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Geological constraints on the dynamic emplacement of cone-sheets – The Ardnamurchan cone-sheet swarm, NW Scotland

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ABSTRACT

Cone-sheets are a significant constituent of many central volcanoes, where they contribute to volcano growth by intrusion and through flank eruptions, although the exact emplacement mechanisms are still controversially discussed. In particular, it is not yet fully resolved whether cone-sheets propagate as magma-driven, opening-mode fractures or as shear fractures, and to what extent pre-existing host-rock structures and different stress fields influence cone-sheet emplacement. To shed further light on the role of these parameters in cone-sheet emplacement, we use detailed field and remote sensing data of the classic Ardnamurchan cone-sheet swarm in NW-Scotland, and we show that the cone-sheets primarily propagated as opening-mode fractures in the $\sigma1$–$\sigma2$ plane of the volcanic stress field. In addition, more than one third of the Ardnamurchan cone-sheet segments are parallel to lineaments that form a conjugate set of NNW and WNW striking fractures and probably reflect the regional NW–SE orientation of $\sigma1$ during emplacement in the Palaeogene. Cone-sheets exploit these lineaments within the NE and SW sectors of the Ardnamurchan central complex, which indicates that the local volcanic stress field dominated during sheet propagation and only allowed exploitation of host-rock discontinuities that were approximately parallel to the sheet propagation path. In addition, outcrop-scale deflections of cone-sheets into sills and back into cone-sheets (also referred to as "staircase" geometry) are explained by the interaction of stresses at the propagating sheet tip with variations in host-rock strength, as well as the influence of sheet-induced strain. As a consequence, cone-sheets associated with sill-like segments propagate as mixed-mode I/II fractures. Hence, cone-sheet emplacement requires a dynamic model that takes into account stress fields at various scales and the way propagating magma interacts with the host rock and its inherent variations in rock strength.

1. Introduction

Cone-sheets usually occur in dense swarms above and around shallow magma reservoirs and as part of saucer-shaped sills in sedimentary basins (e.g. Walker, 1993; Schirnick et al., 1999; Burchardt and Gudmundsson, 2009; Hansen and Cartwright, 2006; Galerne et al., 2011; Burchardt et al., 2011, 2013). Cone-sheets are exposed in many volcanic areas and are held responsible for significant contributions to the intrusive growth of volcanic edifices and the crust itself, for the formation and propagation of sills and magma reservoirs, and for eruptions from volcano flanks (e.g. Le Bas, 1971; Chadwick and Dieterich, 1995; Burchardt, 2008; Siler and Karson, 2009). However, in contrast to dyke and sill emplacement, the dynamics of cone-sheet formation remain controversial. In fact, since cone-sheets were recognised in the British–Irish Palaeogene central complexes (e.g. Harker, 1904), their emplacement mechanism has been a matter of debate (e.g. Phillips, 1974).

The Ardnamurchan central complex (Fig. 1) has been instrumental to our conceptual understanding of cone-sheet emplacement being dominantly controlled by the influence of a volcano-scale stress field induced by overpressure along the roof and walls of a shallow magma reservoir that interacts with the free surface (e.g. Bailey et al., 1924; Anderson, 1936, 1951; Robson and

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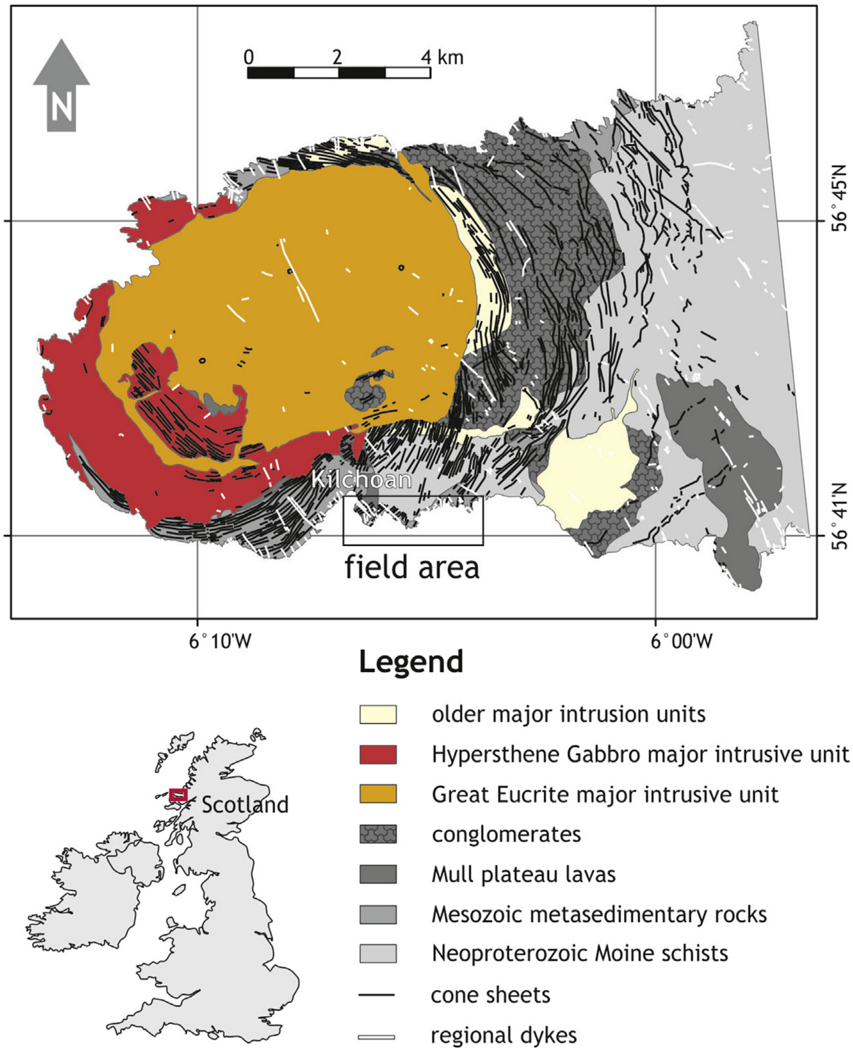

