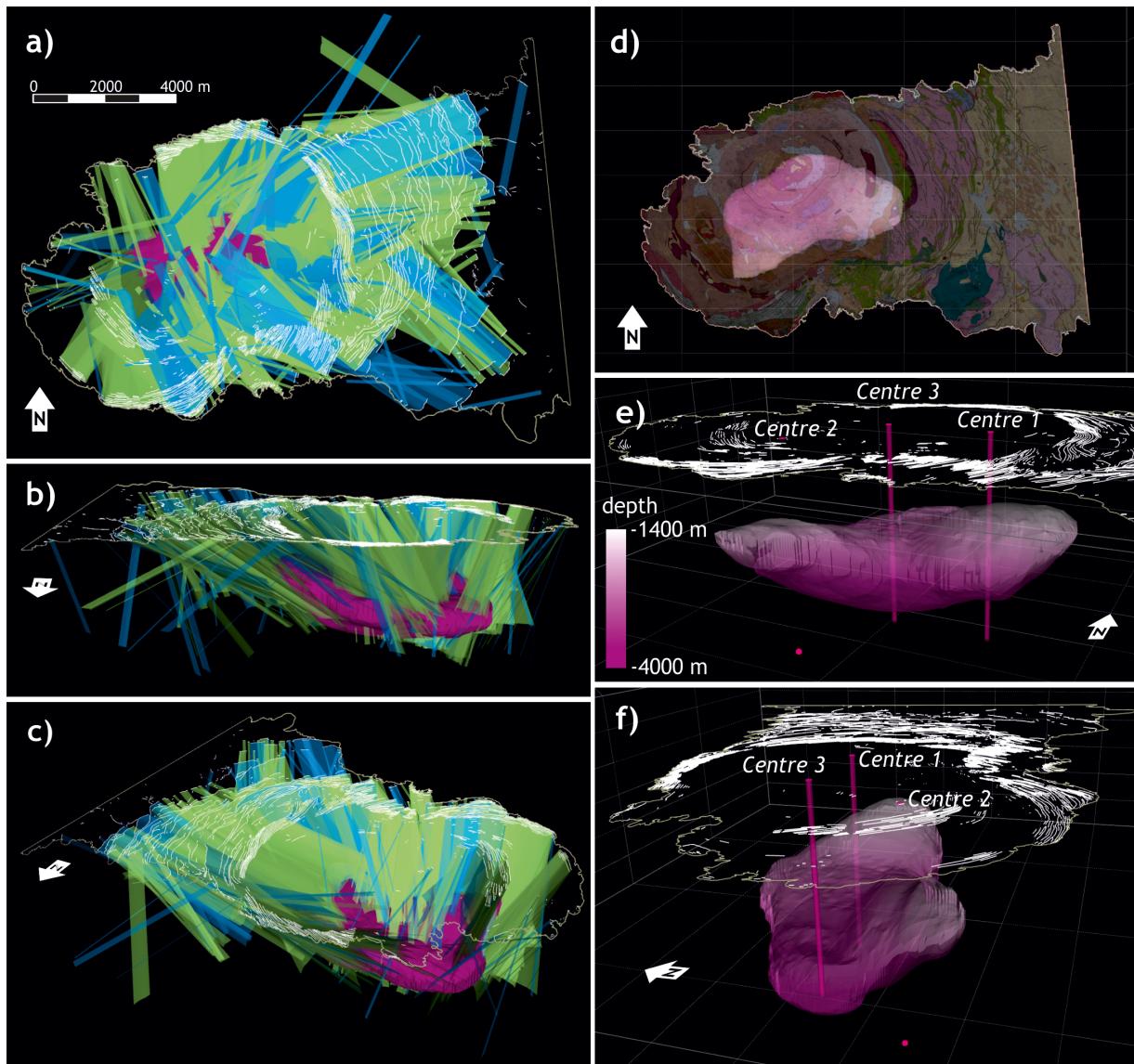


Figure 3 | Interpretation of the 3D cone-sheet projections. The source region (purple body) depicts the area of cone-sheet convergence (focal area) and a single, saucer-shaped elongate source reservoir is able to account for the majority of Ardnamurchan cone-sheets. Colours as in Fig. 2. Scale varies with perspective; see Fig. 1 for location and approximate scale and Supplementary Information for details on the construction method. a) Map view. b) Perspective view S. c) Perspective view SE. d) Map view of the modelled source volume based upon Emeleus (2009)¹¹ by permission of the British Geological Survey (CP13/091 British Geological Survey © NERC. All rights reserved.). See a) for scale. e) & f) Perspective views of the source volume with the elevation displayed (min = −1400 m; max = −4000 m). The pink circles and cylinders display the location of Richey and Thomas' (1930)³ centres. The focal point of cone-sheet convergence of Centre 2 is shown as a point at 5000 m depth. However, as Richey and Thomas (1930)³ do not give the depth of the focal points of Centres 1 and 3, we show their location as cylinders extending down to a depth of 5000 m. A movie of the model can be found in the supplementary material.

a chronostratigraphy for the Ardnamurchan cone-sheets with currently available methods. However, the existence of a single but evolving magma reservoir beneath Ardnamurchan would allow for a shorter duration of events at the Ardnamurchan central complex, as a single, long-lived reservoir would probably require less time than several