3D seismic imaging of the shallow plumbing system beneath the Ben Nevis Monogenetic Volcanic Field: Faroe-Shetland Basin

Charlotte E. McLean[1]*; Nick Schofield[2]; David J. Brown[1], David W. Jolley[2], Alexander Reid[3]

[1]School of Geographical and Earth Sciences, Gregory Building, University of Glasgow, G12 8QQ, UK
[2]Department of Geology and Petroleum Geology, University of Aberdeen AB24 3UE, UK
[3]Statoil (U.K.) Limited, One Kingdom Street, London, W2 6BD, UK

*Correspondence (c.mclean.1@research.gla.ac.uk)

Abstract

Reflective seismic data allows for the 3D imaging of monogenetic edifices and their corresponding plumbing systems. This is a powerful tool in understanding how monogenetic volcanoes are fed and how pre-existing crustal structures can act as the primary influence on their spatial and temporal distribution. This study examines the structure and lithology of host-rock as an influence on edifice alignment and provides insight into the structure of shallow, sub-volcanic monogenetic plumbing systems. The anticlinal Ben Nevis Structure (BNS), located in the northerly extent of the Faroe-Shetland Basin, NE Atlantic Margin, was uplifted during the Late Cretaceous and Early Palaeocene by the emplacement of a laccolith and a series of branching sills fed by a central conduit. Seismic data reveals multiple intrusions migrated up the flanks of the BNS after its formation, approximately 58.4 Ma (Kettla-equivalent), and fed a series of scoria cones and submarine volcanic cones. These monogenetic edifices are distributed around the crest of the BNS. The edifices are fed from a complex network of sills and transgressive sheets, involving lateral magma migration of tens of kilometres before extrusion at the surface. This work highlights the importance of underlying basin structures in influencing the sites and development of sub-aerial monogenetic fields, and the importance of lateral magma flow within volcanic systems.

END OF ABSTRACT

An increasing amount of evidence compiled in recent decades supports the assertion that the magma plumbing systems beneath monogenetic volcanic fields are far more complex than the dyke-dominated systems first suggested (Nemeth *et al.* 2003; Nemeth & Martin 2007; Johnson *et al.* 2008; Nemeth 2010; Brown & Valentine 2013; Re *et al.* 2015; Muirhead *et al.* 2016; Albert *et al.* 2016). Understanding the plumbing system structure beneath monogenetic volcanic fields can present significant insight into: (1) the dominant control on the distribution of individual monogenetic volcanic edifices (e.g. tectonic stress orientation vs. local crustal structure) and, therefore, assessment of the location of the next eruption centre in an active field (Buck *et al.* 2006; Le Corvec *et al.* 2013); (2) the estimated total magma volume in a system (Richardson *et al.* 2015; Muirhead *et al.* 2016); (3) the geochemical evolution of magmas and potential magma stalling/assimilation sites (Nemeth *et al.* 2003; Johnson *et al.* 2008; Smith *et al.* 2008; Albert *et al.* 2016); (4) the distance of lateral migration of magma from "source" to surface (Muirhead *et al.* 2012; Airoldi *et al.* 2016; Muirhead *et al.* 2016; Magee *et al.* 2016); and (5) controls on the emplacement mechanics and geometry of intrusions, aiding the prediction of the next eruption site (Thomson & Schofield 2008; Lefebvre *et al.* 2012; Schofield *et al.* 2012; Kavanagh *et al.* 2015; Re *et al.* 2016).

Monogenetic volcanoes are typically defined as small-volume (<0.1 km^3 dense rock equivalent total eruptive products), short-lived volcanoes that generally occur in large numbers in linear or clustered arrangements (Nemeth 2010). Geochemical analysis of monogenetic magmatic systems often assumes a vertical magmatic system, where the magma reservoir is located directly below the volcanic edifice, and does not consider the structure and spatial distribution of monogenetic plumbing systems in the shallow subsurface (Nemeth *et al.* 2003; Johnson *et al.* 2008; Smith *et al.* 2008; Kereszturi & Nemeth 2012;

Albert *et al.* 2016; Magee *et al*. 2016). The incomplete or lack of exposure of eroded plumbing systems in field studies often inhibits a full 3D analysis of monogenetic plumbing systems (Valentine & Krogh 2006; Nemeth & Martin 2007; Polteau *et al.* 2008; Schofield *et al.* 2012; Muirhead *et al.* 2012; Re *et al.* 2015; Magee *et al.* 2016; Muirhead *et al.* 2016). Reliance on geochemical analysis and inadequate field exposures can sometimes prevent a comprehensive assessment of the intrusion characteristics, magma interaction with crustal structures and, spatial and temporal development of shallow plumbing networks beneath monogenetic volcanic fields from being developed (Muirhead *et al.* 2016).

Improved imaging in reflective seismic data of magmatic plumbing systems, particularly in the last 15 years, has significantly enhanced our understanding of shallow sill complexes, their relationship to overlying magmatic vent structures, and the development of monogenetic volcanic fields (Bell & Butcher 2002; Schofield *et al.* 2012; Jackson 2012; Magee *et al.* 2013; Schofield *et al.* 2015; Magee *et al.* 2016). Using a seismic dataset from the north of the Faroe-Shetland Basin (FSB) (the Ben Nevis dataset), we examine an aligned monogenetic volcanic field and its direct relationship to the plumbing system in the subsurface. This seismic dataset allows for an assessment of the complex multi-level plumbing network, the morphology of the intrusions, and the connectivity of the monogenetic plumbing systems beneath the volcanoes.

A significant outcome of this data is the observation that the underlying structure of the basin can strongly influence the distribution of monogenetic edifices. The dataset encompasses the Ben Nevis Structure (BNS), a complex anticlinal structure covering an area of 300 km^2 (Fig. 1B, C). It should be noted that the structure is so called due to its morphological similarity, rather than any geological reason, to the topographic dome of the Ben Nevis Mountain, located on the NW Scottish mainland. This contribution provides an explanation for the presence and timing of the uplift of the Ben Nevis Structure and its interdependent association with local and regional magmatic activity along the Atlantic Margin.

Although this study focuses on one extinct monogenetic volcanic field, its findings have implications for our global understanding of the plumbing systems beneath monogenetic volcanic fields and the effects of the local crustal structure on the distribution of monogenetic volcanoes (Valentine & Krogh 2006; Valentine & Perry 2007; Le Corvec *et al.* 2013; Hernando *et al.* 2014). The significance of lateral offset shallow plumbing systems consisting of a network of sills, dykes and inclined sheets, has implications for the geochemical and petrological signature of magma erupted from monogenetic volcanoes (Magee *et al.* 2016). In addition, this study, and studies like it, can provide significant information for volcanic risk to urbanised areas and infrastructure that are present within active monogenetic fields (e.g. Mexico City, Mexico and Auckland, New Zealand), for example, uplift and overburden deformation due to the lateral emplacement of intrusions pre-eruption.