Fig. 1. Simplified geological map of the Ardnamurchan central complex; modified after Emeleus (2009). This map is displayed using the UTM projection, zone 29N (WGS 84).

Barr, 1964; Le Bas, 1971; Phillips, 1974). Within this volcanic stress field, cone-sheets may either propagate as (a) magma-driven tensile fractures in the σ1–σ2 plane when the magmatic overpressure exceeds the tensile strength of the host rocks (Anderson, 1936, 1951) or (b) within reactivated, i.e. pre-existing, inverted-conical shear fractures that formed at an angle to the σ1 orientation of the volcanic stress field from magma-chamber inflation (Bailey et al., 1924; Durrance, 1967; Phillips, 1974; Troll et al., 2002; Mathieu et al., 2008). Notably, these conceptual models assume a static orientation of the stress field during cone-sheet emplacement, whereas recent studies on the emplacement of saucer-shaped sills indicate that stress fields are highly dynamic during sheet emplacement (e.g. Malthe-Sørenssen et al., 2004). Moreover, the traditional emplacement mechanisms, which assume cone-sheets to be fed from a more or less directly underlying magma reservoir, have recently been challenged by Magee et al. (2012) who proposed that the Ardnamurchan cone-sheet swarm may be a locally deviated NW–SE striking regional dyke swarm. The latter model implies that the sheets are (i) of regional rather than local origin (i.e. they do not strictly belong to the Ardnamurchan central complex) and (ii) that they formed under the dominant control of the regional stress regime at the time. Recent experimental advances show cone-sheet emplacement to be controlled by two main parameters, the geometry of the source reservoir and the interaction of viscous stresses in relation to host-rock properties (Galland et al., 2014). Moreover, host-rock strength also exerts a major control on the initiation and dimensions of sheet intrusions, including cone-sheets (Krumbholz et al., 2014).

To determine (i) in what way the emplacement of cone-sheets in Ardnamurchan was influenced by interacting stress fields at different scales, (ii) whether cone-sheets form along shear or tensile fractures, and (iii) to what extent their propagation is affected by the properties of the surrounding host-rock, we reinvestigate cone-sheet geometries and host-rock structures using a detailed field mapping and remote sensing approach. We combine outcrop descriptions, 3D structural maps, and lineament maps, to derive a conceptual model that suggests that initiation of the Ardnamurchan cone-sheets have may been primarily controlled by the local volcanic stress field. However, sheet propagation reflects the dynamic interaction of stresses at the sheet tip with variations in host-rock strength due to e.g. pre-existing weaknesses that may be a result of regional tectonics.

2. Geological setting

The sub-volcanic complex of Ardnamurchan is part of the North Atlantic Igneous Province (NAIP), which is associated with initiation of the proto-Iceland plume and the opening of the North Atlantic ~62-53 Ma ago (Emeleus and Bell, 2005). The southeastern fringe of the NAIP is found in northeast Ireland and western Scotland and is referred to as the British and Irish Palaeogene Igneous Province (BIPIP). The BIPIP is discussed to have formed within a NW-SE-trending failed rift (England, 1988) or within conjugate strike-slip systems under the influence of NE-SW-directed extension (Cooper et al., 2012) and comprises plateau basalts, a NW-SE-striking regional dyke swarm, and a string of central volcanoes, among them the Ardnamurchan central complex (Fig. 1; Harker, 1904; Thompson, 1982; Emeleus and Bell, 2005).

The central complex of Ardnamurchan formed between ~61 and 59 Ma (Chambers, 2000) immediately south of the SE-dipping Moine thrust that accommodated crustal-scale deformation during the Caledonian orogeny. The local host rocks to the Ardnamurchan central complex are Neo-Proterozoic low-grade metamorphic psammites and pelites of the Moine metasedimentary supergroup (Richey and Thomas, 1930). These "Moine schists" are overlain by formerly sub-horizontal Mesozoic metasedimentary rocks. These were however tilted by up to 30° during the successive intrusion episodes of the Ardnamurchan central complex (Brown and Bell, 2006; Emeleus, 2009).