successive centres that each would need to solidify prior to intrusion of the next one (for an outline of the detailed sequence of local events, see Supplementary Information 3). Thus the single reservoir concept is consistent with available age data from Ardnamurchan and with the rather short lifespan (<1 Ma) suggested for other volcanoes of the Palaeogene British Igneous Province (e.g. Skye²⁵, Rum²⁶, and the Eigg-Canna system²⁷).

The balance of evidence therefore leads us to propose a single, but dynamic and progressively evolving magma chamber with an ENE-elongated shape that fed the cone-sheets of Ardnamurchan. The

model is in agreement with the elongation and shape of the Ardnamurchan peninsula, the shape and depth of the Bouguer anomaly underlying the Ardnamurchan central complex^{8,15} (Fig. 4b), as well as with the ridge-like nature of the former Ardnamurchan volcano (Fig. 4c; e.g.¹⁴). Experimental results moreover indicate that elongated volcanic structures are likely fed by elongate magma chambers (cf²⁸) and these arguments, in combination with our computed cone-sheet projections, lead us to favour a single elongate and roughly saucer-shaped chamber system over multiple distinct centres for the origin of the Ardnamurchan intrusive complex (cf³).

Elliptical, flat-topped magma reservoirs feeding cone-sheets are known from field observations and analogue models (e.g.¹²), as well as from theoretical modelling^{18,19}. Moreover, elongated volcanic structures are well-known in other Palaeogene Scottish and Irish igneous centres (e.g. Skye, Mull, Rum, the Mourne, Carlingford,

