

## Regional magma plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex

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**Regional Magma Plumbing and emplacement mechanisms of the  
Faroe-Shetland Sill Complex:**

**Implications for magma transport and petroleum systems within sedimentary basins**

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**Abstract**

The movement of magma through the shallow crust and the impact of subsurface sill complexes on the hydrocarbon systems of prospective sedimentary basins has long been an area of interest and debate. Based on 3D seismic reflection and well data, we present a regional analysis of the emplacement and magmatic plumbing system of the Palaeogene Faroe-Shetland Sill Complex (FSSC), which is intruded into the Mesozoic and Cenozoic sequences of the Faroe-Shetland Basin (FSB). Identification of magma flow directions through detailed seismic interpretation of

27 approximately 100 sills indicates that the main magma input zones into the FSB were controlled  
28 primarily by the NE-SW basin structure that compartmentalise the FSB into its constituent sub-  
29 basins.

30 An analysis of well data shows that potentially up to 88% of sills in the FSSC are <40 m in  
31 thickness, and thus below the vertical resolution limit of seismic data at depths at which most sills  
32 occur. This resolution limitation suggests that caution needs to be exercised when interpreting  
33 magmatic systems from seismic data alone, as a large amount of intrusive material could potentially  
34 be missed.

35 The interaction of the FSSC with the petroleum systems of the FSB is not well understood.  
36 Given the close association between the FSSC and potential petroleum migration routes into  
37 some of the oil/gas fields (e.g. Tormore), the role the intrusions may have played in  
38 compartmentalization of basin fill needs to be taken fully into account to further unlock the future  
39 petroleum potential of the FSB.

40

41 Keywords: Faroe-Shetland Basin, 3D seismic interpretation, Sills, Magma, Volcanic Rifted Margins

42

## 43 **Introduction**

44 In recent years, our understanding of sub-volcanic magmatic plumbing systems within  
45 sedimentary basins has been revolutionised by the study of petroleum industry 3D seismic  
46 reflection datasets. In particular, 3D seismic reflection data have provided important insights into  
47 sheet intrusion geometry, emplacement mechanisms, and magma flow between multiple intrusions  
48 within sill-complexes in basins located along the Norwegian Margin, the NE Atlantic Margin, and  
49 offshore Australia (e.g. Davies et al., 2002; Smallwood and Maresh, 2002; Thomson and Hutton,  
50 2004; Archer et al. 2005; Planke et al., 2005; Hansen and Cartwright, 2006; Thomson and  
51 Schofield, 2008; Jackson et al. 2013; Magee et al. 2013a, b, c).

52 It is widely acknowledged that magmatic processes play a key role in continental breakup  
53 (e.g. Afar; Wright et al. 2012) and that magmatic sheet (sill) intrusion contributes significantly to  
54 the upper crustal magma transport network. Interconnected sills may also represent a unique type  
55 of magma chamber (Cartwright and Hansen, 2006; Marsh, 2004), whereby the magma hosted  
56 within the sill complex forms an interconnected body of magma, which could serve the same  
57 purpose as a single magma chamber.

58 Whilst previous seismic interpretation-based studies have addressed aspects of the  
59 magmatic plumbing system with regard to how networks of interconnected sills link (Cartwright  
60 and Hansen, 2006), how sills grow and how they exploit structural/stratigraphic anisotropy  
61 (Thomson and Hutton, 2004; Schofield et al. 2012a), most of this work has been conducted using  
62 isolated datasets, often due to limited data availability. These studies are typically focused on scales  
63 of over 10s of km (e.g. Thomson and Schofield; 2008; Schofield et al. 2012; Planke et al. 2005);  
64 however, no basin scale study (over 100s of km) has been undertaken.

65 The Faroe-Shetland Basin (FSB) was a site of extensive extrusive and intrusive igneous  
66 activity during the Palaeogene, as a result of the impingement of the proto-Icelandic Plume and the  
67 onset of sea floor spreading (e.g. Saunders et al. 1997; Passey and Hitchen, 2011). The basin was  
68 heavily intruded by a series of sill intrusions, and these provide an excellent opportunity to  
69 understand the development of shallow crustal, rift-related magmatism within a sedimentary basin.  
70 The FSB also arguably represents one of the last major frontier exploration areas within the  
71 United Kingdom Continental Shelf (UKCS), and contains several large producing fields (e.g. Clair,  
72 Foinaven, Schiehallion). For this reason, unlike many volcanic margin basins, the FSB is covered  
73 extensively by 3D seismic data, such as the high quality regional 3D seismic survey, the FSB  
74 MegaSurvey Plus, which covers a surface area of ~24,000 km<sup>2</sup>.

75 This study presents a detailed, seismic-based characterisation of the Faroe-Shetland  
76 Sill Complex (FSSC), with the central aim of investigating the distribution, timing and emplacement

77 of the FSSC and, in particular, to understand the regional magma flow network and main magma  
78 input points into the FSB. Furthermore, given the prospective nature of the FSB, and the close  
79 association of the FSSC with both source rocks and reservoir intervals, the potential impact of the  
80 sill-network on the hydrocarbon system operating within the basin is investigated.

81 Although this study is focussed on the FSB, its findings have important ramifications for our  
82 global understanding of the evolution and petroleum systems of other sedimentary basins and  
83 rifted margins that have experienced considerable volcanism during their history (e.g. Brazil and  
84 Africa – Gladczenko et al. 1997; Australia – Holford et al. 2012, 2013; China – Lee, 2006;  
85 Greenland – Skogseid et al. 2000).

86

## 87 **Regional Geological History**

88 The FSB is the collective term for a series of rift basins situated between the Faroe Islands  
89 and Shetland Isles that are affected by volcanism (Fig. 1), which are part of a much larger system of  
90 rift basins that extends along the NE Atlantic Margin. The FSB experienced a complex multi-phase  
91 rifting history, with several rift episodes occurring between the Permo-Triassic and Palaeocene,  
92 culminating in breakup at 55 Ma (Ritchie et al. 2011). This was followed by Late Palaeocene and  
93 Mid-Miocene basin inversion events (Smallwood and Maresh, 2002). The rift history has led to a  
94 complex basin structure comprising a series of NE-SW trending “basement blocks”, consisting of  
95 Precambrian crystalline igneous and metamorphic rocks, and incomplete occurrences of  
96 Palaeozoic sedimentary rocks (e.g. Devonian). The blocks are capped with erosional remnants of  
97 pre-rift Mesozoic sedimentary rocks, with adjacent fault bounded basins forming depocentres for  
98 Cretaceous and Palaeocene sediments (Lamers and Carmichael 1999). The northeast Atlantic  
99 region experienced considerable igneous activity prior to, and associated with, the onset of sea  
100 floor spreading in the Late Palaeocene to Early Eocene (Fig. 2) (Passey and Hitchen, 2011; Ellis and  
101 Stoker, 2014 and references therein). The earliest volcanism in the North Atlantic is thought to

102 have occurred ~63 Ma (Hamilton et al. 1998), before the onset of the eruption of the Faroe  
103 Islands Basalt Group (FIBG) ~57 Ma (Passey and Jolley, 2009). Within the FSB, volcanism resulted  
104 in the eruption of thick flood basalt sequences covering an area of at least 40,000 km<sup>2</sup>. Despite  
105 varying thicknesses of extrusive basaltic rocks within the various sub-basins forming the FSB, all  
106 the basins contain a suite of intrusive mafic sills and dykes (Stoker et al. 1993, Gibb and Kanaris-  
107 Sotiriou 1988; Thomson and Schofield, 2008; Schofield et al. 2012b), which are thought to have  
108 been intruded between 55 and 53 Ma (Ritchie and Hitchen, 1996).

109 A series of 'transfer lineaments' are thought to transect the sub-basins in a NW-SE  
110 direction (Rumph et al. 1993; Ellis et al. 2009; Ritchie et al. 2011), roughly perpendicular to the  
111 dominant structural trend of the basin (Fig. 1). The lineaments within the FSB are thought to have  
112 originated during the Phanerozoic/Palaeozoic and formed during the Caledonian Orogeny as deep  
113 seated compressional transfer zones (Rumph et al. 1993; Ellis et al. 2009). Although the presence  
114 and origin of the lineaments is uncertain (Moy and Imber, 2009), they are thought to have had  
115 some control on sediment routing and provenance within the FSB, as well as controlling potential  
116 sites of magma intrusion (Rumph et al. 1993; Jolley et al., 2005; Jolley and Morton, 2007; Ellis et al.  
117 2009; Passey and Varming, 2010).

118 Various stratigraphic schemes have been applied to the FSB over the last 35 years. This  
119 study uses the lithostratigraphy presented in Ritchie et al. (2011) and Stoker and Varming (2011),  
120 which adopts the Palaeocene T-Sequence chronostratigraphy of Ebdon et al. (1995) (Fig. 2).

121

## 122 ***Palaeogene Volcanic History of the Faroe-Shetland Basin***

123 The FSSC has been estimated to cover a minimum area of at least 22,500 km<sup>2</sup>, extending  
124 from the Foinaven and Judd sub-basins in the SW of the FSB to the Møre Basin in the NE (Passey  
125 and Hitchen, 2011). The true extent of this complex is likely to be much larger, as it extends  
126 beneath the lava field(s) of the FSB (Passey and Hitchen, 2011). The sills as a whole form part of a

127 much more extensive series of Late Cretaceous/Palaeogene aged sill-complexes extending for  
128 ~1800 km from the Norwegian Margin to the Southern Rockall Basin (Magee et al. 2014).

129 Limited radiometric dating of the FSSC has been undertaken, with the most reliable and  
130 accepted dates clustering around 55-52 Ma (Passey and Hitchen, 2011), although sills as old as the  
131 Campanian (72.1–83.6 Ma) have been reported (Fitch et al. 1988). The age clustering around 55-52  
132 Ma extends from the Mid-Flett Formation (sequence T40/T45 boundary) through the Balder  
133 Formation (sequence T50) and into the Middle to Early Eocene Horda Formation (Passey and  
134 Hitchen, 2011).

135

## 136 **Methodology and Seismic Resolution**

### 137 *Data*

138 The main 3D seismic dataset used in this study is the Faroe–Shetland PGS MegaSurvey Plus, which  
139 covers an area of ~24,000 km<sup>2</sup> (Fig. 1). The dataset is one of the largest regional seismic datasets  
140 within the FSB, and has undergone substantial reprocessing to improve both sub-basalt and sub-  
141 intrusive imaging within the basin, leading to considerable improvement in imaging of the FSSC.  
142 This has been achieved via improved multiple attenuation, detailed velocity analysis, and utilisation  
143 of improved migration techniques, leading to a greatly enhanced signal-to-noise ratio within the  
144 data. As a result, there is substantial improvement in the quality of definition of deeper structural  
145 elements of the basin, in particular the Base Cretaceous/Top Jurassic surface (Fig. 3).

146

### 147 *Sill Characterisation and Discerning Magma Flow from Seismic Data*

148 Sills imaged within 3D seismic datasets are typically identified by their tendency to crosscut  
149 stratigraphy, their laterally discontinuous nature, and their high seismic amplitudes (Smallwood and  
150 Maresh, 2002). Within a 3D seismic dataset, sill geometry can be constrained by manual picking  
151 and volume visualisation techniques, such as opacity rendering. Opacity rendering techniques work

152 best when a seismic 3D dataset possesses large amplitude contrasts between different  
153 stratigraphic sequences; this allows certain amplitudes to be selected in the volume and their  
154 transparency manipulated (Kidd, 1999; Thomson and Schofield, 2008). This method is highly  
155 effective for the examination of mafic sills intruded into sediments, as the sills exhibit higher  
156 acoustic impedances than the surrounding country rock (Bell and Butcher 2002; Smallwood and  
157 Maresh 2002; Planke et al. 2005). The result is a strong reflection coefficient at the boundary  
158 between sediment and sill.

159         It has been demonstrated from several field and seismic studies that sills typically possess  
160 lobate geometries, which are formed during magma intrusion and propagation (Thomson and  
161 Hutton, 2004; Hansen and Cartwright, 2006; Schofield et al. 2012a). Opacity rendering has proven  
162 particularly successful in enabling imaging of such magma lobes within the subsurface (see  
163 Thomson, 2007; Schofield et al, 2012b), and by mapping these lobate geometries in 3D seismic  
164 datasets, it is possible to interpret detailed magma flow pathways within sills (Fig. 4) (see Thomson  
165 and Hutton, 2004; Hansen and Cartwright, 2006, Miles and Cartwright, 2010). Most previous  
166 work has mapped magma flow pathways within individual sills or small sample populations in 3D  
167 seismic datasets (e.g. Hansen and Cartwright, 2006; Schofield et al. 2012b). However, due to our  
168 large regional dataset, we have been able to image and interpret the flow direction in ~100 sills  
169 across the FSB in three dimensions, and in many cases, map flow directions back to origin/entry  
170 points or zones within the basin (Fig. 5). Magma flow directions and entry points/zones are  
171 discussed in detail below.

172

### 173 *Seismic Resolution*

174 When undertaking seismic interpretation of a basin containing intrusive and extrusive igneous  
175 rock, it is critical to fully understand the changes (and reduction) in seismic resolution with depth,



176 especially as the attenuating effect intrusions have on seismic energy leads to rapid decreases in  
177 frequency content with depth, decreasing the resolvability of deeper intrusions.