The Ardnamurchan volcano was probably a ridge-shaped edifice (Brown et al., 2006), and the current erosional level exposes the volcano's shallow plumbing system initially located approximately 1.5–2 km below the original land surface (Donaldson, 1983). Ardnamurchan's shallow plumbing system comprises sub-circular, mainly gabbroic intrusions, such as the Hypersthene Gabbro and the Great Eucrite (e.g. O'Driscoll et al., 2006, 2008), as well as countless tholeiitic to mildly alkaline basaltic cone-sheets and dykes plus some rhyolitic and composite ones (Fig. 1; e.g. Geldmacher et al., 1998). Based on the attitude of cone-sheets and their relationships with the major gabbro intrusions, the deeper plumbing system was historically proposed to consist of three successive intrusive pulses or "foci of magmatic activity" (Centres 1, 2, and 3; Richey and Thomas, 1930). A recent re-interpretation of the Ardnamurchan cone-sheet swarm, based on the sheets' anisotropy of magnetic susceptibility of magmatic fabrics, considers the cone-sheets to originate from diverted regional dykes emplaced laterally from the adjacent central complex of Mull (Magee et al., 2012). This conclusion is based on the observation that a portion of the magnetic fabrics indicate horizontal magma flow. In contrast to this proposal, three-dimensional reconstruction of the Ardnamurchan cone-sheets implies that a single, but evolving saucer-shaped magma reservoir at about 1.5 km depth directly beneath today's land surface could have fed the Ardnamurchan cone-sheets (Burchardt et al., 2013), thus creating the need for further investigation on this iconic cone-sheet swarm.

3. Data and methods

We analysed the structure of the exposed Ardnamurchan cone-sheet swarm at outcrop and at map scale, using structural field data and remote sensing techniques. The detailed structural field

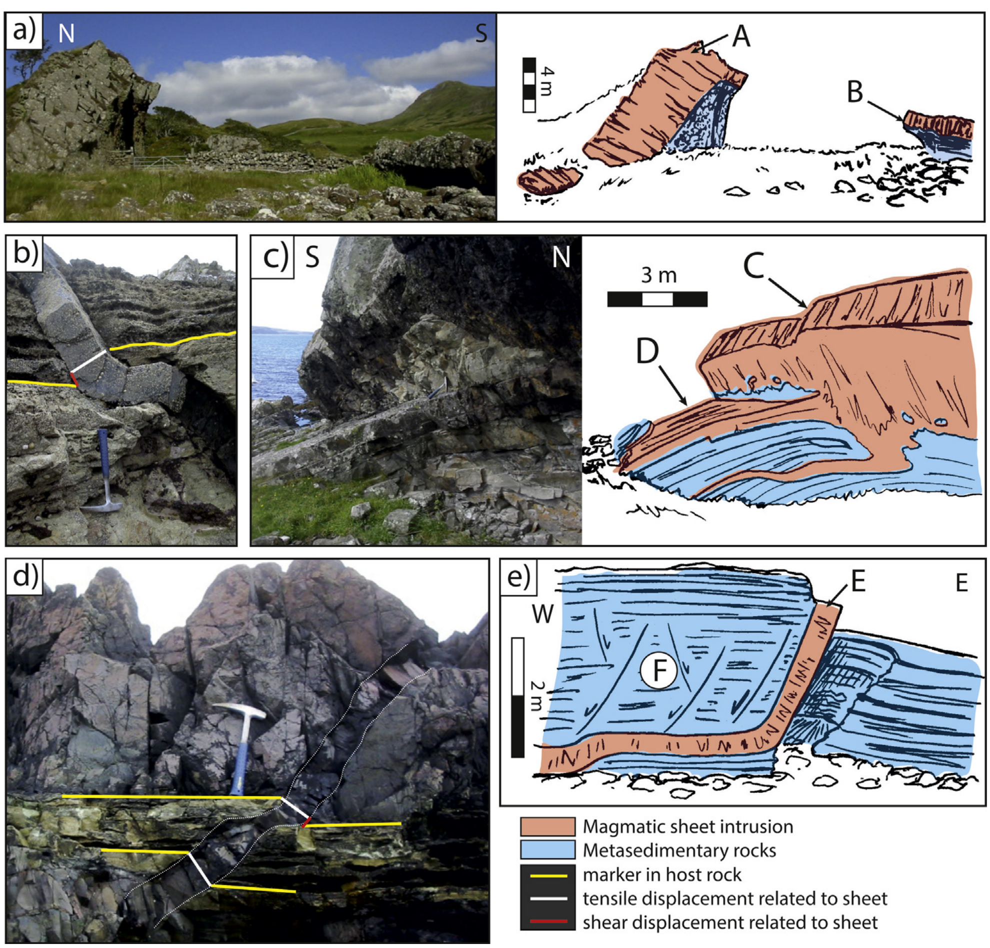

Fig. 2. Field photographs and annotated sketches of cone-sheets and sills intruded into Mesozoic metasedimentary rocks. a) and c) show photographs and sketches of cone-sheets connected to sills. b) Photograph showing the upward translation of host rocks above a cone-sheet intrusion. d) Sketch of conjugate fractures in the vicinity of a cone-sheet connected to a sill (see text for details).

investigations were carried out within a 2 by 0.5 km area east of Kilchoan, along the southern shore of the Ardnamurchan peninsula, where a high density of cone-sheet intrusion is recorded (Fig. 1). There we documented attitude, geometry, and lithology of 220 sheet intrusions, as well as the orientation of bedding and foliation in the Moine schist and Mesozoic sedimentary host rocks. Sheet intrusions were subdivided, according to their dip and their relationship to host-rock structures, into sills (concordant with bedding), cone-sheets (discordant, moderate dip), and dykes (subvertical, discordant). The field data were compiled into 3D maps and projected to 100 m below sea level using the Move software package by Midland Valley Ltd in order to illustrate and analyse the complex three-dimensional interaction between the orientation of host-rock discontinuities and the geometry and attitude of sheet intrusions.