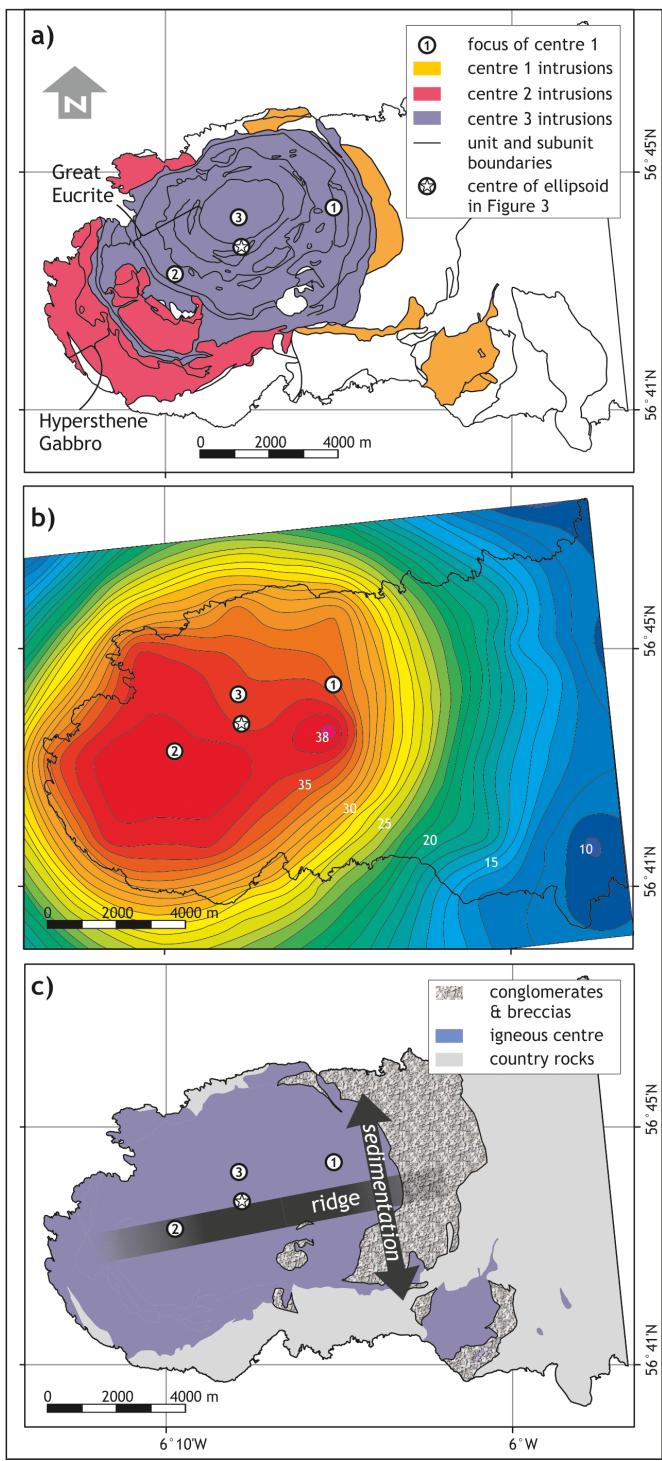


Figure 4 | Structural, geophysical, and sedimentological evidence supporting the single-centre hypothesis. a) Outlines of major intrusive units of the Ardnamurchan centre. Based upon Emeleus (2009)¹¹ by permission of the British Geological Survey (CP13/028 British Geological Survey © NERC. All rights reserved.). b) Bouger gravity anomalies in milligals (mGal) calculated against Geodetic Reference System 1967. Contour interval is 1 mGal (based upon Emeleus (2009)¹¹ by permission of the British Geological Survey (CP13/091 British Geological Survey © NERC. All rights reserved.)). c) Location and elongation of the ridge-like Ardnamurchan edifice based on sedimentation patterns (arrows) after Brown and Bell (2006)¹⁴.

and Slieve Gullion^{5,23,29}), as well as in many ocean islands (e.g. the volcanic rifts on Hawaii and the Canary Islands; e.g.^{30,31}), mid-ocean ridges and volcanoes on Iceland (e.g.^{32,33}), and tectonically active intracontinental volcanic areas (e.g. Long Valley and Valles calderas³⁴). The elongation of magmatic intrusions and volcanic structures is widely accepted to reflect the influence of tectonic stresses and pre-existing structures^{28,35} and would indicate that the elongated shape of the Ardnamurchan complex is likely the result of tectonic influences at the time of emplacement (e.g. in a failed rift segment), and likely exploited pre-existing structures, such as Precambrian or Caledonian deep basement faults (cf³⁶).

Our model of a single magma chamber feeding the Ardnamurchan cone-sheets from directly below contrasts on the one side with the 3-centre concept of Richey and Thomas (1930)³, but on the other side also with a recently proposed model of lateral magma transport from the adjacent Mull igneous centre to feed the Ardnamurchan cone-sheets. The latter model is based on field observations and particularly on sub-horizontal anisotropy of magnetic susceptibility (AMS) fabrics in the Ardnamurchan cone-sheets¹¹. There is a range of difficulties with this model and it does not represent the only way in which the AMS data can be viewed: (1) Syn-emplacement magma flow in magmatic sheet intrusions is highly dynamic and produces local flow phenomena that are not always representative of overall feeding patterns (e.g.^{37,38}). (2) Vertical transport of magma may also be achieved by, e.g. sub-horizontal magma flow, e.g. in a helical fashion (cf⁹). (3) The emplacement-related fabrics in sheet intrusions can be modified by e.g. post-emplacement crystal growth, melt migration, and dyke closure (cf^{40–42}). Hence, the locally observed sub-horizontal flow fabrics in the Ardnamurchan cone-sheets may not be exclusively primary in nature and, even if they were, do not rule out semi-vertical emplacement. Lastly, the crustal contamination pattern of Ardnamurchan cone-sheets is best explained by magma storage beneath the Ardnamurchan central complex (cf¹³). Therefore, we maintain the concept of semi-vertical ascent from a magma reservoir that was located at depth beneath the Ardnamurchan peninsula.