Geological Background

Geological History of the FSB

The Faroe-Shetland Basin (FSB) is a hydrocarbon producing basin between NW Scotland and the Faroe Islands (Fig. 1), NE Atlantic. The FSB is a collective name given to a series of NE-SW trending sub-basins, formed during rifting events post-Caledonian Orogeny (*ca.* 390 Ma) (Ebdon *et al.* 1995). The regional orientation of maximum horizontal compressional stress is largely NW-SE (Holford *et al.* 2016). The FSB is characterised by intra-basinal highs (Rona, Flett, Westray and Corona ridges; Fig. 1A) separating half-grabens that contain accumulations of Jurassic and Cretaceous sedimentary rocks (up to 6 km) blanketed by Palaeocene to Recent sediments (Naylor *et al.* 1999; Moy & Imber 2009). The initiation of rifting of the North Atlantic in the Early Palaeocene, and the speculated impingement of a deep mantle plume, instigated magmatic activity, producing extensive lava fields, widespread ash horizons and large intrusive complexes, comprising a network of sills, connected by sub-vertical dykes and inclined sheets (White 1989; Smallwood *et al*. 1999; Smallwood & White 2002; Ellis & Stoker 2014). Large volcanic centres, that predate the rifting-associated volcanism, are identified in the northern FSB and in the Rockall, West of Scotland by large isostatic gravity and positive, circular free-air anomalies (Passey & Hitchen 2011) (Fig. 1C). The initial volcanic activity occurred at ca. 62 Ma (mid-Thanetian) and extended into the Early Eocene (Dore *et al.* 1997; Naylor *et al*. 1999; Smallwood & White 2002; Schofield *et al.* 2015). The volcanic activity produced a thick flood basalt sequence covering an area of 120,000 km^2 (Passey & Jolley 2008). The lava series is up to 5,000 m thick on the Faroe Islands and thins to the SE (Waagstein 1988; Passey & Jolley 2008). The Faroe-Shetland Escarpment (Fig. 1A, B) marks the palaeo-shoreline-shelf transition where subaerial lavas entered water, producing prograding foresets of hyaloclastite-pillow breccias and migrating the palaeo-shoreline seaward (Wright *et al.* 2012).

NW-SE trending lineaments are recognised in the FSB, cross-cutting the continental shelf (Fig. 1A) (Rumph *et al.* 1993; Lamers & Carmichael 1999; Moy & Imber 2009; Ritchie *et al.* 2011; Schofield *et al.* 2015). The origins of these lineaments are unclear, however, hypotheses include reactivated Pre-Cambrian shears (Knott *et al. 1*993) and oblique extension features formed as a response to Mesozoic rifting (Rumph *et al.* 1993). The lineaments are an important feature in controlling basin segmentation, the location of transfer zones, the source input direction and distribution of Palaeocene and Eocene sediments, and possibly controlling the input and distribution of magma in the FSB in respect to intra-basinal highs (Schofield *et al.* 2015), including the various volcanic centres (Rumph *et al.* 1993; Archer *et al.* 2005; Moy & Imber 2009; Muirhead *et al.* 2015). Post-rifting subsidence and later Oligocene-Miocene localised compression resulted in minor folding of Palaeocene lavas in the FSB and deposition of marine sediments (Doré & Lundin 1996; Ritchie *et al.* 2003).

The Ben Nevis Structure: Hydrocarbon Exploration History

The Ben Nevis Structure (BNS), which forms a broad anticlinal 4-way dip-closed structure, is located 15 km SE of a large Bouguer anomaly referred to as the Brendan's Volcanic Centre (BVC) (Fig. 1C). The BNS is unconformably overlain by a sequence of extrusive Palaeogene basaltic rocks and the Early Eocene monogenetic field, and was drilled by Shell (and partners) in 2003 (Fig. 2). The pre-drill prognosis was a series of alternating Cretaceous shales and sands, however, upon drilling this prognosis was found to be incorrect. The BNS was dominated by Cretaceous (Maastrictian and Campanian) mudstone sequences intruded by a series of Palaeogene dolerite intrusions (Fig. 2). The intrusions gave rise to a series of high amplitude reflections that had been wrongly interpreted in the pre-drill prognosis as potential sandstone-reservoir/mudstone-seal pairs, in an almost identical scenario to a well drilled in 1997 in the Rockall Trough ("Dome Prospect") (Archer *et al.* 2005).

Methods

Acoustic impedance is the product of seismic velocity and density of a rock (Niedell 1979). The high acoustic impedance between igneous material (intrusions, lavas, tuffs) and the surrounding sedimentary host-rock allows for good imaging of igneous features (Smallwood & Maresh 2002; Bell & Butcher 2002; Schofield *et al.* 2015). Intrusions, in particular, are easily identified due to their lateral discontinuity with host-rock, high amplitude seismic reflectors and are laterally limited (Thomson & Schofield, 2008). The 3D data is a time migrated, zero-phase with European polarity, seismic reflection survey. The inlines and cross-lines are oriented NW-SE and NE-SW respectively, with spacings of 25 m between inlines and crosslines. Red reflectors indicate a ‘hard’ impendence response. Significant horizons were picked in detail to constrain the basin structure and are shown in Fig. 2, including top volcanic and base volcanic (red/brown), top of the Cretaceous (BNS) (grey), sills (green) and the Balder Formation, a formation containing multiple tuff horizons (yellow).

It is important to note that due to the depth of the BNS (>2000 m) (low seismic resolution) and overlying basalt cover, imaging of individual intrusions less than *c.* 40 m thick is unlikely (Schofield *et al.* 2015). Schofield *et al.* (2015) suggest that due to the depth of many sills within the contemporaneous basin fill of the FSB, seismic data can omit up to *c.* 88% of the sills within a basin and therefore capturing the full complexity of the sill complex can be difficult, although major magma conduits can be assessed.

Using 3D volume visualisation techniques, such as opacity rendering, the morphology of the key volcanic features are constrained. Opacity rendering allows the transparency of particular amplitudes to be individually controlled, which is highly effective when considering mafic igneous bodies, as they tend to demonstrate much higher acoustic impendence than the surrounding rock (Bell & Butcher 2002; Schofield *et al.* 2015). Spectral decomposition is also used. This imaging technique uses frequency domains to image time-thickness variability of seismic reflectivity data (McArdle & Ackers 2012). Application of this technique, which produces enhanced images of the subsurface, has recently been useful in analysing volcanic vents and lava distribution patterns in the FSB (Schofield & Jolley 2013; Wright 2013).

Seismic observations and interpretations

To better understand the distribution of the monogenetic volcanic field above the BNS, we first need to understand the temporal evolution of the subsurface structure and its influence on the dispersal of volcanic edifices.

Brendan's Volcanic Centre (BVC) and regional stratigraphy

A regional gravity anomaly map shows the centre of a large (c. 50 km), positive Bouguer gravity anomaly (+80mGal) in the northeastern FSB, identified as the Brendan's Volcanic Centre (BVC) (Passey & Hitchen, 2011) (Fig. 1C). The anomaly is interpreted as a result of a large magmatic body intruded at depth, however, equally a collection of smaller igneous intrusions could give rise to a singular gravity anomaly due to their proximity to each other and the low resolution of the geophysical data. The BVC is situated along one of the NW-SE trending lineaments, the Brendan's Lineament, which likely controls the site of the igneous centre (Fig. 1A) (Archer *et al.* 2005).