For volcano-scale analysis, we mapped lineaments that correspond to planar geological discontinuities (e.g. faults, joints) in the host-rock, using a total of 20 aerial photographs of the Ardnamurchan peninsula with a scale of 1:25,000 and a cloud coverage of ~1% (acquired in 1988 by the British Royal commission; Ancient and Historical Monuments of Scotland). Initially the aerial photographs were scanned, merged, and georeferenced in the UTM 29N geographic system (WGS 84 datum) to produce a black-and-white image with a resolution of 2.8 m per pixel. This mosaic was processed in ArcGIS to produce a sharpened image applying a combination of a convolution and a directional filter (orientation 132°, kernel size 7). We then mapped lineaments and computed their strikes in ArcGIS 10. To test for observational bias due to the shape of the sampling window (an E–W elongated peninsula), we separately analysed lineament strikes within two arbitrarily chosen circular areas sampled from the complete image.

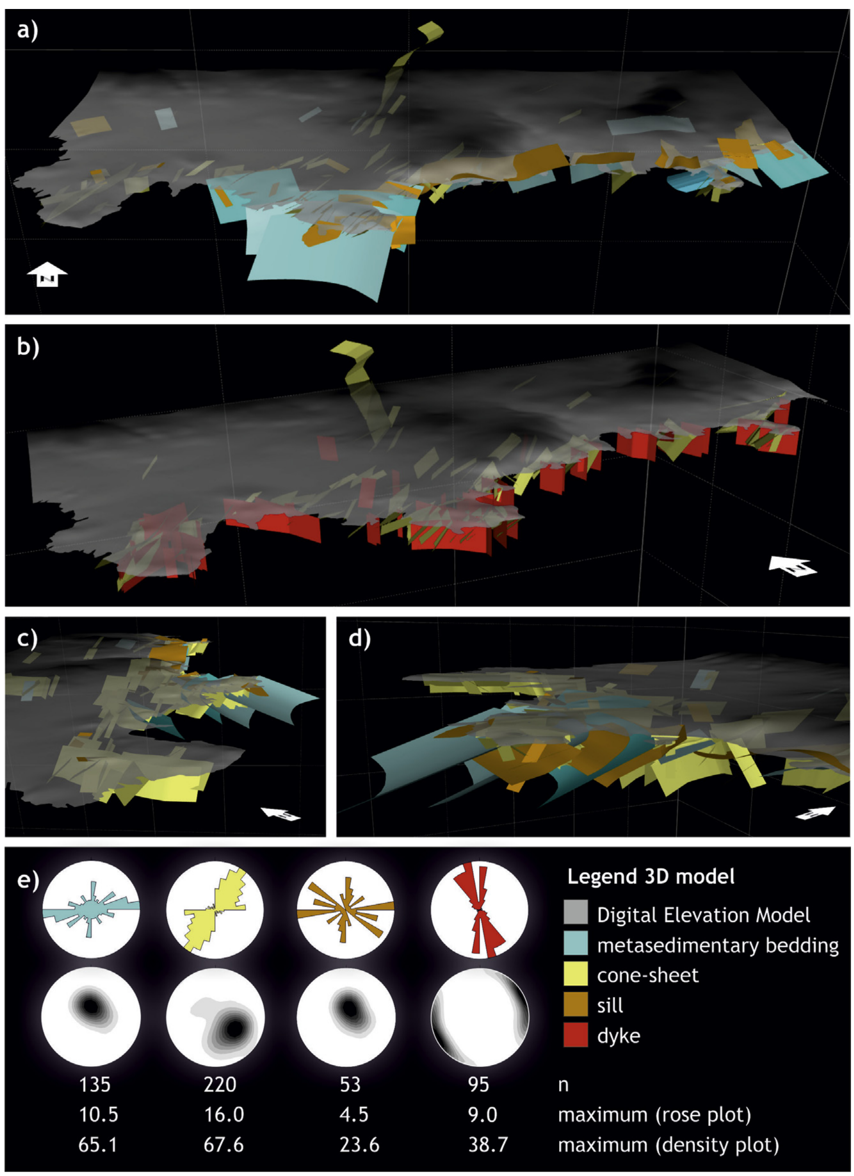

Fig. 3. 3D perspective views of the map of the southern part of the Ardnamurchan peninsula (see Fig. 1 for location and scale). The DEM (Digital Elevation Model) has been produced by digitizing the elevation contours of the 1:25000 topographic map released by the Geological Survey of Scotland. a) Orientation of the bedding in metasedimentary rocks, as well as attitude of cone-sheets and sills. b) Orientations of cone-sheets and dykes. c) & d) Relationship between metasedimentary bedding, cone-sheets, and sills in part of the field area. e) Upper row: rose diagrams (linear scaling, 10° classes) of the strike of field measurements. Lower row: density plots of poles to the measured planes in equal area, lower hemisphere stereographic projection. Densities are plotted in 10° classes. The structural measurements and 3D map show that sills follow the host-rock bedding, dyke orientations are dominantly in agreement with the direction of regional dyke swarms (Jolly and Sanderson, 1995), and cone-sheets strike SW in this sector of the Ardnamurchan sheet swarm.

Using the geological map by Emeleus (2009), we digitised cone-sheet traces as a succession of straight line segments (n = 986) in ArcGIS to determine their strike and their distribution density with respect to different stratigraphic and intrusive units (search radius 300 m, resolution 20 m). This approach enabled us to compare the strike of cone-sheet segments with the strike of nearby host-rock lineaments (within 200 m). Cone-sheet segments with a strike identical to a lineament (within ±1°) were classified as parallel to lineaments.

