Interaction between volcanic and non-volcanic systems and its implication for prospectivity in the Faroe–Shetland Basin, NE Atlantic continental margin

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Abstract: Exploration in the Faroe–Shetland Basin has revealed thick and complex volcanic successions and discovery of inter-volcanic oil-bearing siliciclastic sandstone fan deposits in the central parts of the basin. The possibility for such play types to exist was recognized but could not be tied to regional volcanic successions and the recognition of seismically visible volcanic successions was hindered by the high resistivity of the volcanic units. The well control was limited, and the relevance of the volcanic successions for exploration was not understood. The first 3D seismic surveys in the basin allowed for regional mapping of volcanics, and the high-density well data were subsequently tied to 2D seismic interpretations which allow for chemostratigraphical correlation of wells to the absolute radiometrically age-constrained Faroe Islands Basalt Group. Early exploration for hydrocarbons on the Faroese Continental Shelf (FoCS) was driven by the discovery of large volumes of hydrocarbons in Paleocene sands in the Foinaven and Schiehallion fields (Fig. 1) on the adjacent UK Continental Shelf (UKCS) (Lamers and Carmichael 1999). The first wells on the FoCS were chasing the same play but did not provide analogous discoveries (Varming 2009). The Paleocene sand play was subsequently chased further northwards into areas where the Paleocene sands are covered by or interbedded with lavas. These lavas are part of the North Atlantic Igneous Province (NAIP) as defined by Saunders et al. (1997). The Paleocene sand play was proved as a valid play when hydrocarbons were found in fluvial, estuarine, and shallow marine sandstones within the flood basalt sequence in the Rosebank discovery (Helland Hansen 2009; Schofield and Jolley 2013; Sætre et al. 2018; Hardman et al. 2019; Duncan et al. 2020). Despite the low success rate in wells targeting intra- and sub-basaltic targets, Austin et al. (2014) proposed that the largest undrilled prospects in the Faroe–Shetland Basin will be found within or under the volcanic successions.

Sequences of flood basalts negatively impact the ability to map intra- and pre-volcanic units on conventional seismic data (White et al. 2005) and other geophysical methods. The expected prospectivity within and under the volcanic cover led to several attempts to improve imaging and thus also hydrocarbon exploration. Most tests revolved around the seismic data, where normal incidence reflection seismic data acquisition with different source/receiver configurations was attempted, as well as refraction seismic data modelling (e.g. Richardson et al. 1999; Raum et al. 2005), in order to unravel the velocities of the different units. Additional geophysical methods, such as the mapping of conductive/resistive units (Hoversten et al. 2001; Orange et al. 2002), density variations, and magnetic properties (e.g. Sweetman 1997; Morgan and Murphy 1998), were also utilized in order to understand different physical properties of the intra- and sub-volcanic sequences. There was some success in improving our understanding of the intra- and sub-volcanic sequences, but the goal of being able to map individual units on a regional scale was not achieved until Gallagher and Dromgoole (2009) demonstrated a significant improvement in seismic data quality within basalt covered areas. In addition, recent advances utilizing multi azimuth acquisition of ocean bottom node data with big sources towed deep has enabled high resolution mapping of thin intra basaltic units where the volcanic section is of limited thickness (Duncan et al. 2020). These advances have enabled regional mapping of intra- and sub-volcanic units as demonstrated by Millett et al. (2020).

Even with better seismic data, it remained a challenge to understand how volcanism and paleoenvironment affected emplacement, sedimentary processes, and geometry in an area where the volcanic units extend into a dominantly sedimentary succession as demonstrated by the transition from more than 1400 m of basaltic material in well 6005/13-1A (William) to 32 m of basalt in well 6005/15-1 (Longan) over a distance of only 20 km (see Fig. 1 for location of wells) (Varming et al. 2012).

We utilize high-quality 2D seismic data, acquired By Western Geophysical in 1994 and 1995 and reprocessed by TGS in 2012 to map the volcanic succession in the greater Judd Sub-basin area, which includes the Judd Sub-basin, Sjúður High, southern part of Brynhild Sub-basin and the Mid Faroe High (Fig. 1) with the purpose of improving our understanding of the structural geometry...
of the transition from the basaltic succession to the non-basaltic succession. We re-evaluate the lithology of igneous units from cuttings of relevant wells and tie the well stratigraphy to the seismic interpretations in order to calibrate the seismic interpretation. The structural relationships are examined and the spatial variability and temporal changes in the palaeo-depositional environment are assessed, enabling a better understanding of the cyclic nature of volcanism relative to the more continuous sedimentary processes in the study area. This understanding enables us to propose different trapping mechanisms where siliciclastic sandstones constitute reservoirs, with the volcanic units acting as seals.