178         Within the FSB, this aspect is further compounded by the relatively large depth ranges  
179 within the contemporary basin fill of the FSSC. For example, within the central Flett Basin, the sill  
180 complex (e.g. Fig. 4) occurs at 3.5 sec TWT (equivalent to ~3 km below the sea-bed) and deeper.  
181 At these levels, the dominant frequency of the seismic data is already significantly decreased via  
182 normal attenuating effects of the overlying sedimentary overburden.

183         Quantifying how vertical seismic resolution decreases with depth is therefore essential in  
184 understanding what thickness of intrusions can be imaged at different stratigraphic levels within the  
185 FSB. Vertical seismic resolution is the minimum thickness that a geological unit (e.g. sand bed or an  
186 intrusion) needs to be for it to be visible as a discrete event on seismic data. Below this thickness,  
187 events can ideally still be detected as a reflector, but in reality may be rendered indistinguishable  
188 against the overall reflectivity of surrounding strata and/or seismic noise; this is known as the  
189 thickness of detectability.

190         Within the Palaeocene sedimentary sections of the central Flett Basin (~3.5 sec TWT), the  
191 average dominant frequency of seismic reflection data is 17 Hz, decreasing to approximately 14 Hz  
192 within the Cretaceous sections. Average velocity values for the Palaeocene from well data (Well  
193 205/10-2b) are around 2819 m/s, giving a vertical seismic resolution of just over 40 m, and a  
194 thickness of detectability of ~20 m. Within the Cretaceous sedimentary section, which contains  
195 the majority of the identified intrusions, the velocity varies from 3048 m/s at the top Cretaceous  
196 to 4572 m/s at the base. This velocity range gives a vertical resolution ranging from 54 m (26 m  
197 detectability) at the top of the Cretaceous, to 81 m (40 m detectability) towards the base of the  
198 Cretaceous.

199           This decrease in seismic resolution is problematic, as it means that even thick intrusions (>  
200 40 m) are potentially unresolvable in the deeper (~3.5 seconds TWT and below) sections of the  
201 data.

202

### 203 **Constraints on the FSSC from well data**

204 Although the vertical seismic resolution and limits of seismic detectability can be determined for  
205 each intruded Palaeocene and Cretaceous sequence across the FSB, these calculations only  
206 provide a broad indication of the thickness of intrusions that can be easily defined from the seismic  
207 data. It does not provide any constraints of intrusions in the basin that may be *unresolved*, and what  
208 total thickness of intruded material this may represent, potentially leading to a skewed and  
209 incomplete view of the FSSC from seismic data.

210           Figure 6a represents an analysis of 19 wells within the FSB that have penetrated the FSSC.  
211 The wells run approximately along the strike of the basin from NE to SW (Fig. 1). Two additional  
212 wells that penetrated the sill complex were not included in this analysis because they also  
213 penetrate buried volcanic complexes of the Palaeocene Erlend Volcano and Brendan Volcanic  
214 Centre. These centres potentially represent areas of highly focussed localized magmatism within  
215 the FSB, and therefore may be unrepresentative of magma intrusion of the FSSC as a whole. The  
216 analysed wells penetrated a total of 149 separate intrusions, with a cumulative vertical thickness of  
217 just under 2.4 km of igneous rock. It should be noted that it is unlikely, given the location and areal  
218 spacing of the wells, that the same intrusions have been sampled twice by different wells.

219           The analysis provides several important results. Firstly, it is apparent that the distribution  
220 of sill thicknesses is positively skewed, with 110 of 149 intrusions measured (73%) being <15 m in  
221 thickness. This is far below the range of seismic resolution and detectability in most areas of the  
222 seismic dataset. The total thickness of sills in the 0-15 m range is 562 m, which represents ~24% of  
223 the total thickness of sill material penetrated by the wells.

224 Sills in the 0-40 m thickness range account for 132 of the 149 intrusions, or ~88% of all sills  
225 penetrated, and for almost half of the total thickness of all sills penetrated (1152 m). Given the 40  
226 m vertical seismic resolution, the well data implies that up to 88% of the total sills will therefore,  
227 not be expressed as discrete reflections in seismic data. A detailed analysis of well 205/10-2b  
228 provides a striking illustration of this discrepancy (Fig. 6b). Only two of the intrusions  
229 (representing ~40% of the intruded material in this well) can be clearly interpreted in the seismic  
230 data as sills (and are each actually composed of two closely spaced separate intrusions). The other  
231 sills penetrated by the well are either not imaged, or form indistinguishable interference events.

232 It is important to note that this inability to clearly image all the intrusions is a function of  
233 the geology, and not the seismic data used in this study, which arguably represents some of the  
234 best re-processed legacy data available regionally within the FSB (see Fig. 3). The same issues  
235 would apply to any and all seismic datasets that currently exist in this region and in other igneous-  
236 affected basins (i.e., it is not dataset specific), and would be even more profound on older legacy  
237 data which that has not undergone substantial reprocessing.

238

### 239 **Sill Geometry, Distribution and Interpretation of Magma Flow Pathways in the FSSC**

240 Although a large proportion of the smaller intrusions may be potentially unresolvable seismically  
241 within the FSB, it is apparent from the regional seismic data that large intrusions (> 40 m in  
242 thickness), can often be easily identified and mapped. This section will consider the overall  
243 geometry and distribution of the FSSC (Figs. 7, 9 and 11), in addition to the main magma flow  
244 pathways discerned from 3D mapping of sill morphology (Fig. 5). For clarity in description, the FSB  
245 is split into five areas (northern Flett and Sissal Sub-basins, northern Foula Sub-Basin, central Flett  
246 and Foula Sub-basins, southern Flett Sub-basin, Corona Ridge) (Fig. 1) on the basis of distinct  
247 trends in sill emplacement and/or the nature of the sills (e.g. size and morphology).

248

250 The northern Flett and Sissal Sub-basins contain a heavily intruded Cretaceous section (Line A-A'  
251 Fig. 1, Fig. 7), with the sills forming a complex, laterally and vertically stacked series of  
252 interconnected sheets. The large number of intrusions within the Cretaceous makes seismic  
253 definition of the underlying basin fill and structure (including Jurassic sequences) challenging. The  
254 sills within the heavily intruded Cretaceous section represent a ~1.5-2 km thick section containing  
255 vertically stacked intrusions, with individual sills showing a general decrease in diameter from tens  
256 of kilometres in diameter in deeper parts of the Cretaceous (at a depth of 5.5 km in the  
257 contemporary basin fill), to 1-3 km in diameter close to the presumed palaeo-landsurface at the  
258 time of intrusion (now at a depth of ~4 km in the contemporary basin fill), as constrained by  
259 penetration of sub-aerial lava flows by well 214/9-1 and penetration of the uppermost part of the  
260 sub-aerial volcanic sequence by well 214/4-1 (Fig. 7). The sill complex is bounded to the southeast  
261 by basement highs, and to the northwest by the segmented Corona Ridge (Fig. 1), which forms the  
262 highs and half-graben structure of the Sissal Basin between wells 214/4-1 (the Tobermory Gas  
263 Field discovery well) and well 214/9-1 (Fig. 7).

264 Flow directions identified in intrusions (e.g. from magma lobes) within the northern Flett  
265 and Sissal Sub-basins indicate two distinct trends of sill emplacement. The first trend, seen within  
266 the Sissal Basin, is characterised by sills that are fed away from the NE-SW trending bounding  
267 Sissal Basin Fault, in a NW to SE direction, and which climb mainly strata-bound towards the  
268 southerly segment of the Corona Ridge and the intra-basin high penetrated by well 214/9-1. The  
269 second trend, within the northern Flett Sub basin, shows a *diverging* set of magma flow directions  
270 that also climb towards the bounding highs (Fig. 7), namely the southerly Corona Ridge splay  
271 (penetrated by 214/9-1) to the NW and the Rona Fault and Rona Ridge to the SE.

272           These observations suggest that within the Sissal Basin, magma appears to have been  
273   inputted away from the Sissal Basin Fault, whereas within the northern Flett Sub basin, magma  
274   input into the basin was generally from several zones running through the central axis of the basin.

275

#### 276   *Northern Foula Sub-basin*

277   The northern Foula Sub-basin is characterised by a series of rotated fault blocks, buttressed  
278   against the intra-basinal high drilled by well 208/21-1 (Line A-A' Fig. 1, Fig. 7). The morphology and  
279   size of the intrusions within this part of the FSSC are markedly different from those within the  
280   northern Flett Sub-basin. This part of the FSSC is characterised by a series of small (1-3 km in  
281   diameter) saucer-shaped and half-saucer-shaped intrusions, which climb and cut through the  
282   Cretaceous and Lower Palaeocene basin fill towards the intra-basin high penetrated by well  
283   208/21-1 (Figs. 7 and 8). Importantly, well 208/21-1 penetrated a series of sub-aerial basalt lava  
284   flows (with notable reddening and weathering profiles) interbedded with siltstones, between  
285   1667–1811 m below the seabed. The sedimentary interbeds contain terrestrial pollen and spore  
286   flora, and based on palynological and stratigraphical relationships, the age of these sub-aerial lavas  
287   is, at the latest, sequence T36 (~58.4 Ma). This age pre-dates the main sequence T40-T45 (~56.1–  
288   55 Ma) phase of volcanism, which manifested in the eruption of the Faroe Island Basalt Group  
289   (Passey and Jolley, 2009; Schofield and Jolley, 2013) and suggests that this area of the basin acted as  
290   one of the first foci for magmatism and volcanism during Kettla Member times (~58.4 Ma).

291

#### 292   *Central Flett and Foula Sub-basins*

293   The overall spatial distribution of sills in this part of the FSB narrows and follows the main Flett  
294   Sub-basin (Line B-B' Fig. 1, Fig. 9), which becomes confined between the Flett Ridge and Corona  
295   Ridge. The two largest (~20 x 10 km in dimension), discrete, seismically definable intrusions within  
296   the FSB occur here, having been intruded along the Cretaceous-Palaeocene boundary. Below this

297 depth, the Cretaceous is pervasively intruded, with the FSSC forming a series of vertically stacked  
298 intrusions, particularly within the central part of the sub-basin. This series of intrusions terminates  
299 downwards against the inferred base of the Cretaceous sequence at a depth of ~6 km beneath the  
300 present day seabed. The heavily intruded nature of this part of the basin makes it difficult to  
301 distinguish deeper pre- and syn-rift structure and stratigraphy (e.g. the Jurassic).

302 The magma flow directions interpreted from the sills in this region suggest a magma source  
303 slightly off-centre from the basin axis (to the west), and running parallel to the strike of the Flett  
304 Sub-basin (Figs. 5 and Fig. 9). The main area of magma input seems to be the south-easterly dipping  
305 Flett Basin Fault (FBF) (Figs. 1, 5 and 9), which appears to have acted as the main controlling fault  
306 defining the half-graben geometry of the Flett Sub-basin.

307 Towards the Corona Ridge (left side of Fig. 9), sills have interacted with and preferentially  
308 intruded Cretaceous-age syn-rift faults, exploiting the edge of the tilted fault blocks to climb to  
309 stratigraphically higher levels (Thomson, 2007). These interconnected intrusions can be traced  
310 back in three dimensions to the magma input zone of the FBF, demonstrating over 25 km of lateral  
311 and ~3 km of vertical magma movement away from the inferred entry point of magma into the  
312 basin fill (Fig. 5).

313 The intrusions in the central Flett Sub-basin have also led to the formation of a prominent  
314 forced fold (Figs. 9 and 10) above the intrusions (Moy and Imber, 2009), which has an amplitude of  
315 ~180 m (not corrected for compaction). The formation of the fold caused doming of the overlying  
316 Vaila and Lamba formations, above the central Flett Sub-basin. This has created a large double-  
317 domal structure with near four-way dip closure, measuring approximately 18 × 40 km in areal  
318 extent (Fig. 10). This forced fold structure is well illustrated by Moy and Imber (2009) using the  
319 Kettla Tuff regional horizon (sequence T36; 58.4 Ma), which forms an easily definable seismic  
320 reflector. The crest of the fold is, however, actually higher in the stratigraphy, as evidenced by

321 clear onlap onto the top surface of the forced fold, demonstrating that the fold had palaeo-  
322 surface/seabed topographic expression by late Lamba Formation times (i.e., 56.1 Ma).

323 Another noteworthy occurrence in the central Flett Sub-basin is the presence of sediment  
324 volcanoes (Fig. 10). Grove (2013) identified a sediment volcano (~6.5 km in diameter, penetrated  
325 by well 214/28-1), which appears to have erupted sand-rich sediment (~13 km<sup>3</sup>, non-decompacted)  
326 in a series of underwater sediment turbidites emanating from a central “vent”. These sediments  
327 clearly onlap the forced fold (Figs. 9 and 10). Grove (2013) also stated that the mound was draped  
328 by sequence T45 sediments; however, our re-interpretation of biostratigraphic data suggests that  
329 the drape is actually equivalent to the base of sequence T40 (Base Flett), and that the sediment in  
330 the vent is composed of reworked Lamba Formation (Fig. 10d).