4. Results

4.1. Outcrop-scale observations of magmatic sheet intrusions

In the selected field area, magmatic sheet intrusions are dominantly doleritic in composition and commonly between 1 and 2 m thick. They intrude the well-exposed Mesozoic metasedimentary rocks that cover the sporadically exposed underlying Moine schists (Figs. 1 and 2). Notably, sills are observed within the Mesozoic metasedimentary rocks only. Overall, sheet intrusions in the mapping area exhibit a spacing of 2–10 m and frequently intersect each other. Cross-cutting relationships between different types of sheet intrusions reveal that dykes are cut by, and are cutting, sills and cone-sheets, which points to coeval cone-sheet and dyke emplacement. Dykes in the mapped area are subvertical and strike on average 150°, while cone-sheets dip at moderate angles (37–47°) and dominantly to the W-NNW (Fig. 3).

We investigated the outer margin of cone-sheets and sills, following observations made by Kuenen (1937), who reported that the walls of cone-sheets usually lack evidence for brittle shearing during emplacement, such as slickensides, crushing, and dragging structures. Indeed, in the studied area, only two out of the 220 cone-sheets exhibit crushed metasedimentary rocks along their margins, while most cone-sheets have smooth margins with limited dip variations. Where possible, we used sedimentary strata as markers and observed that cone-sheet opening generally occurred perpendicular to the sheet walls, i.e. likely by internal inflation (Fig. 2d). Bedding planes of the metasedimentary rocks dip at shallow angles to the SSE or NNW (Fig. 3a–e). This variation is controlled by faulting in the eastern part of the study area and, in one outcrop, by monoclinal folding in the immediate vicinity (<2 m) of two cone-sheets. These monoclinal folds are thus unrelated to pre-existing tectonic folds, but resulted from ductile deformation of host rock that was induced by emplacement of a "hot sheet intrusion" (cf. Delcamp et al., 2012; Schofield et al., 2012).

Some NNW- to NW-dipping cone-sheets propagated as sills over short distances (≤5 m) by intruding along bedding planes of metasedimentary host rocks (Fig. 2; Fig. 3a–e). Consequently, sills dip at shallow angles (20–25°) to the SSE or the NNW away from their feeding cone-sheets (Fig. 2c). Several of these sills are then observed to connect to cone-sheet type intrusions again, thus producing an overall "staircase" geometry (see, e.g. Goulty, 2005). Above these sills, cone-sheet emplacement is accommodated by tensile and shear displacement of the host rock (Fig. 2c,d). Conjugate sets of normal faults that strike NNE and NE occur within ≤3 m from such 'staircase' (i.e. cone-sheet-and-sill) intrusions within the metasedimentary host-rocks and are seen to have accommodated displacements of ≤5 cm (Fig. 2d).

4.2. Distribution and orientation of cone-sheets across the Ardnamurchan peninsula

At the scale of the Ardnamurchan central complex, cone-sheets occur within a 7 km thick girdle, the inner limit of which is the outer margin of the major intrusions (Fig. 4). Cone-sheet density is generally higher towards this inner limit of the cone-sheet girdle, i.e. in the vicinity of the outer margins of the Great Eucrite and Hypersthene Gabbro intrusions. The outer limit of the cone-sheet girdle is only exposed in the eastern part of the peninsula where most cone-sheets are found within 10 km from the centre of the Ardnamurchan complex (Fig. 4).

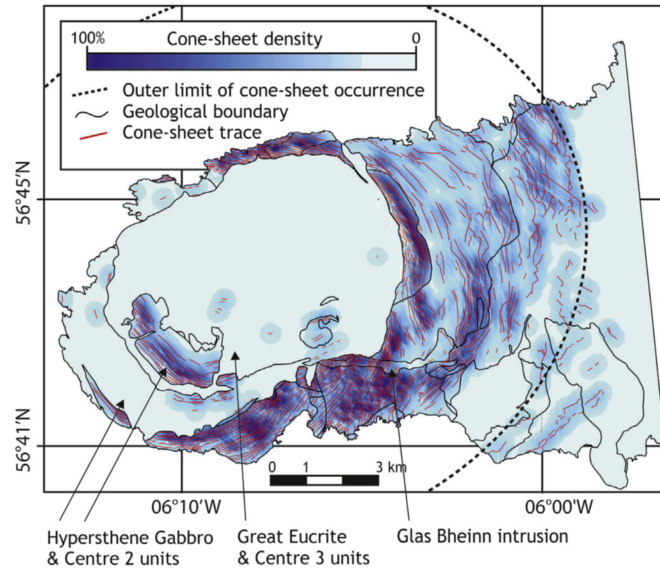

Fig. 4. Map displaying the traces of Ardnamurchan cone-sheets and their distribution density using a density grid with a resolution of 20 m. A relative density scale is used, with density values ranging from 0 to 100%. Data are based on the geological map and assoiated field notes (Emeleus, 2009) and represent minimum numbers of minor intrusions per area.

