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# Emplacement of the Little Minch Sill Complex, Sea of Hebrides Basin, NW Scotland

(Abb. **The Little Minch Sill Complex**)

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The Little Minch Sill Complex is comprised of a series of stacked, multi-leaved Paleocene aged dolerite sills, which have been primarily intruded into Mesozoic sedimentary rocks and Paleocene tuffs/?hyaloclastites within the Sea of Hebrides Basin, situated on the NE Atlantic margin. Two previously proposed models for the emplacement of the sill complex have opposing ideas for the location of magma input and emplacement mechanisms. Both models have been constructed using data primarily from onshore outcrops, located on the Isle of Skye, Raasay and the Shiant Isles. However, onshore outcrops only represent a quarter (1040 km$^2$) of the entire extent of the sill complex, which is largely situated offshore. In order to understand how the sill complex as a whole was emplaced within the basin, both onshore and offshore magma transport needs to be considered. Using high resolution multibeam bathymetry data (up to 2m resolution) obtained between 2008 and 2011 along with supporting seismic reflection, sparker and pinger data, a new assessment of the offshore extent and character of the sill complex has been constructed. Mapping of large-scale relationships between intrusions and the host rock, along with morphological features such as magma lobes, magma fingers, transgressive wings, en-echelon feeder dykes and the axis of saucer/half-saucer shaped intrusions, has indicated magma flow directions within the intrusive network. Assessing the flow kinematics of the sills has provided insights into magma transport and emplacement processes offshore. Combining data from previously mapped onshore sills with data from our newly constructed model for magma emplacement offshore has allowed us to construct a new model for the emplacement of the Little Minch Sill Complex. This model demonstrates that major basin bounding faults may play a lesser role in channelling magma through sedimentary basins than previously thought. Applying the knowledge obtained from this study could further progress understanding of the effect of sill emplacement on fluid flow within volcanic rift basin worldwide, with direct impacts on the exploitation of petroleum and geothermal systems.

*End of Abstract.*

Intrusions play a fundamental role in the transport of magma within Earth's crust and can be found in many sedimentary basins across the world, including the Faroe-Shetland Basin (UK), Pearl River Mouth Basin (China), Vøring and Møre Basins (Norway), Karoo Basin (South Africa) and Northern Carnarvon Basin (Australia) (e.g. Planke et al. 2005; Sun et al. 2014; Schofield et al. 2017; Mark et al. 2019). The transport of magma within sedimentary basins can be influenced by many different parameters (e.g. faulting and fracturing, host-rock lithology), but is often more complex in highly structured basins compared to those with limited faulting and fracturing, due to the interaction of the magma with a structural framework (Liss 2003; Magee et al. 2013; Mark et al. 2019). Understanding how magma is emplaced and distributed throughout sedimentary basins is important for potential petroleum and geothermal systems, as intrusions can affect parameters such as source rock maturity, reservoir compartmentalisation and can influence fluid flow within a basin, which can ultimately lead to drilling and production issues (Planke et al. 2005; Mark et al. 2019). On a larger scale better understanding of the volumes and mechanisms of magma emplacement provides increased insights on how large magmatic events, such as the emplacement of the North Atlantic Igneous Province, can affect changes in the earth's climate as a result of an increased release of carbon-based greenhouse gases (Jones et al. 2019).

Extensive Paleocene-Eocene aged sill complexes, identified within rift basins situated along the NE Atlantic margin, are interpreted to have been emplaced as part of the North Atlantic Igneous Provence, which developed in response to the eventual opening of the NE Atlantic Ocean (England 1992; Skogseid et al. 1992; Bell & Williamson 2002; Emeleus & Bell 2005; Planke et al. 2005; Schofield et al. 2017). Within the Sea of Hebrides Basin, located on the NE Atlantic margin to the NW of the Scottish mainland, a Paleocene-aged sill complex has been intruded across a 4,000 km$^2$ area, primarily within Mesozoic (primarily Lower and Middle Jurassic) sedimentary rocks (Harker 1904; Anderson & Dunham 1966; Gibb & Gibson 1989; Fyfe et al. 1993; Bell & Williamson 2002; Schofield et al. 2016). This sill complex, known as the Little Minch Sill Complex (Gibb & Gibson 1989), crops out on Skye, Raasay and the Shiant Isles, in the form of dolerite sills ranging in thickness from a few metres to over 100 m (Harker 1904; Anderson & Dunham 1966; Emeleus & Bell 2005). On Skye, the sills have an estimated aggregate thickness of over 250m and are often stacked, with bifurcations, transgressions and terminations of the sills common (Emeleus & Bell 2005).

Mapping of large-scale relationships between sills and the host rock, as well as morphological features of the sills such as magma lobes, magma fingers, transgressive wings, en-echelon feeder dykes and the axis of saucer/half-saucer shaped sills can provide indications of magma flow directions, both locally and within the intrusive network (Hutton 2009; Schofield et al. 2010; Schofield et al. 2012a & b; Hoyer & Watkeys 2017). Assessing the flow kinematics of sills provides insights into magma transport and emplacement processes (e.g. Magee et al., 2016; Hoyer & Watkeys 2017). Earlier models of how the Little Minch Sill Complex was emplaced within the Sea of Hebrides Basin have been developed by Anderson & Dunham (1966) and Schofield et al. (2016). Anderson & Dunham (1966) proposed that the sills were emplaced into the basin from a location close to central Skye, whereas Schofield et al. (2016) proposed it was from the basin-bounding fault along the western margin. These models put forward opposing ideas for both the method of sill emplacement and the location of magma input into the basin. Both studies have previously only relied on data from onshore outcrops of the sills, which represent only ~26% (or 1040 km$^2$) of the entire geographical extent of the sill complex (Anderson & Dunham 1966; Schofield et al. 2016). In the late 1960's acquisition of seismic reflection data, sparker data, pinger data and bathymetric data confirmed that the Little Minch Sill Complex extends offshore, showing a much greater footprint than that part which crops out onshore (Chesher et al. 1983). Although the sills were imaged cropping out on the sea floor, limited data quality and resolution of early datasets did not allow accurate mapping of sills geometries, nor identification of magma transport indicators such as magma lobes and magma.

High resolution multibeam bathymetry data (up to 2m resolution), collected from 2008 to 2011 as part of the Civil Hydrography Programme, has provided a more detailed visualisation of these offshore sills and associated geology. The increased resolution has allowed the authors to map the sills with greater accuracy and assess them for magma transport indicators, which was not previously possible. Mapping of the detailed geometries and internal structures preserved in sills that crop out on the sea floor has allowed for interpretation of magma emplacement directions and relationships of the sills to local and regional structures. Some key examples of these high-resolution submarine exposures are presented in this study, along with outcrop analogues and references to known onshore structures. Previous onshore datasets, on which the two earlier models were based, have been combined with newly mapped offshore datasets of magma flow direction in order to build a more complete view of sill emplacement across the entire basin. The outcome from our work is a new model for the emplacement of the Little Minch Sill Complex within the Sea of Hebrides Basin. Our model suggests that the emplacement of sills has been partly controlled through regional and intra-basinal faults. The ability to map sills and assess magma transport indicators within high resolution bathymetry data could be potentially replicated in other sedimentary basins which have had significant sill complexes emplaced and where expression of these sills is found on the seafloor. Our study of the onshore and offshore Little Minch sill complex gives an important insight into intrusions into the Jurassic of the NE Atlantic Margin, which is often not available in offshore studies, due to the sill complex within the overlying Cretaceous sequence obscuring imaging of the sills below (see Schofield et al. 2015).

## Geological background and context of the Little Minch Sill Complex

The Sea of Hebrides Basin (SOHB), situated between the NW Highlands of Scotland and the Outer Hebrides, developed upon the Precambrian Hebridean Terrane to the west of the Moine Thrust (Fig.1) (Stein 1992; Fyfe et al. 1993). The basins long axis stretches for 195 km in a NE-SW direction, with the northern margin of the basin defined by the NW-SE trending Rubha Reidh Ridge composed of Precambrian (Torridonian) rocks, and the southern margin bounded by an W-E orientated fault, which divides the SOHB from the Stanton Trough (McQuillin & Binns 1975; Fyfe et al. 1993). The short axis of the SOHB basin extends perpendicular to strike for 75km in a SE-NW direction, from the present-day coastline of mainland Scotland in the east to the NNE-SSW trending Minch Fault in the west, which is located offshore a few kilometres east of the of the Outer Hebrides Isles (Fig.1) (McQuillin & Binns 1975; Fyfe et al. 1993). The SOHB developed during the Late Paleozoic and the Mesozoic through normal displacements on the Minch Fault and thermal subsidence (Fyfe et al. 1993). Subsequent inversion of the basin during the Early Cretaceous and the Mid-Late Cenozoic has created a more complex basin structure (McQuillin & Binns 1975; Holford et al. 2010), resulting in the basin having been interpretated both as a classical half-graben, with sedimentary rocks thickening towards its fault-bounded western margin (Stein & Blundell 1990; Roberts & Holdsworth 1999), as well as a synclinal structure (Smythe et al. 1972; McQuillin & Binns 1975; England et al. 1993; O'Neill & England 1994).

Strata from the SOHB are exposed on both the Isle of Skye and the Shiant Isles (Walker 1930; Anderson & Dunham 1966). The basin fill is primarily composed of Triassic to Jurassic sedimentary rocks, which are intruded by Paleocene to Early Eocene igneous rocks and overlain by extrusive Paleocene to Early Eocene igneous rocks (Fig.2) (Fyfe et al. 1993). Offshore, Jurassic sedimentary rocks either crop out at the seabed or are buried beneath a thin veneer of Quaternary/Recent sediment across the majority of the basin, except on its margins where older (Proterozoic/Permian/Triassic) sedimentary rocks crop out (Fig.2) (Fyfe et al. 1993). The SOHB differs from most adjacent Atlantic margin basins, such as the Faroe-Shetland Basin, in the fact that the basin did not experience significant rifting and sedimentation during the Cretaceous (McQuillin & Binns 1975; Ritchie et al. 2011). This has led to the Early to Middle Mesozoic strata within the SOHB not undergoing burial beneath significant thicknesses of Cretaceous sedimentary rocks (McQuillin & Binns 1975).

### *Geological Development of the Sea of Hebrides Basin (SOHB)*

The SOHB is thought to have initially developed during the Permian, as a result of NW-SE directed extension associated with the early opening of the Atlantic Ocean (Morton 1992a & b; Coward 1995). This rifting occurred over the Archean to Paleoproterozoic (3000-1600 Ma) Lewisian Gneiss Complex, and the sedimentary and low-grade metamorphic rocks of the Meso- to Neoproterozoic Torridonian Supergroup (Watson 1977; Stein 1992; Park et al. 2002; Mendum et al. 2008). During the Paleoproterozoic (~2400 Ma) a kinematically linked set of shear zones, trending NW-SE and NE-SW, is thought to have developed within the lower crust, strongly influencing the basin's tectonic development up to the present day (Watson 1977; Watson 1985; Stein 1992). Evidence of these regionally extensive shear zones is visible within outcrops of the Lewisian Gneiss Complex on the western coast of the Scottish Mainland and across the Outer Hebrides Isles, where the shear zones extend for a minimum of 10 to 60 km in length (Watson 1977). Pulses of extension and subsidence throughout the Permian, Triassic and Jurassic led to the deposition of over 2500 m of Permian-Triassic and Jurassic sedimentary rocks within the basin (Morton 1992a & b; Fyfe et al. 1993). This was followed by period of uplift during the Early Cretaceous, which led to the regional erosion of strata, followed by a period of non-deposition during the Early Cretaceous (Harker 2002; Holford et al. 2010). By the Late Cretaceous (Cenomanian (100 Ma)), western Scotland experienced a progressive relative sea level rise, allowing for the regional deposition of Late Cretaceous sedimentary rocks, fragments of which (<15 m thick) are preserved on Skye, Raasay and Scalpay (Braley 1990; Harker 2002; Holford et al. 2010).

During the Paleocene and Early Eocene, significant volcanic activity took place across the North Atlantic region, from eastern Canada in the southwest to Greenland in the northeast (Saunders et al. 1997; Emeleus & Bell 2005). The region influenced by this volcanism, a 2000km long pre-rift area which includes the SOHB, is known as the North Atlantic Igneous Province (NAIP) (Saunders et al. 1997; Emeleus & Bell 2005). This volcanic activity occurred as a result of the thinning of the lithosphere beneath western Britain, occurring in response to the early opening of the North Atlantic Ocean and the arrival of the proto-Icelandic plume in the vicinity of western Scotland (Bell & Williamson 2002). Within the SOHB, volcanism occurred from around 60.5 Ma to 53.5 Ma, evidenced by extrusive lavas and tuffs, along with the intrusion of sills, dykes and large central igneous complexes (Fyfe et al. 1993; Bell & Williamson 2002; Fowler et al. 2004).

Middle-Late Cenozoic uplift, associated with the Alpine orogeny, led to the erosion of any thin veneer of Upper Cretaceous strata deposited in the SOHB, as well as some Paleocene volcanic deposits (Holford et al. 2010). Minor localised tectonic activity during the Oligocene formed a series of small basins (e.g. the Canna Basin) within the SOHB (Knox, 2002). These contain isolated deposits of continental Oligocene-age sedimentary rocks (Knox, 2002). The SOHB geological history is completed by a thin veneer of glacial Quaternary sediments deposited across the basin (Fyfe et al. 1993).

### *The Little Minch Sill Complex*

The Little Minch Sill Complex (LMSC) comprises of a series of stacked, multi-leaved Paleocene aged dolerite sills, which have been intruded into Mesozoic sedimentary rocks and Paleocene palagonite tuffs within the SOHB (Harker 1904; Anderson & Dunham 1966; Gibb & Gibson 1989; Gibson 1990; Bell & Williamson 2002). The sill complex has been previously referred to as the Great Group of Basic Sills (Harker 1904), Minch Sill Complex (Schofield et al. 2016), Trotternish Sill Complex (Geikie 1897; Gibson 1988) or the Shiant Isle Sill Complex (Gibb and Henderson 1984). Crosscutting field relationships and geochemical modelling suggest that intrusion of the sill complex post-dates the extrusion of the bulk of the Skye Main Lava Series, but pre-dates the intrusion of the majority of the Skye Central Igneous Complex (Gibson & Jones 1991; Fowler et al. 2004; Emeleus & Bell 2005). The LMSC spans an area of 4,000km$^2$ and extends both onshore and offshore, from SW Raasay in the east, to the Minch Fault in the west and the Rubha Reidh Ridge in the north (Fig.2) (Gib & Gibson 1989; Gibson & Jones 1991; Emeleus & Bell 2005; Schofield et al. 2016). The sill complex is currently best exposed onshore across northern Skye, particularly on the Trotternish Peninsula, where the sills form sheer cliffs tens of metres high (Fig.2) (Anderson & Dunham 1966; Emeleus & Bell 2005; Schofield et al. 2016). The sills also compose the majority the Shiant Isles, located 24 km NW of Skye and isolated outcrops of the complex are found on the Duirinish and Waternish peninsulas of Skye and on the west coast of Raasay (Fig.2) (Anderson & Dunham 1966; Emeleus & Bell 2005; Schofield et al. 2016). On the Trotternish peninsula individual sills range from a few metres to more than one hundred metres in thickness and are observed to be tabular and sheet-like (Anderson & Dunham 1966; Emeleus & Bell 2005; Schofield 2009). On the Shiant Isles the largest single sill is 140 m thick (Gibb & Henderson 1996). The LMSC continues offshore, where dolerite sills crop out across the seafloor (Chesher et al. 1983; Bell & Williamson 2002; Schofield et al. 2016).

The geochemistry and petrography of the LMSC have been previously studied by Walker (1930), Drever & Johnston (1965), Anderson & Dunham (1966), Gibb & Henderson (1984), Gibson (1990), Gibson & Jones (1991), Fowler et al. (2004), Gibb & Henderson (2006) and Nicoli et al. (2018). These studies identified that the LMSC is predominantly composed of genetically related picritic (>40% Olivine), picrodoleritic (15-40% Olivine) and crinanitic (<15% Olivine) melts, which are thought to have been derived from the differentiation of an alkaline olivine basalt magma (Gib & Henderson 1984; Gibson 1990; Gibson & Jones 1991; Anderson & Dunham 1996; Gibb & Henderson 2006; Nicoli et al. 2018). There is variation in the petrography of the sills onshore Skye, Raasay and the Shiant Isles, both between individual sills and within a single sill (Gibb & Gibson 1989; Gibb & Henderson 1989; Gibson & Jones 1991). This has led to the interpretation that the sills were formed by multiple episodes of magma emplacement (Gibb & Gibson 1989; Gib & Henderson 1989; Gibson & Jones 1991; Gibb & Henderson 2006; Schofield 2009). A detailed contamination study of preserved crystals within the Skye Main Lava Series and some localised dyke intrusions has revealed a complex multi-tiered plumbing system for these magmas, with contributions from both Lewisian basement and shallower stratigraphic levels (Font et al. 2008).