331 Other inferred sediment volcanoes matching the characteristics of the one identified by  
332 Grove (2013) and at the same stratigraphic level, are visible along the NW and NE flank of the  
333 central Flett forced fold (Fig. 10e). This suggests that a basin-wide series of sediment eruptions  
334 occurred at approximately the same time.

335

#### 336 *Southern Flett Sub-basin*

337 The southern Flett Sub-basin (Line A-A' Fig. 1 and Fig 11) contains relatively few visible intrusions  
338 within the Cretaceous section, in comparison to both the central and northern Flett sub-basins.  
339 Consequently, and in contrast to many other parts of the basin, imaging of the Base  
340 Cretaceous/Top Jurassic sequences is possible. The Base Cretaceous/Top Jurassic stratigraphy in  
341 this area is characterised by a zone of heavily intruded, laterally continuous, generally strata-bound  
342 intrusions, which occupy a series of small half-graben structures (Fig. 11). The potential significance  
343 of a pervasively intruded Base Cretaceous section for the petroleum system in the basin is  
344 discussed later.

345           As with the central Flett Sub-basin, the FBF appears to have acted as the controlling  
346 influence on the magma input point into this part of the basin. Magma flow directions within the  
347 sills appear to diverge away from the south easterly-dipping FBF in a predominantly west to east  
348 direction.

349

#### 350 *Corona Ridge (Rosebank Field)*

351 The Corona Ridge has undergone increased hydrocarbon exploration activity since 2004, when a  
352 major oil and gas discovery (Rosebank Field) was made in the Palaeocene lava flows and intra-  
353 volcanic sediments that directly overlie it (Schofield and Jolley, 2013) (Fig. 12). The Cretaceous  
354 sequences immediately adjacent to and above the Corona Ridge (including the intra-volcanic  
355 hosted Rosebank Field) have some of the lowest density of intrusions throughout the FSB. The  
356 major saucer-shaped intrusions in this area climb in a SW- to NE direction from the Corona Basin  
357 towards the Corona Ridge (Fig. 5). A roughly 27 m thick sill was penetrated by well 213/27-2, but  
358 the Rosebank discovery well (213/27-1z), which also penetrated Jurassic sequences, did not  
359 encounter any sub-volcanic intrusions around the Base Cretaceous unconformity, in contrast to  
360 the central Flett Sub-basin where intrusions at this level appear common (Fig. 11)

361           The saucer-shaped intrusion penetrated by well 213/27-2 is isolated and is seemingly not  
362 connected to any sub-horizontal sill complex in the surrounding area, which may have acted as its  
363 magma source (Fig. 5). The isolated nature of the intrusion, atop the Corona Ridge, therefore  
364 suggests that it was sourced sub-vertically (dyke-fed) through the Corona Ridge itself, possibly via  
365 one of the ridge bounding faults.

366

#### 367 **Magmatic Plumbing: Transport through Sedimentary Fill or Crystalline Basement?**

368 Our interpretations appear to show that the vast majority of intrusive sheet magmatism within the  
369 FSB was focused through the sub-basins (i.e., sedimentary depocentres). However, some isolated



intrusions on both the Corona Ridge and the Rona Ridge occur without any apparent connection to the sill complexes present within the sub-basins (Figs. 5 and 9). These isolated intrusions suggest magma transited through or close to (perhaps constrained by ridge bounding faults?) the crystalline basement of the basement ridges. The low number of intrusions, however, suggests that any magmatic system that became established through the basement ridges during the Palaeogene appears to have been relatively minor compared to other areas of the FSB.

The timing of the intrusions associated with the basement ridges is not easy to determine. However, on the Corona Ridge, near to the southern extent of the Rosebank Field, a small conical volcano (1 km in diameter), which fed a series of lava flows (Fig. 12b, c and d), indicates that a sub-vertical magmatic system existed until at least sequence T45 (Flett Formation; 55.2 – 55.9 Ma) (Schofield and Jolley, 2013) (Fig. 12).

381

## **Discussion Part I – Magmatic Plumbing of the Faroe-Shetland Sill Complex**

### ***Age and Phases of Sill Intrusion***

The exact ages and phases of sill intrusion into the FSB have long been debated and various attempts at constraining the age of the sills from radiometric dating have been attempted, with a general clustering of ages between 55 and 52 Ma (Passey and Hitchen, 2011), representing Mid-Flett (the sequence T40/T45 boundary) to Balder times (Fig. 2). This timing is generally accepted as reliable (Smallwood and Harding, 2009; Passey and Hitchen, 2011), and constrains FSSC emplacement to after the first main phase of volcanism of the FIBG (Passey and Jolley, 2009). However, some of the stratigraphic relationships appear at odds with this interpretation.

On the Rona Ridge, well 208/21-1 penetrated sequence T36 (~58.4 Ma) Kettla Member lava flows (Figs. 7 and 8). Critically, intrusions appear to connect to the base of these flows and the palaeo-surface upon which they were emplaced (Fig. 8), suggesting a genetic connection between the fissure systems that fed the sequence T36 lava flows and the underlying sills. This

395 connection suggests that the intrusions in the vicinity of this area of the Rona Ridge are equivalent  
396 in age to the sequence T36 Kettla Member lava units (or 58.4 Ma) and therefore, related to an  
397 earlier phase of volcanism in the basin.

398 The identification of forced folds and onlap by subsequent sediment packages onto palaeo-  
399 seafloor/surfaces above sills has been shown in many basins to be an accurate method for  
400 determining the relative ages of intrusions (e.g. Hansen and Cartwright, 2006; Magee et al. 2014).  
401 As described earlier, evidence of forced folding can be seen within the central Flett Sub-basin,  
402 above the two sills located along the basin axis (Figs. 9 and 10). Onlaps onto this forced fold  
403 suggest that within the central Flett Sub-basin, palaeo-seafloor topography was in existence as a  
404 result of at least one major phase of sill intrusion having occurred by at least Top Lamba  
405 Formation times (~56.1 Ma).

406 Absolute ages of sills within the FSSC obtained via radiometric dating of sills are limited  
407 within the FSB. However, well 207/01a-4z, drilled on the Rona Ridge, approximately 24 km NE of  
408 the Clair Field, intersects a sill that has been dated at  $52.4 \pm 1.5$  and  $52.5 \pm 1.5$  Ma, with the age  
409 regarded as 'reliable' (Fig. 13) (see Passey and Hitchen, 2011). This age would constrain the  
410 emplacement of this sill to after the deposition of the Balder Formation (54.3 Ma). However,  
411 above this particular intrusion a domal forced fold at the Top Cretaceous surface (Fig. 13), with  
412 clear onlap of Lamba and Sullom/Vaila formation-aged sediments onto the fold, demonstrates that  
413 by at least the lower Vaila Formation (61.6 Ma), the sill intrusion had occurred. Based on these  
414 stratigraphic relationships this would place the age of the sill ~7 Myr earlier than the radiometric  
415 age.

416 This discrepancy between stratigraphic relationships and radiometric age questions the  
417 validity of the published radiometric date for this sill, and also other dates on the age of the FSSC.  
418 Currently available dates, especially those based on K-Ar dating techniques, which can be  
419 erroneous due to unquantified argon loss (Kelley, 2002), should now be treated with caution,

420 unless supported by other evidence (e.g. utilization of forced folds) or more robust dating  
421 techniques (e.g., U-Pb dating of baddeleyite/zircon).

422         Given these discrepancies, we conclude that the FSSC was not simply emplaced between  
423 Mid-Flett to Balder times (55.2 Ma – 54.3 Ma), as is often accepted based on published data  
424 (Passey and Ritchie, 2011), and that several older phases of intrusion have occurred starting at  
425 least through the Late Cretaceous/Sullom into early Vaila (pre-T10 - T28), through to Lamba  
426 Formation and Flett Formation times (56.1 Ma – 55.2 Ma; T36 – T45).

427

#### 428 ***The Intra-Lamba/Flett Sediment Eruption Event***

429 Within the central Flett Sub-basin, the material erupted from the sediment volcanoes onlaps the  
430 forced fold in the centre of the basin (Fig. 10). However, the angle of onlap and downlap from the  
431 vent material does not appear to change onto the forced fold (Fig. 10c and e). This lack of change  
432 in angle of the onlaps and downlaps discounts any model of incremental growth of the forced fold  
433 with sediment eruption, and suggests that the sediment volcano eruptive event actually post-dated  
434 the formation of the forced fold and thus, presumably intrusion of the underlying sills (Fig. 9).  
435 Importantly, the onlap and downlap of the erupted sediments onto the Top Lamba Formation  
436 surface, followed by the subsequent onlap of the Base Flett Formation onto the top of the  
437 sediment volcano suggests that the sediment vents in the Flett Basin are neither Lamba Formation  
438 (sequence T38) or Flett Formation (sequence T40) in age, but instead represent an Intra-  
439 Lamba/Flett sediment eruption event.

440         Chimneys beneath the sediment volcanoes extend downwards (as denoted by zones of  
441 seismic noise) and coincide with the tips of the underlying sills, suggesting that the sills were the  
442 origin of the fluids that mobilised the sediment, a mechanism previously invoked on the Norwegian  
443 Margin for hydrothermal vents (Svensen et al. 2004). However, the timing discrepancy between  
444 sill emplacement and sediment eruption implies that either a second phase of sill intrusion

445 occurred (after that which formed the forced fold), or that the fluids themselves are not directly  
446 related to the sills, and are instead related to a basin wide overpressured fluid expulsion event, as  
447 is often invoked in other sand injection/expulsion complexes (e.g., North Sea – Huuse et al. 2007;  
448 California - Vigorito and Hurst, 2009). Although it is logical to invoke a second phase of sill  
449 intrusion, it is unclear why the first phase of sill intrusion, which possessed enough magma volume  
450 to dome the palaeo-seabed, did not trigger rapid heating and sand remobilization at the time.

451 It may therefore be the case that the coincidence of the potential origin or source of the  
452 vents with sill tips is more a function of the sills acting as ‘baffles’ to fluid expulsion during a release  
453 of overpressure from the Cretaceous rather than as a direct result of sill intrusion triggering  
454 sediment fluidization (*sensu* Kokelaar, 1982; Schofield et al. 2010).

455 Overpressure in basins is thought to be largely caused by two mechanisms: disequilibrium  
456 compaction and gas generation (Osborne and Swarbrick, 1997). We suggest that the first phase of  
457 sill intrusion, which led to the forced folding, may therefore have created the correct geological  
458 conditions to form effective side seals and low permeability barriers (Rateau et al. 2013). Fluid  
459 expansion, due to gas generation by heating (e.g., Svensen et al. 2004) then occurred, leading to  
460 overpressure formation. This overpressure was then released during the second phase of sill  
461 intrusion by breaching of sedimentary seals, and fluid escape being baffled through the basin fill by  
462 the intrusion network.

463

## 464 ***Regional Magma Plumbing***

### 465 *Seismic Imaging of Intrusive Rocks - what are we missing?*

466 From our analysis of well data, it may be the case that up to 88% of total sill intrusions within the  
467 sedimentary fill of the FSB are not imaged clearly in seismic reflection data (Figs. 6). The ability  
468 therefore, of seismic studies (including this one) to fully capture the true characteristics of  
469 magmatic plumbing systems in sedimentary basins must be questioned. Any studies in the FSB, or

470 other basins globally, in which volumetric deductions are made about the amount of magma  
471 present within a basin that are derived solely from the interpretation of either 2D or 3D seismic  
472 data, needs to be treated with caution, as such studies are likely to underestimate the total volume  
473 of intruded igneous rock. In the FSB, the potentially large amount of seismically-unresolvable  
474 intrusions within the Cretaceous, particularly within the Flett Sub-Basin, raises the possibility that  
475 the thickness of the sedimentary component of the Cretaceous succession has been considerably  
476 overestimated in previous studies. Instead, a large proportion of the current thickness (~2-2.5 km  
477 in thickness parts) could be potentially composed of igneous material in the form of un-imaged sill  
478 intrusions. This scenario has profound implications for basin modelling and sediment budget  
479 calculations with the pre-sill intrusion Cretaceous sedimentary thickness being overestimated.  
480 Despite this, through well analysis, at least some constraints on the upper limit of intrusion volume  
481 can be applied to basins along the north-east Atlantic margin.

482         We are unable to constrain the role of unimaged vertical, dyke-like sources in transporting  
483 magma through the sedimentary fill of the FSB. Studies of sill complexes in other Large Igneous  
484 Provinces (e.g. Karoo-Ferrar), have demonstrated that dykes often form a volumetrically minor  
485 component of the magma plumbing system within sedimentary basins (Muirhead et al. 2014). The  
486 extensive imaged network of interconnected sills in the FSB that can be traced both horizontally  
487 and sub-vertically (e.g. central Flett Sub-basin) and appear to represent significant pathways of  
488 magma suggest that true dykes (i.e., those cutting vertically through the system) may play a  
489 relatively minor role in magma movement through the FSB.

490

#### 491 *Regional Magmatic Plumbing of the Faroe-Shetland Sill Complex (FSSC)*

492 Magma flow directions in the FSSC appear to show that magma input into the FSB is controlled  
493 primarily by the heavily structured nature of the sub-basins, and the strong underlying NE-SW  
494 basement trend. This control of the basin structure is not necessarily surprising, given the long-

495 lived tectonic nature of the basin and reactivation of major structures (Dore et al. 1997; Johnson  
496 et al. 2005). In particular, the bounding faults of half-grabens, and their hanging walls, appear to be  
497 critical in acting as sites for magma intrusion into the FSB (Fig. 5).