Geological setting

The primary NE–SW oriented structural tract within the Faroe–Shetland Basin is associated with the Caledonian Orogeny (Doré et al. 1999; Coward et al. 2003). Extension in latest mid to late Jurassic times led to fully marine conditions within the Faroe–Shetland Basin (Doré et al. 1999; Ritchie et al. 2011). That in turn was followed by non-volcanic rifting events in the early Cretaceous (e.g. Dean et al. 1999; Lamers and Carmichael 1999; Stoker and Ziska 2011) resulting in a series of NE/SW trending sub-basins including the Judd, Brynhild and Guðrun Sub-basins. During the upper Cretaceous the Faroe–Shetland Basin was characterized by the deposition of thick deep marine clastic successions (e.g. Grant et al. 1999; Stoker and Ziska 2011).

The Faroe–Shetland Basin underwent post rift thermal subsidence during the lower-middle Paleocene (e.g. Turner and Scrutton 1993), possibly with some rifting with a slight rotation relative to the primary rift axis during the Mesozoic (Dean et al. 1999). A Paleocene rotation in stress orientation relative to the Mesozoic rift episodes (Geoffroy et al. 1994), is possibly caused by the stress regime which resulted in a NNW/SSE oriented Early Paleocene transient rift west of the Judd Sub-basin (Ziska and Varming 2008). From middle Paleocene to early Eocene widespread and voluminous volcanism of the NAIP, associated with continental breakup between Eurasia and North America, covered large parts of the FoCS (Horni et al. 2017).

The deposition in the Vaila formation changes from aggradation in the lower Vaila to progradation in the upper Vaila (Ebdon et al. 1995; Lamers and Carmichael 1999), where especially the upper part of the section is characterized by the large Cuillin and Kintail fans (Ebdon et al. 1995). The provenance of the sands changes throughout Vaila formation times, with westerly sourced sands dominating in the lower Vaila, while an increasing amount of sands sourced from the SE are found upp through the Vaila formation (Morton et al. 2012), which are interdigitated with the westerly sourced sands. Heavy mineral analyses suggest that westerly
sourced sands dominate in the Marjun well and partly in the Svinoy well, but not the Longan well located further west (Morton and Hallsworth 2002), which could indicate a sedimentary bypass.

The Longan well drilled through what was interpreted as a series of sills in the lower Vaila formation, which Smallwood and Harding (2009) subsequently reinterpreted as lava flows based on log response and seismic character. This supports radiometric age determinations which suggests that the pre-breakup flood basalts succession (the Beinisvírð and Lopra formations) of the Faroe Islands Basalt Group (FIBG) was active in mid Vaila times (e.g. Storey et al. 2007), at odds with claims that palynological data constrain the entire FIBG as contemporaneous with the Flett formation (T40–T45) (e.g. Jolley 2009). Watson et al. (2017) acknowledge the presence of volcanlastic material in the Vaila formation but ascribe its origin to a ‘Munkagrunnur Volcanic Province’. This province would thus be active during the period, which e.g. Storey et al. (2007) have dated pre-breakup volcanism of the Faroe Islands Basalt Group to be active. Jolley et al. (2021) speculate that the volcanlastic material in the well is part of a T31–T36 age volcanic succession in the Annika Basin, sourced from a previously undocumented very large (c. 20,000 km²) igneous centre under the Faroe Islands. Ziska et al. (2019) mapped this volcanic succession and subsequently tested the interpretation through potential field profile modelling and concluded that this unit belongs to the pre-breakup volcanic succession.