The relative density of the cone-sheets that intersect the main lithological units of the peninsula has been characterised using the dimensionless parameter CSD (Cone-Sheet Density) (Fig. 4), which is defined as the ratio between the percentage of cone-sheets intersecting a given lithological unit and the percentage of the area of the lithological unit. Some 88.7% of the cone sheets intruded either metasedimentary rocks (CSD = 3.53), Moine schists (CSD = 1.11), plateau basalts (CSD = 1.34), or the Glas Bheinn intrusion (CSD = 1.82). In contrast, the Hypersthene Gabbro and the intrusive units traditionally attributed to the Centre 2 focus of magmatic activity (Richey and Thomas, 1930) are intruded by as little as 8.5% of the cone sheets (CSD = 0.73), while the Great Eucrite and those units traditionally attributed to Centre 3 are intersected by only 2.8% of the mapped cone sheets (CSD = 0.10) (Fig. 4). Cone-sheet segments strike at a wide range of angles across the Ardnamurchan peninsula and outline an overall circular to slightly elliptical pattern (Fig. 5).

4.3. Lineament distribution and orientation and relationship with cone-sheets

Lineaments across the Ardnamurchan peninsula are roughly evenly distributed (Fig. 6) and form a conjugate set of NNW and WNW striking host-rock discontinuities (Fig. 5). The orientation of the conjugate set is in agreement with the regional direction of σ1, which is also evident from the orientation of regional dykes formed during the Paleogene (cf. Jolly and Sanderson, 1995).

The even distribution and orientation of lineaments across the peninsula contrast the distribution and orientation of cone-sheets that occur preferentially in distinct stratigraphic units and outline a semi-circular pattern (Figs. 4 and 6). Hence, the mapped lineaments are not identical to cone-sheets, but rather represent host-rock discontinuities.

Notably, about 34% of cone-sheet segments are parallel (within $\pm 1^{\circ}$) to a nearby (within 200 m) lineament. These lineament-parallel cone-sheets occur predominantly in the NE and SW sectors of the Ardnamurchan central complex, while cone-sheets in other sectors strike at a wide range of angles to nearby lineaments (Fig. 5a).

5. Discussion

5.1. Cone-sheet emplacement along tensile vs. shear fractures

In our field area, cone-sheets have opened predominantly perpendicular to their walls, i.e. as mode I fractures. These sheets do not show evidence for sheet-parallel shear, which is consistent with observations previously reported on the Ardnamurchan minor intrusions (Kuenen, 1937; Magee et al., 2012) and elsewhere (e.g. Le Bas, 1971; Burchardt and Gudmundsson, 2009; Tibaldi et al., 2011). However, a small component of shear, in addition to tensile, displacement of host-rock markers above sill-like steps in the sheets indicate that sheet emplacement in some cases was through mixed-mode, i.e. mode I–II, fracturing. Hence, these sheets propagated at an angle to the main principal compressive stress direction.

5.2. The influence of host-rock properties on cone-sheet emplacement

At outcrop-scale, cone-sheets frequently intrude pre-existing host-rock discontinuities, such as the bedding planes in the Mesozoic metasedimentary country rocks (Fig. 2). The resulting transgressive cone-sheet and sill configuration (staircase geometry) has previously been documented by Kuenen (1937) and Magee et al. (2012) and is known from other cone-sheet swarms (e.g. Walker, 1993), as well as sill complexes worldwide (e.g. Francis, 1982; Thomson and Hutton, 2004; Muirhead et al., 2014).

Since the metasedimentary rocks of the Ardnamurchan peninsula are strongly anisotropic due to e.g. sedimentary bedding and other pre-existing mechanical discontinuities (e.g. joints and foliation planes), rock strength is highly heterogeneous. As sheet

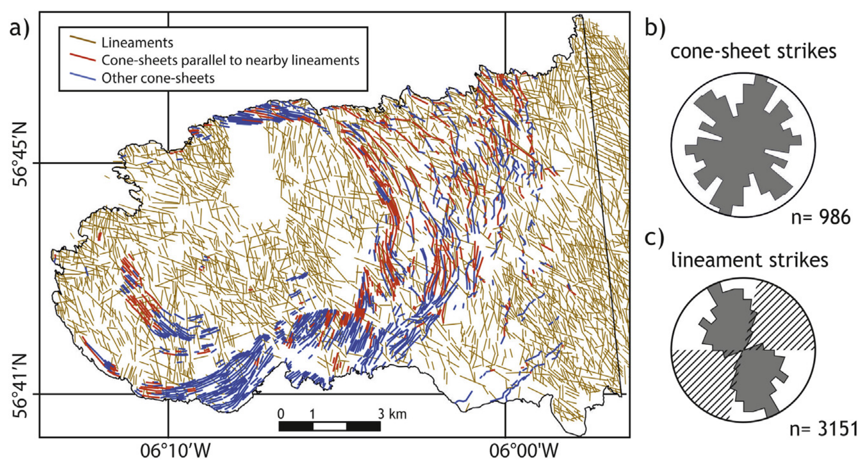

Fig. 5. Comparison of the strike of cone-sheets and lineaments. a) Distribution of cone-sheets parallel to nearby lineaments (red) shows that in the NE and SW sectors of the Ardnamurchan central complex, cone-sheets strike preferentially parallel to nearby lineaments. This indicates an influence of pre-existing host-rock structures during sheet emplacement. b) Rose diagram of the strike of all cone-sheet segments (10° classes). Apparent peaks of cone-sheet strikes result from uneven distribution of cone-sheet exposure across the swarm. c) Rose diagram of the strike of all lineaments (10° classes). Shaded area marks fracture orientations unfavourable for dilational opening in the regional tectonic stress field according to Jolly and Sanderson (1995). Hence, most lineaments observed in the area were 'favourably oriented' for dilational opening at that time. Selective intrusion into these lineaments in the NE and SW sectors indicates the interplay of the volcanic and the regional tectonic stress fields (see text for further details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