The lithostratigraphy in the Ben Nevis (219/21-1) and Lagavulin (217/15-1z) wells have been extrapolated across a newly acquired regional line in Figure 3, constraining the stratigraphy across the northern margin of the FSB (Fig. 4). Onlapping onto the BNS from the west is a sequence of T38 – T31 sedimentary rocks (Sullom-Lamba Formation), locally intruded by sills (Fig. 3 and 4). This T38 - T31 sequence is onlapped from a westerly direction by a sequence of T40 volcanic rocks (Flett Formation) (Fig. 4). The T40 volcanic package thickens towards the Lagavulin prospect and is comprised of tabular lavas, volcaniclastics and hyaloclastites (Millett *et al*. 2015) (Fig. 3). The T36 lava field (Lamba Formation), which is situated around the BNS, is also discretely onlapped by the T40 flows. The T36 lava field is a Kettla Member-correlative (a regional ash horizon marker) and is age equivalent to a number of small-scale rift flank volcanoes and associated lava fields in the Northern Foula Sub-basin (208/21-1) and in the Judd Sub-basin (204/28-1) (Schofield *et al.* 2015) (Fig. 1). The T36 lava field (and age-equivalent volcanic rocks in the FSB) marks the onset of widespread volcanism in the basin ca. 58.4 Ma (Schofield *et al.* 2015).

The Ben Nevis Structure (BNS) and Thanetian volcanic rocks

The BNS is situated 15 km SE of the centre of the Bouguer anomaly of the Brendans Volcanic Centre (Fig 1C). The BNS is defined by several high amplitude reflectors, that record a series of sills intruded into the Cretaceous stratigraphy, and which delineate the morphology of the anticlinal 4-way dip-closed structure (Fig. 2). The sills are generally laterally extensive for tens of kilometres within the structure and are likely concordant to the bedding of the Cretaceous stratigraphy (Fig. 2). The intrusions appear to exploit the Kyrre Formation in particular, allowing the boundary between the Kyrre Formation and the later Jorsalfare Formation to be more readily identified (Fig. 2). The sills along the NW flank and crest of the BNS terminate at the Upper Cretaceous-Palaeocene unconformity and are subsequently onlapped by T38 - T31 sediments and volcanic rocks (Fig. 5). The truncation of sills demonstrates that the sills were in place prior to the uplift, erosion and creation of the Upper Cretaceous angular unconformity. Surrounding wells to the east of the BNS (219/20-1, 219/27-1 and 219/28-2Z; Fig. 1) record between 262 m and 317 m of Selandian-aged stratigraphy (Lista Formation, Fig. 4). However, across the crest of the BNS, the Lista Formation, or equivalent Vaila Formation (Fig. 4), are absent and the T36 lava field (*ca.* 58 Ma) directly overlies the Upper Cretaceous unconformity. At the top margin of the anticline, sills are offset by normal faults, defining rotated ~1 km across fault blocks in the Jorsalfare Formation (Fig. 2). Normal faulting is also evident within the Kyrre Formation (Fig. 2).

Above the unconformity, the T36 lava field (*c.* 270 m thick) is represented on the seismic data by a series of bright, hard-kick reflectors that are relatively smooth and laterally continuous (Fig. 6). The T36 volcanic sequence generally thickens towards the NW from a few tens of metres in the SE to hundreds of metres in the NW. From well data, the lava sequence is divided by a thin, seismically unresolved shale unit (18.6 m thick) into an upper and lower lava sequence (Fig. 2). The lower lava sequence is organised in a series of low-angle dipping reflectors separated by disorganised reflector packages (Fig. 6). In contrast, the upper lava sequence is characterised by laterally continuous, flat reflectors. The Faroe-Shetland Escarpment (FSE) (~200 – 300 m high) marks the NW margin of the Erlend Sub-basin (Fig. 1 and 6). The FSE is reflected by a change in seismic responses over the scarp from continuous reflectors to a series of prograding foresets characterised by highly disorganised, bright reflector packages over the scarp (Fig. 6A). The reflector package thickens over the FSE but thins out into the basin (Fig. 6A).

The thickness of the Shetland Group on either side of the BNS is also markedly different (Fig. 2). The thickness of the Shetland Group is exclusively related to the thickness of the overlying volcanic succession (e.g. a reduced Upper Cretaceous strata underlies a thick volcanic succession).

The Ben Nevis Monogenetic Volcanic Field (BNVF) and plumbing system

The seismic data reveals a series of well-preserved monogenetic volcanic edifices (up to 10 possible edifices), primarily located on the top surface (~1900 ms to 2300 ms) of the T36 lava field (Fig. 7), hereafter referred to as the Ben Nevis Monogenetic Volcanic Field (BNVF). The edifices are estimated to be between ~145 m to 380 m in height, <2 km in diameter, and have an estimated external slope of between 11° and 35°. The internal structure of each cone is represented by ordered, discrete seismic packages and when observed on time-slices (horizontal slices through data), the edifices are circular or elliptical, signifying a highly organised internal structure (Fig. 7; Edifices 1,6 & 7). On several of the edifices, bright seismic reflectors cap the top of the cone and extend for several kilometres (Fig. 7; Edifice 6). Edifices 8 and 9 are present in the Erlend Sub-basin along the Faroe-Shetland Escarpment (Fig. 7; Edifice 9). These edifices (8 and 9) are represented by an internal chaotic zone beneath bright reflectors and are typically steep sided with a large central crater (Fig. 7; Edifice 9).

The edifices are underlain by vertical zones of reflector discontinuity (<2 km) that appear to connect with the lateral tips of very high amplitude reflectors, identified as sills (Fig. 7; Edifices 1,6 and 7). The sills appear to feed upwards into these conical zones of disruption and terminate. The clear spatial connection between edifice and underlying sill indicates that the two features are intimately related (Fig. 7 and 8). The high amplitude reflectors display a complex, vertically stacked and laterally extensive series of interconnected sheets and sills (Fig. 6). The sills are intruded between 4200 ms and 2500 ms which equates to <500 m to 3 km beneath the monogenetic edifices at the time of intrusion (based on time-depth data of well) (Fig. 8A-C). The intrusions are expressed as tuned reflection packages and so thickness can only be estimated, with an estimated maximum thickness of ~100 m. The intrusions are relatively small in diameter (<1–3 km). Several intrusion morphologies have been identified and are shown in Fig. 8A-C, including: (A) saucer-shaped intrusions composed of a concordant inner sill that transgresses upwards at the margins forming a radial or bilateral geometry (Magee *et al.* 2014) (Fig. 8A); (B) climbing saucer-shaped intrusions composed of a saucer-shape intrusion that is typically less transgressive on one rim than another (Planke *et al.* 2005) (Fig. 8B); and (C) inclined sheets comprised of reflections that are inclined and discordant to surrounding strata (Planke *et al.* 2005) (Fig. 8C). The majority of the saucer-shaped and half-saucer shaped intrusions are located beneath the Erlend Sub-basin (Fig. 8D). The high amplitude reflectors interpreted as inclined sheets are located along the inclined Upper Cretaceous unconformity (Fig. 6), and delineate the structure of the BNS (Fig. 8D.