The progradational depositional setting during upper Vaila formation times continued to dominate through Lamba Formation times (Lammers and Carmichael 1999), where deltaic clinoforms, which indicate the palaeowater depth, are up to 500 m high (Smallwood and Gill 2002). The prograding sandstones in the Lamba formation are predominantly sourced from the SE (Morton and Hallsworth 2002). The last occurrence of westerly sourced sediments in the Judd area is found in the Kettla Member in the lower part of the Lamba formation in the Marjun well (Morton and Hallsworth 2002). The sediment provenance is supported by the presence of Greenlandic pollen assemblages at this level in wells further SE (Jolley and Morton 2007). Thickness variations and changes in sorting of the Kettla member sediments suggest a proximal source to the Anne Marie and Svinoy wells, most likely close to the Corona High (Eidesgaard and Ziska 2012). The composition of the tephra in the Kettla member is andesitic (LOI 9.7), as well as the Kettla member tuff (LOI < 6.9) as well as the Kettla member tuff (LOI < 6.9).

Geochemical analyses including major and trace elements of 10 samples from the Longan well were sampled for further lithological descriptions (Table 1). These samples are from depths (TVDDS) of 2158 to 4023 m (Fig. 2). The Longan well shows two distinct volcanic successions: an older succession assigned to the pre-breakup volcanism (T32–T34, Vaila Fm equivalent) and a younger syn-breakup succession (T40, Flett Fm equivalent). Furthermore, the Kettla member (G65) is also present in the sample collection from the well.

Fifteen cutting samples (G14–G27) from the William well were sampled at depths of 1958 to 3341 m (Table 1). In some of the sample intervals, two or three adjoining samples were merged in order to get enough material for geochemical analyses. Geochemical analyses including major and trace elements of 10 samples from the Longan well and 6 samples from the William well are presented (Table 2). Before analysis, the samples were washed in ultrasonic bath and leached in 10 M HCl acid for 2 hours. This was done to remove any secondary mineralization, primarily zeolites and calcite. The samples represent the least altered subaerial lavas (Loss on Ignition (LOI) < 6.9) as well as the Kettla member tuff (LOI 9.7).
Lithological descriptions of sampled volcanic sequences

**Well 6004/15-1 (Longan)**

The cuttings from the syn-breakup volcanic sequence (G58–G64) are comprised of angular fine-grained basalt, some with clay filled vesicles (G59, Fig. 3a). The other lithologies present are comprised of mixed brown and black claystone. These cutting assemblages are indicative for a subaerial extrusive volcanic environment with epiclastic sedimentation and development of saprolite boles.

The cuttings from the Kettla member (G65) comprise mixed sedimentary clasts and slightly abraded tuffaceous material (Fig. 3b). The observation corroborates with findings from a regional study of the Kettla member, as a redeposited volcaniclastic unit (Eidesgaard and Ziska 2012).

The lowermost volcanic sequence comprises five separate volcanic intervals identified on the composite logs. These were sampled between 3443–4023 m depth. The samples (G66–G78) display broad variety of volcanic facies (Table 1). Samples G73 (Fig. 3d) G75 and G77 are predominantly constituted by fragmental vesicular glass shards mixed with dull matrix fragments while lithic fragments with phenocrysts are also present (Fig. 3d). These assemblages are typical of subaqueous volcanic deposits in the form of hyaloclastites. A series of samples (G66, G69, G71, G72, G74, G76) are comprised of blocky angular clasts of fine-grained basalt. These samples also comprised volcaniclastic sediments and tuff (G68, G70). These samples are typical for subaerial volcanic environments. Cuttings of sample G77 are predominantly coarse-grained with a massive texture and interpreted to represent a dolerite sill intrusion.

**Fig. 2.** Re-interpreted well lithologies for William and Longan plotted together with Marjun, Svinoy and Anne-Marie wells. The logs are based on composite logs as well as new sampling and analysis of the volcanic sequences.
The detailed petrographic studies of the cuttings from Longan, document the presence of both subaerial lavas (Fig. 3a), subaqueous hyaloclastites, and dolerite sills (Fig. 3c) in the lower volcanic sequence. Importantly, this observation is at odds with the End of Well report (Hovden et al. 2002), that stated that the deeper part of the well is solely comprised of sill intrusions, but it is supported by petrophysical and seismic data (Smallwood and Harding 2009).

**Well 6005/13-1A (William)**

The volcanic lithologies show distinct sequences of predominantly hyaloclastites (Fig. 2) or subaerial basaltic lava flows throughout the well. Figure 3c, f shows examples of fine-grained basaltic lava and fragmented, glassy, and vesicular hyaloclastite cuttings, respectively.