Several hypotheses have been proposed for the emplacement of the LMSC within the SOHB. Harker (1904) suggested that a general thinning of the sills to the SE of Skye and a thickening of sills to the NW, indicated that the sills were derived from a source location to the north of the Trotternish peninsula, likely near the Shiant Isles. This hypothesis was refuted by Anderson & Dunham (1966), who noted that Harker (1904) did not distinguish between the overlying Skye Main Lava Series and the LMSC. Their mapping showed an overall thinning of the total thickness of volcanics away from the centre of Skye. This led the authors to suggest that the sill complex was intruded from a primary source location, probably located in the centre of the Isle of Skye, close to the Skye Central Igneous Complex (Anderson & Dunham 1966). It was noted, however, that the sills have compositional variation localised to different areas of onshore Skye, with some correlation to the composition of the overlying lavas (Anderson & Dunham 1966; Gibson 1990). This led to the suggestion that there could be multiple source locations (e.g. parallel fissures) from which the LMSC was sourced, with the magma for the sills potentially issuing from the same set of fissures that supplied magma for the Skye Main Lava Series (Anderson & Dunham 1966; England 1992). While mapping the LMSC on the Trotternish Peninsula, Anderson & Dunham (1966) indicated that the sills maintain a relatively consistent overall aggregate thickness of around 250 m across the peninsula and that they maintain an isobaric level of intrusion. A constant depth of intrusion would be produced if the pressure of the magma was equalled by the pressure of the overlying rock (Anderson & Dunham 1966).

Schofield et al. (2016) proposed that the sills originated from a source located in the west of the SOHB, on the basis of a difference in geochemistry of the LMSC sills compared to the Skye Main Lava Series lavas, a predominance of magma being transported up major faults in adjacent basins on the Atlantic margin (e.g. The Faroe-Shetland Basin) and the general west-to-east emplacement direction of the sills. They suggested that the basin bounding Minch Fault had acted as the main source zone for the LMSC, with magma transiting up this basin bounding fault and then intruding into the basin in an easterly direction, away from the fault. This would imply a lateral magma transport of some 40-60 km within the LMSC, which is credible, as mafic sills complexes have been shown to transport magma over distances of 10's of km's laterally and vertically (Cartwright and Hansen, 2006; Schofield et al. 2015).

## Datasets and methods

High-resolution (up to 2 m) bathymetric data obtained using a multibeam echosounder was collected in shallow water across the SOHB between 2008-2011 as part of the Civil Hydrography Programme (CHP), led by the Maritime & Coastguard Agency (Howe et al. 2012; Dove et al. 2015). This high-resolution bathymetric data covers the majority of the northern part of the SOHB (~3585 km$^2$), including the Little Minch sedimentary depocentre (Fig.3 & 4). Single beam echosounder data from the General Bathymetric Chart of the Oceans (GEBCO) gridded bathymetry datasets (GEBCO 2020) has been used within this study, where the high-resolution bathymetry data is unavailable (e.g. in the south of the SOHB) (Fig.1). Using Global Mapper software, bathymetric data has been combined with NEXTMap airborne radar data and Digital Terrain Models (DTMs), to create a 3D model of the topography and bathymetry of the SOHB, Northern Skye and the Outer Hebrides (Fig.4).

Onshore, geological data, including boundaries between geological formations and faulting and fracturing, is provided by Digimap (Digimap 2020). The onshore geographical extent of the LMSC has been determined from data provided by Digimap and the British Geological Survey (BGS) regional 1:50 000 geological maps, along with data acquired by previous authors, such as Anderson & Dunham (1966) and Schofield (2009). Subsurface geological information has been previously collected by the Institute of Geological Sciences, now known as the British Geological Society, in the form of boreholes and solid rock sampling stations, providing information about the near-surface bedrock geology within the SOHB (Fig.3). Deeper subsurface geological information is provided by the Upper Glen 1 onshore exploration well, which was drilled in NW Skye to a total depth of 2707m in 1989 and the Hebrides-1 (134/5-1) offshore exploration well, which was drilled in the SE of the SOHB to a total depth of 2472m in 1991 (Fig.1) (Pentex 1990; Chevron 1991). Publicly available data from these wells has been obtained from the UK's National Data Repository.

Two 2D offshore regional seismic surveys shot over the SOHB have been included within this study: West of Britain – WB93, shot in 1993; and JS-Minch, shot in 1984. The former was provided by WesternGeco and with sections publicly available from the National Data Repository, with the latter provided by IHS Markit. The JS-Minch survey is generally of better quality than the West of Britain survey, although they both suffer significantly from multiples and poor imaging below the igneous intrusions. A total of 84,465 km of offshore Sparker/Pinger data imaging the top 200-300 ms of the subsurface has also been collected within the study area for the British Geological Survey. The Deep seismic BIRPS line (GRID 9) over the Minch Basin is used as a guide for the deeper structures within the Minch Basin (Brewer & Smythe 1984; Chadwick & Pharaoh 1998).

*Sea of Hebrides Basin Exploration Well Data*

The Upper Glen 1 well encountered 469 m of basaltic Paleocene lavas of the Skye Main Lava Series, overlying a 124 m thick sequence which has been interpreted in the well logs as consisting of a Paleocene palagonite tuff intruded by eight dolerite sills, A to H, which range in thickness from 2m to 31m (Fig.5) (Pentex 1990). The palagonite tuff is likely genetically related to the Portree Hyaloclastite Formation, which consists of palagonitised hyaloclastite breccias, locally developed pillow lavas, tuffaceous sandstones and a variety of volcaniclastic sedimentary rocks (Emeleus & Bell 2005). The Portree Hyaloclastite Formation, which unconformably overlies Jurassic strata crops out at Portree, Staffin, Flodigarry, Uig and Loch Bay and the Lealt River (Emeleus & Bell 2005). The volcanic sequence in the Upper Glen 1 well sits unconformably over 1911m of marginal marine to marine Lower and Middle Jurassic sedimentary rocks, dated from the Bathonian to the earliest Hettangian (Pentex 1990). Between depths of 710 m and 789 m the Bathonian-age Lealt Shale Formation is intruded by three dolerite sills, I to K, which range in thickness from 1 m to 57 m, and within the Lower Jurassic (Hettangian) Lower Broadford Beds Formation to Latest Triassic Penarth Group the interbedded mudstones and limestones are intruded by nine basaltic sills, L to T, with thicknesses of between 0.3 m and 2 m (Fig.5) (Pentex 1990). The Jurassic strata within the well overlie 159m of continental Late Triassic strata (Pentex 1990). The total thickness of the sills of the

LMSC within the Upper Glen 1 well is 181 m (constituting 9% of the section drilled beneath the volcanics).

The first 361 m of depth drilled within the Hebrides 1 well was not recorded through logging or sampling (Chevron 1991). At depths below 361 m the well encountered 1335 m of Lower Jurassic (Late Pliensbachian to Earlies Hettangian) marine to marginal marine sedimentary rocks, overlying 32 m of transitional Latest Triassic Penarth Group strata and 605 m of continental Triassic New Red Sandstone Group sedimentary rocks (Fig.5) (Chevron 1991; Ainsworth & Boomer 2001). From 1250 m to 2219 m depth the Late Sinemurian to Late Triassic strata has been intruded by eleven dolerite sills, which range in thickness from <1 m to 18 m. The total thickness of the sills of the LMSC within the Hebrides 1 well is 50.5 m (accounting for 2% of the drilled section within the well).

## Offshore Expression of the Little Minch Sill Complex

The high-resolution bathymetric data collected across the SOHB, reveals numerous craggy/irregular topographic highs, protruding a few metres to tens of metres from the otherwise bathymetrically smooth seafloor (Fig.6). Direct sampling of the offshore bathymetric highs by IGS borehole cores and solid rock sampling sites has confirmed their igneous origin, with dolerite and occasionally basalt sampled; for example, dolerite was sampled by BH88/05 at a high in the west of the SOHB (Fig.3) (Geoindex 2020). These topographic highs often exhibit a sharp scarp face in one orientation and a shallower lee slope in the opposing orientation (Chesher et al. 1983). They possess morphologies typical of intrusions, including saucers, half-saucers and inclined sheets (Fig.7). The morphology of the offshore highs, combined with the compositional data from sampling of the sub-surface and outcropping islands, suggest that the seabed highs form part of the LMSC (Chesher et al. 1983; Gibb & Gibson 1989; Fyfe et al. 1993; Bell & Williamson 2002).

The morphology of the offshore sills within the SOHB differs from the majority of sills recorded onshore Skye, which are more sheet-like in appearance. The difference in morphology could be a function of the appearance of the intrusion within limited outcrop exposures, which are often only 2D cliff exposures (Schofield 2009). However, at Neist Point on the Waternish Peninsula, which represents the most westerly point on the Isle of Skye, half-saucer shaped sill intruded into the Middle Jurassic (Late Bathonian) Lealt Shale Formation does crop out with a diameter of ~ 1.3 km (Schofield 2009).

Features such as moraines, mega flutes and drumlins, created by Quaternary glaciation, can be identified within the bathymetry data across the west coast of Scotland (Bradwell & Stoker 2015; Howe et al. 2015; Howe et al. 2012), but can be differentiated from the sills by their size, morphology and direct sampling of bedrock.

The emplacement of the LMSC is generally confined to the sedimentary rocks of the SOHB, with the exception of a single dolerite sill which has been intruded into the Lewisian Gneiss of the Outer Hebrides, 1.5 km to the west of the basin bounding Minch Fault (MacKinnon 1974; Fyfe et al. 1993). Its compositional similarity with the LMSC sills located on the Shiant Isles and northern Skye suggests that they are potentially all part of the same sill complex (MacKinnon 1974).

The concentration of sills cropping out at seabed within the Little Minch, between the Trotternish Peninsula of northern Skye and the Outer Hebrides Isles is high, at approximately 0.13 $km^2$ of intrusions per square kilometre. Their concentration decreases to 0.09 $km^2$ per 1 $km^2$ to the south of 57° 30'N and to 0.06 $km^2$ per 1 $km^2$ to the east of 6° 10'W (Fig.4). North of the Rubha Reidh Ridge (north of 58° 00'N) no intrusions are observed to crop out on the seafloor or have been identified within either seismic reflection or sparker profiles, other than potentially one large dyke identified as the 'Minch Anomaly' (Ofoegbu & Bott 1985; Fyfe et al. 1993). The Minch Anomaly is a 1.1 km wide by 110 km long magnetic anomaly which crosscuts the Minch Basin from Loch Ewe to north of the Isle of Lewis (Ofoegbu & Bott 1985). It has been interpreted as resulting from the presence of a single large dyke, situated 0.3 - 2 km below the current seabed (Ofoegbu & Bott 1985).

South of 57° 30'N a lack of high-resolution bathymetric data has made it difficult to identify sills cropping out of the seafloor. Some topographic highs were identified in this area on the lower resolution bathymetry data, which have been interpreted as sills, though it is not possible to distinguish individual sill intrusions (Fig.1 & 4). Dolerite sills have been interpreted on seismic reflection profiles within the SOHB south of 57° 30'N, and within the Hebrides 1 well drilled in the south of the basin (Kurjanski 2015). The topographic highs south of 57° 30'N are fewer and more widely distributed compared to those further north.

The dimensions of individual sills identified within the SOHB are variable, with the outcropping escarpment of individual sills on the seabed ranging from a few metres in length to greater than 22 km in length (Fig.4). The heights of the scarp face of the intrusions outcropping on the seabed range from tens of metres to up to 125 m, similar in thickness to the sill cropping out onshore Skye and the Shiant Isles (Emeleus and Bell, 2005; Schofield, 2009; Schofield et al. 2016). In general, the sills protrude vertically between 20 m to 50 m from the surrounding seabed. In the Little Minch, which has the highest density of intrusions, the relief of some sills means that they stand above sea level, for example the islands of Fladda Chuain, Gearran and Ascrib, along with many smaller un-named islets, all of which are composed entirely of dolerite. The sills which compose Fladda Chuain rise from 80 m below sea level to crop out at a maximum of 18 m above sea level, while the sills composing the Ascrib isles rise from 95 m below sea level to crop out to a maximum of 21 m above sea level. The Shiant Isles archipelago is formed almost entirely from dolerite sills of the LMSC (Fig.6) (Walker 1930). The Shiant Isles are situated on an approximately 60 km$^2$ elevated bathymetric platform which is predominantly composed of dense sill intrusions (Fig.6). The two largest islands, Garbh Eilean and Eilean an Tighe, are composed of a single dolerite sill, which crops out above sea level to approximately 140 m and dips 10-15° to the southwest (Walker 1930).

## Constraining Sill Emplacement Directions

Constraining the flow kinematics of sills within a sedimentary basin can provide information about the magmatic feeder system and the transport of magma within a basin (Schofield et al. 2012a and b. Hoyer & Watkeys 2017). At onshore outcrops features, including bridge structures, intrusive steps, magma fingers and magma lobes, can help determine magma transport directions, particularly when supported with petrographic and textural observations (e.g. Hutton 2009; Schofield et al. 2010; Schofield et al. 2012a & b; Magee et al. 2016; Hoyer & Watkeys 2017). The morphological and textural features, used for the identification of sill emplacement, have been employed by Schofield (2009), Schofield et al. (2016) and Martin et al. (2019) to assess the emplacement direction of sills of the LMSC across the Trotternish peninsula.

Onshore Skye, the morphology of the sills displayed at outcrop is predominantly a function of the direction of magma emplacement (Schofield 2009). Flow indicators, such as broken bridges and magma fingers identified in outcrops on the Trotternish Peninsula, indicate a general northwestwardly emplacement of magma, except in the east of the Trotternish Peninsula, around Valtos, where it is emplaced in a more easterly/northeasterly orientation (Schofield 2009; Schofield et al. 2016). A study of an individual sill at Inver Tote quarry by Martin et al. (2019), using anisotropy of magnetic susceptibility (AMS) and anisotropy of anhysteretic remanent magnetization (AARM), indicated that while magma flow can be indicated by the sill morphology, in this case magma fingers showing magma flow to the SSE, if the sill is a composite of multiple intrusions, as are many of the sills of the LMSC, its emplacement history can be more complex (Martin et al. 2019). At Inver Tote, AMS signals and the morphology of the magma fingers indicated that magma flow was initially in a SSE orientation but subsequent magma emplacement internally within the sill, identified by AARM, indicated that subsequent magma flow was in a northeasterly orientation, consistent with the regional direction of magma emplacement on the eastern coast of the Trotternish Peninsula (Schofield 2009; Martin et al. 2019).

Because the internal crystalline structure of the offshore intrusions cannot be directly observed and regularly sampled, techniques like AMS and AARM cannot be used to confirm internal magma flow within a sill. Hence large-scale relationships between the intrusion and the host rock and morphology of the intrusions are therefore used as the primary method to assess the first order emplacement direction of the sills. Sills are often observed to consist of a flat lying, lower inner sill connected to outer inclined sheets and outer sills (Galland et al. 2018). The inclined sheets, with a steep scarp face and a gentler lee face (Fig.8 & 9), characteristic of the majority of the SOHB sills exposed at the seafloor could represent the outer inclined sheets of saucer shaped sills (Fig.8 & 9). The inclined sheets have been interpreted to represent magma propagation through the host rock strata, with the furthest point from the source indicated by the sharp face of the sill profile (Thomson & Hutton 2004). The direction of emplacement of sills can also be indicated by observing the divergence of magma flow lobes, which are expected to expand (increase in width) away from the source (Schofield et al. 2012a). Within the SOHB, magma lobes can occasionally be identified on bathymetric data (Fig.9).

Where seismic reflection profiles, sparker profiles and pinger profiles image bathymetric highs, highly reflective, discordant, crosscutting strata can be observed, showing characteristic igneous geometries and impedance contrasts (Fig.10). While large sills in the very shallow subsurface (<0.2s TWT) can be identified within the seismic reflection profiles, the nature of imaging volcanics using echo-sounding techniques has led to poor imaging beneath igneous bodies (Fig.10). This is due to the high reflection coefficients at the interface between igneous bodies and the host rock leading to a reduction in the energy penetration of the transmitted seismic waves (Smallwood & Maresh 2002). This, along with intrinsic attenuation, interference effects, refraction and scattering of the seismic energy leads to sub-optimal imaging of strata below igneous bodies (Smallwood & Maresh 2002). As many igneous bodies crop out offshore across the SOHB, imaging issues occur immediately below the seabed in the seismic reflection profiles. Hence much of the available seismic reflection data is difficult to interpret accurately. For this reason, the majority of our emplacement interpretations have focussed on the interpretation of bathymetry data, with seismic reflection data used occasionally as a secondary source, when it is of sufficient quality to make an interpretation.

Sparker data collected within the SOHB only images the upper approximately 200-300 ms (50-70 m) of the subsurface due to its high frequency sound waves (Fig.10). Below this interval, poor energy penetration and multiples have limited the interpretation of the underlying stratigraphy. Interpretation of sparker data has been useful in mapping sills in the very shallow subsurface and interpreting the general orientation from where the sills have originated. From both seismic reflection profiles and sparker data the inclined sheets, sometimes referred to as 'wings' of the sill, can sometimes be traced from the subsurface to the seabed, where there is commonly surface expression (Fig.10). The transgressive relationship of the wings of the sill, crosscutting the Mesozoic sedimentary rocks, provides a two-dimensional indication the direction of sill emplacement (Thomson & Hutton 2004; Thomson 2007).

Magma fingers, magma lobes, flatter inner saucers and transgressive outer inclined sheets (rims), have all been identified in the morphology of the offshore sills within the SOHB (Fig.6). These morphological features are also common in the sill complexes within other North Atlantic Margin basins e.g. within the Rockall Basin and the Faroe-Shetland Basin, and can also be identified globally e.g. within the Exmouth sub-basin situated offshore to the northwest Australia and the Pearl River Mouth Basin, located offshore in the northern section of the South China Sea (Planke et al., 2005; Holford et al. 2013; Magee et al. 2013; Sun et al. 2014; Magee et al. 2016; Hafeez et al. 2017; Schofield et al., 2017). Saucer shaped intrusions are fed by a centrally located linear magma source running down the major axis of the elliptical intrusion (Goulty & Schofield 2008). Identifying the 'axis' of a saucer shaped intrusion provides a central linear source location from which the magma is intruded away (Goulty & Schofield 2008; Schofield et al. 2010). In circular shaped sills the source location is more commonly a point source in the centre of the circular sill (Schofield, 2009).