498         Within the Flett Sub-basin, the flow directions and general morphology of the sills  
499 indicates that their axial feeders were located at the lowest part of the basin, and hence likely the  
500 thinnest crust. This relationship suggests that magma input was focused in these regions during  
501 sequence T40 (~56.1–55.2 Ma). Within the northern Flett Sub-basin, magma input appears to have  
502 taken place across a broad zone (Figs. 5 and 7). Towards the central and southern Flett Sub-basins,  
503 the half-graben bounding Flett Basin Fault appears to have been a major zone of magma input for  
504 ~80 km along strike (Figs. 5, 7 and 9). Within the Sissal Sub-basin, which is bounded between the  
505 northern and southern splay of the Corona Ridge, the half-graben bounding Sissal Basin Fault has  
506 also acted as a major magma input zone along strike for ~40 km (Figs. 5 and 7).

507         The existence and origin of the rift-oblique lineaments thought to cut the FSB (see Fig. 1)  
508 have been debated by many workers (Dore et al. 1997; Lamers and Carmichael 1999; Naylor et al.  
509 1999; Rumph et al. 1993; Jørgensen 2006; Jolley and Morton 2007; Ellis et al. 2009; Passey and  
510 Varming 2010), with the placement of the lineaments even changing between publications, as  
511 noted by Moy (2010). Moy and Imber (2009) concluded that there was no definitive evidence that  
512 the Victory, Clair and Judd lineaments imparted a significant structural or geomorphological  
513 control on basin development during the Cenozoic. However, to the SW of the study area, in the  
514 Rockall Basin, it has been suggested that lineaments have focused magmatism, in particular igneous  
515 centres (Archer et al. 2005; Hole et al. 2015).

516         Regional mapping of sills and magma flow directions in the FSB adds some interesting  
517 aspects to this lineament debate. Firstly, it is not overly apparent that the lineaments correspond  
518 with zones of increased intrusion density throughout the basin. For example, within the southern  
519 Flett Sub-basin, the relative intrusion density between the Corona Lineament and Grimur Kamban

520 Lineament actually appears to be lower than the rest of the basin. Furthermore, the axial feeding  
521 zones for the sills within the Flett Sub-basin appear to cut across several different lineaments  
522 without any major change in either the emplacement direction or nature of intrusions sourced  
523 from these input zones, with most magma being interpreted to have been fed into the basin fill via  
524 normal faults (Fig. 5).

525         It should be noted however, that some areas of magma input in the basin do appear to  
526 coincide with the traces of lineaments. In particular, the SE trace of the Clair Lineament appears to  
527 directly correspond with a suite of isolated sills intruded above the Rona Ridge (Fig. 5), away from  
528 the main sites of magma intrusion into the basin. The magma feeding these sills must have either  
529 transited sub-vertically through or adjacent to the ridge, as no intersection with other sill  
530 complexes can be seen.

531         Fracture systems within crystalline basement are typically inherited from older structures  
532 or tectonic grain (Dore et al. 1997), and often undergo reactivation, especially if a basin has  
533 experienced a protracted rift history, such as the FSB (Lamers and Carmichael 1999). Evidence  
534 from deep seismic reflection profiles indicates that, in some cases, lineaments such as the Westray  
535 Lineament may connect to the Moho (England et al. 2005). Therefore, where the Clair Lineament  
536 has intersected the Rona Ridge, the confluence of the deep seated fracture systems may have led  
537 to the creation of a preferential, but still restricted, pathway of magma through or adjacent to the  
538 Rona Ridge.

539

## 540 **Discussion Part 2 - Impacts of the Faroe-Shetland Sill Complex on the Petroleum** 541 **System of the FSB**

542 The FSB represents a highly important petroleum province within the UKCS and has significant  
543 future implications towards the energy security of the UK, with the potential in-place  
544 hydrocarbons in the Atlantic margin thought to be ~7.15 billion barrels of oil equivalent (Gray,

2013). The FSSC has a close spatial association with both the Jurassic source rocks and Jurassic-Palaeocene reservoir intervals. It is therefore important to explore the potential impact and interaction of the FSSC with the petroleum system of the FSB.

548

#### 549 ***Implications for Hydrocarbon Migration***

550 Given the high density of intrusions within the Flett, Sissal, Foula and Guorun sub-basins, (Figs. 5, 551 7, 9 and 11), it seems conceivable that the intrusions may have interacted with the FSB petroleum system. The exact effect of sill intrusions on hydrocarbon and fluid migration in the subsurface of 552 the FSB is still uncertain. It has been suggested that the intrusions may possess a dual role with 553 respect to hydrocarbon and fluid migration within the subsurface of the FSB (Rateau et al. 2013). 554 The intrusions (or the surrounding contact metamorphic zones) may create barriers and baffles to 555 fluid flow within the subsurface; however, some of the intrusions within the Flett Sub-basin may 556 have also acted as fractured conduits to migrating gas (and possibly other HC types) (Rateau et al. 557 2013). It is currently not possible to know which intrusions within the FSB acted as low 558 permeability barriers or fractured conduits (potentially compartmentalizing reservoir and source 559 rock intervals); however, both scenarios occurring are likely.

561 The close spatial relationship between intrusions and the Laggan and Tormore gas fields 562 atop the Flett Ridge is striking (see Rateau et al. 2013) (Fig. 14). Detailed examination of the 563 seismic data demonstrates that the Tormore Field, in particular, has a close relationship with the 564 underlying intrusions, with sill tips extending close to the down-dip extent of the Tormore 565 reservoir sandstone body (Fig. 15). Although the sill tips themselves are exploiting normal faults 566 within the Vaila Formation, which could itself offer a HC pathway (Scotchman, 2006), the Vaila 567 Formation sequences within the FSB are shale rich and composed of a series of hemipelagic muds 568 interbedded with marine sandstone bodies (Knox et al. 1997). They are therefore susceptible to 569 the formation of shale smears along fault planes (Lindsay et al. 1993). The addition of intrusive sills



570 may have acted as a fractured and preferential migration conduit through otherwise impermeable  
571 Vaila Formation mudstones, raising the suggestion that Tormore could have been charged via  
572 hydrocarbons migrating up through the fractured intrusion (Fig. 15d) (*sensu* Rateau et al. 2013).

573

#### 574 ***Role of the FSSC in the generative potential of the Jurassic source rocks***

575 The increasing amount of hydrocarbon discoveries within the FSB (e.g., Rosebank, Tormore,  
576 Laggan, Tornado) demonstrate that a viable petroleum system does exist, even in close association  
577 with the intrusive sill network. Within the FSB, the Jurassic represents the main source rock  
578 region (Scotchman et al., 1998); however, the Jurassic is generally poorly imaged across large areas  
579 of the FSB due to the overlying sill complex within the Cretaceous. Therefore, assessing the  
580 potential role of intrusions on the source kitchen of the Jurassic is difficult, especially as most well  
581 penetrations of the Jurassic are restricted to structural highs, where intrusions are generally  
582 absent or of low frequency. However, the most recent reprocessed seismic data appears to show  
583 that the Lower Cretaceous/Uppermost Jurassic is heavily intruded (Figs. 11).

584         Given our interpretation that faults bounding the structural highs act as the main magma  
585 pathways into the basin, it seems likely that at least some of the Jurassic source kitchen was in  
586 close proximity to magma during the Palaeogene, and that some magma may have intruded into  
587 the poorly imaged Jurassic sections. In such a situation, direct heating of the Jurassic sequences  
588 may have led to over-maturation of the source rock. Furthermore, compartmentalisation of the  
589 source rock by interconnected intrusions may hinder migration efficiency from the source kitchen,  
590 as although some intrusions within the FSB are thought to act as fractured conduits, others appear  
591 to have fractures filled by secondary minerals (see Rateau et al. 2013).

592         The notion that as much as 88% of the intruded material in the basin is not properly  
593 imaged is significant because the effect of igneous intrusions on the petroleum systems and their  
594 distribution and geometry has not traditionally been considered in basin modelling of the FSB (e.g.,

595 Scotchman et al. 2006). It is likely that within the FSB at least, the FSSC had some effect on the  
596 maturity of source rock regions. Where seismic data quality is good, a laterally continuous and  
597 heavily intruded zone, ~500-1000 m in thickness, sits directly above the top Jurassic (e.g., Fig. 5  
598 and 11). The resolvability of intrusions at this depth, where vertical resolution is around 114 m,  
599 would suggest that the section is dominated by either a series of >114 m thick intrusions, or a  
600 series of smaller intrusions forming an interference effect. The potential heating impact on the  
601 underlying source kitchen from the overlying, heavily intruded section is significant, and we suggest  
602 it should be properly considered in future basin models of the FSB.

603 The highly intruded nature of the lowermost Cretaceous (and possibly uppermost  
604 Jurassic?) within the FSB could have led to hydrocarbon migration issues, if the intrusions (or  
605 surrounding contact metamorphic zones) are acting in a sealing capacity, by trapping  
606 hydrocarbons, in particular oil phases, close to the source. This scenario would have resulted in  
607 reduced migration efficiency and charge into reservoirs in the basin since the emplacement of the  
608 FSSC in the Palaeocene.

609

## 610 **Conclusions**

611 This paper provides a comprehensive overview of the Faroe-Shetland Sill Complex in the  
612 Faroe-Shetland Basin, and represents the first basin-wide study of a sub-volcanic plumbing system  
613 in a hydrocarbon-producing basin. The study provides the first high-quality regional map of sub-  
614 volcanic intrusions in the FSB. We suggest that magma enters the basin at localities related to key  
615 structural features and is emplaced both vertically and laterally in a complex network of stacked  
616 sheets, that are typically strata-bound and/or exploit sub-basin faults. Magma flow directions are  
617 resolved from detailed mapping of magma flow lobes and their interaction with host strata. We  
618 have identified a prominent NE-SW axial feeding zone to the sills in the FSB. This feeding zone  
619 cuts across many NW-SE structural ("transfer") lineaments, and suggests that these lineaments

620 may not exert as important a tectonic control on the basin as previously suggested. The seismic  
621 data, however, do provide evidence of lateral movement of magma through the crust and  
622 demonstrate that existing models of vertically stacked volcanic-magmatic systems are potentially  
623 oversimplified.

624 Despite the very high quality seismic data used in this study, comparisons of resolvable  
625 intrusions with well data indicate up to 88% of sills in the basin may not be identified (this figure  
626 could be potentially greater on older datasets). Although many such intrusions may be small, their  
627 combined volume represents a significant amount of magma. These volumes are considerably  
628 underestimated in existing basin models and may have significant impact on the hydrocarbon  
629 system of the basin.

630 We have also identified the important effect of intrusions on the petroleum system.  
631 Intrusions may be closely linked to oil and gas fields and may act as potential pathways for  
632 hydrocarbon migration (e.g., due to fractures). The pervasive emplacement of intrusions into  
633 particular strata in a basin such as the FSB can, however, lead to compartmentalization of the  
634 petroleum system and significantly inhibit hydrocarbon migration and extraction.

635 The study demonstrates the consequences of magma intrusion into sedimentary basins.  
636 We have provided a comprehensive regional case study of magma movement in the shallow crust  
637 and its clear implications for petroleum systems, and suggest that similar studies will enhance  
638 future basin analyses and exploration.

639

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654

#### 655 **Conflict of Interest**

656 No conflict of interest declared

657

658

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**Figures:**

**Fig. 1** - A) Main structural configuration of the Faroe-Shetland Basin. Note the predominant SW-NE structural trend of the basin (from Ritchie et al. 2011), consisting of a series of intra-basinal basement highs separating sub-basins. B) Approximate outline of the study area, with wells and seismic lines referred to in the text indicated.

**Fig. 2** – Palaeogene stratigraphy West of Shetland (modified from Schofield and Jolley, 2013), with British Geological Survey lithostratigraphy (Ritchie et al. 2011) and BP T-sequence framework (after Ebdon et al. 1995), and the stratigraphical position of the Faroe Island Basalt Group (FIBG) (after Passey and Jolley 2009).

**Fig. 3** – Comparison between seismic line from PGS FSB MegaSurvey data (**A**) against the same seismic line from the re-processed PGS FSB MegaSurveyPlus data (**B**). Note the improvement in signal to noise levels, reduction in multiples and increased definition of deeper Cretaceous and Top Jurassic structure in the re-processed data. Data courtesy of PGS.

**Fig. 4** – **A**) Opacity render showing Sills A and B within the seismic data. **B**) Enlargement of A showing the detailed structure of the two sills. Note the ragged, lobate nature of the outer edge of the sills. **C**) The interpretation of magma flow directions within sills A and B, based on the lobate geometries examined in three dimensions, following the methodology of Thomson and Hutton (2004), Hansen and Cartwright (2006) and Schofield et al. (2012b).

**Fig. 5** – **A**) Map showing the flow directions interpreted in sills across the FSSC (see main text and Fig. 4 for details), along with major basin structure (after Ritchie et al 2011). **B**) Map showing a schematic representation of the main zones of magma input into the FSB based on interpreted flow directions within the sills of the FSSC, overlain on the basin structure map (from Ritchie et al. 2011).