Opacity rendered views of the seismic data enables the intrusion morphologies in the subsurface to be evaluated. The intrusions are shown to consist of a series of lobes, or coalesced fingers, which allow interpretation of the direction of magma migration (Hansen & Cartwright 2006; Schofield *et al.* 2010; Schofield *et al*. 2012) (Fig. 8E, F). Magma lobes are also evident on the inclined sheets and are seen climbing upwards to the base of the volcanic edifice (Fig. 8E, F).

Cone-like structures are identified near the base of the volcanic succession and are onlapped and subsequently buried by 1.5 km of volcanic rocks (later lavas and hyaloclastite) (Fig. 9A). High amplitude reflectors outline the cone edifice and an organised internal structure can be identified. On the timeslice views (plan view), these "cones" are near-circular, up to 380 m in height and <2 km in diameter. Bright reflectors are identified emanating away from the buried cones and are laterally extensive for up to *c.* 2 km (not consistently surrounding the cone), suggestive of localised lava flows (Fig. 7).

Edifice distribution

The edifices are arranged around the crest of the underlying BNS (Fig. 10A). There is an apparent ENE-WSW alignment of five edifices that lies sub-parallel to the axis of the BNS (Fig. 10). A statistical alignment analysis of the monogenetic edifices was conducted to assess the spatial relationship between the edifices in the alignment using the method of Paulsen & Wilson (2010). Best-fit ellipsoids of each of the edifices were used to determine the centroid of the edifice and a best-fit line was established. The total length of the proposed alignment is 28.42 km. The alignment can be classified into four reliability grades (A > B > C > D) by considering four factors: (1) number of edifices in alignment; (2) the orthogonal distance from the centroid of an edifice to the best-fit line; (3) spacing distances between edifices; and (4) angle of deviation from the best fit line to the long axis of elliptical edifices (Fig. 10B) (Paulsen & Wilson 2010; Bonini & Mazzarini 2010; Magee *et al.* 2015). The results of the analysis are provided in the supplementary data.

The alignment has been assigned a reliability grade of 'D' primarily due to the large spacing distances between edifices (3.36 km to 14 km) and the lack of elongate edifices. Elongate edifices (axial ratios >1.2) are useful for defining reliable regional vent alignments

(Fig. 10B) (Paulsen and Wilson 2010; Magee *et al.* 2015), however only two edifices in the BNVF have a long-short axis ratio of >1.2. The 'D' reliability grading suggests the alignment is statistically invalid on the basis of the parameters of the analysis (spacing distances, elongation axis), however, there is a clear visual alignment (Fig. 10A).

Discussion

Establishing the timing and mechanism of uplift of the BNS

The sills at the top of the BNS structure (not feeding the BNVF) were dated using Ar/Ar to an age of 55.6 ± 0.8 Ma (sequence T40; Flett Fm.) (Fig. 2; Fig 4; Rohrman 2007), however, reliance on argon dating techniques in mafic systems is highly questionable due to the lack of potassium in basic igneous bodies, high levels of alteration, and particularly small radiogenic ^{40}Ar yields (Fitch *et al.* 1988, Archer *et al.* 2005). Conversely, it is clear from the seismic data that, due to the truncation of these intrusions (Fig. 5), they were emplaced much earlier than the Ar/Ar age suggests. The sills are truncated by the Upper Cretaceous unconformity which is onlapped by the T38 – T31 stratigraphy (ca. 60 Ma).

From the absent Selantian-aged Vaila/Lista Formations (Fig. 4) above the BNS, it is assumed that uplift and updoming of stratigraphy forming the BNS occurred between the end of the Cretaceous and the Early Palaeocene (Danian and Selantian), *c.* 65 - 59 Ma. The angular unconformity and truncation of the top of the Jorsalfare Formation and sills suggests the uplift of the dome structure formed a local topographic high during the Early Palaeocene, which caused significant subaerial erosion of the Cretaceous sequences (Fig. 11).

Vitrinite reflectance analysis from Well 219/21-1 shows 3.0% to 5.0%, in the sub-volcanic BNS stratigraphy (2000 – 3000 m depth), corresponding to 220°C to 270°C (Rohrman 2007). Furthermore, a reconstructed temperature history (Rohrman 2007) shows a heat spike at 65–60 Ma of 90 mW/m^2 which cannot be explained by just heat conduction from the sills (Rohrman 2007). This elevated heat signature implies that there was a deep-seated heat source directly below the BNS before the onset of Late Palaeocene volcanism (Rohrman 2007). It is therefore likely that the intrusions were emplaced synchronously with an underlying laccolith that created the mechanism for uplift (Fig. 12A). The laccolith uplifts the overburden causing forced folding that induces bedding plane slip in the overlying stratigraphy (Fig. 12B; Archer *et al.* 2005). The sills exploit the weakness in the bedding planes during early inflation of the pluton creating stacked sills that emanate from the larger body (Fig. 12B; Archer *et al.* 2005). Continuous doming caused by inflation of the laccolith is assisted by the inflation of the sills, producing a significant amount of updoming of the overburden. Both magmatic events (laccolith and associated intrusions) caused significant heating of the Upper Cretaceous stratigraphy (Fig. 12A).

In the Rockall Basin, 530 km to the SW (Fig. 1), a similar structure to the BNS is recorded in the Cretaceous stratigraphy (Archer *et al.* 2005). The intrusions forming the Rockall Dome Structure were dated to 63.3 Ma to 64.2 Ma using Ar/Ar in biotite, a much more reliable dating source (Archer *et al.* 2005). The occurrence of very similar structures in the Danian approximately 530 km apart suggests a potential regional magmatic event in the Late Cretaceous/Early Palaeocene across the NE Atlantic Margin. Furthermore, this magmatic episode (around *c.* 63-64 Ma) appears to be focussed along NW-SE trending lineament structures (Brendan's Lineament and Wyville Thomson Lineament Complex; Fig. 1) and/or transfer zones, and may appear elsewhere along the North Atlantic Margin.

Effect of the BNS palaeo-high on T36 volcanic rocks

During the Late Palaeocene, the uplifted BNS was exposed subaerially forming a broadbacked palaeo-high (Fig. 11). By assessing the original height of the BNS, it is estimated that up to 700 m of eroded material was removed from the top of the BNS. Differential compaction of the Cretaceous stratigraphy occurred on either side of this palaeo-high due to the variable thickness of the overburden (volcanic succession) (Smythe *et al.* 1983; Passey & Hitchen 2011). Sediment accumulation in the west increased compaction and subsidence of the Cretaceous strata, forming accommodation space on the west side of the BNS, which filled with T38–T31 sediments, hyaloclastite packages and later lavas (T40), represented on the seismic as bright reflectors onlapping the top Cretaceous unconformity (Fig. 3 and 11). It is likely the lack of T38-T31 sediments on the east side of the BNS is partially depositional, however, sagging onlap reflectors on the west margin of the BNS (Fig. 5) provide evidence that subsidence occurred synchronously with deposition, which is not evident on the east margin.