Linear en-echelon dykes can indicate vertical/sub vertical magma transport, which may occur when laterally propagating magma interacts with faults (Mark et al. 2019; Siregar et al. 2019). Such dykes can be magma input points to source overlying sills (Mark et al. 2019). Onshore Skye, Anderson and Dunham (1966) interpreted a vertical dyke striking from an underlying sill feeding a sill higher in the stratigraphy. Offshore within the SOHB, a NW-SE orientated en-echelon dyke is observed to intercept the axis of a saucer shaped sill at 57° 46' 53.2778" N 6° 33' 59.3032" W (Fig.7). Within this sill magma transport indicators suggest that magma is being transported away from the NW-SE orientated dyke, predominantly to the SW and NE (Fig.7). This may represent an example of a dyke feeding a sill and can provide information on magma transit.

## Interpretation of Direction of Magma Sourcing/Movement of the Little Minch Sill Complex (Offshore)

Our interpretation of the orientation of both magma flow and sill emplacement within the SOHB suggests an overall high degree of variability. However, within this variability two main sets of intrusions can be interpreted as having similarities in morphology, magma transport directions and potential sources. One set of intrusions occurs in a zone parallel to the Minch Fault and extends 5 km into the basin, in the northern section of the Little Minch, just offshore of Harris and southern Lewis (Zone 1, Fig.11). Here the Mesozoic sedimentary rocks are heavily intruded by sills, with 0.28 km$^2$ of intrusions per square kilometre of seabed (Fig.11). Most of these sills indicate magma transportation in a SE direction (from their sharp scarp faces being on their southeastward sides and their lee slopes on the northwest) (Fig.12). Interpretation of the sparker and pinger reflection profiles indicates most of sills in the 5 km zone have been intruded towards the E or SE (Fig.10). Some of the sills form concentric rings of inclined sheets which display overall magma flow towards the SE (Fig.12). The predominantly SE direction of flow of these intrusions infers a probable source to the NW (i.e. towards the Minch Fault) (Fig. 10 & 11).

Following the Minch Fault south, the density of intrusions located in the 5 km zone to the east of the Minch Fault (east of North Uist) decreases and there is no strong indication of an eastward transport of magma away from the fault into the SOHB (Fig.11). The reduction in number of sills identified on the seafloor, as well as within the sub-surface reflection profiles (Sparker, Pinger), in this area potentially suggests that the volume of magma being transported into this region was lower than further north.

Further east, beyond the 5 km zone directly adjacent to the Minch Fault (Zone 2, Fig.11), a second set of intrusions do not appear to follow the same trend of inferred emplacement towards the SE. There is instead a higher diversity of intrusion orientations. Many of the sills are observed to show flow directions to the west, south and east (Fig.11), suggesting a potentially different magma input source.

To the NE of the Trotternish Peninsula the sill density is low, around 0.06 km$^2$ per square kilometre of seabed, but the individual sills are observed to be larger in size, with one sill (Sill X) interpreted to crop out continuously for 22 km (Fig.11). These generally saucer/half saucer-shaped sills, intrude northwards and eastwards away from Skye (Fig.11). The interpreted emplacement direction of these offshore sills is similar to the regional emplacement orientation of sills mapped on the eastern coast of the Trotternish Peninsula, around Valtos (Schofield 2009; Schofield et al. 2016; Martin et al. 2019). The axis of these offshore saucer shaped sills is generally N-S to NNW-SSE.

Between the northern tip of the Trotternish Peninsula and the Outer Hebrides, sill density is higher, with 0.13 km$^2$ of intrusions per square kilometre of seabed (Fig.11). Many sills have been intruded as inclined sheets, saucer or half saucer shaped intrusions with a variety of magma flow directions, although overall the inferred emplacement direction is towards the NE or SW (Fig.11). The axes of the more saucer shaped sills and the orientation of an en-echelon dyke, located along the axis of one of the larger saucer shaped intrusions, indicate a general NW-SE alignment, similar to the strike of faults on the Trotternish peninsula and the Isles of Harris and Lewis. To the west of the Trotternish Peninsula, the sills are observed to be sheet like in morphology and the regional emplacement trend is towards the west and the south (Fig.11).

## Stratigraphic Level of Sill Intrusion

Earlier work suggests that onshore Skye the sills of the LMSC maintain a reasonably consistent stratigraphic level of emplacement (Anderson & Dunham 1966; Schofield 2009). Across the Trotternish peninsula, they have been intruded into strata dating from the Bathonian (Middle Jurassic) to the Kimmeridgian (Upper Jurassic) as well as the Paleocene-Early Eocene. While there is a range in the age of strata into which the sills on the Trotternish Peninsula are intruded, the sills preferentially intrude into Middle Jurassic (Bathonian) sedimentary rocks and Early Paleocene ?hyaloclastite/palagonite tuff, which were deposited just prior to the extrusion of the Skye Main Lava Series (Anderson & Dunham 1966; Schofield 2009). Within the Upper Glen 1 well sills have been intruded into similar geological formations to those which have been intruded into on the

Trotternish Peninsula i.e. Paleocene ?hyaloclastite/palagonite tuff and Middle Jurassic (Bathonian) sedimentary rocks (Fig.5) (Pentex, 1990). Intrusions were also identified within Upper Triassic – Lower Jurassic sedimentary rocks within the Upper Glen 1 well. On Raasay, LMSC sills are predominantly within the Bathonian Lealt Shale Formation and the Bathonian Valtos Sandstone Formation (Morton & Baird 2015), whereas on the Shiant Isles, the intrusions are identified within Lower Jurassic (?Toarcian) to Middle Jurassic Bajocian strata (Penn & Merriman 1978).

Constraining the level of emplacement of the LMSC offshore is less precise, although data from boreholes in the Little Minch suggests that the sills have intruded into Jurassic strata, ranging from the Early Jurassic (Late Toarcian) to Late Jurassic (Kimmeridgian) (Geoindex 2020). In the south of the SOHB, our interpretation of seismic reflection data indicates that intrusions occur primarily within Lower to Middle Jurassic strata. In the Hebrides 1 well, eleven dolerite intrusions were intruded into strata dated from the Latest Triassic to the Early Jurassic (Late Sinemurian) (Fig.5) (Chevron 1991).

Observations of the stratigraphic level of intrusion for sills of the LMSC at onshore outcrops, offshore on the seafloor and within the subsurface (in hydrocarbon exploration wells) show that the sills have been intruded throughout the entire Jurassic succession of the SOHB. Middle Jurassic (particularly Bathonian), strata appear to be preferentially intruded by the sills, potentially due to the presence of rheologically weak formations throughout the Middle Jurassic (i.e. those containing significant carbonate horizons) (Schofield 2009). The LMSC appears to have also preferentially intruded Paleocene aged tuffs/? hyaloclastite, where they have been preserved onshore Skye. Tuffs/? hyaloclastite are a rheologically weak lithology, which can allow magma to intrude laterally within this lithological horizon with relative ease, in comparison to the harder, overlying basaltic lavas (Schofield 2009). While the sills appear to have an overall preferred stratigraphic level of emplacement, they are also found within younger strata (Early Paleocene lavas) and older strata (Permian-Triassic and rarely Lewisian Gneiss).

It is likely that there is also additional complexity to the emplacement of the sill complex, with intrusions on the Duirinish Peninsula in west Skye, 10 km to the SW of the Upper Glen 1 well, showing complex intrusive relationships (Angkasa et al. 2017). Thick sills intrude into the Middle Jurassic Lealt Shale Formation and smaller cross cutting intrusions cut up through the stratigraphy and into the volcanic sequences (Schofield et al. 2016). Additionally, localised disruption of the overlying lava sequences, interpreted as venting from the sills interacting with organic rich sediments, indicates that there were significant thicknesses of lavas present at the time of emplacement of the sills (Angkasa, et al. 2017).

## Discussion

### *Magma Source of the Little Minch Sill Complex (LMSC)*

To understand the regional emplacement of the Little Minch Sill Complex (LMSC), we first need to assess its spatial and temporal relationships with the Paleocene magmatic history of Skye. Lavas of the Skye Main Lava Series are thought to have been extruded across the SOHB between 60.53 ±0.08 Ma and 58.91 ±0.07 Ma, with the emplacement of the Skye Central Complex, occurring between 59.3 ±0.07 Ma and 53.5 ±0.08 Ma (Chesher et al. 1983; Fowler et al. 2004). Field observations indicate that sills of the LMSC crosscut some of the oldest lavas of the Skye Main Lava Series, indicating that the LMSC post-dates the extrusion of at least part of the Skye Main Lava Series (Gibson 1990; Fowler et al. 2004; Emeleus & Bell 2005; Angkasa, et al., 2017). Energy-Constrained Recharge, Assimilation, and Fractional Crystallization (EC-RAFC) geochemical modeling by Fowler et al. (2004) suggests that the LMSC was intruded potentially before the final lavas of the Skye Main Lava Series were extruded and before the bulk of the main intrusion of the Skye Central Complex. A combined radiometric and palaeomagnetic study, along with cross-cutting field relationships, indicate that the mafic regional dyke swarm that forms part of the North Britain Paleogene Dyke Suite, was intruded throughout the period of volcanism in the SOHB (England 1994).

There is a difference in the geochemical signature between the bulk of the Skye Main Lava Series lavas and the sills of the LMSC (Gibson 1990; England 1992; Fowler et al. 2004). The magma which supplied the LMSC differs from the Lower Lavas of Skye Main Lava Series in that it contains an enrichment of large ion lithophile elements (enrichment in Ba and K) and is relatively Mg-rich (up to 30 wt% MgO) (Gibson 1990; Fowler et al. 2004). Schofield et al. (2016) suggests that this difference can be attributed to each having a different magma source. This supports their idea that the LMSC sills are being fed from a different location to that of mainland Skye, where the Skye Main Lava Series lavas appear to have been fed through a series of fissures (England 1992; Schofield et al. 2016). An investigation by Fowler et al. (2004) into the geochemical composition of the Skye Main Lava Series and the LMSC concluded that the parental magmas supplying both the lavas and the sills evolved in the same, or a set of closely related magma reservoirs, which were part of a single magmatic plumbing system. They suggest that the compositional differences between the lavas and the sills can be explained by a complex combination of fractional crystallization, assimilation, re-charge events and the progressive shallowing of the magma reservoir through time (Fowler et al. 2004). The enrichment of LMSC magma with large ion lithophile elements (Ba and K) could only have occurred through crustal assimilation (Gibson 1990; England 1992; Fowler et al. 2004). Gibson (1990) and Fowler et al. (2004) both suggest that contamination of the LMSC magma took place before it was intruded in the very shallow crust (some of which occurred <1km below the surface) (Emeleus & Bell 2005). The LMSC parental magma is modeled to have undergone assimilation of Lewisian gneiss during fractionation within the lower to middle crust, enriching it with the large ion lithophiles (Gibson 1990; Fowler et al. 2004). Fowler et al. (2004) suggest that this could have occurred as the magma reservoir progressively shallowed as the magmatic system matured through time. They indicate that later LMSC magmas could originate from a magma reservoir situated within the Lewisian gneiss basement, which was shallower than the one which supplied the main bulk of the earlier Skye Main Lava Series lavas. Evidence of this complex plumbing is revealed in the Skye Main Lava Series contamination history (Font et al., 2008), which showed that as magmatism continued, greater degrees of contamination within the magmas took place, likely resulting from a shallowing of the magma reservoir and/or increased contamination of the now heated country rocks.

It therefore seems likely, given the evidence presented, that the magmatic source for the LMSC is likely part of the same magmatic plumbing system which fed the volcanic activity across Skye, with the magma which sourced the sills originating from a magmatic reservoir predominantly contaminated while residing within Lewisian gneisses of the lower to middle crust (Gibson 1990; Fowler et al. 2004; Font et al. 2008).

### *A Discussion on Previous Theories of Emplacement of the Little Minch Sill Complex (LMSC)*

Schofield et al. (2016) suggested that the magma which sourced the sills of the LMSC was transported into the shallow crust via the Minch Fault, and emplaced into the basin by the intrusion of magma in an easterly direction away from the fault. If this hypothesis is correct, the majority of sills, with allowance for some natural divergence, caused by potential structural and lithological anisotropies, would intrude away from the Minch Fault, in a general eastward direction. Whilst this is the case in the NW of the SOHB, adjacent to the Minch Fault, our mapping of flow directions of the sills shows a high level of variation elsewhere. Onshore Skye, on the Trotternish Peninsula, sills have been shown to have been intruded in a regional northwesterly orientation (Schofield 2009), opposite to that which would be expected if magma was sourced from west to east across the basin (i.e. magma indicating emplacement in an easterly orientation). The suggestion by Schofield et al. (2016) that the difference in geochemical composition between the Skye Main Lava Series and the LMSC means it is likely that they had different magmatic sources is at odds with Fowler (2004), who considered that both the sills and the lavas could have originated from the same magmatic source.

Anderson & Dunham (1966) suggested that the LMSC sills onshore Skye were potentially sourced from a series of fissures, which were linked to a magmatic plumbing system located below central Skye. If this was the case, magma flow indications within the morphology of the sills should indicate transport away from the center of Skye. Our interpretation indicates that most sills located onshore Skye and the majority of sill located offshore in zone 2 indicate magma transport away from

Skye (Fig.11). However, the theory of the sills being intruded into the basin away from central Skye is not consistent with the magma transport indicators of the sills in the NW of the basin, which we have interpreted as having been intruded from the NW to the SE, opposite to the expected direction had they been sourced from central Skye.

The data collected and interpreted within this study supports elements of proposals for LMSC emplacement within the SOHB by both Schofield et al. (2016) and Anderson & Dunham (1966) but suggest that emplacement is more complex than either individual proposal suggests.

### *Structural Framework and Inheritance of the Sea of Hebrides Basin (SOHB) and affect on Paleocene Magma Pathways*

The SOHB exhibits two dominant intra-basinal fault clusters; one which strikes NW-SE and another which strikes NE-SW (England 1992; McCaffrey et al. 2020). The dominant fault orientations mirror the Proterozoic (potentially Laxfordian) structural shear zones, which likely had an influence on later faulting, along with the subsequent stress regime (Fig.15) (England 1988; Johnston & Mykura 1989; Imber et al. 2002; McCaffrey et al. 2020). A set of NE-SW normal striking faults probably initially formed within the SOHB during the Late Paleozoic, when NW-SE extension occurred across the west of Scotland as a consequence of stresses related to the opening of the proto-Atlantic Ocean. The most significant fault developed as a response to this extension is the NE-SW trending Minch Fault, which controlled the majority of extension within the basin, though additional intra-basinal NE-SW orientated faults developed simultaneously (England 1988). NE-SW striking faults also developed, after Paleocene volcanism ceased during the Eocene/Oligocene, as a result of the continuous opening of the North Atlantic Ocean (England 1988).

It is thought that within the SOHB that during the Paleocene, NW-SE to N-S normal or dextral strike-slip faulting was initiated contemporaneously with Paleocene volcanism, forming a series of intra-basinal faults that are oblique to the main Minch fault (England 1988). England (1992) has interpreted from the crosscutting field relationships and the presence of dykes emplaced along

NW-SE orientated faults, that the intrusion of the sills of the LMSC, dykes of the North Britain Paleogene Dyke Swarm, and the development of NW-SE orientated faults occurred synchronously. England (1988) proposed that the change from a predominantly NW-SE orientated extension, throughout the Late Paleozoic and Mesozoic (out with Late Jurassic/Early Cretaceous exhumation), to a NE-SW orientated extension during the Paleocene, could be as a result of the collision of the European and African/Iberian plates in NE Europe, as well as the onset of continental rifting in the NE Atlantic.

It is clear, that at the time of emplacement of the LMSC during the Paleocene, that the SOHB was already highly structured, containing pre-existing structural fabrics which were orientated NW-SE and NE-SW (England 1988). The sills were emplaced in an active stress regime, which resulted in extension in a NE-SW orientation (England 1988). This structuration in the basin prior to the emplacement of the LMSC therefore likely played an important role in the emplacement of the sills, as is further discussed in next sections.

### *New Model for the Emplacement of the Little Minch Sill Complex (LMSC)*

Our interpretation of the trends of magma flow directions suggests that there could potentially be two distinct magma input zones for the SOHB. One has magma transported in an easterly/southeasterly direction into the basin from a location on the basin's NW margin and the other has magma distributed from a location to the SE of the Trotternish Peninsula. From the data presented by Fowler et al. (2004), we believe that it is likely that the magma for the two input zones originated from a single magmatic plumbing system, which also supplied the main bulk of the earlier Skye Main Lava Series lavas. Confirmation of whether the sills intruded into the shallow crust originated from the same single magma reservoir would require a detailed geochemical comparison of sills originating from the two input zones.