**Fig. 6** - **A**) Histogram of 19 wells across the FSB, which collectively penetrated 149 separate sill intrusions. It should be noted that most intrusions within the FSB intrude into the base Palaeocene and throughout the Cretaceous sequences. At these depths in the basin, vertical seismic resolution is at best ~40 m. From the sills penetrated by wells, 73% of all the intrusions are <15 m thick, substantially below the vertical resolution of seismic data, and 88% are <40 m thick. Therefore,

969 within the FSB potentially up to 88% of the total sills are not being imaged clearly within seismic  
970 data. **B)** Lower zone of sills penetrated by well 205/10-2b. From the synthetic seismic well-tie  
971 generated using the wavelet extracted from the range in which the sills occur, only the two largest  
972 intrusions (representing 40% of the total thickness of intrusions in this zone) are clearly imaged as  
973 discrete seismic reflectors. Although the other intrusions (representing 60% of the total thickness  
974 of intrusions in this zone) form interference effects, they are not discernable as discrete intrusions,  
975 meaning that based on seismic alone, the majority of the total thickness of intruded material has  
976 been missed. Data courtesy of PGS (FSB MegaSurveyPlus).

977

978 **Fig. 7** – NW-SE trending seismic line through the northern Flett and Sissal Sub-basins intersecting  
979 key wells (Fig. 1, A-A'), with accompanying geo-seismic interpretation and sub-basin divisions  
980 marked (data courtesy of PGS FSB MegaSurveyPlus). Within the Sissal Basin, the main input point  
981 of magma into the basin fill appears to be the Sissal Basin Fault (see Fig. 1). Within the northern  
982 Flett Sub-basin, the magma input points into the basin fill appear to occur over a broad ~40 km  
983 zone located along the central axis of the sub-basin. Well 208/21-I penetrated an intra-basinal high  
984 and sequence T36 sub-aerial lava flows, suggesting that volcanism in this area predated the main  
985 eruption of the Faroe-Island Basalt Group (see Fig. 2).

986

987 **Fig. 8 – A)** Opacity rendered image of sills underlying the sequence T36 sub-aerial lava flow  
988 penetrated by well 208/21-I. **B)** The sills form a series of interconnected intrusions that climbed  
989 and fed magma towards the intra-basinal high penetrated by 208/21-I, and came into close contact  
990 with the base of the sequence T36 sub-aerial lava. The close spatial relationship of these intrusions  
991 with the sub-aerial lava flow suggests that the intrusions in this area of the basin are also sequence  
992 T36 in age. The lava flows themselves appear to have an origin from a paleo-high and flowed down  
993 a paleo-slope basinward in a westerly direction. Data courtesy of PGS (FSB MegaSurveyPlus).

994

995 **Fig. 9** - NW-SE trending seismic line through the central Flett Sub-basin intersecting key wells  
996 (Fig. 1, B-B'), with accompanying geo-seismic interpretation and sub-basin divisions marked (data  
997 courtesy of PGS FSB MegaSurveyPlus). Within the central Flett Sub-basin, the main input point of  
998 magma into the basin appears to be the Flett Basin Fault. Over 25 km of lateral and 3 km of  
999 vertical magma movement is interpreted to have occurred through interconnected sills exploiting  
1000 a series of tilted fault blocks (see Thomson and Schofield, 2008). A prominent forced fold has  
1001 domed the Top Lamba surface Sediment volcanoes erupted sediment onto this surface and fold

1002 (Intra-Flett/Lamba event; see text and Fig. 10 for details). The Foula Sub-basin is relatively devoid  
1003 of sill intrusions, but above the Rona Ridge isolated intrusions occur, from magma likely sourced  
1004 through the basement high.

1005

1006 **Fig. 10 - A)** Top Lamba surface with closure of forced folds and location of sediment volcanoes  
1007 marked. **B)** Oblique view showing sediment volcano onlapping onto the forced fold, and  
1008 downlapping onto Top Lamba surface. Data courtesy of PGS (FSB MegaSurveyPlus) **C)**  
1009 Enlargement of seismic line shown in Fig. 9 showing sediment volcano (as described by Grove,  
1010 2013) within the central Flett Sub-basin. Note the onlaps onto the sill induced forced fold, and  
1011 downlaps onto the Top Lamba surface, demonstrating that the forced fold had paleotopographic  
1012 expression before the eruption of the sediment volcano. Base Flett position is marked. **D)**  
1013 Stratigraphic palynology of section from well 214/28-1, which penetrated the sediment volcano  
1014 and overlying sediments. The sediment volcano is composed of a series of recycled flora from  
1015 sequence T36, suggesting that mobilized sand which fed the volcano was sourced from the Lower  
1016 Lamba Formation; however, the zone of seismic disturbance (A), possibly representing the fluid  
1017 pipe, extends towards the Base Cretaceous, suggesting that the fluids which mobilized the sands  
1018 may have been sourced from a deeper basinal level. **E)** Enlargement of another sediment volcano  
1019 situated on the NW flank of the forced fold (Fig. 9). This sediment volcano sits at the same  
1020 stratigraphic level as the one described by Grove (2013). Data courtesy of PGS (FSB  
1021 MegaSurveyPlus)

1022

1023 **Fig. 11 - NW-SE trending seismic line through the southern Flett Sub-basin intersecting key wells**  
1024 **(Fig. 1, C-C'),** with accompanying geo-seismic interpretation and sub-basin divisions marked (data  
1025 courtesy of PGS FSB MegaSurveyPlus). Magma input into the southern Flett Sub-basin continues to  
1026 be dominated by the Flett Basin Fault. Compared to other areas of the Flett Sub-basin, the  
1027 southern Flett Sub-basin contains a lower frequency of intrusions, allowing for imaging of the base  
1028 Cretaceous unconformity, which appears to be heavily intruded by a series of generally strata-  
1029 bound intrusions that may cause a significant risk of igneous compartmentalization of the Jurassic  
1030 source rocks.

1031

1032 **Fig. 12 – Data courtesy of the Rosebank Joint Venture Project. A)** Sequence T45 upper volcanics  
1033 TWT surface map of the Rosebank Field located above the Corona Ridge. **B)** Seismic line through  
1034 a 2 km wide volcanic edifice. **C)** Oblique view of the volcanic edifice, showing the central crater.

1035 **D)** Spectral decomposition conducted on the upper volcanic surface displayed as a RGB Blend (R=  
1036 11 Hz, G=12 Hz, B = 13 Hz), which differentiates the lava field morphology, and illustrates that the  
1037 volcanic edifice has fed a series of SE-flowing lava flows. This series of upper Flett, sequence T45  
1038 lava flows illustrates that the Corona Ridge had undergone volcanism during these times.

1039

1040 **Fig. 13- A)** Seismic line tying well 214/30A-2 (Glenlivet Field) and well 207/01a-4z, which  
1041 intersected a 146 m thick sill that was dated radiometrically at ~52.4 Ma, constraining its  
1042 emplacement to post-deposition of the Balder Formation. The sill created a forced fold above the  
1043 intrusion, which domed the Upper Cretaceous surface. Subsequent onlaps of the Lamba and Vaila  
1044 sequences suggest that the forced fold had topography by Vaila times (63 – 58 Ma). Therefore, the  
1045 underlying intrusion, which caused the forced fold, must pre-date the radiometric age by some 10  
1046 to 5 Ma years, questioning the validity of the radiometric dating. **B)** Map of the Upper Cretaceous  
1047 horizon in the vicinity of well 207/01a-4z showing the forced fold. **C)** Oblique view of the forced  
1048 fold developed on the Upper Cretaceous horizon, and underlying sill intrusion. All data courtesy  
1049 of PGS (FSB MegaSurveyPlus).

1050

1051 **Fig. 14 - A)** Opacity rendered image showing the sills within the central Flett Sub-basin, and the  
1052 relative position of the Laggan and Tormore oil/gas fields. **B)** Enlargement of the Tormore oil/gas  
1053 field showing the underlying sill complex. See Fig. 16 for detailed relationship. All data courtesy of  
1054 PGS (FSB MegaSurveyPlus).

1055

1056 **Fig. 15- A)** Seismic line through the central Flett Sub-basin showing a sill in close association with  
1057 the Tormore oil and gas field (205/5a-1) (Fig. 1, D-D'). **B)** Geo-seismic interpretation showing how  
1058 the edge of the sill tips climb faults and extend close to the down-dip extent of the  
1059 Laggan/Tormore Vaila-aged sand body. **C)** Enlargement of seismic line showing how the sill tip has  
1060 climbed sub-vertically and extends close to down-dip extent of the Tormore sand body. Note the  
1061 amplitude anomaly within the down-dip sand body located directly above the sill tip. **D)** Rotated  
1062 phase (90°) envelope image illustrating the high amplitudes of the sill and Tormore gas leg. The sill  
1063 tip can be seen within the fault plane, suggesting that hydrocarbon migration has taken place  
1064 through the fractured sill into the Tormore Field. All data courtesy of PGS (FSB MegaSurveyPlus).

1065

1066



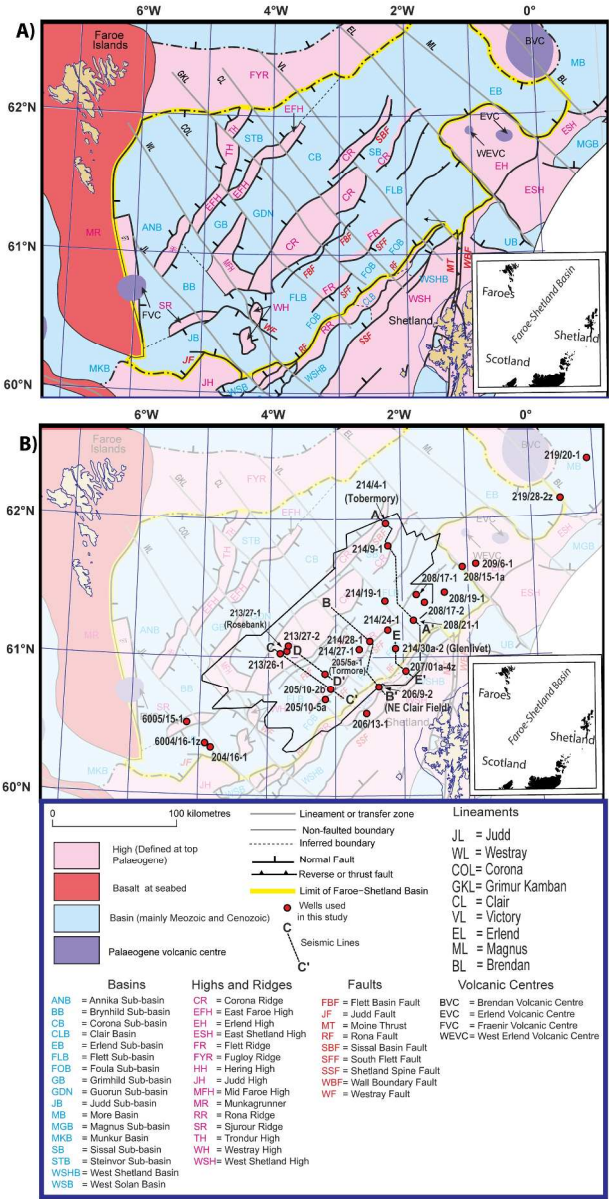


Fig 1  
207x404mm (300 x 300 DPI)