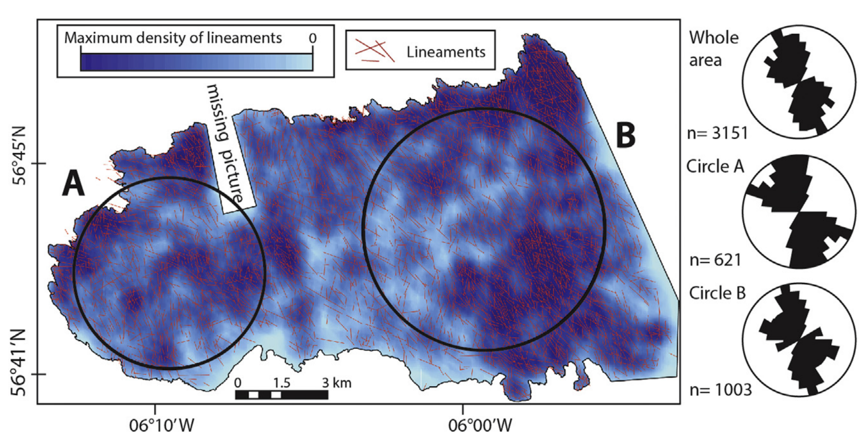

Fig. 6. Results of lineament mapping of the Ardnamurchan peninsula based on a mosaic of aerial photographs. A convolution and a directional filter were applied to the image (see text for details). The density distribution of lineaments (density grid 50 m) is roughly even, suggesting that lineaments formed in response to regional stresses and independent of lithology. Lineament strikes in the whole area, as well as in arbitrarily chosen circular sub-areas (circles A and B) are displayed as rose diagrams with class sizes of 10° and linear scaling.

intrusions preferably intrude planes of weakness, the strong anisotropy of Ardnamurchan rocks favoured diversion of cone-sheets along bedding planes to form sill-like sheet segments.

Magee et al. (2012) proposed that the staircase geometry of Ardnamurchan magmatic sheet intrusions is a result of sheet emplacement along pre-existing conjugate discontinuities, reactivating shear-mode fractures as opening-mode fractures. However, since these conjugate fractures occur only locally in the vicinity of sheet intrusions and because their strikes (NNE and NE) do not coincide with main lineament strikes on the Ardnamurchan peninsula (NNW and WNW), we argue that the conjugate fractures observed at outcrop scale do actually not predate sheet emplacement, but are rather associated with it (see Figs. 2, 5 and 6). Moreover, intrusion along reactivated shear fractures is unlikely because cone-sheets also occur within host rocks that lack doming-related fractures (cf. Burchardt et al., 2011). Furthermore, experimental modelling of cone-sheet emplacement into homogeneous analogue media is able to reproduce their conical shape (Mathieu et al., 2008; Galland et al., 2014), which implies that cone-sheet emplacement does not *per se* require reactivation of pre-existing shear fractures.

Instead, we explain the staircase geometry of cone-sheets in Ardnamurchan by the dynamic interaction of the volcanic stress field, the small-scale stress field at sheet tips, variations in rock strength at pre-existing host-rock discontinuities, and strain caused by sheet propagation (Fig. 7). Ardnamurchan cone-sheets initially propagated along a $\sigma1-\sigma2$ plane of the volcanic stress field, i.e. as mode I fractures, and penetrated the rocks surrounding and overlying a shallow magma reservoir (Fig. 7). Once a propagating sheet met a sufficiently weak pre-existing host-rock discontinuity with a favourable orientation, e.g. a sub-horizontal bedding plane, it was deflected into a sill, because rock strength at the discontinuity varied and allowed for propagation along the plane of weakness (Fig. 7a). Subsequent sill inflation resulted in either differential uplift or vertical shortening associated with conjugate fracturing of the overburden, which are both observed in the vicinity of Ardnamurchan cone-sheets (see Figs. 2 and 7b; cf. Burchardt et al., 2012). Differential stresses at the tip of the inflating sill then led to shear failure and the deflection of the sill into a cone-sheet type intrusion (Fig. 7c; cf. Malthe-Sørenssen et al., 2004; Mathieu et al., 2008; Polteau et al., 2008; Galland et al., 2009). To accommodate the uplift caused by the sill-like sheet segment, further sheet propagation occurs through mixed-mode I/II fracturing (Fig. 2c,d and Fig. 7c). This phenomenon has also been observed in, e.g., some of the cone-sheets of the Cuillin Complex, Skye (Tibaldi et al., 2011) and the sill-cone-sheet complexes of the Ferrar Large Igneous Province (Muirhead et al., 2014), as well as in a number of analogue experiments (Mathieu et al., 2008; Abdelmalak et al., 2012; Galland et al., 2014). In this context, the staircase geometry of Ardnamurchan sheet intrusions reflects the complex and dynamic interaction between stresses at sheet tips, strength variations in the host rock, and deformation in the host rock caused by sheet emplacement. Hence, cone-sheet propagation may primarily occur by mode I fracturing, which is documented in subvolcanic complexes worldwide (e.g. Kuenen, 1937; Klausen, 2004; Burchardt and Gudmundsson, 2009). However, in rocks with pre-existing planar discontinuities, sill formation will favour subsequent cone-sheet emplacement by mixed-mode fracturing. This implies that the inclined sheets connected to saucer-shaped sills are mixed-mode sheet intrusions (cf. Galland et al., 2009).