The cluster of sills within a 5km zone to the east of the Minch Fault in the NW of the SOHB indicates that magma flowed from the NW to the SE. The basin bounding Minch Fault, which bounds the western margin of the SOHB, intercepts the Outer Isles Thrust at a depth of around 2000 to

4000 ms TWT (Peddy 1984; Fyfe et al. 1993). The Outer Isles Thrust is a major crustal structure, which has been mapped as penetrating through the entire crust (Peddy 1984; Fyfe et al. 1993). The Minch Fault/Outer Isles Thrust could have provided a route for magma stored in the lower crust to have been transported and intruded into the shallow crust of the SOHB. Though as there is not a strong trend of magma flow away the Minch Fault along its entire length, it appears as if only some sections of the fault acted as magma transport pathways. Its contribution to the total volume of magma intruded into the SOHB may be relatively low, as the majority of the sills in the SOHB do not show magma flow in easterly direction and hence do not appear to be sourced from this fault.

Sills in the SOHB not sourced from the Minch Fault, show much more variation in magma flow orientations. This makes it difficult to identify a specific location for the input of magma for these sills, though some deductions can be made about magma transport direction. Assessment of magma transport indications within both offshore and onshore sills shows apparent clusters of dominant magma flow orientations for different sections of the basin. On the east coast of the Trotternish Peninsula and offshore to the NE of Skye there is a general easterly/northeasterly flow of magma (Schofield 2009; Martin et al. 2019). On the north of the Trotternish Peninsula magma flow is in a NW orientation (Schofield 2009) and offshore to the NW of Skye magma flows vary from east to north to west. Offshore to the west of Skye the sills indicate a more westerly and southerly flow of magma. The change of dominant flow orientation, from easterly in the NE of the SOHB to westerly/southerly in the west of the basin, indicates a potential radial flow of magma away from the Skye landmass, which may indicate magma input into the SOHB from a location on or close to Skye. Magma could have been transported into the basin, away from a magmatic plumbing system located beneath central Skye, which Anderson and Dunham (1996) identifies as the source of magmatic activity for the onshore sills of the LMSC.

There is a possibility that the transport of magma across the SOHB away from a potential magma source in Skye has been influenced by both pre-exisiting faults and NW-SE orientated faults, which developed concurrently with sill emplacement during the Paleocene. Continuation of the onshore faults into the offshore domain is difficult to interpret from seismic reflection data, due to imaging issues caused by the large number of intrusions. However, magnetic data over the offshore SOHB between the Trotternish Peninsula and Outer Hebrides shows a strong NW-SE lineation trend, potentially related to the presence of dykes, which may have exploited existing NW-SE faults and fracture zones (Fig.15). The en-echelon dyke identified to the east of Harris, which could possibly be sourcing a saucer shaped sill (Fig.7), also has the same NW-SE orientation suggesting that this dyke, could be utilising these NW-SE-striking faults. We have identified that the axes of some of the saucer shaped sills within the SOHB are orientated parallel to that of NW-SE striking onshore faults in northern Skye (Fig.15). This could indicate that the faults have influenced and potentially enabled magma transport across the basin. We also identify an increased sill density to the NW of Skye, corresponding with this NW-SE zone of magnetic lineations, compared to other sections of the basin e.g. to the north of Skye and to the SW of Skye. This may be due to magma being transported to the NW of Skye from the central Skye area through NW-SE orientated faults, which could offer readily accessible transportation pathways.

The idea that faulting influences the distribution of magma within the SOHB is supported by the observation that as the regional strike of the dominant faults change across the basin, becoming more E-W in the southwest and more N-S in the northeast, this is mirrored by the orientation of associated sills axes (Fig.15). This change in strike is likely influenced by gradual changes in the underlying basement trend (pre-existing Proterozoic shear zones) which can be mapped on the Outer Hebrides (Fig.15). Once the magma has been transported through fault planes into the shallow upper crust it would meet lithologically weak horizons in the stratigraphy, commonly found in the Middle Jurassic. It would then likely intrude horizontally/sub-horizontally along these horizons, before potentially transgressing to a younger horizon, through dykes or interaction with another fault plane (Fig.14).

### *What Explains the Absence of Intrusions within the Minch Basin north of the Rubha Reidh Ridge?*

In the Minch Basin, north of the Rubha Reidh Ridge, intrusions abruptly become non-existent (Fig.2), with no identifiable intrusions visible within either bathymetric data and/or within seismic reflection profiles. While an increasing distance from the source on Skye is likely to reduce the number of intrusions, their sudden, rather than gradual reduction suggests that there is a more complex reason for their general absence in the Minch Basin. The sharp reduction in intrusions is observed to coincide with a significant decrease in NW-SE orientated lineaments within the magnetic data, with no trend observed north of the Rubha Reidh Ridge. The NW-SE orientated lineaments have been interpreted to represent dykes exploiting NW-SE oriented normal faults (Fig.15) (Fyfe et al. 1993) and their reduction could indicate a decrease in presence of both dykes and NW-SE-striking faults. A reduction in the number of NW-SE-striking faults is also observed onshore Lewis, although this could be partly due to the presence of obscuring Quaternary deposits over the majority of the north of Lewis (McCaffrey et al. 2020). A lack of Paleocene-age NW-SE striking intra-basinal faults north of the Rubha Reidh Ridge, which can enable magma transport, could be the reason for the lack of magma transitioning into the upper crust.

The lack of intrusions north of the Rubha Reidh Ridge also coincides with a change in strike of the Minch Fault, which is usually depicted as a continuous NE-SW trending 300 km long fault (Johnstone & Mykura 1989; Fyfe et al. 1993). However, our interpretation of gravity and bathymetric data suggest that the fault is composed of several individual but linked segments. Three of these are apparent from distinct changes in the strike of the Minch Fault. Its northern segment strikes NNE-SSW for 115 km, from west of the Rubha Reidh Ridge to west of the Nun Rock-Sule Skerry High and bounds the western margin of the Minch Basin (Fig.15) (Stein 1988; Fyfe et al. 1993). A central segment strikes 120 km NE-SW from west of the Rubha Reidh Ridge to east of South Uist, with its strike interpreted to change from a NE-SW orientation in the north to a more N-S orientation in the south (Fig.15). It is probable that this section of the fault is further segmented by a shear zone, situated between Harris and North Uist, although this is not accompanied by a clear change in strike (Imber et al. 2002). The southern segment of the fault appears to bifurcate into two strands south of South Uist, with the west strand striking NE-SW and the eastern strand striking more NNE-SSW (Fig.15). The differences in strike and nature of each section of the basin bounding fault may have influenced the volume of magma able to travel up the fault plane. As there is a strong trend in magma flow away from the central segment of the Minch Fault, but not along either the northern segment or the southern segment, the central segment appears to have been the primary location for magma transport up the Minch Fault (Fig.1, 11 & 15).

Deep seismic reflection profiles (BIRPS) across the Minch Basin shows a layer of highly reflective sub-horizontal reflections in the west of the basin, at two-way travel times of around 8500-9500 ms (Fig.16). While the exact nature of these reflectors is uncertain, they may represent strata of igneous origin, as suggested by their very high amplitude reflections. These reflectors could represent either a solidified pooling of magma (underplating) at the bottom of the crust or an extensive suite of sills intruded into the lower crust. Sills intruded into the lower crust have been identified in the Icelandic Basin to the northwest of the Minch Basin (White et al. 2008) and in the Northern North Sea to the east of the Minch Basin (Wrona et al. 2019). Within the Minch Basin it is possible that magma was stored at depth within the lower crust and was not intruded into the upper crust, in contrast to the SOHB, possibly due to a lack of suitable pathways for magma to transit through to reach the upper crust.

The presence of the Rubha Reidh Ridge, which Stein (1988) interpreted as having formed during Early-Middle Cretaceous exhumation over an older NW-SE orientated Precambrian shear zone, may have potentially acted as a barrier to the northward migration of magma into the Minch Basin. The LMSC has preferentially intruded into Mesozoic/Paleocene strata within the SOHB and has not been found to have been emplaced within Torridonian strata. Hence the presence of a Torridonian cored high, both in terms of structure and lithology, may have prevented the LMSC from intruding northwards into the Minch Basin.

While there is uncertainty regarding the exact reason why intrusions are absent to the north of the Rubha Reidh Ridge, there are notable changes in the geology and structure of the region around the Rubha Reidh Ridge which coincide with the reduction in intrusions. The combination of distance from the source located close to central Skye, a potential lack of NW-SE-striking intra-basinal faults, the changes in the orientation of the Minch Fault and the presence of the

Rubha Reidh Ridge are likely to have prevented the transit of magma into the upper crust of the Minch Basin.

### *Wider Implications for sedimentary basins containing Sill Complexes*

Our interpretation of emplacement of the LMSC within the SOHB, suggests that the a major crustal fault (Minch Fault), has not acted as a sole source of magma input into the basin, and that magma input from Skye, and potentially also up intra-basinal faults has played an important role. In offshore basins along the Atlantic Margin, basin bounding faults can often be seen to have influenced magma input pathways into sedimentary sub-basins (Schofield et al. 2015). However, our work suggests that pre-existing intra-basinal faults, potentially oblique to the main structural grain, may act as important, but potentially undepreciated routes to magma input into a sedimentary basin.

The influence of faulting and pre-existing structural lineaments on magma transport within sedimentary basins has been shown in other volcanic basins around the world e.g. within the Exmouth Sub-basin, offshore Western Australia (Magee et al. 2013; Mark et al. 2019), within the North Sea, United Kingdom (Quirie et al. 2019) and within the Faroe-Shetland Basin, United Kingdom (Schofield et al. 2017). Additionally, understanding structural controls on magma transport is important in predicting where volcanism is active in the present-day (Kenny 2012; Hopkins et al. 2020; Phillips & Magee 2020).

Within basins located along the NE Atlantic Margin, the Jurassic strata are often obscured on seismic reflection data by extensive Paleocene sill complexes sitting within the overlying Cretaceous sequences. This makes assessing the amount of intrusive material within the Jurassic regions challenging over large areas of the Atlantic Margin. The SOHB provides direct unprecedented insight into the nature of intrusions within Lower and Middle Jurassic strata, not available in other areas of the NE Atlantic Margin. Within the SOHB, although preferential intrusion appears to occur within certain zones of the Jurassic strata (e.g. Bathonian), intrusions are found throughout the entire Jurassic succession and some Upper Triassic strata. This suggests that in areas of pervasive sill complexes in basins across the NE Atlantic Margin that the Jurassic (which over much of the FSB has similar lithologies and facies to the SOHB), may have been pervasively intruded by igneous intrusions in a similar fashion. Aside from the direct hydrocarbon implications on potential Jurassic source rocks zones, the emplacement of intrusions into high TOC intervals of the Jurassic within the NE Atlantic Margin (if matching the pervasive nature of the intrusions seen in the Jurassic of the SOHB), could potentially represent a further unconstrained source of carbon-based greenhouse gases, which could have contributed to the Paleocene-Eocene Thermal Maximum (PETM) (Jones et al. 2019). Further work needs to be undertaken on models of the PETM to see if a potential carbon rich fluid release from the Jurassic along the Atlantic Margin caused by sills (e.g. FSB) could impact models of both the cause and duration of the PETM (see Jones et al. 2019).

## Conclusion

Dolerite sills of the Paleocene-aged Little Minch Sill Complex have been emplaced throughout the Sea of Hebrides Basin, primarily within Mesozoic and Paleocene strata. The sill complex crops out onshore within the Sea of Hebrides Basin on the Isle of Skye, Raasay and the Shiant Isles, where extensive investigations into both composition and emplacement have been previously undertaken (Walker 1930; Drever & Johnston 1965; Anderson & Dunham 1966; Gib & Henderson 1984; Gibson 1990; Gibson & Jones 1991; Fowler et al. 2004; Gibb & Henderson 2006; Schofield et al. 2016 and Nicoli et al. 2018). It has been known since the 1960s that the sill complex extends offshore but accurate mapping of the complex was not previously possible, due to the low resolution of the data available. Our interpretation of high-resolution bathymetric data (up to 2 m resolution), obtained between 2008-2011, has provided greater insight into the extent and characteristics of the offshore section of the sill complex offshore. This work also highlights the potential for improving the interpretation of the architecture of intruded basins, using sea floor morphologies created by resistant igneous lithologies within softer sedimentary host rocks.

The resolution of the bathymetric data used in this study has enabled the identification of large-scale morphological features such as saucer-shaped sills, inclined sheets as well as magma flow indicators such as magma lobes and fingers. The morphology of the sills and magma flow indicators within the offshore sills, has allowed the authors to interpret first-order magma emplacement orientations of the offshore sills. This interpretation suggests that the emplacement of the Little Minch Sill Complex has been influenced by lithological controls, pre-existing structures and the predominant stress field at the time of emplacement.

Our interpretation of the emplacement of the Little Minch Sill Complex within the Sea of Hebrides Basin suggests there were two primary zones where magma has been inputted into shallow upper crust of the basin. Magma flow indicators of offshore sills in the west of the basin provide evidence that magma has been transported up the NE-SW trending basin bounding Minch Fault, which separates the Precambrian Lewisian gneiss platform of the Outer Hebrides from the Sea of Hebrides Basin. After transportation up the fault plane the magma reached a lithological zone of weakness, commonly within Middle Jurassic strata, from where it intruded horizontally/sub-horizontally across the basin in an easterly direction. This is in broad agreement with the Schofield et al. (2016) model for the emplacement of sills into the half graben hanging wall away from the Minch Fault, with the fault itself being a conduit for the magma transport from depth. Away from the Minch Fault, the emplacement orientation of the sills suggest that magma was transported away from the Skye landmass, with transport of magma being supplied and controlled by NW-SE orientated intra-basinal faults, which were thought to have been active during the Paleocene (England 1992). The emplacement of the sills and utilisation of faults have resulted in an interconnected suite of dolerite sills and dykes, which extends across the majority of the northern section of the Sea of Hebrides Basin. The predominant stress field at the time of emplacement of the sills, NE-SW orientated extension, has significant influence over how they are emplaced within the basin, with contemporaneous faulting providing pathways for the transport of magma through the shallow upper crust.

The distribution of sills is not uniform, with some zones of higher density sill intrusion, eg. to the NW of Skye and others where sills are sparse to non-existent eg. in the Minch Basin, to the north of the Rubha Reidh Ridge. Differences in faulting orientation can provide one explanation as to why magma has been transported into some parts of the upper crust more readily than others.

Within the SOHB the majority of sills appear to be transported through NW-SE orientated intra-basinal faults, which suggests that the basin bounding Minch Fault might not have played as significant role in magma transport as Schofield et al. (2016) suggested.

The overriding conclusions drawn for the emplacement of the Little Minch Sill Complex within the Sea of Hebrides Basin have potentially wider implications for the understanding magma transit within other sedimentary rift basins, which contain intrusive complexes. Large basin bounding faults can provide important magma pathways but may not be solely responsible for the input of magma into basins. Smaller subsidiary fault systems within a basin, even if oblique to main basin structure, can also play an important part in the emplacement of magma and can affect how sills are distributed within a structured basin. Understanding the controls on magma transport within a basin is important, as these can directly affect distribution of magma within the subsurface. Poor understanding can lead to the construction of inaccurate geological models of the subsurface, with potentially adverse implications for the successful identification and utilisation of potential petroleum and geothermal systems.

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**Fig. 1** – Bathymetry of the Sea of Hebrides Basin. IHB, Inner Hebrides Basin, ST, Stanton Trough, BEN, Benbecula, E, Eigg, R, Raasay, S, Scalpay. (Chesher et al. 1983; Fyfe et al 1993).

**Fig. 2 -** Simplified geological map of northwest Scotland. This map does not include stratigraphy younger than the Eocene. IHB, Inner Hebrides Basin. (Chesher et al. 1983; Fyfe et al 1993; BGS 2020a).

**Fig. 3** – Offshore data available over the Little Minch (BGS 2020b; Oil & Gas Authority 2020).

**Fig. 4** – Multibeam bathymetry data combined with NEXTMap digital terrain model (DTM) of the Little Minch and surrounding islands (Intermap Technologies 2007).

**Fig. 5 -** Well Logs for the Upper Glen 1 well, drilled onshore Skye and the Hebrides 1 well (134/5-1) drilled in the south of the Sea of Basin. Location of the wells is highlighted in Figure 1 (Pentex 1990; Chevron 1991).

**Fig. 6 -** Bathymetry data highlighting topographic highs on the seafloor between Skye and the Outer Hebrides Isles (Intermap Technologies 2007; BGS 2020a).

**Fig. 7 -** Sills of the Little Minch Sill Complex located offshore within the Sea of Hebrides Basin, UK, compared to saucer-shaped sills located onshore within the Karoo Basin, South Africa. Location of the Sea of Hebrides Basin bathymetry data is highlighted in Figure 4. Google Earth Image Data Source: Maxar Technologies, CNES/Airbus, Camera: 59km, 31°59'21"S, 26°26'30"E, 1231m (Google Earth 2020).

**Fig. 8 -** 3D image of inclined sheets of sills, located onshore South Africa and offshore UK. Similarities in the morphology can be seen for both the onshore and offshore outcrops. Location of the sills are highlighted in Figure 4. Google Earth Image Data Source: CNES/Airbus, Landsat/Copernicus, Maxar Technologies, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Camera: 3594m, 31°57'23"S, 26°10'03"E, 1330m (Google Earth 2020).

**Fig. 9 -** 3D diagram of a series of offshore sills which can be observed on bathymetric data within the Sea of Hebrides Basin. Flow lobes and the morphology of the sills can help in identifying magma flow orientations. Location of the sills are highlighted in Figure 4.

**Fig. 10 -** Pinger, Sparker and Seismic Reflection profiles across the Little Minch. Igneous intrusions can be identified within the profiles, though all of the sub-surface imaging profiles suffer from multiples and sub-optimal imaging below igneous intrusions. Location of the profiles is shown in Figure 3. Source: Seismic Reflection data taken from IHS Market upsteam E&P content. ©2020 IHS Markit™. Pinger and Sparker data obtained from the British Geological Survey Offshore Geoindex (BGS 2020b).