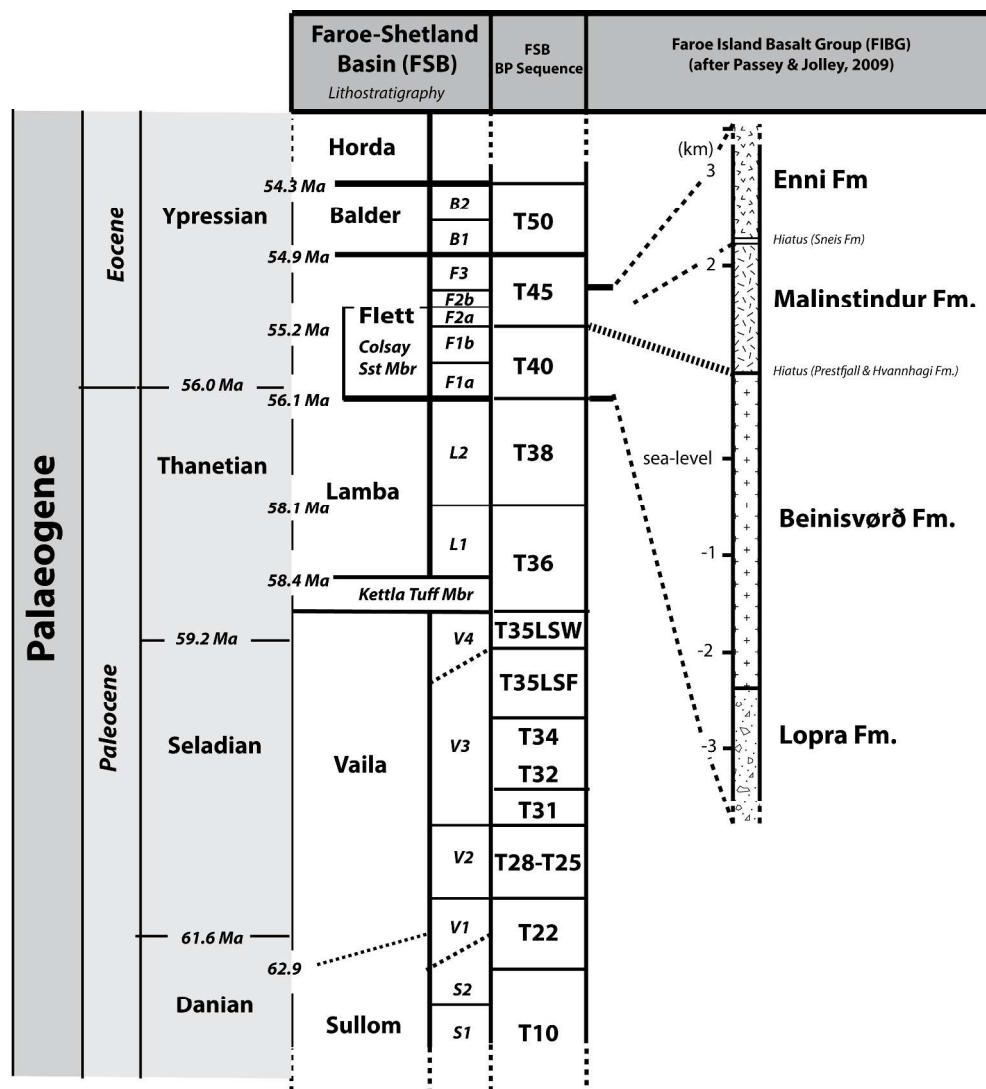


Fig 2  
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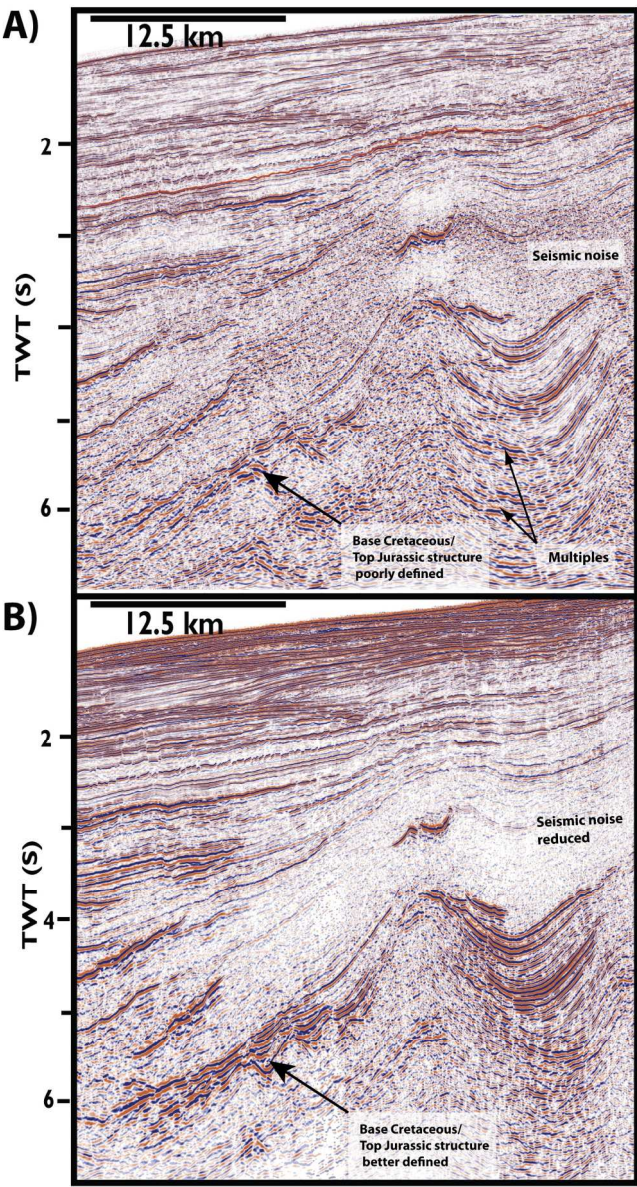


Fig 3  
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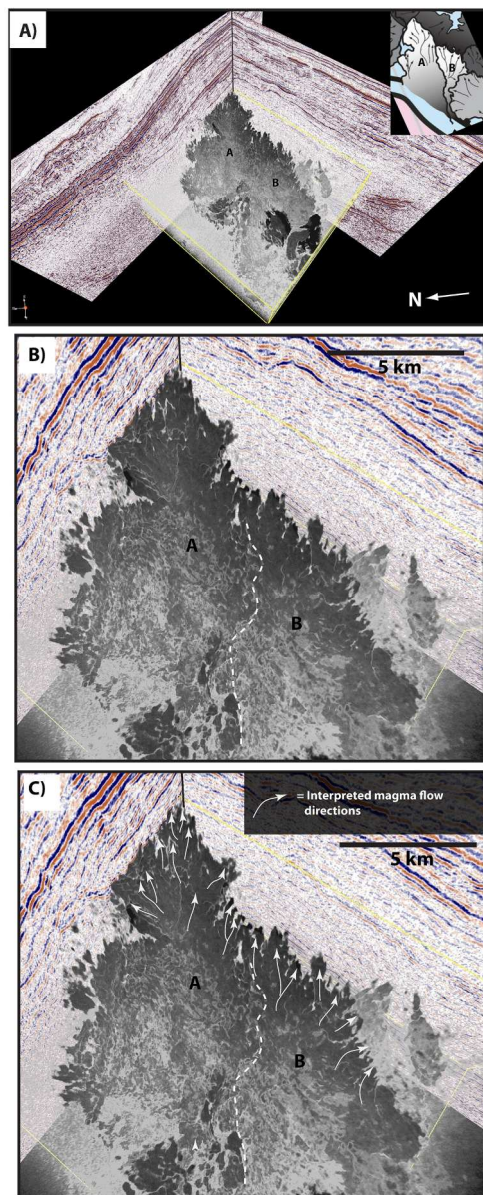


Fig 4  
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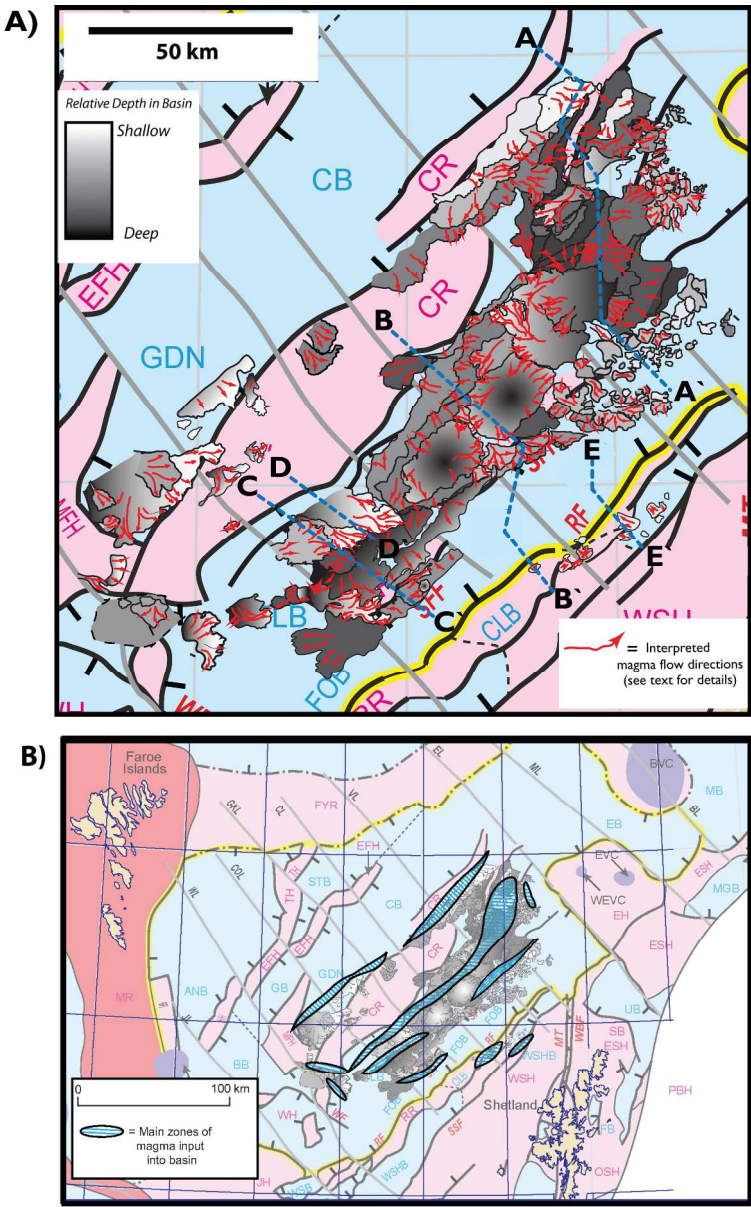


Fig 5  
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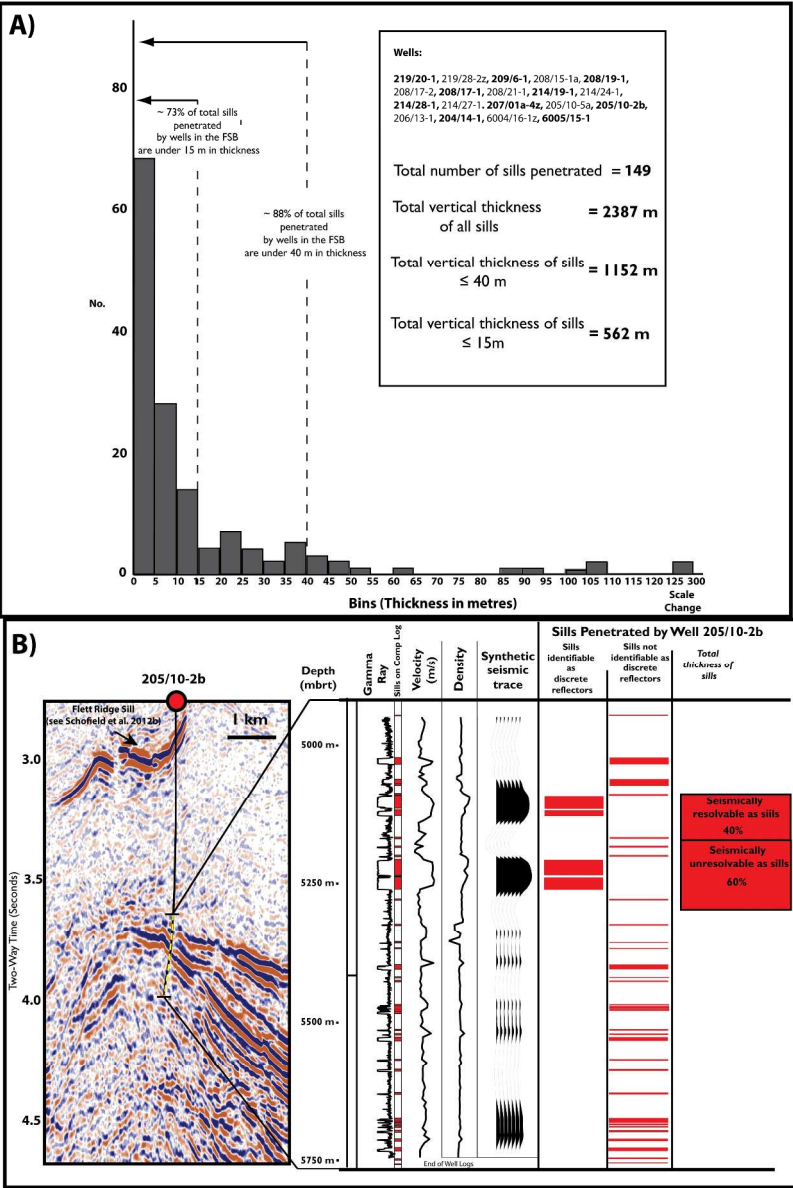