Eruption of the T36 lava field (*ca*. 58.4 Ma) was likely sourced from localised, rift-flank volcanoes similar to other T36 lava fields, for example in the Northern Foula Sub-basin and the Judd Basin (Schofield *et al.* 2015). By assessing the thickness of the volcanic succession (thickens towards the NW), the source of the lavas are expected to be NW of the dataset. The BNS palaeo-high prevented the earliest lava flows in the T36 lava field from advancing towards the east. Subsequent lava flows were able to breach the palaeo-high and flowed towards the east and the FSE (Fig. 11). A change in seismic responses over the FSE (Fig. 6) are attributed to shallow hyaloclastite deltas fed by the lavas and are indicative of where subaerial lavas entered the Erlend Sub-basin (Naylor *et al.* 1999; Passey & Hitchen, 2011). Small-volume lavas produced by the BNVF edifices add to the complexity of the lava field.

Ben Nevis Monogenetic Volcanic Field (BNVF) and underlying plumbing system

The plumbing system and linking to edifices

In the Late Palaeocene/Early Eocene, the Cretaceous stratigraphy in the NE Erlend Sub-basin was heavily intruded by an extension of the Faroe-Shetland Sill Complex (FSSC) (Bell &

Butcher 2002; Passey & Hitchen 2011; Schofield *et al.* 2015), comprising >130 resolvable saucer-shaped and half-saucer-shaped intrusions (Fig. 8). The FSSC is part of a wider complex of sills across the North Atlantic Margin (Schofield *et al.* 2015). The intrusion of these sills is thought to have occurred relatively synchronously across this margin around 55 Ma, however, earlier magmatic phases are reported throughout the FSB, beginning from the Late Cretaceous through to Flett Formation times (55.2 Ma) (Schofield *et al.* 2015).

During the emplacement of the sill complex, as magma encountered the BNS, the magma appears to have exploited the Upper Cretaceous unconformity and the boundary between the Jorsalfare and Kyrre Formations (Fig. 8). Mechanical contrasts across these boundaries creates conditions that promote intrusion parallel to bedding (Kavanagh et al. 2006). This channelled magma to the surface, resulting in inclined sheets intruding up the flanks of the dome structure feeding edifices around the crest of the underlying BNS on the contemporaneous surface (Fig. 10A). Alignment analyses suggest the alignment corresponding to the northern flank of the BNS crest is statistically invalid (Fig. 10B). More statistically reliable (hydrothermal and magmatic) vent alignments tend to form in response to magma (or hydrothermal fluids) exploiting faults, if magma exploits along the entire fault length (Paulsen & Wilson 2010; Bonini & Mazzarini 2010; Magee *et al.* 2015). Magee et al. (2015) suggest the convex-upwards, upper tip-line geometry of faults can direct fluids to the fault centre, locally limiting hydraulic failure of the overburden and localizing vent distribution along the fault trace. This effective channelling of magma does not occur as efficiently beneath the BNVF as the magma exploits bedding planes, not faults, which results in a less definitive alignment due to the irregular structure of the underlying anticline (BNS).

Conical zones of disruption are identified in seismic data between the feeder sills and some of the edifices in the BNVF (Edifice 1 in Fig. 7). This feature is commonly found beneath all vent/mound types (e.g. hydrothermal, sediment and magmatic) (Bell & Butcher, 2002; Svensen *et al.* 2006; Grove 2013 Magee *et al.* 2014; Galland *et al.* 2014; Jackson 2012; Manton 2015) and may represent: (i) vertically mobilised sediment induced by hydrothermal fluids around sills (Grove 2013); (ii) the migration of phreatic fluids (hydrothermal complexes) (Svensen *et al.* 2006); (iii) phreatomagmatic diatreme structures formed by several hundred phreatomagmatic explosions in the subsurface (White & Ross 2011); and (iv) dense, magmatic feeder dykes. In the case of the BNVF, disrupted zones beneath edifices most likely represent abundant feeder dykes due to the magmatic nature of the edifices.

Monogenetic volcanic edifices

The formation of the BNVF was contemporaneous with the T36 lava field suggesting that the intrusions feeding the BNVF were associated with an early phase of FSSC emplacement at *ca.* 58 Ma, near the onset of widespread volcanism in the basin (Fig 11). The majority of the monogenetic volcanic field is comprised of scoria cones, represented as constructional edifices with typically steep external slope angles and internal craters, and capped by bright reflectors reflecting individual low-volume lava flows (< 0.1 km^3; Nemeth 2010) (Fig. 7; Edifices 1,6 & 7). Using spectral decomposition, imaging of these lava flows has been obtained and individual lava flows can be mapped (Fig, 7). The edifices differ from hydrothermal vents, commonly represented as craters, mounds or eye-shaped seismic structures (Planke *et al.* 2005; Svensen *et al.* 2006; Hansen *et al*. 2008). Although hydrothermal vents are typically located above the tips of sills, like the BNVF edifices, they tend to have a disorganised internal structure and an underlying sag-like structure, representative of a subsidence-formed crater, which are not apparent beneath the BNVF edifices (Fig. 7) (Jamtveit *et al.* 2004; Svensen *et al.* 2006; Hansen *et al.* 2008). Furthermore, the internal structure of the BNVF edifices is clearly defined by high amplitude reflectors indicating a well-organised structure comprised of lavas and volcanic material (Fig. 7).

The edifices present on the margin of the Faroe-Shetland Escarpment (Fig. 7; Edifice 9) are inferred as submarine magmatic vents due to their location next to the FSE (which marks the palaeoshoreline during the Late Palaeocene/Early Eocene), and their internal chaotic seismic character (Fig. 7; Edifice 9). The type of submarine edifice (pillow-lava dominated or hyaloclastite dominated) is determined by the water depth at point of magma extrusion (Kokelaar 1986). Where water depths are greater than 130 m, vesiculation of magma is suppressed and pillow lavas will be extruded typically forming low angle mounds (Kokelaar 1986). At shallow water depths (<130 m), submarine fountaining of magma can occur, causing intensive quenching and fragmentation of magma and the production of edifices comprised of hyaloclastite, tephra, pillow lavas and reworked material (Kokelaar 1983). The submarine edifices (Fig. 7; Edifice 9) are steep sided with a large central crater, suggesting that high rates of submarine magma fountaining (and therefore instantaneous quenching and fragmentation of magma) built hyaloclastite dominated submarine volcanic cones (Kokelaar 1983; Bell & Butcher 2002).