**Fig. 11 -** Onshore and offshore sill emplacement orientation of sills of the Little Minch Sill Complex within the Sea of Hebrides Basin. The arrows indicate magma flow direction as determined through interpreting magma transport indicators e.g. magma lobes, magma fingers, transgressive wings (lee and scarp slopes) at outcrop and offshore within bathymetry data. Offshore these indicators of magma transport are supported, where possible, with interpretation of crosscutting sub-surface reflection profiles from sparker, pinger and seismic reflection data. For each sill cropping out onshore and on the seafloor an overall direction of magma transport has been inferred, with green suggesting an easterly movement of magma, orange suggesting an southerly movement of magma, purple suggesting an westerly movement of magma and blue suggesting an northerly movement of magma.

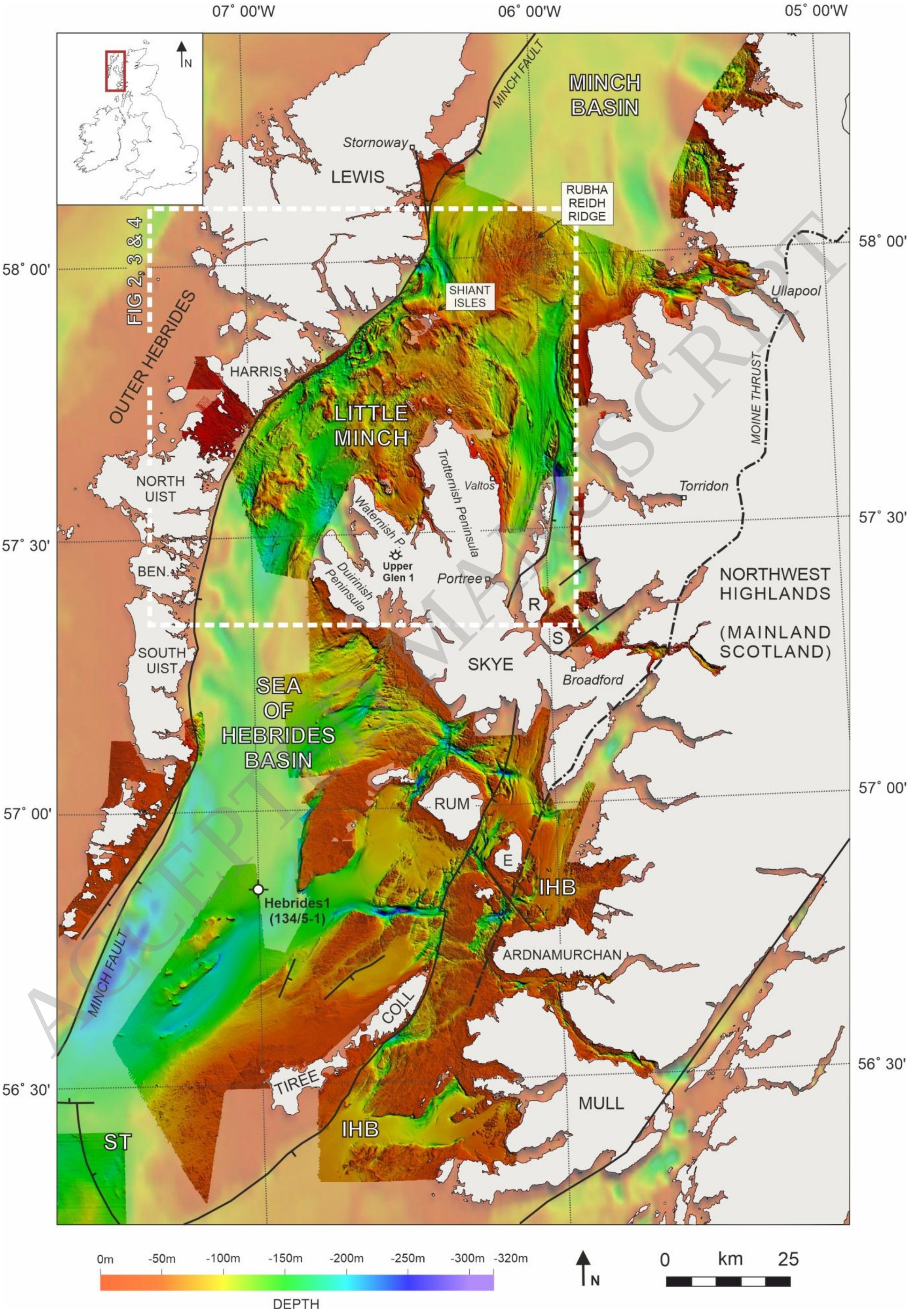
**Fig. 12 -** Sills located in the NW of the Sea of Hebrides Basin, adjacent to the Minch Fault. The sills are observed to form concentric semi-circle rings of intrusions which are interpreted to intrude to the southeast, away from the Minch Fault. Location of the sills are highlighted in Figure 4.

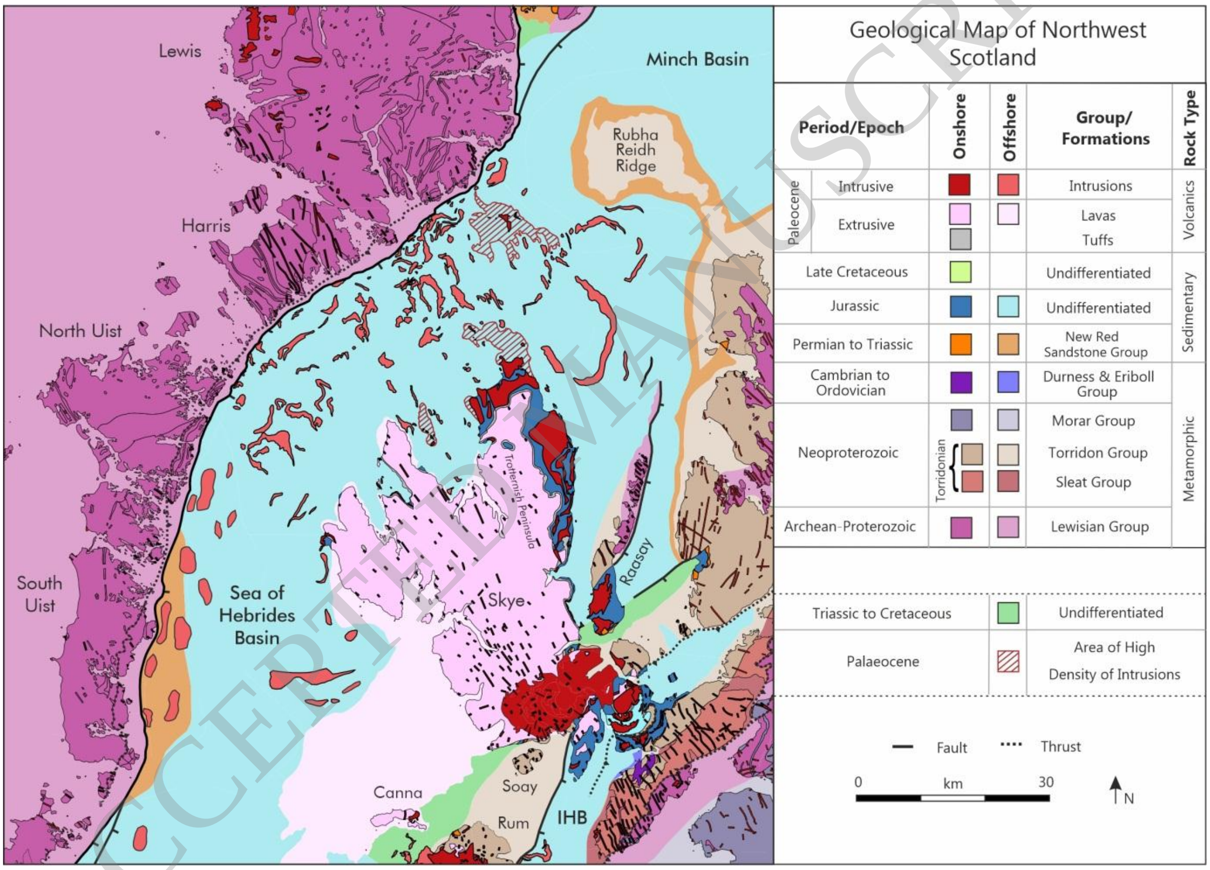
**Fig. 13 -** Cross-section through the Little Minch and across the Shiant Isles sub-surface bathymetric plateau. In the Little Minch transect the sills can be observed to be emplaced into the basin from both the NW and SE. The direction of sill emplacement for the Shiant Isles is more complex.

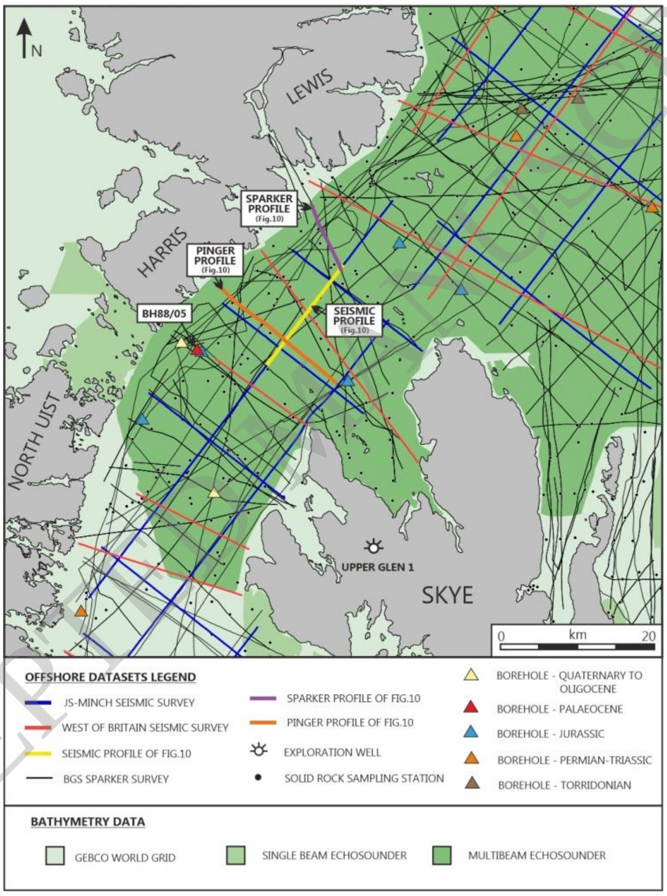
**Fig. 14 -** Schematic diagram showing the emplacement of the Little Minch Sill Complex within the Sea of Hebrides Basin.

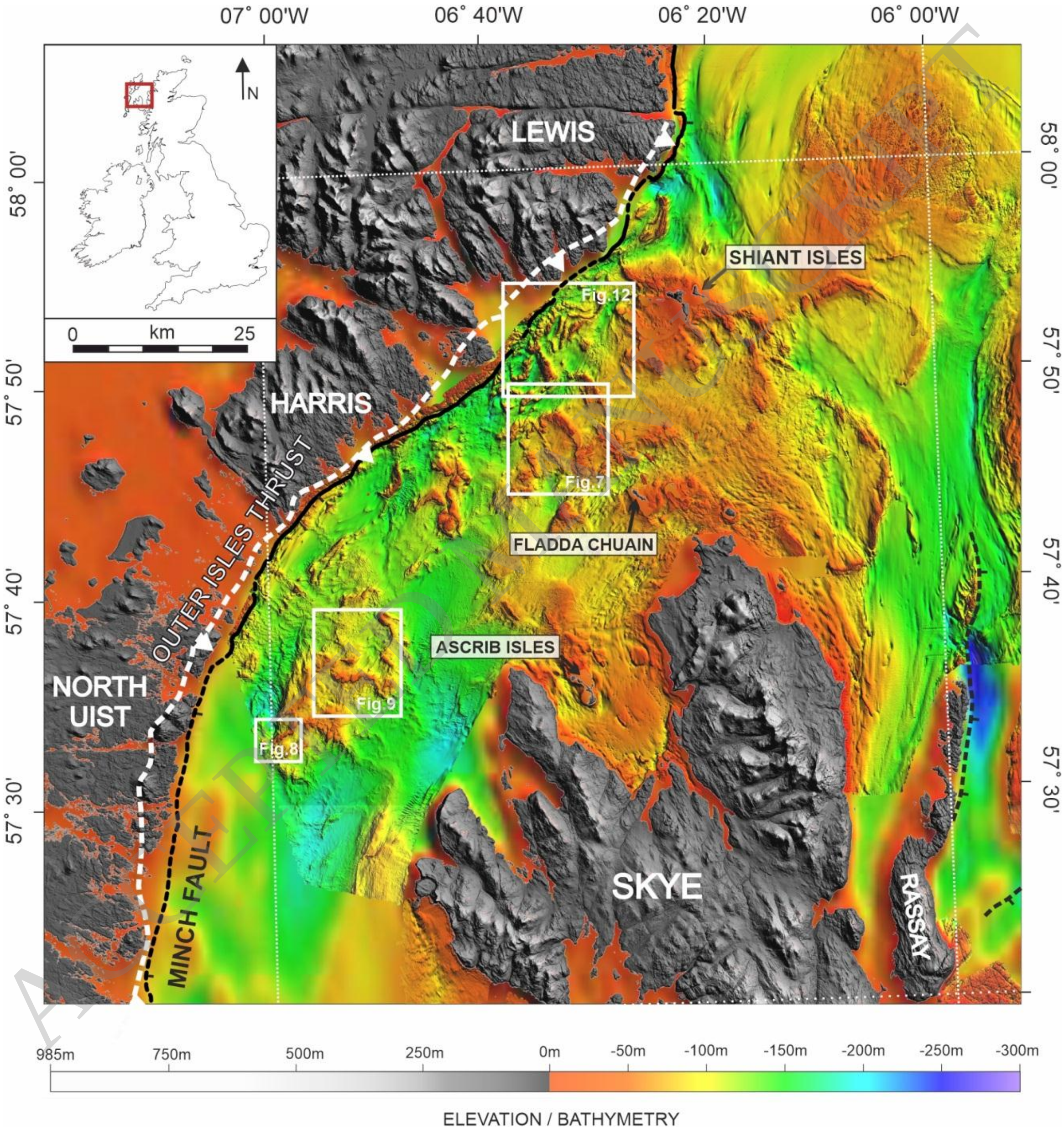
**Fig. 15** – Onshore fault orientations and offshore magnetic map. An overall NW-SE trend in the faults and magnetic anomalies can be interpreted. This trend corresponds with some of the long axis of saucer shaped sills and the en-echelon dyke. The map also highlights the different sections of the Minch Fault (north, central and south) as well as the shear zones identified by Imber et al. (2002). OIT, Outer Isles Thrust. (BGS 2020c; Digimap 2020)

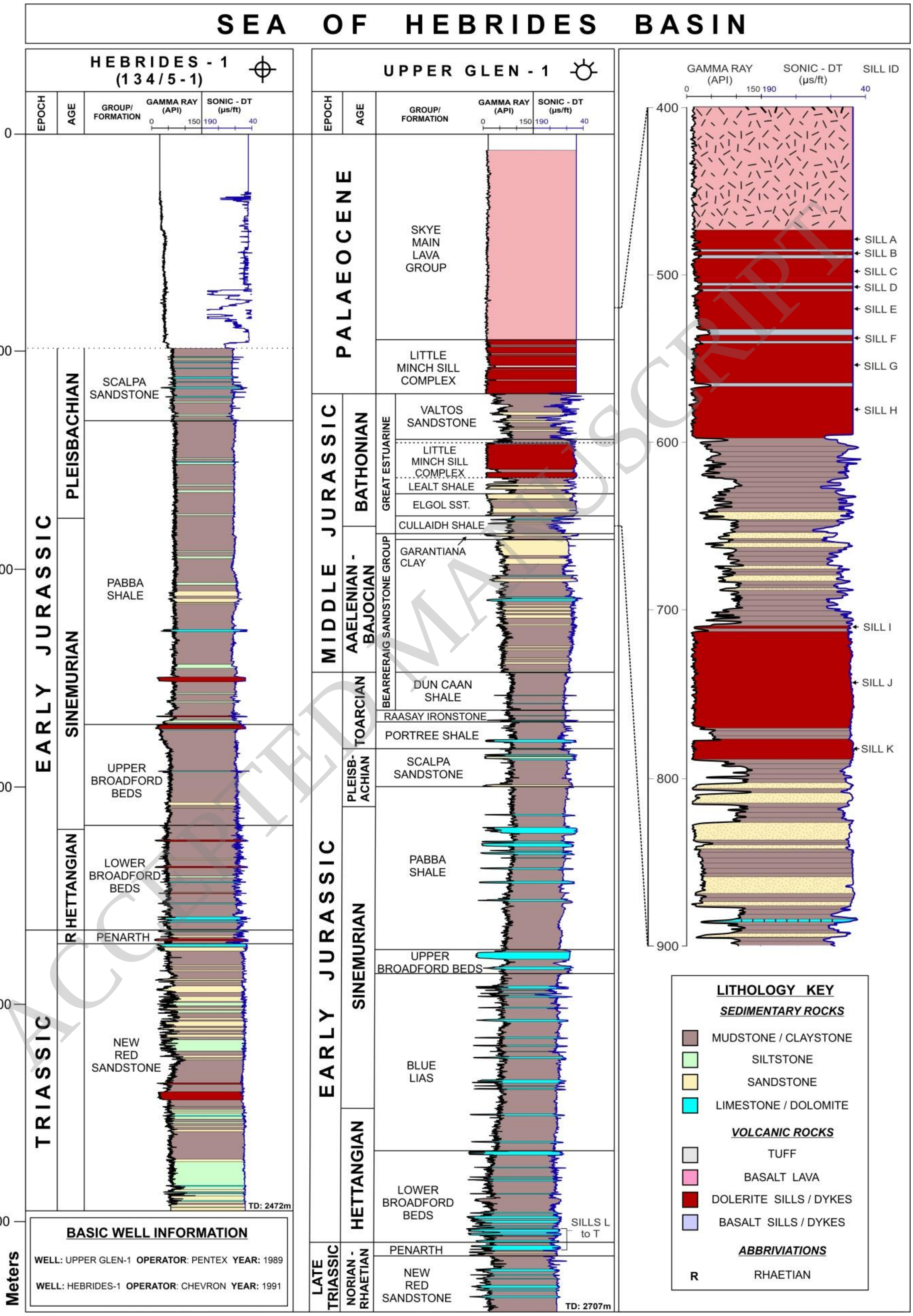
**Fig. 16** – NW-SE orientated deep seismic reflection BIRPS line (GRID 9) across the Minch Basin. (Brewer & Smythe 1984; Chadwick & Pharaoh 1998)