At the base of the well, from 3344 m (G27) to 2933 m (G20), the volcanic sequence consists predominantly of hyaloclastites. However, at three intervals, subaerial basaltic lavas are found interlayered with the hyaloclastites. Furthermore, a dolerite sill is present near the base of the well. In the interval from 2850 to 2400 m only subaerial basaltic lavas are seen, while hyaloclastite is the only volcanic facies in the interval from 2400 to 2250 m. The uppermost interval from 2250 to 1900 is predominantly subaerial basaltic lavas.

**Geochemistry of volcanic sequences in Longan and William wells**

Major element concentrations of the samples show that the syn-breakup lavas are low-Ti type basalts (TiO$_2$/FeOt = 0.10–0.11), while the pre-breakup lavas comprise a wider compositional range from basaltic to basalt-andesitic (48.48–49.02 wt% SiO$_2$) (Fig. 4a). The Rare Earth Element (REE) patterns reinforce the distinct compositional signatures of pre- and syn-breakup sequences (Fig. 4b). The pre-breakup lavas are light REE (LREE) enriched expressed by normalized trace element ratios (La/SmN = 1.32–3.30) and display modest Eu anomalies, while the syn-breakup lavas have patterns of light and middle REE depletion and no Eu anomalies. Comparing the REE ratios of the syn-breakup lavas in Longan (La/SmN = 0.80–1.05Dy/YbN = 0.92–1.11) to onshore geochemical data from the FIBG (Søager et al. 2014) environment T-seq. Formation
| Sample_ID | G58 | G59 | G63 | G65 | G66 | G69 | G71 | G72 | G74 | G76 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Depth (m) | 2158 | 2167 | 2185 | 2760 | 3443 | 3570 | 3585 | 3627 | 3834 | 4023 |
| Lithology | Basalt | Basalt | Basalt | Tuff | Basalt | basalt | basalt | basalt | basalt | basalt |
| Major elements (wt%) | | | | | | | | | | |
| SiO₂ | 48.48 | 49.02 | 48.80 | 57.12 | 50.44 | 50.18 | 50.58 | 50.11 | 57.04 | 55.01 |
| Al₂O₃ | 13.97 | 14.02 | 14.40 | 17.43 | 14.28 | 14.38 | 13.56 | 13.39 | 16.68 | 16.28 |
| FeO⁺ | 14.13 | 13.60 | 13.10 | 9.58 | 13.11 | 14.29 | 14.36 | 13.98 | 9.98 | 10.31 |
| MgO | 6.92 | 7.06 | 7.52 | 5.13 | 6.30 | 7.11 | 5.89 | 7.54 | 4.83 | 4.93 |
| CaO | 12.09 | 11.83 | 12.15 | 1.57 | 10.86 | 7.92 | 10.24 | 9.80 | 3.73 | 6.72 |
| Na₂O | 2.09 | 2.13 | 1.99 | 3.21 | 2.40 | 2.69 | 2.46 | 2.24 | 2.51 | 1.95 |
| K₂O | 0.43 | 0.49 | 0.41 | 4.11 | 0.77 | 1.36 | 0.96 | 3.40 | 3.60 | 3.08 |
| P₂O₅ | 0.11 | 0.11 | 0.11 | 0.21 | 0.15 | 0.16 | 0.14 | 0.14 | 0.32 | 0.24 |
| Trace elements (ppm) | | | | | | | | | | |
| Nb | 3.7 | 3.3 | 2.9 | 15.00 | 3.3 | 6.8 | 4.3 | 4.9 | 15.7 | 11.6 |
| Zr | 75.5 | 74.9 | 64.5 | 177.70 | 89.5 | 113.6 | 109.5 | 105 | 197.4 | 182 |
| Y | 32.2 | 31.9 | 29.2 | 25.90 | 28.6 | 31 | 39.6 | 34 | 27.8 | 23 |
| Nb/Y | 0.11 | 0.10 | 0.10 | 0.58 | 0.12 | 0.22 | 0.11 | 0.14 | 0.56 | 0.50 |
| Nb/TiO₂ | 0.11 | 0.10 | 0.10 | 0.58 | 0.12 | 0.22 | 0.11 | 0.14 | 0.56 | 0.50 |
| La/Yb | 0.11 | 0.10 | 0.10 | 0.58 | 0.12 | 0.22 | 0.11 | 0.14 | 0.56 | 0.50 |
| Trace elements (ppm) | | | | | | | | | | |
| La | 5 | 3.9 | 3.3 | 27.30 | 7.5 | 12.4 | 9.1 | 8.6 | 35.5 | 28.4 |
| Ce | 10 | 10 | 8.9 | 57.90 | 17.7 | 28.4 | 22.4 | 20.7 | 75.6 | 63.8 |
| Sm | 3.06 | 2.83 | 2.65 | 5.76 | 3.13 | 3.66 | 2.77 | 3.09 | 7.10 | 7.91 |
| Eu | 1.07 | 1.14 | 1.14 | 1.22 | 1.24 | 1.41 | 1.33 | 1.74 | 1.33 | 1.44 |
| La/Yb | 0.11 | 0.10 | 0.10 | 0.58 | 0.12 | 0.22 | 0.11 | 0.14 | 0.56 | 0.50 |
| Trace elements (ppm) | | | | | | | | | | |
| La | 5 | 3.9 | 3.3 | 27.30 | 7.5 | 12.4 | 9.1 | 8.6 | 35.5 | 28.4 |
| Ce | 10 | 10 | 8.9 | 57.90 | 17.7 | 28.4 | 22.4 | 20.7 | 75.6 | 63.8 |
| Sm | 3.06 | 2.83 | 2.65 | 5.76 | 3.13 | 3.66 | 2.77 | 3.09 | 7.10 | 7.91 |
| Eu | 1.07 | 1.14 | 1.14 | 1.22 | 1.24 | 1.41 | 1.33 | 1.74 | 1.33 | 1.44 |
| La/Yb | 0.11 | 0.10 | 0.10 | 0.58 | 0.12 | 0.22 | 0.11 | 0.14 | 0.56 | 0.50 |