Fig 6  
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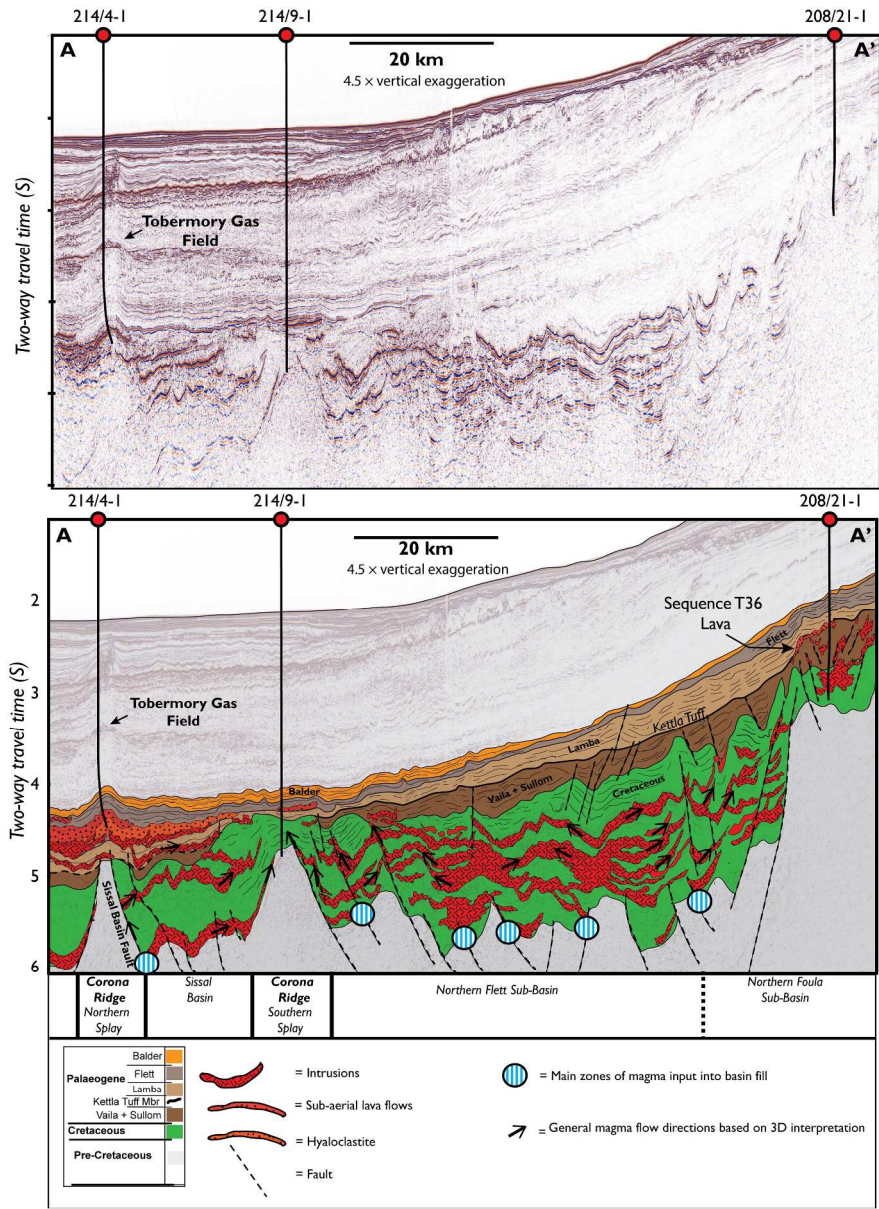


Fig 7  
211x288mm (300 x 300 DPI)

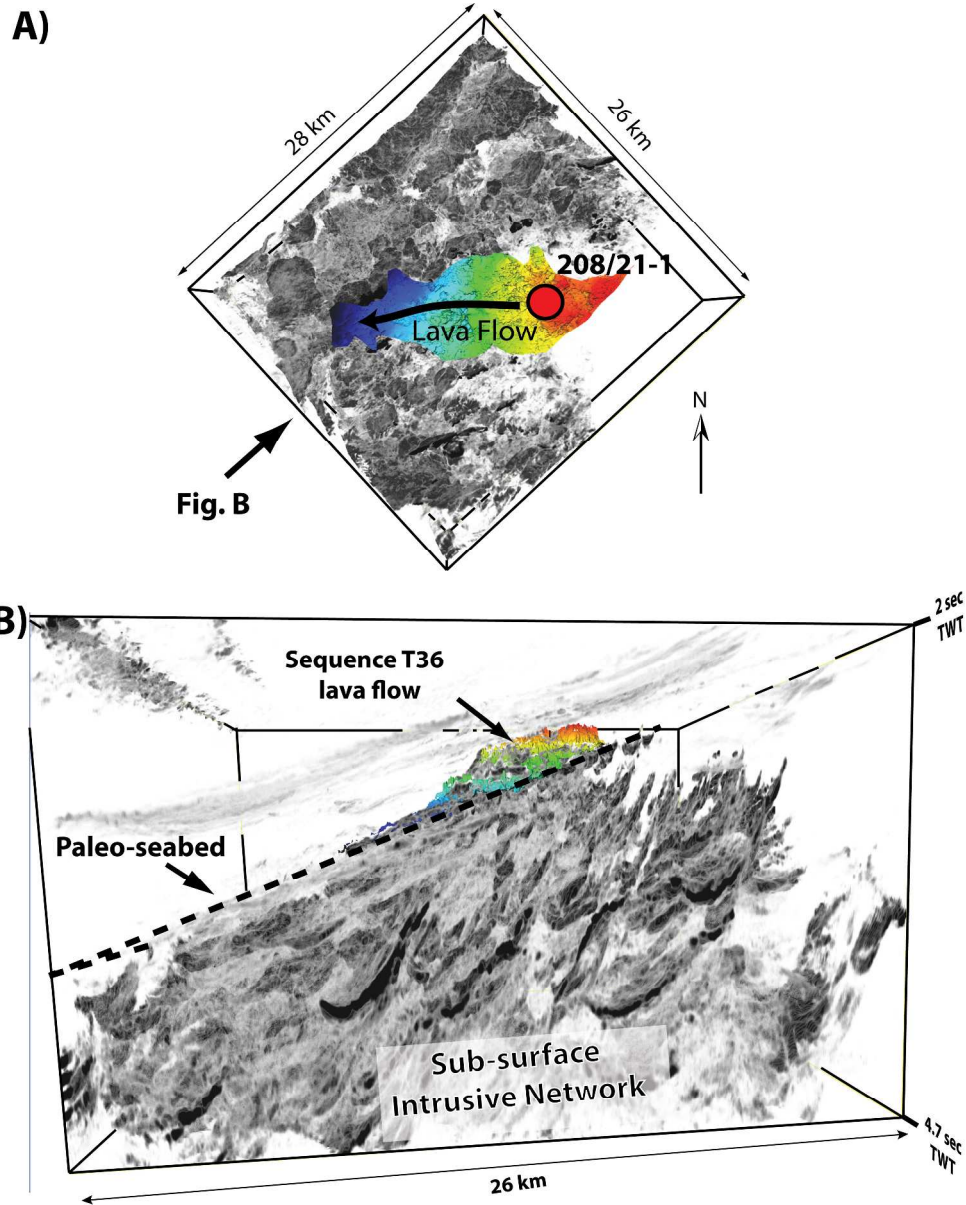


Fig 8  
278x344mm (300 x 300 DPI)



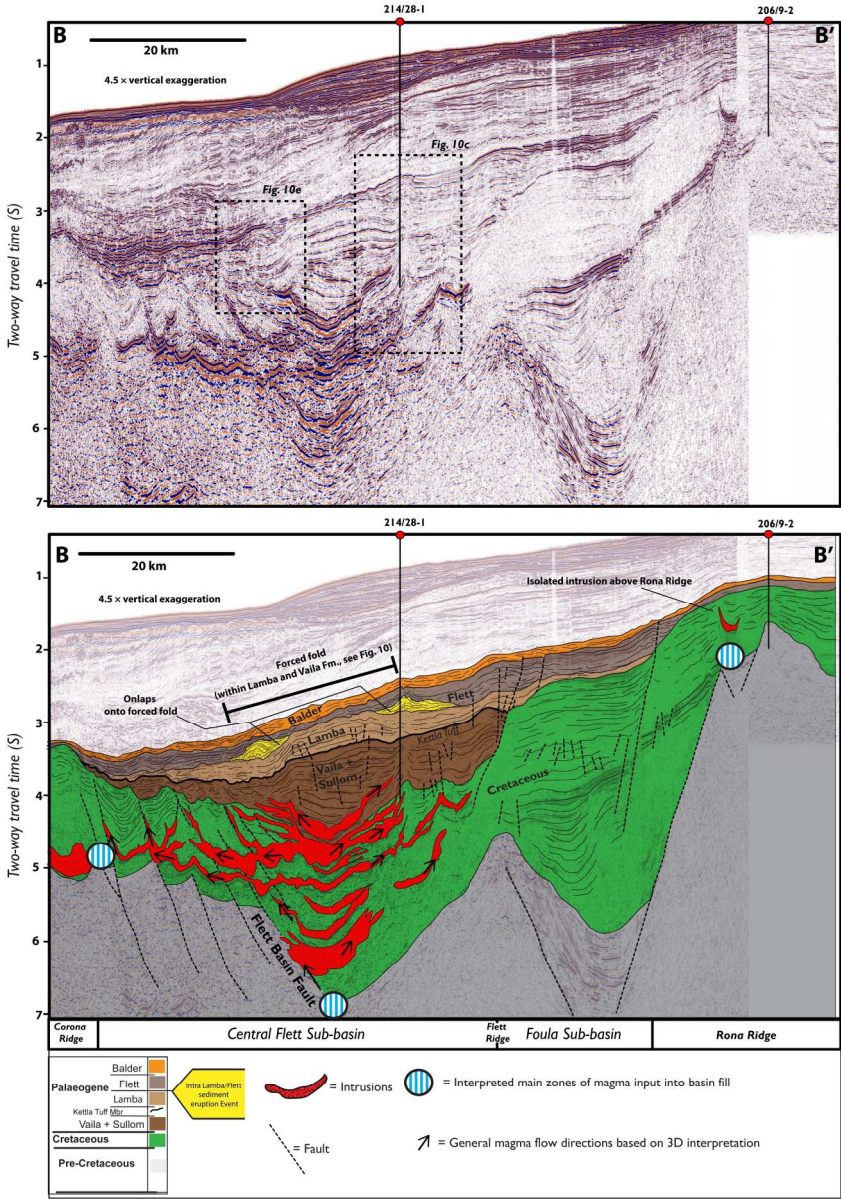


Fig 9  
338x474mm (150 x 150 DPI)

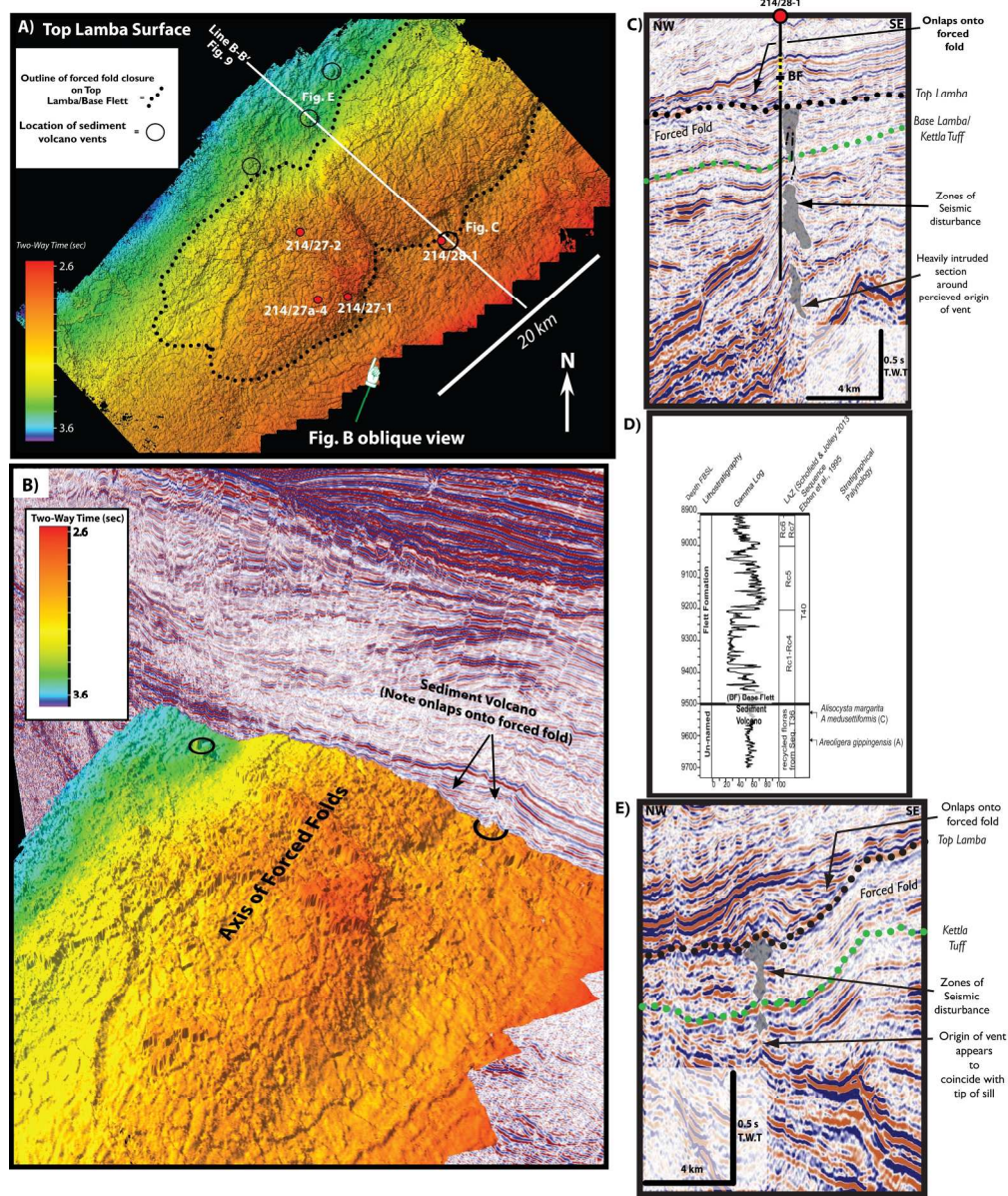


Fig 10  
211x253mm (300 x 300 DPI)