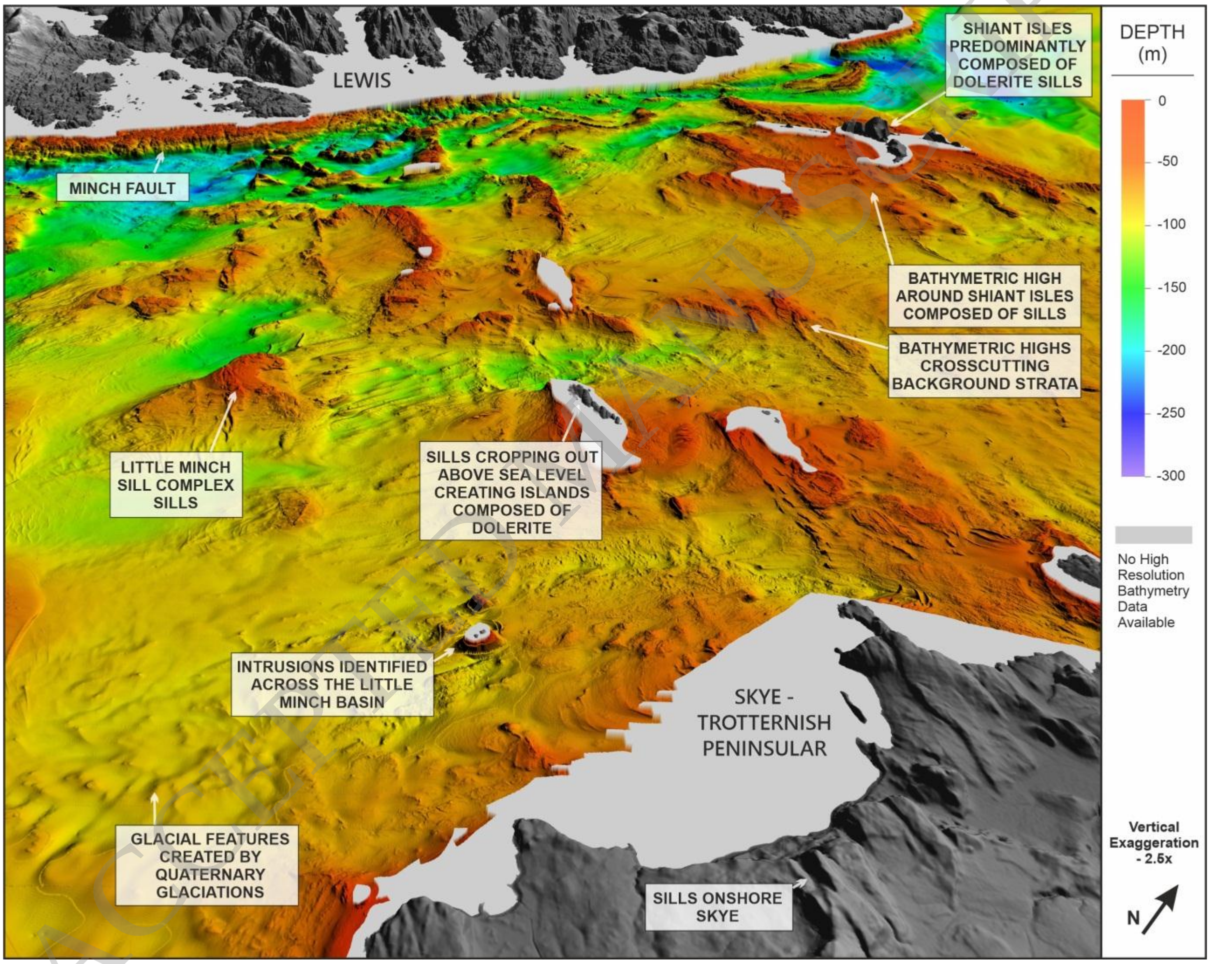

07° 00'W
06° 00'W
05° 00'W
N
MINCH FAULT
MINCH BASIN
Stornoway
LEWIS
RUBHA REIDH RIDGE
58° 00'
58° 00'
FIG 2, 3 & 4
SHIANT ISLES
Ullapool
OUTER HEBRIDES
HARRIS
LITTLE MINCH
MOINE THRUST
NORTH UIST
Trotternish Peninsula
Valtos
Torridon
57° 30'
57° 30'
Waternish P.
Duirinish Peninsula
Upper Glen 1
Portree
BEN.
R
NORTHWEST HIGHLANDS
(MAINLAND SCOTLAND)
S
SOUTH UIST
SKYE
Broadford
SEA OF HEBRIDES BASIN
57° 00'
57° 00'
RUM
E
IHB
Hebrides1 (134/5-1)
ARDNAMURCHAN
MINCH FAULT
COLL
56° 30'
56° 30'
TIREE
MULL
ST
IHB
0m
-50m
-100m
-150m
-200m
-250m
-300m
-320m
DEPTH
N
0
km
25

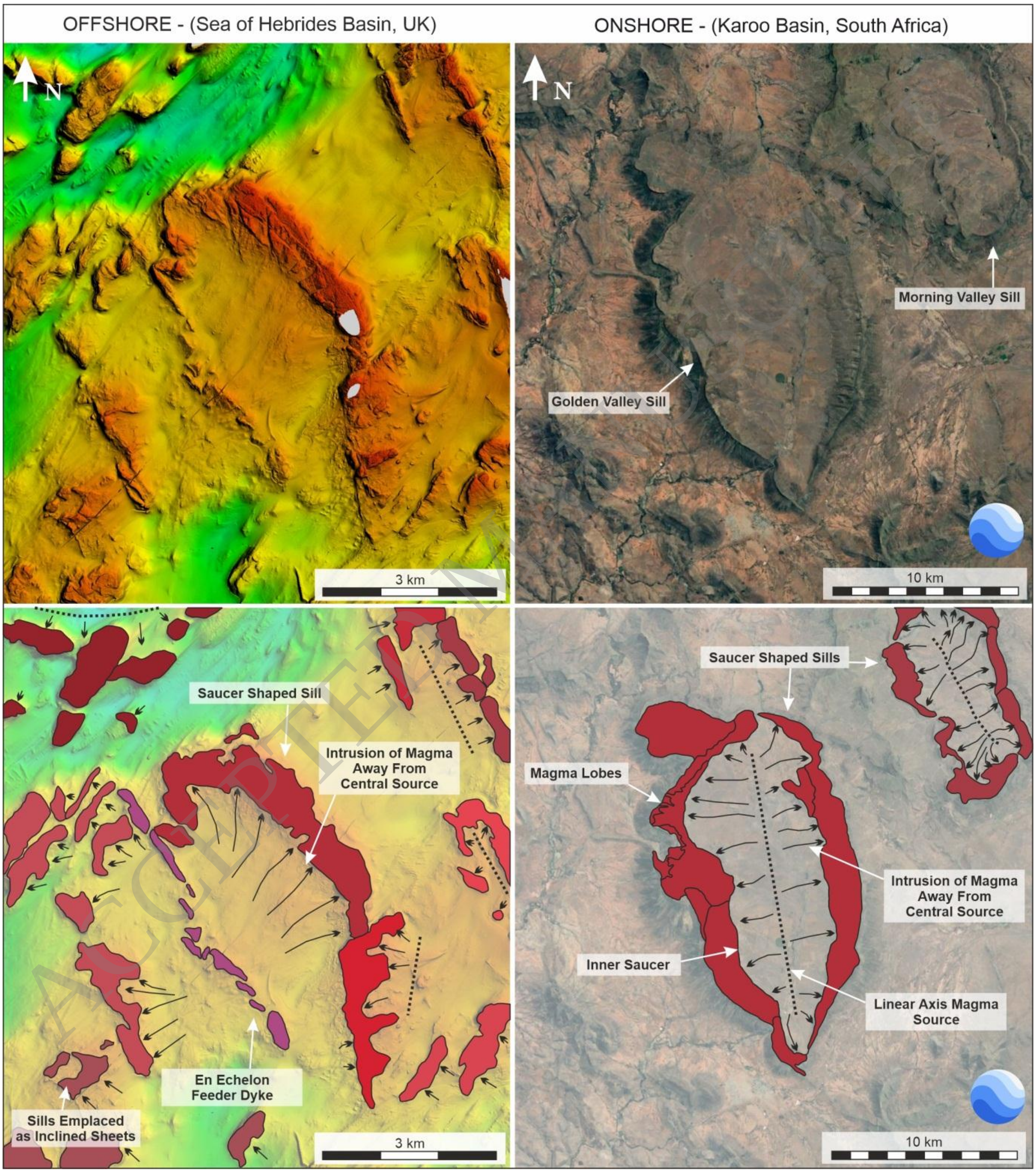

Geological Map of Northwest Scotland
Lewis
Minch Basin
Rubha Reidh Ridge
Harris
North Uist
Trotternish Peninsula
Raasay
South Uist
Sea of Hebrides Basin
Skye
Canna
Soay
Rum
IHB
Period/Epoch
Onshore
Offshore
Group/ Formations
Rock Type
Paleocene
Intrusive
Intrusions
Extrusive
Lavas
Tuffs
Volcanics
Late Cretaceous
Undifferentiated
Jurassic
Undifferentiated
Sedimentary
Permian to Triassic
New Red Sandstone Group
Cambrian to Ordovician
Durness & Eriboll Group
Neoproterozoic
Torridonian
Morar Group
Torridon Group
Sleat Group
Metamorphic
Archean-Proterozoic
Lewisian Group
Triassic to Cretaceous
Undifferentiated
Palaeocene
Area of High Density of Intrusions
Fault
Thrust
0
km
30
N

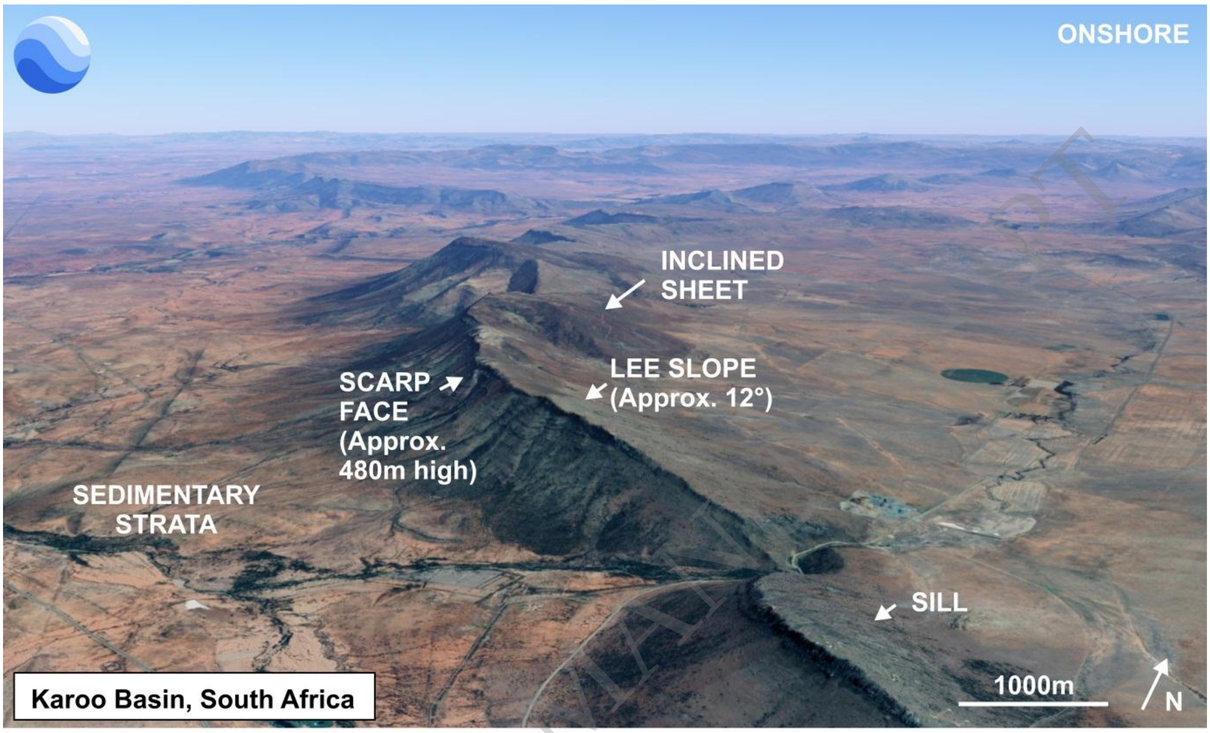

N
LEWIS
HARRIS
NORTH UIST
SKYE
SPARKER PROFILE (Fig.10)
PINGER PROFILE (Fig.10)
SEISMIC PROFILE (Fig.10)
BH88/05
UPPER GLEN 1
0 km 20
OFFSHORE DATASETS LEGEND
JS-MINCH SEISMIC SURVEY
WEST OF BRITAIN SEISMIC SURVEY
SEISMIC PROFILE OF FIG.10
BGS SPARKER SURVEY
SPARKER PROFILE OF FIG.10
PINGER PROFILE OF FIG.10
EXPLORATION WELL
SOLID ROCK SAMPLING STATION
BOREHOLE - QUATERNARY TO OLIGOCENE
BOREHOLE - PALAEOCENE
BOREHOLE - JURASSIC
BOREHOLE - PERMIAN-TRIASSIC
BOREHOLE - TORRIDONIAN
BATHYMETRY DATA
GEBCO WORLD GRID
SINGLE BEAM ECHOSOUNDER
MULTIBEAM ECHOSOUNDER

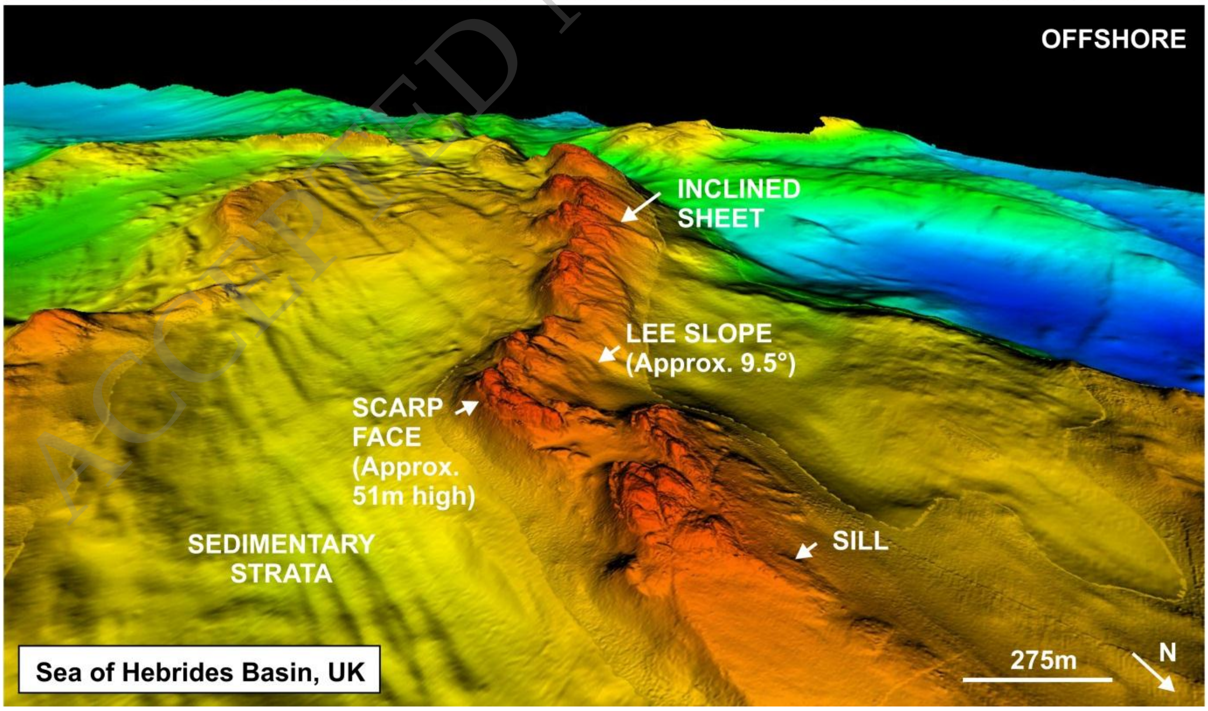

07° 00'W
06° 40'W
06° 20'W
06° 00'W
58° 00'
57° 50'
57° 40'
57° 30'
N
0
km
25
LEWIS
HARRIS
NORTH UIST
SKYE
RASSAY
SHIANT ISLES
FLADDA CHUAIN
ASCRIB ISLES
OUTER ISLES THRUST
MINCH FAULT
Fig.12
Fig.7
Fig.9
Fig.8
985m
750m
500m
250m
0m
-50m
-100m
-150m
-200m
-250m
-300m
ELEVATION / BATHYMETRY