Significance of sills and transgressive sheets in monogenetic plumbing systems

Kereszturi & Nemeth (2012) consider lateral migration of magma to be minimal beneath monogenetic fields and imply that the location of the edifice is a good approximation of the location of magma source in the subsurface. The Ben Nevis seismic data indicates that lateral migration of magma can occur for up to 10 km before the eruption of magma at the surface (Fig. 6). Vertically extensive, stacked sill complexes (<10 km) feeding monogenetic edifices, similar to the BNVF, are also recorded in the Møre and Vøring basins in offshore Norway and the Ceduna Sub-basin offshore Australia (Cartwright & Hansen 2006; Jackson 2012; Magee *et al.* 2013; Manton 2015). Seismic imaging and field based studies of such intrusion networks clearly shows sills and inclined sheets can provide the dominant magma storage and transport pathway beneath monogenetic volcanic fields in primarily extensional tectonic settings (and back arc extensional regimes) (Cartwright & Hansen 2006; Valentine & Krogh 2006; Nemeth & Martin 2007; Jackson 2012; Kiyosugi *et al.* 2012; Muirhead *et al.* 2012; Magee *et al.* 2013; Magee *et al.* 2014; Re *et al.* 2015; Richardson *et al.* 2015; Magee *et al.* 2016; Muirhead *et al.* 2016).

Interrelated sills and inclined sheets at Hopi Buttes, Arizona, featuring ramped step and stair, saucer-shaped and half-saucer-shaped intrusion morphologies, form at least 30% of the total magma volume of the monogenetic plumbing system (Muirhead *et al.* 2016). At San Rafael Monogenetic Volcanic Field, this percentage increases to 93% (Richardson *et al.* 2015). An absence of dykes in the Crown Butte complex at Hopi Buttes, and the ratio between magma storage in sills versus dykes at San Rafael demonstrates the significance of sills and inclined sheets in transporting magma to the surface beneath monogenetic fields (Muirhead *et al.* 2016). However, the total volume of magma storage in sills and transgressive sheets cannot be fully elucidated by just field data due to the current level of exposure of some fields, where the complex, stacked nature of the sill complexes are not fully exposed.

Seismic unrest studies have suggested stalling of magma in the upper crust can occur up to two years before a monogenetic eruption, indicating multiple potential intrusion events pre-eruption. For example, the 2011 eruption offshore of El Hierro in the Canary Islands was preceded by 4-5 years of seismic unrest activity, suggestive of the development of a complex plumbing system (Albert *et al.* 2016). The evidence for shallow plumbing systems is further corroborated by geochemical studies which allude to the presence of sub-horizontal, shallow plumbing systems where crustal assimilation, crystallization and melt storage is recorded (Nemeth *et al.* 2003), especially beneath relatively long-lived scoria cones such as Jorullo and Paricutin (15 yr and 9 yr respectively) in the Michoacán–Guanajuato Volcanic Field of the Trans-Mexican Volcanic Belt (McBirney *et al.* 1987; Johnson *et al.* 2008).

The BNVF demonstrates that although each individual monogenetic edifice stems from a discrete magma “reservoir” or intrusion, the overall plumbing system of a volcanic field can be interconnected and genetically related. Consequently, two distinct magma batches feeding separate edifices can share a common plumbing system and still produce different compositional trends due to the isolation of the individual feeding intrusions. In other words, assimilation trends for each individual edifice may not be identical across a monogenetic volcanic field but would record the trends of a separate branch of a shared plumbing system.

Emplacement of monogenetic plumbing systems and influence of the local crustal structure

It is important to consider why sill-dominated plumbing systems form as opposed to dyke-dominated systems. For sub-horizontal intrusions (including saucer-shaped sills and inclined sheets) to form, two main constraints must be overcome to convert magma from a vertical pathway to a horizontal one: (1) magma driving pressure must exceed host-rock strength or, in this case, the tensile strength of a pre-existing plane of weakness (Valentine & Krogh 2006); (2) the rotation of the principal stress (sigma 1) from vertical to sub-horizontal (and compressive stress, sigma 3, to a sub-vertical orientation) (Kavanagh *et al.* 2006; Valentine & Krogh 2006; Menand 2008). In extensional tectonic settings the principal stress (sigma 1) is vertical and the compressive stress (sigma 3) is horizontal (Anderson 1951; Burchardt 2008). Unconformities or host-rock interfaces with sufficiently contrasting mechanical and rheological properties (rigidity, strength, pore fluid pressure) can cause the rotation of the principal stress (sigma 1) from vertical to horizontal, and can subsequently promote the propagation of a sub-horizontal intrusion (Kavanagh *et al.* 2006; Menand 2008; Thomson & Schofield 2008; Gudmundsson 2011; Magee *et al.* 2013; Kavanagh *et al.* 2015; Tibaldi 2015; Magee *et al.* 2016). In some cases sill intrusion into a pre-existing weakness or bedding plane does not require a rotation of sigma 3 to horizontal. This occurs when the sill intrudes obliquely to the least compressive stress (sigma 3) (Jolly & Sanderson 1997). Horizontal or sub-horizontal propagation is, therefore, a function of magma pressure, tectonic stress and the strength of the weakness.

Compliant lithologies are exploited by magma through ductile deformation of the host-rock, for example: coal (e.g. Raton Basin, Colorado, USA; Schofield *et al.* 2012); salt (e.g. Werra-Fulda Basin, Germany; Schofield *et al.* 2014); and shale (e.g. Golden Valley Sill, South Africa; Schofield *et al.* 2010). The mechanically weak layers can inhibit vertical crack propagation, limiting vertical migration of magma and promoting horizontal migration along the compliant layer (Thomson 2007; Schofield *et al.* 2012). Therefore, in thick sedimentary sequences, it is likely that sill complexes will develop either by exploiting host-rock interfaces in the strata, and/or by exploiting compliant horizons (Fig. 13) (Eide *et al.* 2016).

The abundance of saucer-shaped and half-saucer shaped intrusions in the BNVF plumbing systems is likely a result of strong host-rock control and exploitation of compliant horizons in the Upper Cretaceous stratigraphy (e.g. shales). In the case of the inclined sheets, the magma exploited the mechanical difference along the inclined Cretaceous-Palaeocene unconformity (claystones and extrusive volcanic rocks) and between the Jorsalfare Formation (Fig. 14A). Due to the orientation and nature of the BNS structure, these planes of weakness were inclined and supported the injection and propagation of magma upwards towards the surface (whilst also contributing to lateral magma migration), forming inclined sheets and dictating the location of the edifice (Fig. 14A).

Inclined sills have been found to be formed by various other mechanisms. The formation of the inclined limbs of a saucer-shaped sill may be instigated by forced folding of the overburden above a sill, where extensional fractures form near the termination of the sill (Thomson 2007) (Fig. 14B). The rapid decrease in hydrostatic pressure due to the opening of these fractures, instigates localised host-rock fluidisation (also caused by heating of host-rock pore-fluids) (Schofield *et al.* 2010). Magma exploits these failures, propagating upwards into the fluidised host-rock as a series of localised flow pathways ("magma fingers") which coalesce into a singular sheet (Fig. 14B) (Thomson 2007; Schofield *et al.* 2010). The "saucer" morphology is formed by radially upward-propagating magma fingers surrounding an inner sill (Schofield *et al.* 2012). Field evidence for this type of structure is found at the Golden Valley Sill in the Karoo Basin, South Africa, where undulations in the transgressive rim, provide evidence for coalesced discrete magma pathways, or "fingers", and host-rock fluidisation structures are observed surrounding magma fingers (Schofield *et al.* 2012). Alternatively, transgressive sheets may also develop as a result of changes to the lithostatic pressure of the host-rock environment. Re *et al.* (2015) suggest that the application or destruction of a load at the surface (e.g. by the development of a volcanic edifice), or the development of a diatreme, will alter the compressive stress regime (sigma 1 and 3) in the host-rock strata, preventing vertical dyke propagation and resulting in an inclined magma pathway (Fig. 14C).