*Normalized relative to C1 chondrite (Sun & McDonough, 1989)
and Holm 2011), and the East Greenland plateau lavas (Larsen et al. 1999), this signature is typical of the well-characterized low-Ti Mid Ocean Ridge Basalt (MORB) basalts that are only found in the syn-breakup lava formations. The lowermost sampled sequences of the pre-breakup lavas (samples G76 and G74) are both compositionally evolved basaltic andesites with greater LREE enrichment and highest Zr/Y and Nb/Y ratios of all samples (Table 2) and hence distinctly different from the other two groups (Fig. 4).

The geochemistry (Fig. 4 and Table 2) from the William well classifies the sampled sections as low-Ti lava types, having a primitive major element signature and TiO$_2$/FeOt ratios are all consistently around 0.1. The REE signatures show well defined LREE depleted trends in all the samples. These LREE depleted signatures are only seen in the syn-breakup sequences onshore. The collective major and trace element data do thus suggest that all the volcanic rocks in this well are of syn-breakup affinity.

**Seismic interpretation**

The seismic interpretation within the study area is tied into a regional seismic interpretation. The key horizons are top basalt, base syn-breakup volcanics, Kettla member, top pre-breakup volcanics, and base basalt. Here we define each of the key horizons:

- **Top basalt** is here defined as the uppermost extrusive basalt unit. Top basalt is characterized as a strong positive reflection on the seismic data. The reflection is continuous in some places, while it is characterized by rapid depth variations (steps) in other locations, most likely due to termination of individual flows or flow groups within an otherwise sedimentary section. The extrusive basalt sequence has been drilled in a number of exploration wells in the Faroe–Shetland Basin, including three of six wells in the study area.

- **Base syn-breakup volcanics** is here defined as the base of the oldest occurrence of volcanics associated with
continental breakup. The horizon, which is tied to onshore observations and boreholes, is characterized as a relatively strong continuous positive reflection on seismic data. The seismic facies of the syn-breakup volcanic unit is mostly seen as plane-parallel reflections. Where these overly pre-breakup volcanic units, the horizon is seen as a transition into a chaotic to hummocky section. In areas where the syn-breakup volcanics overlie non-volcanic strata, the transition is seen as a strong continuous reflection. The base of the syn-breakup volcanics is drilled in wells 6104/21-1&2 (Brugdan I/II), 6104/25-1 (Súlan/Stelkur) and the William well, where it marks a transition from a succession with variable volcaniclastic lithologies below to a succession dominated by subaerial basalt above. A hiatus is seen in the Anne Marie well at this level. The Longan well penetrated this horizon at a higher stratigraphic level compared to other wells (Fig. 2).