The balance of evidence presented and discussed herein hence leads us to put forward the concept of a single, elongate magma reservoir that fed the cone-sheet swarm of Ardnamurchan, as illustrated by our 3D model (Figs. 2 and 3). A single elongate but evolving magma reservoir is consistent with (i) the ellipticity of major intrusions (e.g. the elongate lopolithic intrusion including the Great Eucrite), (ii) the shape of the Bouguer gravity anomaly beneath Ardnamurchan, (iii) the overall sedimentary depositional record and the deformation pattern in the country rocks, and (iv) the shape of the Ardnamurchan peninsula. The Ardnamurchan volcano might thus have been analogous to ridge-like volcanic edifices on ocean islands (e.g.⁴⁴) or the elongate volcanic structures of active continental areas (e.g.²⁴). Hence, the activity of the Ardnamurchan volcano was not characterised by three distinct and successive centres as previously proposed³. Instead, Ardnamurchan was fed by a single magma reservoir that dynamically evolved throughout the volcano's lifetime, a concept that may be applied to eroded and active central volcanic complexes worldwide, where numerous vents are fed from larger underlying reservoirs (e.g.⁴⁵).

Methods

At outcrop scale, the Ardnamurchan cone-sheets show a variety of small-scale complexities due to the interaction with pre-existing structures⁴⁶, while their overall map-scale geometry is cone-like, producing an arcuate exposure at the land surface seen in the geological maps by Richey and Thomas (1930)³ and Emeleus (2009)¹¹. We used ArcGIS 10®, to digitise the map traces of 985 cone-sheets from these maps. The cone-sheet traces were then exported as input parameters into the 3D software Move 2011® (Midland Valley Ltd.) designed to build three-dimensional geological models. We did not distinguish the cone-sheets of the different swarms or centres defined by Richey and Thomas (1930)³, because an assignment to a certain centre is not always unambiguously possible (see also below) and because this would introduce a predefined interpretation.



On the available maps, cone-sheets are assigned dip directions, but dips are recorded with an accuracy of $\pm 5^\circ$, and not every cone-sheet has an individual dip measurement reported. Many of the cone-sheets occur in dense swarms of sub-parallel inclined sheets along the northern coast, in an elongated girdle at Beinn an Leathaid, and around Kilchoan along the southern shore (Fig. 1). Richey and Thomas (1930)¹ record the trends of individual cone-sheets in these dense swarms by lines that are occasionally separated by lenticular host-rock screens. For these areas, we have taken the reported dip values and dip directions also as representative for directly neighbouring cone-sheets, and for apparent prolongations of cone-sheets that are shown as segmented on the maps. We did not project cone-sheets without dip values and for which no dip value could be adapted. We projected a total of 145 cone-sheets for which dip direction and dip values were available and 652 cone-sheets and cone-sheet segments for which dip direction and dip values could be extrapolated (see Supplementary Information 1 for a list of all cone-sheets employed). Down-dip projection for a distance of 5000 m along a linear trajectory was then performed. The assumption of a linear trajectory is a necessary simplification as the subsurface geometry of cone-sheets in Ardnamurchan is not known (*cf.*), but is expected to broadly follow the outcrop measurements (*cf.*).

The resulting three-dimensional model illustrates the possible sub-surface geometry of the Ardnamurchan cone-sheet intrusions (Fig. 2) and can be used to derive information about regions that likely represent source magma reservoir(s) from the intersection of projected cone-sheets. We infer the size, shape, and location of a source magma reservoir from the region where cross-cuttings between cone-sheets from the same side of a swarm concentrate. We consider such regions to correspond to the area of stress concentration along the upper lateral ends of a magma reservoir, the location from where cone-sheets are thought to originate (as documented from field data, analogue experiments, and numerical modelling; *e.g.*¹²), and which thus define the upper perimeter of a magma reservoir (or reservoirs) in 3D space. For additional details on the method see Supplementary Information 2.

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Author contributions

S.B. & V.R.T. developed the concept of the study. The 3D modelling was performed by S.B. & L.M., V.R.T., C.H.E., C.H.D. & L.M. contributed field data. All authors discussed the results and implications and jointly wrote the manuscript.

Additional information

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