Extensional monogenetic volcanic fields tend to show one or more edifice alignment orientations, typically a regional stress-controlled orientation and/or alignments controlled by pre-existing (dipping) crustal fractures and normal faults (Le Corvec *et al.* 2013; Magee *et al.* 2013; Muirhead *et al.* 2015; Schofield *et al.* 2015; Mazzarini *et al.* 2016; Muirhead *et al.* 2016b). Pre-existing faults are known to influence the distribution of monogenetic edifices depending on the fault dip angle, the orientation of the fault plane, the mechanical properties of the adjacent host-rock, and the localised stress regime around the fault (Gaffney *et al.* 2007; Magee *et al.* 2013; Le Corvec *et al.* 2013). Basin-scale flexures in the hanging wall of half-graben basins in rift settings can trigger extensional faulting and fracturing, and may also control the alignment of edifices (Muirhead *et al.* 2016b). The BNVF consistently demonstrates just one vague alignment orientation (corresponding to the crest of the BNS structure; Fig 10). This ENE-WSW alignment of edifices contradicts the regional stress orientation (NW-SE) (Holford *et al.* 2016) and no fault pathways have been identified on the seismic data (although potential faults could be obscured by the poor sub-basalt imaging). As a result, we suggest that the primary influence on edifice distribution in the BNVF is the inclined rheological boundaries in the subsurface strata. Magma interaction with local crustal structures (e.g. folds, inclined rheological boundaries), has been significantly overlooked as a dominant influence over the distribution of monogenetic edifices but should be considered when assessing future eruption sites of active monogenetic fields.

Reactivation of magma migration pathways during the lifetime of a monogenetic volcanic field

The observation of buried volcanic edifices beneath the BNVF (Fig. 9) gives a unique perspective of the distribution of monogenetic edifices and how they are distributed spatially and temporally. The offset between the buried cones and the later monogenetic edifices is less than 1 km (Fig. 9). The lateral proximity between the buried cones and later edifices suggests a similar magma pathway for both edifice-forming events. One example, beneath Edifice 1 (Fig. 9A), shows a high amplitude reflector inclining vertically into the base of an earlier cone and then transgressing further into the base of a later edifice (Fig. 9A). The timescale between the emplacement of magma beneath the earlier cone (onset of lava, *ca.* 59 Ma) and the emplacement of magma beneath the later cone (final stages of lava field development, *ca*. 58 Ma) is too long for the magma pathway to stay molten in a <80 m thick intrusion at such a shallow depth (<1.5 km beneath the palaeosurface) due to high cooling and crystallisation rates (Fig. 9A). It is therefore suggested that the high amplitude reflector signifies multiple stacked intrusions (Fig. 9B). The majority of sills observed in seismic are expressed as tuned packages of reflectors, thus making it difficult to discern whether a thick bright reflector is the product of one sizable intrusion or a series of incrementally emplaced or stacked intrusions (Magee *et al.* 2016). A newly-developed intrusion can impart a thermal, rigidity or strength anisotropy on to subsequent injections and further promote horizontal propagation of future intrusive events (Fig. 13) (Gudmundsson & Brenner 2004; Kavanagh *et al*. 2006; Menand 2008; Burchardt 2008). We interpret that after feeding the earlier (buried) cone, the sill provided a strong mechanical discontinuity between the sill and the surrounding host-rock (Annen *et al.* 2015; Magee *et al.* 2016) (Fig. 13). The new magma pulse, feeding the monogenetic edifices on the top volcanic surface, exploited this contact, stacking the intrusions and increasing the apparent thickness of the sill in seismic (Magee *et al.* 2016) (Fig. 13). This stacking of intrusions spatially and temporally can have significance for the thermal and chemical evolution of the later magma batch (e.g. slower cooling intrusions) (Annen *et al.* 2015; Magee *et al.* 2016).

Conclusions

The seismic data presented here offers an insight into how monogenetic volcanic fields are fed, and how the distribution of edifices can be primarily influenced by the structure of the substrate. This data can give an understanding of the characteristic and distribution of plumbing systems in active volcanic fields, or where ancient volcanic fields are poorly exposed in the field. The Ben Nevis seismic data adds to the growing body of evidence that monogenetic plumbing systems are far more complex than first suggested, where shallow saucer-shaped intrusions and inclined sheets form the majority of the magmatic system. Our research shows that the anticlinal Ben Nevis Structure beneath the Ben Nevis Volcanic Field significantly influenced the structure of the plumbing system and the subsequent distribution of volcanic edifices on the surface. Magma exploited the distinctive rheological boundary along the inclined Upper Cretaceous unconformity and between the Jorsalfare and Kyrre Formations, and fed an indefinite alignment of edifices along the axis of the BNS. The plumbing system beneath the BNVF is characterised by an intricate overlapping series of saucer-shaped sills, half-saucer shaped sills and inclined sheets, which are connected by seismically unresolvable feeder dykes, over a vertical thickness of ~3 km. These intrusions are connected to a series of scoria cones and submarine volcanic cones. Vertically-stacked edifices suggest that magma pathways in the subsurface are exploited multiple times during the lifetime of a volcanic field.

We suggest that the sill-dominated plumbing system, seen beneath the Ben Nevis Monogenetic Volcanic Field, is present beneath other monogenetic volcanic fields. Further work is required to use this study, and others like it, to aid the forecasting of magma migration beneath active fields, and produce accurate hazard assessments of the next eruption site.

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Figure Captions

Fig. 1: (A) Structural map of the Faroe-Shetland Basin and NE Rockall, highlighting the NE-SW trending sub-basins and NW-SE trending lineaments. Faroe-Shetland Escarpment marked by dashed line (from Ritchie *et al.* 2011 and Archer *et al.* 2005). Location of the Rockall Dome (Dome 164/7-1) marked by dotted line. Cross-section B-B’ shown in Fig. 3.

Inset shown in (B). (B) Location of 3D seismic dataset (dashed line) and distribution of wells are marked. Cross-sections A-A' in Fig. 2 and C-C' in Fig. 5 (solid black line). (C) Gravity data over the Brendan's Volcanic Centre (BVC). Green shading shows high (positive) gravity response; blue shows low (negative) gravity response. Locations of gravity anomalies highlighted by red solid lines. Bouguer anomaly across the BVC is +80mGal. White dotted lines highlight the proposed structural highs including the BNS. Black solid line shows location of (B).

Fig. 2: **(A)** Representative seismic line and interpreted line of the Ben Nevis Structure (BNS) (A-A') displaying location of well 219/21-1. Note the variation in thickness of the Upper Cretaceous on either side of the BNS and the truncation of bright reflectors on the flank of the NW BNS. Location of cross-section shown in Fig.1B. **(B)** Chronostratigraphic log of well 219/21-1. Sills in Kyrre Formation dated by Rohrman (2007). **(C)** 3D structural map of the BNS showing 4-way dip structure.