- **Top pre-breakup volcanics** is here defined as the top of the youngest occurrence of the extrusive volcanics belonging to the pre-breakup basalt succession. It is tied to onshore observations and boreholes. Top pre-breakup volcanics is on most of the FoCS, within the resolution of the data, coincident with the base-of the syn-breakup volcanics, as seen onshore Faroe Islands where the two horizons are separated by 3–15 meters of lacustrine sediments of the Prestfjall Formation (Fig. 2) (e.g. Rasmussen and Noe-Nygaard 1970; Passey and Jolley 2009). In the study area, the base syn-breakup volcanics and top pre-breakup volcanics are separated by sedimentary section that in the Longan well is more than 1000 meters. The Longan well drilled into subaerial basalt, which is seen as a high amplitude continuous reflection. Further towards the north and NW, the reflection is seen as a slope separating a volcanic unit with chaotic reflection pattern below, from a non-volcanic unit above, that predominantly exhibits a plane-parallel reflection character.

- The volcaniclastic Kettha member, also referred to as the Kettha tuff, resides within the lower Lamba formation (T36) (Eidesgaard and Ziska 2012; Watson et al. 2017). The horizon is characterized as a strong continuous reflection on seismic data in the eastern part of the study area. It is plane-parallel with another deeper strong continuous reflection 100–150 ms deeper. The latter is referred to as ‘lower tuff’
We present four 2D seismic profiles that illustrate how the geometry of the transition from the volcanic section to the non-volcanic section changes on a sub-basin scale (Fig. 1 for location of profiles). In addition, we present a profile from a 3D dataset that resolves individual flow packages within Vaila Formation siliciclastic sediments. None of the seismic profiles intersect the shown wells directly, with the closest being 2.3 km offline, consequently no synthetic well tie modelling was performed.

**Profile A**

Profile A (Fig. 5a–c) runs from Brynhild Sub-basin southeastwards across Sjúðrúur High and into the Judd Sub-basin. It ties the three wells William (7.1 km offline), Longan (3.0 km offline), and Marjun (2.7 km offline), where the first two drilled through both pre- and syn-breakup lavas. The Marjun well did not encounter any subaerial lavas.

The Base Basalt interpretation is tied to a regional interpretation. In the northwestern part of the profile, this horizon is mapped as a series of high amplitude discontinuous reflections. These reflections change to a strong continuous reflection between the William and Longan wells. The top of pre-breakup volcanics is seen as a strong continuous reflection towards the SE, NW, towards the William well, the reflection extends to the base of an escarpment. The southeastward dipping units behind this escarpment were proven to consist of hyaloclastite deposits in the William well (bottom section, Fig. 2).

The Kettla member is seen as a strong continuous reflection towards the SE. The reflection loses strength towards the NW, which means it is not possible to follow it all the way to the volcaniclastic delta front.

The base syn-breakup volcanics reflection is mapped as a strong continuous reflection, separating an underlying almost seismically opaque section, with hints of plane-parallel reflections from an overlying section with similar internal seismic characteristics. Towards the SW, it overlies an angular unconformity. The top basalt reflection is a strong discontinuous reflection. Figure 5c shows a schematic representation of the interpreted section at the same scale. The interpretation is constrained by the three wells shown in Figure 5b. The volcanic facies is based on the seismic interpretations described above and supported by cuttings descriptions.

**Profile A2**

Three continuous high amplitude reflections are seen on the western part of the east–west oriented profile A2 (Fig. 6). These reflections are tied to the Longan well. The well is located at the edge of the dataset, 2 km north of profile A2, where the presence of syn-breakup lavas compromises data quality.

The high amplitude reflections of the pre-breakup volcanic flow fields on the seismic profile (A, B and C on Fig. 6) represent from bottom to top: a lower extrusive unit that the well was terminated within, a middle extrusive unit overlying a siliciclastic sedimentary section, and an uppermost extrusive unit overlying a volcaniclastic sedimentary unit. The thickness of the sedimentary successions between the lava flows differs from observations in the well, with the lowermost siliciclastic unit being the dominant sedimentary unit south of the well (Fig. 6), while the sedimentary unit separating the two overlying lavas is thicker in the well (c. 130 v. c. 200 m). Amplitude extractions of the volcanic units are shown in Figure 7, in order to visualize the areal extent of each unit within the 3D survey area.