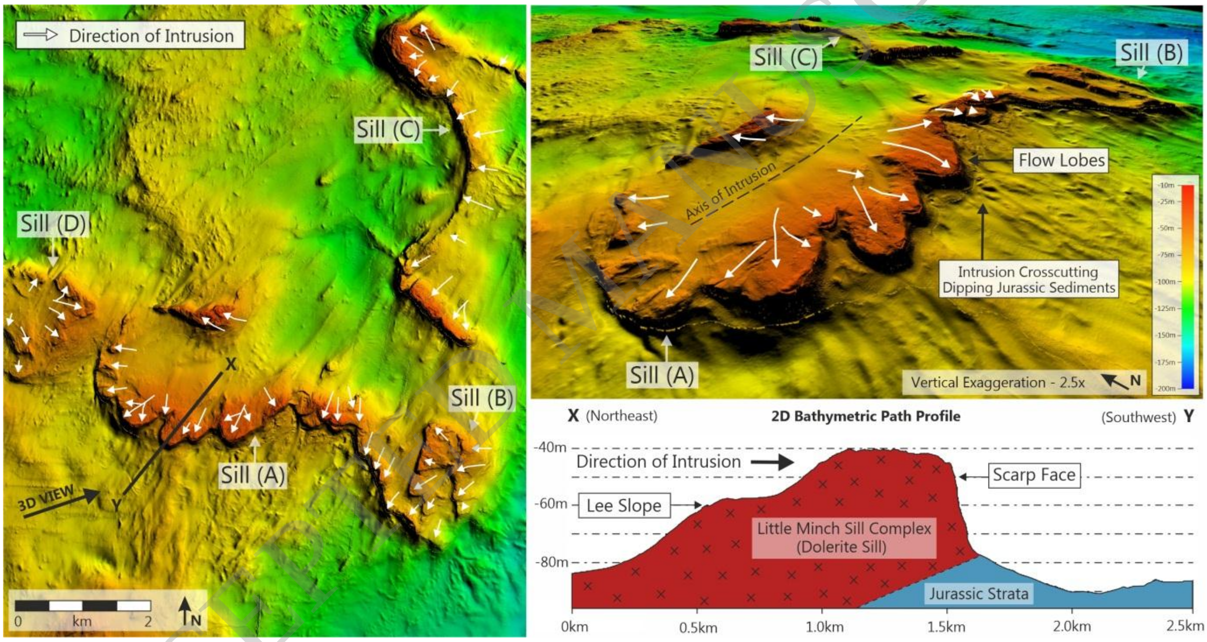

SEA OF HEBRIDES BASIN
HEBRIDES - 1 (134/5-1)
UPPER GLEN - 1
EPOCH
AGE
GROUP/ FORMATION
GAMMA RAY (API)
SONIC - DT (µs/ft)
0
150
190
40
Meters
0
500
1000
1500
2000
2500
EARLY JURASSIC
TRIASSIC
PLEISBACHIAN
SINEMURIAN
HETTANGIAN
R
SCALPA SANDSTONE
PABBA SHALE
UPPER BROADFORD BEDS
LOWER BROADFORD BEDS
PENARTH
NEW RED SANDSTONE
TD: 2472m
BASIC WELL INFORMATION
WELL: UPPER GLEN-1 OPERATOR: PENTEX YEAR: 1989
WELL: HEBRIDES-1 OPERATOR: CHEVRON YEAR: 1991
PALAEOCENE
MIDDLE JURASSIC
EARLY JURASSIC
LATE TRIASSIC
BATHONIAN
AAELENIAN - BAJOCIAN
TOARCIAN
PLEISB-ACHIAN
SINEMURIAN
HETTANGIAN
NORIAN - RHAETIAN
GREAT ESTUARINE
BEARRERAIG SANDSTONE GROUP
SKYE MAIN LAVA GROUP
LITTLE MINCH SILL COMPLEX
VALTOS SANDSTONE
LITTLE MINCH SILL COMPLEX
LEALT SHALE
ELGOL SST.
CULLAIDH SHALE
GARANTIANA CLAY
DUN CAAN SHALE
RAASAY IRONSTONE
PORTREE SHALE
SCALPA SANDSTONE
PABBA SHALE
UPPER BROADFORD BEDS
BLUE LIAS
LOWER BROADFORD BEDS
SILLS L to T
PENARTH
NEW RED SANDSTONE
TD: 2707m
GAMMA RAY (API)
SONIC - DT (µs/ft)
SILL ID
0
150
190
40
400
500
600
700
800
900
SILL A
SILL B
SILL C
SILL D
SILL E
SILL F
SILL G
SILL H
SILL I
SILL J
SILL K
LITHOLOGY KEY
SEDIMENTARY ROCKS
MUDSTONE / CLAYSTONE
SILTSTONE
SANDSTONE
LIMESTONE / DOLOMITE
VOLCANIC ROCKS
TUFF
BASALT LAVA
DOLERITE SILLS / DYKES
BASALT SILLS / DYKES
ABBRIVIATIONS
R RHAETIAN

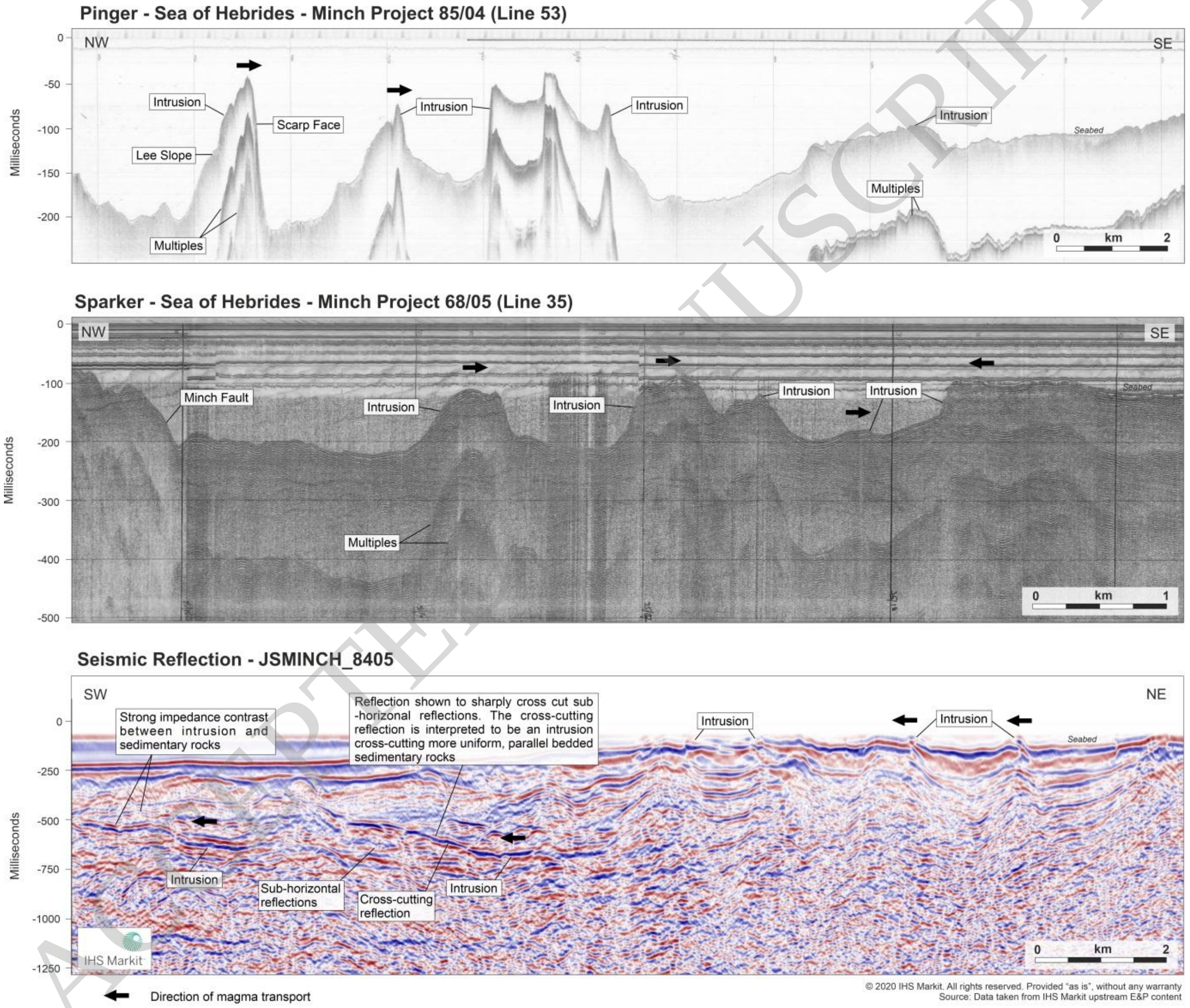

LEWIS
SHIANT ISLES PREDOMINANTLY COMPOSED OF DOLERITE SILLS
MINCH FAULT
BATHYMETRIC HIGH AROUND SHIANT ISLES COMPOSED OF SILLS
BATHYMETRIC HIGHS CROSSCUTTING BACKGROUND STRATA
LITTLE MINCH SILL COMPLEX SILLS
SILLS CROPPING OUT ABOVE SEA LEVEL CREATING ISLANDS COMPOSED OF DOLERITE
INTRUSIONS IDENTIFIED ACROSS THE LITTLE MINCH BASIN
SKYE - TROTTERNISH PENINSULAR
GLACIAL FEATURES CREATED BY QUATERNARY GLACIATIONS
SILLS ONSHORE SKYE
DEPTH (m)
0
-50
-100
-150
-200
-250
-300
No High Resolution Bathymetry Data Available
Vertical Exaggeration - 2.5x
N


OFFSHORE - (Sea of Hebrides Basin, UK)
ONSHORE - (Karoo Basin, South Africa)
N
N
3 km
Golden Valley Sill
Morning Valley Sill
10 km
Saucer Shaped Sill
Intrusion of Magma Away From Central Source
En Echelon Feeder Dyke
Sills Emplaced as Inclined Sheets
3 km
Saucer Shaped Sills
Magma Lobes
Intrusion of Magma Away From Central Source
Inner Saucer
Linear Axis Magma Source
10 km


ONSHORE
INCLINED SHEET
LEE SLOPE (Approx. 12°)
SCARP FACE (Approx. 480m high)
SEDIMENTARY STRATA
SILL
Karoo Basin, South Africa
1000m
N


OFFSHORE
INCLINED SHEET
LEE SLOPE (Approx. 9.5°)
SCARP FACE (Approx. 51m high)
SEDIMENTARY STRATA
SILL
Sea of Hebrides Basin, UK
275m
N


Direction of Intrusion
Sill (C)
Sill (D)
X
Sill (B)
Sill (A)
3D VIEW
Y
0 km 2
N
Sill (C)
Sill (B)
Axis of Intrusion
Flow Lobes
Intrusion Crosscutting
Dipping Jurassic Sediments
Sill (A)
Vertical Exaggeration - 2.5x
N
-10m
-25m
-50m
-75m
-100m
-125m
-150m
-175m
-200m
X (Northeast)
2D Bathymetric Path Profile
(Southwest) Y
-40m
-60m
-80m
Direction of Intrusion
Lee Slope
Scarp Face
Little Minch Sill Complex
(Dolerite Sill)
Jurassic Strata
0km
0.5km
1.0km
1.5km
2.0km
2.5km