Fig. 3: Interpreted regional seismic line across between the Ben Nevis Structure (BNS) and Lagavulin prospects (Data courtesy of PGS CRRG 2D GeoStreamer®). The location of the cross-section shown in Fig. 1A (B-B'). "B" is on the left and "B'" is on the right of the seismic line. Well sites labelled. Interpreted stratigraphy shows the western margin of the BNS is onlapped by T38-T31 sediments and T40 volcanic rocks extrapolated from the Lagavulin well shown in Fig. 1A. The lava sequence in the Ben Nevis seismic dataset (Fig. 2) is an earlier and localised T36 lava field (blue). T-sequence stratigraphy in Fig. 4.

Fig. 4: Palaeogene stratigraphy of the Faroe-Shetland Basin (FSB) (adapted from Schofield & Jolley 2013), with BGS lithostratigraphy (Ritchie *et al.* 2011); BP T-sequence stratigraphy

(after Ebdon *et al*. 1995), and the North Sea equivalent Hordaland Group lithostratigraphy (found in wells east of the BNS).

Fig. 5: Truncation of sills along the Upper Cretaceous unconformity (green arrows) and subsequent onlapping of Upper Palaeocene stratigraphy. Location of Fig. 5 shown in Fig. 2. Location of seismic line in inset.

Fig. 6: **(A)** Seismic line and interpreted line (C-C' in Fig. 1B) showing the relationship between the BNS and the underlying sill complex. Magma migrates from the Faroe-Shetland Sill Complex (FSSC) towards the palaeo-high (BNS), where it encounters the inclined flank of the BNS, allowing magma to migrate towards the surface. Lateral magma migration is up to 10 km. The Faroe-Shetland Escarpment (FSE) is clearly distinguished, marked by a change in seismic responses from high amplitude, continuous reflectors to chaotic package of discontinuous bright reflectors over the scarp, representative of lavas feeding hyaloclastite foresets. **(B)** Top volcanic surface with the FSE indicated. Mounds in the Erlend Sub-basin highlighted as a series of forced folds, caused by the emplacement of shallow intrusions.

Fig. 7: Seismic cross-sections with interpretations through some of the monogenetic edifices showing an affinity between the volcanic cone on the top volcanic surface and an underlying sill. Solid yellow lines highlight prominent interpreted lava flows, dashed blue lines indicate (approximately) the base of the volcanic sequence and solid green lines highlight intrusions. Time slices of each edifice show an organised internal structure. Edifice 9, the submarine volcanic cone, appears to have a more disorganised structure. Spectral decomposition of the top volcanic surface highlights the lava flows emanating from edifice 6 and 7. Map insets show location of each edifice.

Fig. 8: Comparison of sill morphologies. Bright reflectors indicate intrusions. **(A)** saucer-shaped; **(B)** climbing saucer-shaped; and **(C)** planar transgressive sheet (Planke *et al.* 2005). **(D)** Distribution of sill morphologies, where transgressive sheets are located along the flanks of the BNS, whereas saucer and climbing-saucer shaped sills are exclusively within the Erlend Sub-basin. **(E)(F)** Opacity rendered images of transgressive sheets feeding edifices on the top volcanic surface. Coalesced magma lobes are evident and are used as a magma flow indicator. Map insets show direction of view.

Fig. 9: **(A)** Seismic line and interpreted line through a buried cone (A) beneath a later edifice (B). Edifice A is onlapped by lavas and inter-lava sediments. A singular intrusion appears to feed both edifice-forming events, however the high amplitude reflector likely represents multiple, stacked intrusions. Sill A fed Edifice A and sill B fed Edifice B. Map inset shows location of seismic line **(B)** Structural map of the top volcanic surface showing the location of the Edifice B. Location of the buried cone, Edifice A, is highlighted by circle. The structural map shows the lateral proximity of the cones to each other.

Fig. 10: Structural map of the top volcanic surface. Edifices are highlighted by solid white lines and appear to be distributed around the axis of the BNS pericline (black dashed line). On the NW side of the BNS axis, an ENE-WSW and NE-SW alignment is apparent. (B) Outlines of the edifices were used to create a best-fit line and each spacing distance was measured. Inset, the angle between the longest axis and the best-fit line was also measured. Using the Paulsen & Wilson (2010) method for statistical alignment analysis, this alignment was deemed statistically invalid, however an alignment is clearly evident.

Fig. 11: Illustrated reconstruction of the evolution of the BNS structure and subsequent volcanic activity. Not to scale. Time 1: Emplacement of laccolith and associated intrusions created uplift and updoming of the U. Cretaceous stratigraphy, creating a local palaeohigh which was subsequently exposed to subaerial erosion. Time 2: Continued erosion of the palaeohigh causing truncation of intrusions and creation of the U Cretaceous unconformity. Upper Palaeocene stratigraphy deposited into sub-basin to the NE of the palaeohigh, likely sourced from the erosion of the structure and from products and reworked products of the Brendans Volcanic Centre (to the NE). Compaction of the U. Cretaceous stratigraphy occurs only on the NE of the palaeohigh due to localised deposition of Palaeocene strata. Time 3: Onset of main volcanic activity initiated by deposition of hyaloclastite packages, and lava flows. The former palaeohigh (now fully eroded) is overstepped by subsequent lava flows feeding hyaloclastite packages when they reach the FSE on the SE of the BNS. Monogenetic volcanism occurs throughout main volcanic activity, producing isolated lavas.

Fig. 12: **(A)** Preferred interpretation for the uplift of the Ben Nevis Structure, involving the emplacement of a laccolith and associated intrusions. Inflation and updoming of the laccolith and intrusions cause localized uplift, and significant heating of the Upper Cretaceous stratigraphy (adapted from Jackson & Pollard, 1988 and Archer *et al.* 2005). **(B)** Jackson and Pollard (1988) three-stage model on the progression of laccolith emplacement and uplift at the Henry Mountains, Colorado Plateau, USA.

Fig. 13: Schematic diagram illustrating the development of stacked intrusions (adapted from Kavanagh *et al.* 2006). Sub-horizontal propagation occurs at a host-rock interface where there is a high rigidity contrast. Arrows show direction of magma migration. When the sill

freezes, it creates a rigidity contrast with the surrounding host-rock, generating a favourable environment for later magma emplacement.

Fig. 14: Mechanisms of transgressive sheet propagation. **(A)** Inclined rheological boundary with a sufficient rigidity contrast to rotate σ_1, allows propagation of magma along an inclined pathway. **(B)** The inflation of an intrusion causes forced fold formation in the overburden. Extensional fractures develop at the tip of the sill, instigating host-rock fluidisation around the sill tip. Magma exploits fluidised host-rock. Adapted from Schofield *et al.* (2010). **(C)** Application of load to the top surface (in this case, the development of a scoria cone), reorients the compressive stresses of the host-rock, promoting the migration of magma in an inclined sheet. Adapted from Re *et al.* (2015).