Regarding the interaction of Ardnamurchan cone-sheets with host-rock discontinuities at volcano-scale, pre-existing discontinuities were preferentially exploited in areas where discontinuities strike parallel to cone-sheets. According to Jolly and Sanderson (1995), the regional tectonic stress field at the time enabled

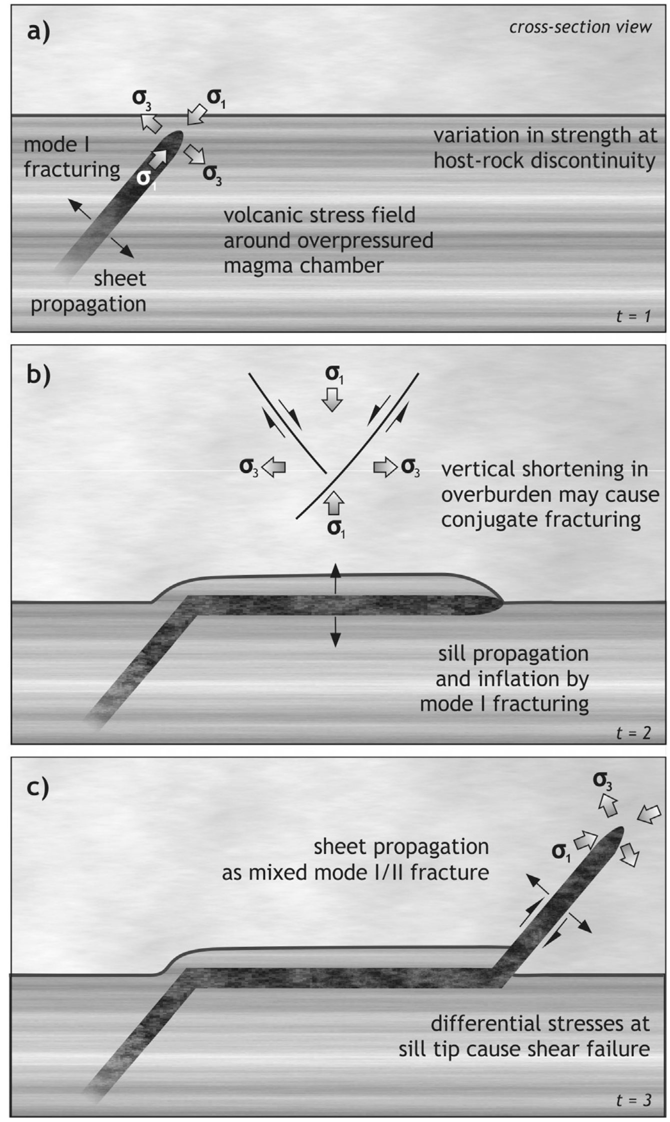

Fig. 7. Conceptual sketch of dynamic emplacement of the Ardnamurchan cone-sheets and sills (see, e.g. Fig. 2). a) Cone-sheet emplacement primarily occurs through mode I fracturing is controlled by a volcanic stress field generated by overpressure in a shallow magma chamber interacting with the free surface (Anderson, 1936). At planar host rock discontinuities, variations in rock strength may cause cone-sheets to deflect into a sill (cf. Burchardt, 2008). b) Sill inflation by mode I fracturing causes differential uplift and vertical shortening of the overburden rocks may result in the formation of conjugate fractures (cf. Burchardt et al., 2012). c) Differential stresses at the sill tip then produce shear failure (Malthe-Sørenssen et al., 2004; Galland et al., 2009). Subsequent upward propagation and inflation of the sheet occurs through mixed-mode fracturing.

dilational opening of fractures by dykes in the adjacent Mull dyke swarm striking between ~270 and 010°. It follows then that the majority of host-rock discontinuities on the Ardnamurchan peninsula would have been available for exploitation by propagating cone-sheets at the time (Fig. 5c). The selective exploitation of lineaments in the NE and SW sectors of the cone-sheet swarm (Fig. 5a) thus indicates the dominance of the volcanic stress field over an overall extensional regional one (see also Bureau et al., 2013).

6. Conclusions

From the results of detailed field and remote sensing analyses of the cone-sheets of the Ardnamurchan central complex we draw the following conclusions regarding cone-sheet emplacement:

Cone-sheet emplacement is a dynamic process that operates in response to stress fields at different scales and the interaction between propagating magma and the host rock with its inherent variations in rock strength.

(1) Ardnamurchan cone-sheets originate as self-formed, opening-mode fractures that propagated in the $\sigma1-\sigma2$ plane of a volcanic stress field caused by an underlying shallow magma chamber.
(2) The staircase configuration of cone-sheet and sill intrusions observed at outcrop-scale reflects the dynamic interaction of small-scale stress field at the tip of a propagating sheet with variations in host-rock strength, due to e.g. bedding, deformation, and fracturing.
(3) The spatial and directional relation between cone-sheets and pre-existing host-rock discontinuities at volcano-scale demonstrates that cone-sheets exploited host-rock weaknesses only when the latter were favourably oriented, i.e. roughly parallel to the sheet propagation path, underlining the significance of variations in rock strength.

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