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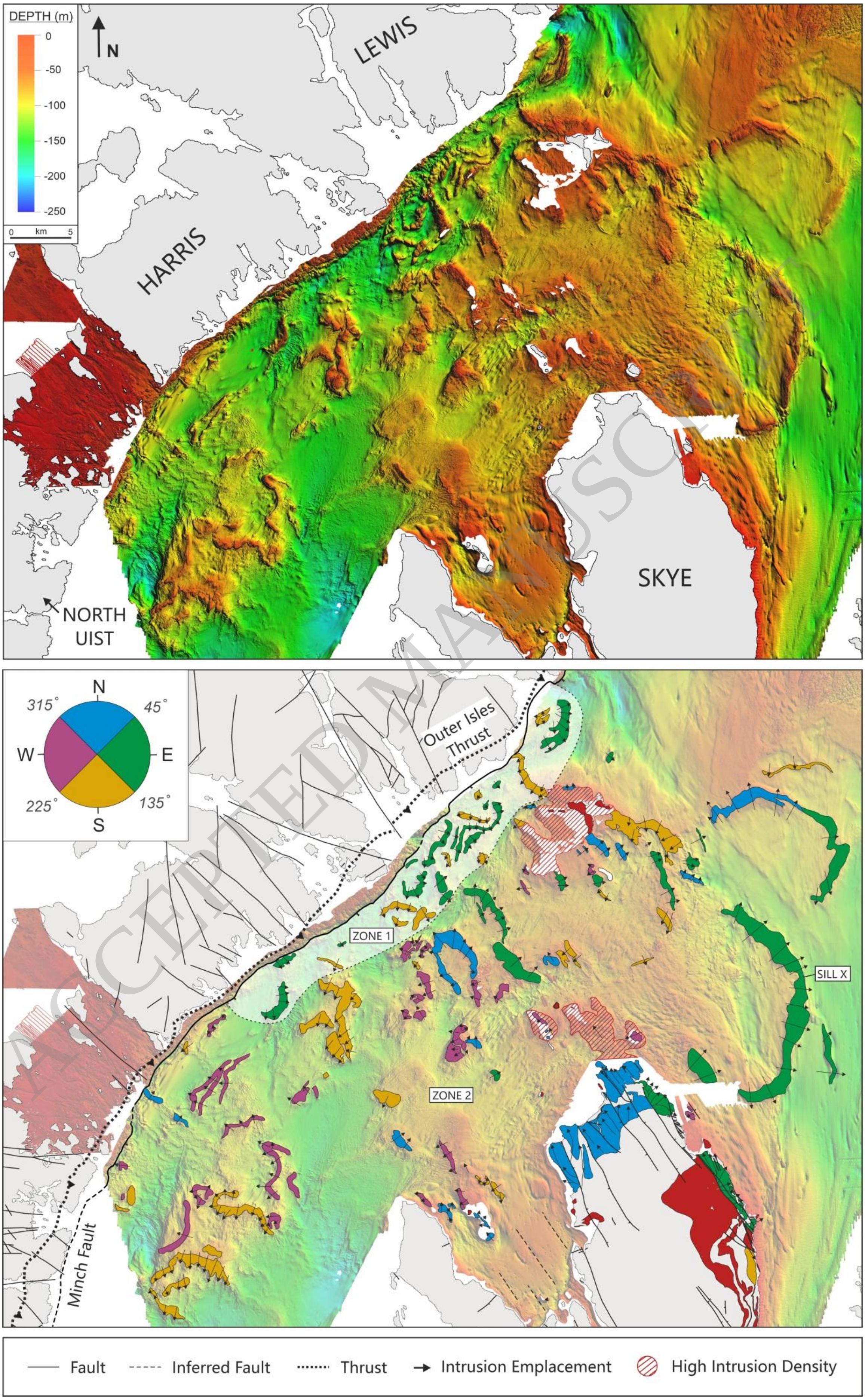
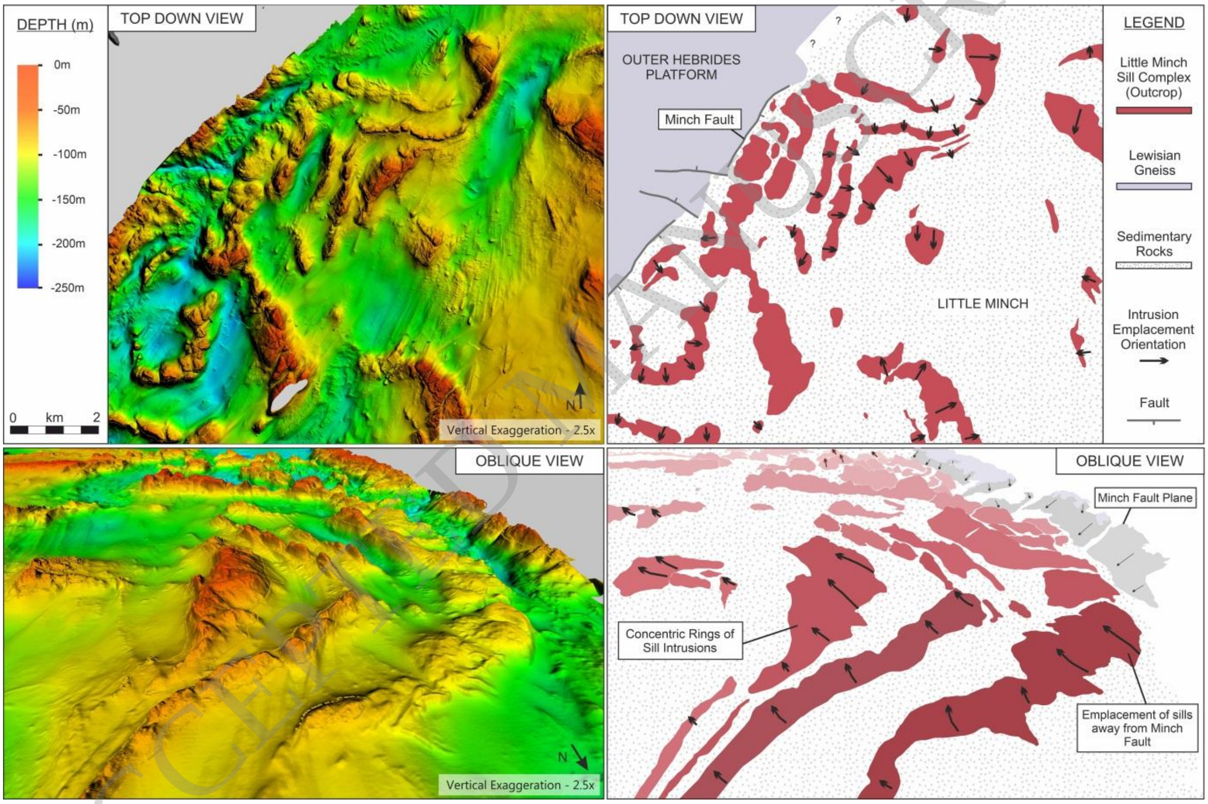
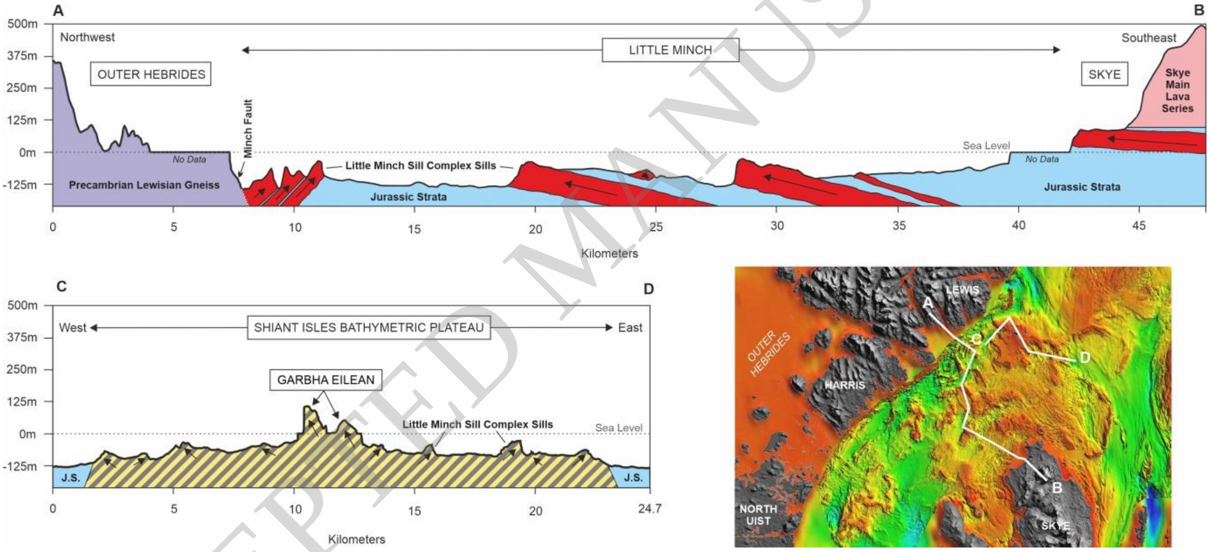
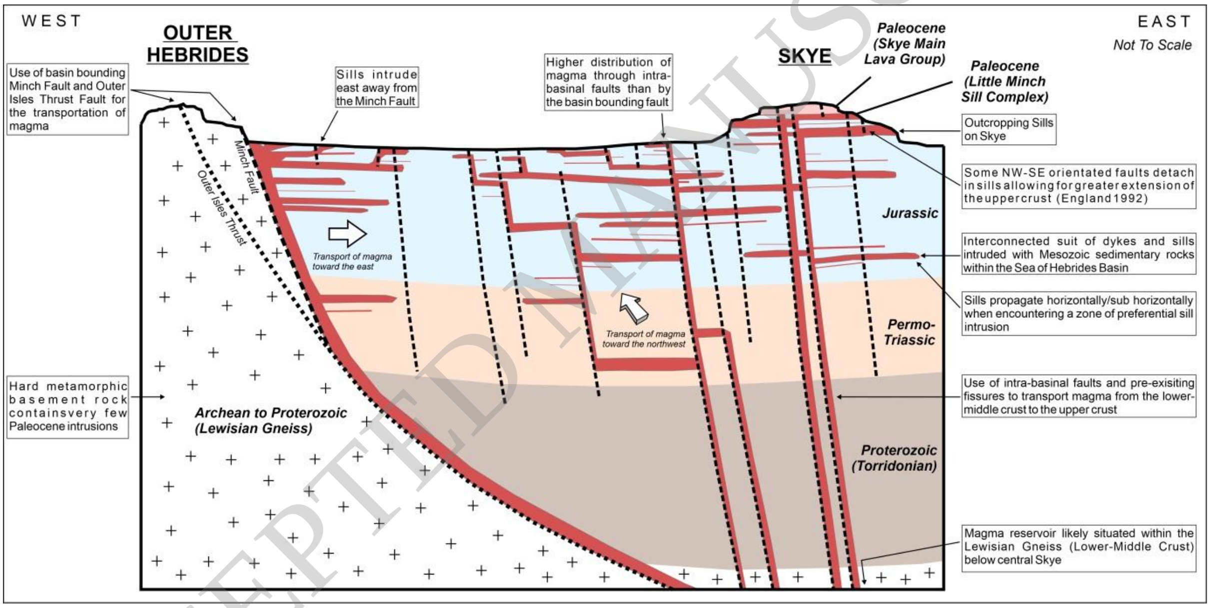
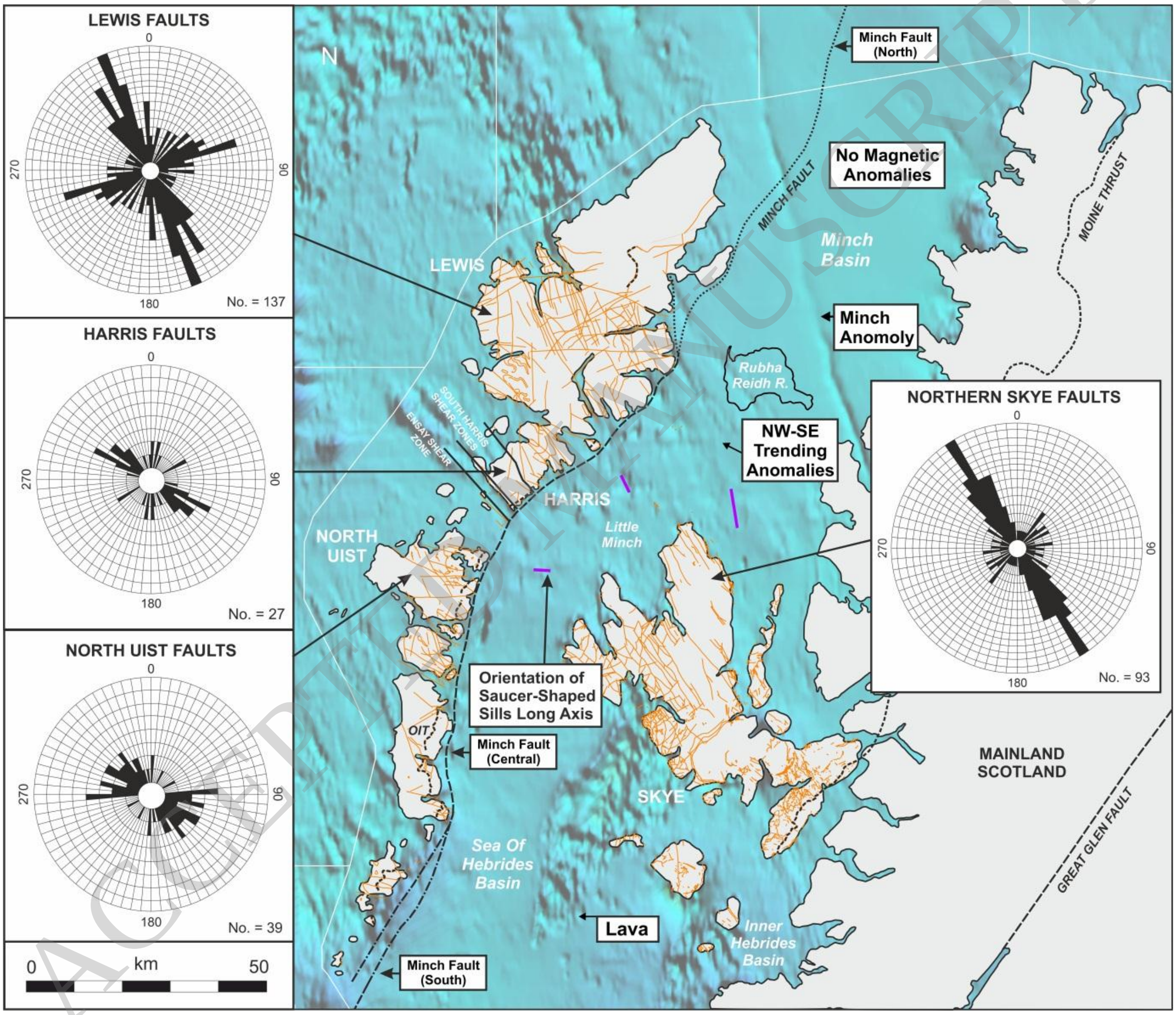
Source: Data taken from IHS Markit upstream E&P content

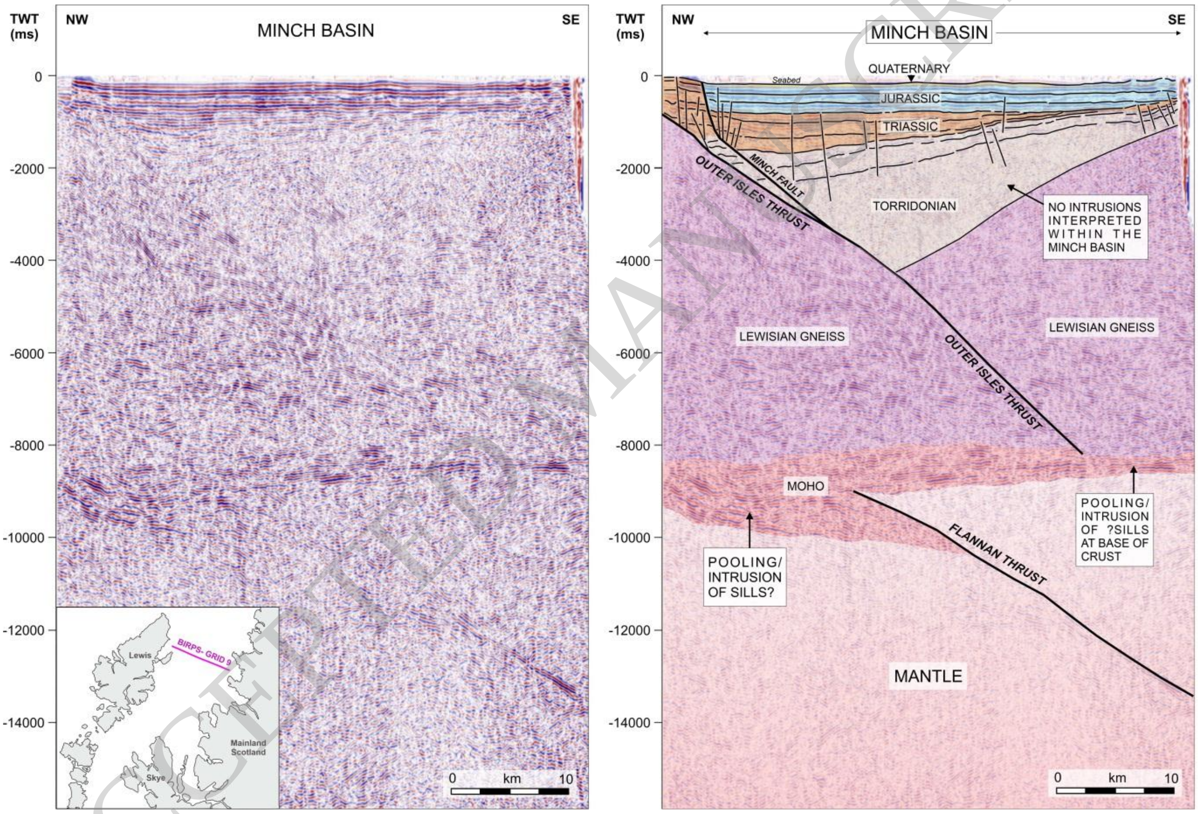

DEPTH (m)
0
-50
-100
-150
-200
-250
0 km 5
N
LEWIS
HARRIS
NORTH UIST
SKYE
N
315°
45°
W
E
225°
135°
S
Outer Isles Thrust
ZONE 1
ZONE 2
SILL X
Minch Fault
Fault
Inferred Fault
Thrust
Intrusion Emplacement
High Intrusion Density


DEPTH (m)
0m
-50m
-100m
-150m
-200m
-250m
0 km 2
TOP DOWN VIEW
N
Vertical Exaggeration - 2.5x
TOP DOWN VIEW
OUTER HEBRIDES PLATFORM
Minch Fault
?
LITTLE MINCH
LEGEND
Little Minch Sill Complex (Outcrop)
Lewisian Gneiss
Sedimentary Rocks
Intrusion Emplacement Orientation
Fault
OBLIQUE VIEW
N
Vertical Exaggeration - 2.5x
OBLIQUE VIEW
Minch Fault Plane
Concentric Rings of Sill Intrusions
Emplacement of sills away from Minch Fault


A
B
500m
375m
250m
125m
0m
-125m
Northwest
Southeast
LITTLE MINCH
OUTER HEBRIDES
SKYE
Skye Main Lava Series
Minch Fault
Sea Level
No Data
No Data
Little Minch Sill Complex Sills
Precambrian Lewisian Gneiss
Jurassic Strata
Jurassic Strata
0
5
10
15
20
25
30
35
40
45
Kilometers
C
D
West
East
SHIANT ISLES BATHYMETRIC PLATEAU
GARBHA EILEAN
Little Minch Sill Complex Sills
Sea Level
J.S.
J.S.
24.7
LEWIS
OUTER HEBRIDES
HARRIS
NORTH UIST
SKYE


WEST
OUTER HEBRIDES
SKYE
Paleocene (Skye Main Lava Group)
Paleocene (Little Minch Sill Complex)
EAST
Not To Scale
Use of basin bounding Minch Fault and Outer Isles Thrust Fault for the transportation of magma
Sills intrude east away from the Minch Fault
Higher distribution of magma through intra-basinal faults than by the basin bounding fault
Outcropping Sills on Skye
Some NW-SE orientated faults detach in sills allowing for greater extension of the upper crust (England 1992)
Minch Fault
Outer Isles Thrust
Transport of magma toward the east
Jurassic
Interconnected suit of dykes and sills intruded with Mesozoic sedimentary rocks within the Sea of Hebrides Basin
Transport of magma toward the northwest
Permo-Triassic
Sills propagate horizontally/sub horizontally when encountering a zone of preferential sill intrusion
Hard metamorphic basement rock contains very few Paleocene intrusions
Archean to Proterozoic (Lewisian Gneiss)
Use of intra-basinal faults and pre-exisiting fissures to transport magma from the lower-middle crust to the upper crust
Proterozoic (Torridonian)
Magma reservoir likely situated within the Lewisian Gneiss (Lower-Middle Crust) below central Skye


LEWIS FAULTS
0
270
90
180
No. = 137
HARRIS FAULTS
0
270
90
180
No. = 27
NORTH UIST FAULTS
0
270
90
180
No. = 39
0
km
50
N
Minch Fault (North)
No Magnetic Anomalies
MINCH FAULT
Minch Basin
MOINE THRUST
LEWIS
Minch Anomoly
Rubha Reidh R.
NW-SE Trending Anomalies
NORTHERN SKYE FAULTS
0
270
90
180
No. = 93
SOUTH HARRIS SHEAR ZONES
ENSAY SHEAR ZONE
HARRIS
Little Minch
NORTH UIST
Orientation of Saucer-Shaped Sills Long Axis
OIT
Minch Fault (Central)
SKYE
MAINLAND SCOTLAND
Sea Of Hebrides Basin
GREAT GLEN FAULT
Lava
Inner Hebrides Basin
Minch Fault (South)


TWT (ms)
NW
MINCH BASIN
SE
0
-2000
-4000
-6000
-8000
-10000
-12000
-14000
Lewis
BIRPS- GRID 9
Mainland Scotland
Skye
0 km 10
TWT (ms)
NW
MINCH BASIN
SE
Seabed
QUATERNARY
JURASSIC
TRIASSIC
MINCH FAULT
OUTER ISLES THRUST
TORRIDONIAN
NO INTRUSIONS INTERPRETED WITHIN THE MINCH BASIN
LEWISIAN GNEISS
OUTER ISLES THRUST
LEWISIAN GNEISS
MOHO
FLANNAN THRUST
POOLING/ INTRUSION OF ?SILLS AT BASE OF CRUST
POOLING/ INTRUSION OF SILLS?
MANTLE
0 km 10