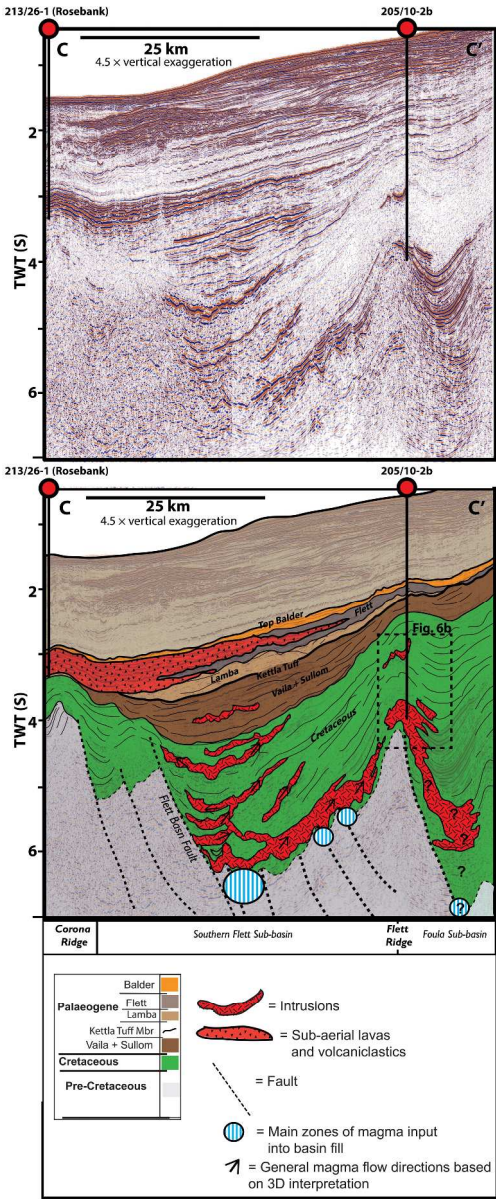


Fig 11  
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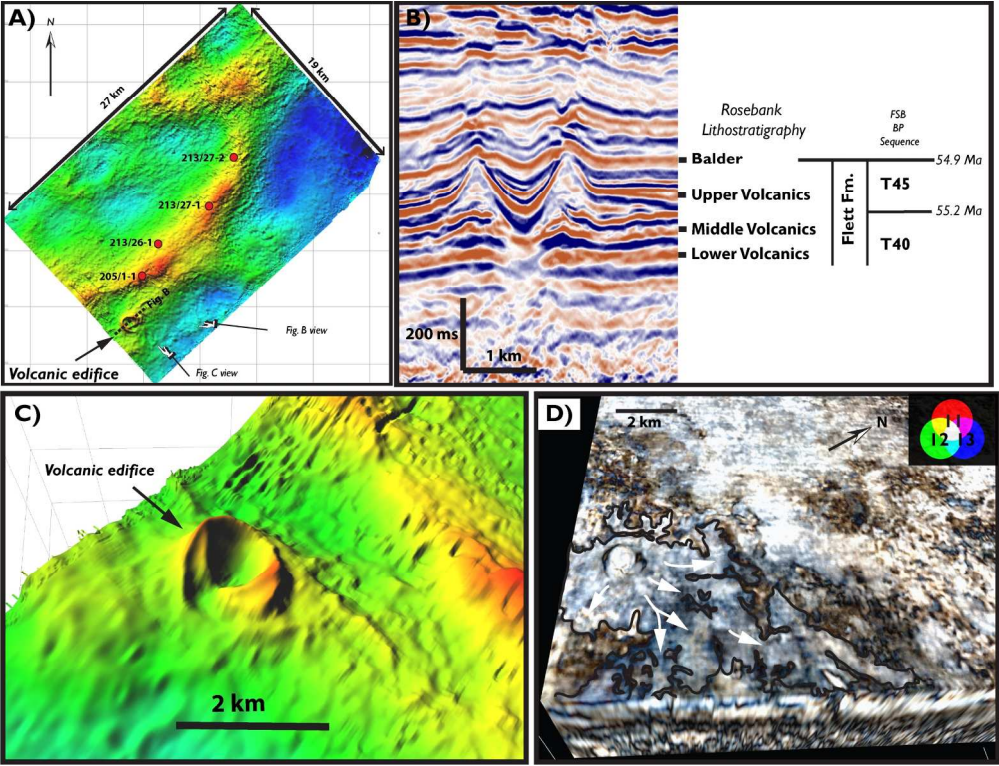


Fig 12  
211x161mm (300 x 300 DPI)

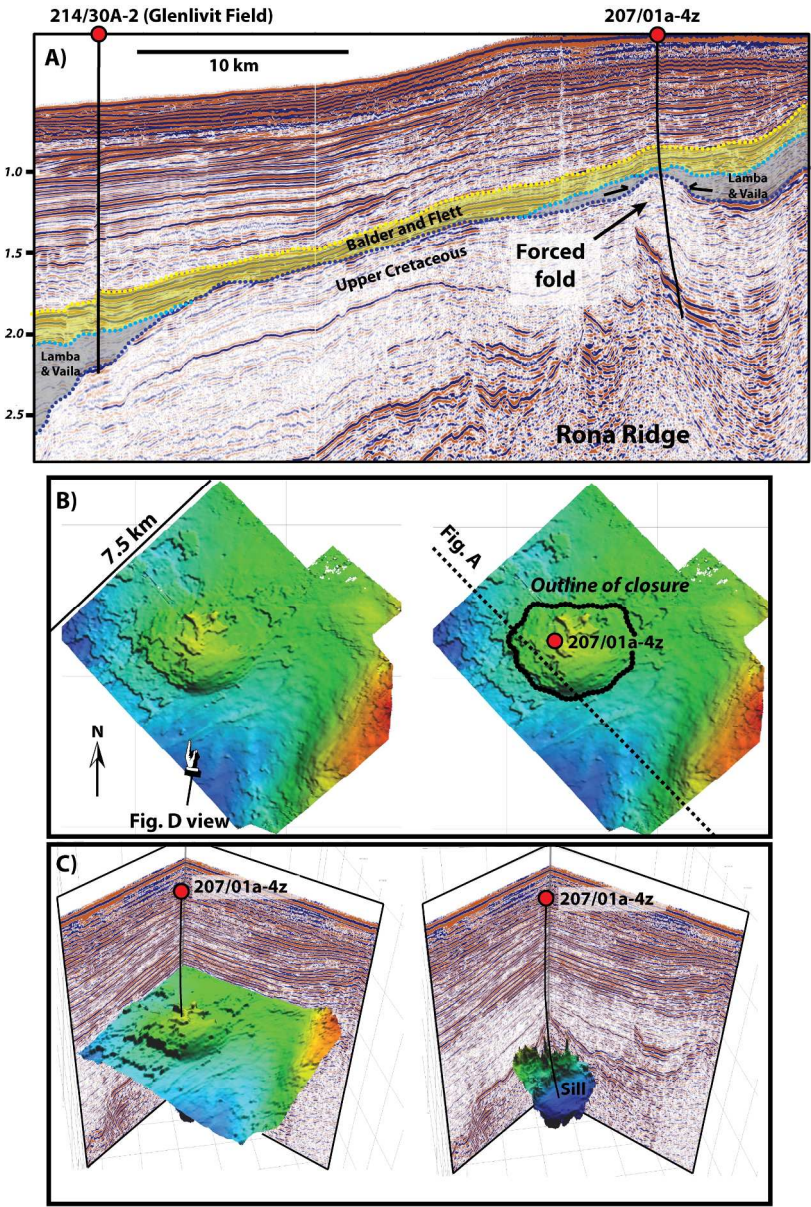


Fig 13  
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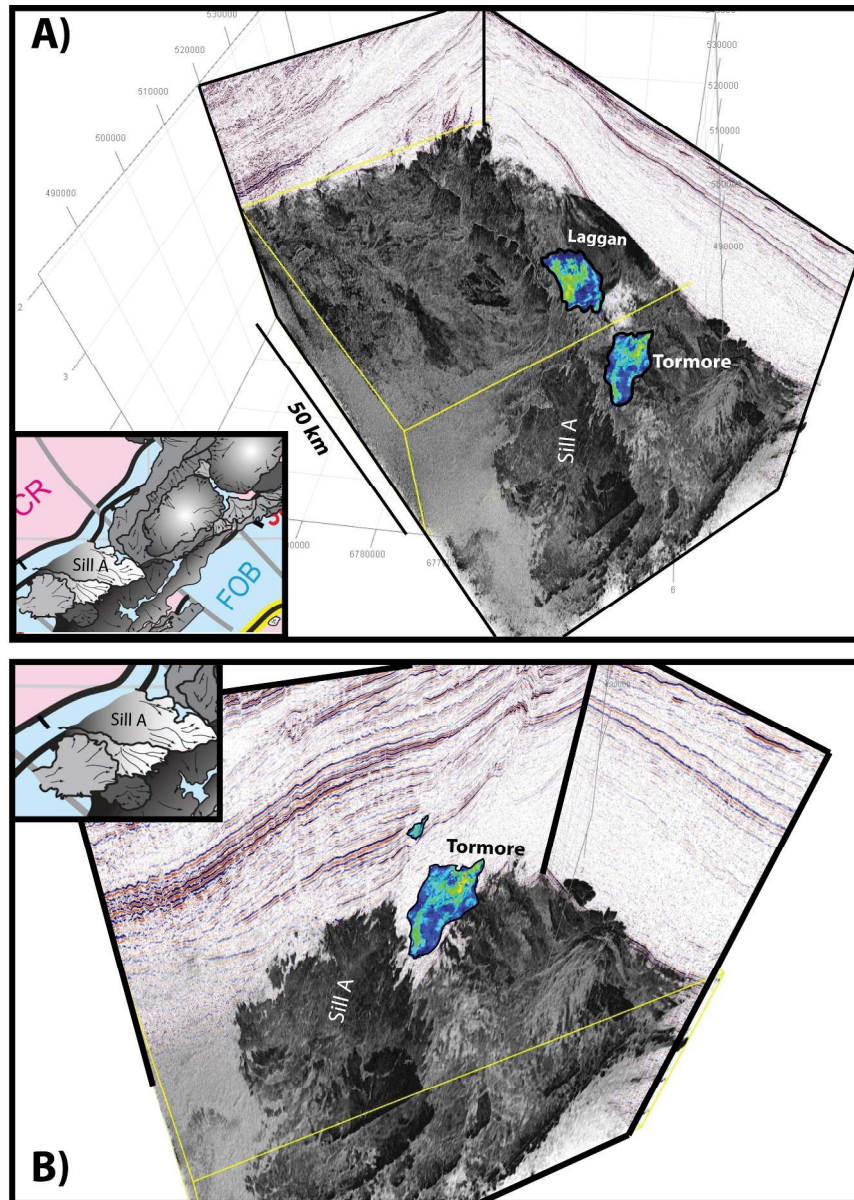


Fig 14  
201x281mm (300 x 300 DPI)

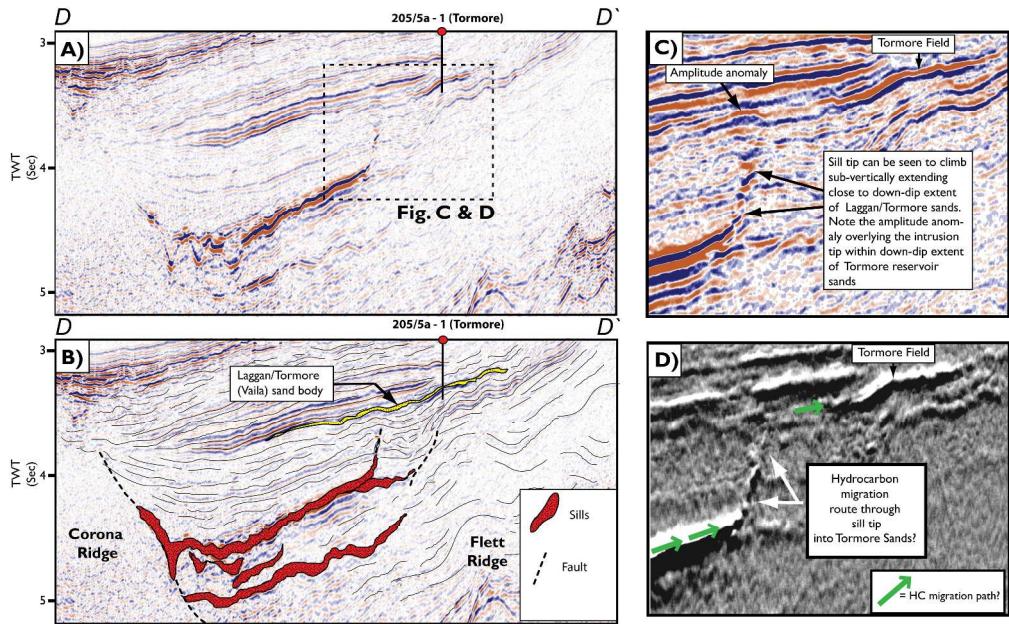


Fig 15  
339x210mm (300 x 300 DPI)