The lowermost subaerial lava (Fig. 7a) is only present in patches, as indicated by the discontinuous nature of the high absolute amplitude reflections on Profile A2 (Fig. 6). Three 6–8 km long east–west oriented areas characterized with higher absolute amplitude extend toward the eastern edge of the unit. This unit is separated from the lowermost subaerial unit by a siliciclastic section. The middle volcanic unit (Fig. 7b) displays a much larger coherent area characterized by high absolute amplitude and broadly sinuous limit. The uppermost volcanic unit (Fig. 7c), which is separated from the middle subaerial unit by a volcaniclastic unit, is, similarly to the lowermost unit, only present in patches, but does overall maintain a broad, sinuous and well-defined eastern limit of the high-amplitude area.

The strong amplitude features under the pre-breakup basalt sections are interpreted to represent a series of sills (Fig. 6). These are characterized by their upward transgressive nature, with upward curved edges with one of the larger saucer shaped sills feeding a sill that is situated just below the lowermost extrusive basalt unit (indicated by arrows on Fig. 6). This transgressive nature is distinctly different from the subaerial basalt units above, which are conformable with the sedimentary units.

**Profile B**

Profile B (Fig. 8a–c) runs from the southwestern part of the Judd Sub-basin towards, but not crossing, the southern part of profile A (above). The resolution of this seismic profile is more challenging compared to the other profiles, which hinders detailed interpretations of the subvolcanic units.

Base Basalt is tied to a regional interpretation performed by the authors. It is seen as a continuous reflection towards the NE, where the data quality is best. It can be traced with some confidence c. 10 km’s towards the SW under the top pre-breakup 2 horizon.

The top of the older pre-breakup volcanics reflection (lower yellow horizon in Fig. 8b) is characterized by strong positive reflection, which lose its continuity where it is overlain by the upper yellow horizon, which becomes the top pre-breakup reflection, while the lower yellow reflection thus becomes an intra-pre-breakup reflection at this location. The lower yellow reflection separates an underlying section, which is dominated by the strong basalt reflection, from a homogeneous section above, with plane-parallel continuous reflections. There are indications that the same style of transition is repeated under the upper yellow reflection, but the degradation in seismic data quality inhibits confidence in this regard.

The second incursion of pre-breakup lavas is seen as a strong semi-continuous reflection towards the NE but loses its continuity and becomes more rugose further towards the SW (upper yellow horizon in Fig. 8b). The horizon marks a transition from an underlying section with strong discontinuous reflections to a
Fig. 5. Seismic profile A, see Figure 1 for location. Top: uninterpreted seismic section. Middle: seismic section with interpretations. Bottom: geoseismic interpretation of the seismic section at the same scale. BSB, Brynhild Sub-basin; SH, Sjúrður High; JSB, Judd Sub-basin (data courtesy of TGS). See main text for introduction to the interpreted seismic horizons.

Fig. 6. Seismic profile A2, see Figure 1 for location. (a) oldest pre-breakup basalt, (b) middle pre-breakup basalt and (c) youngest pre-breakup subariel basalt. Simplified composite log from the Longan well.
seismically almost transparent section above. The data indicates a continuation of the plane-parallel reflections towards the NW continuing under the second pre-breakup section. The top of this unit seems to be contemporaneous with the Kettla member, as indicated with a dashed orange line in the figure. The density of seismic data in this area precludes a confident tie. The interaction between the siliciclastic sediments and the volcanic units under top-breakup volcanic succession 2 cannot be interpreted on available data on this profile, but the presence of a hyaloclastite delta is a likely explanation, as indicated in Figure 8c.

The top basalt reflection is quite rugose. It is tentatively interpreted to extend into the basin, where it becomes more continuous. A better delineation of the extent into the basin requires 3D seismic data, which are not available in this area. Towards the SW the seismic fascies of the underlying unit changes to a hummocky character, which is interpreted to represent a change from predominantly non-volcanic section to a predominantly volcanic section (Fig. 8b).

Data quality limits interpretation of the different units, but an attempt to illustrate how the volcanic and non-volcanic units could be interpreted to interact is shown schematically in Figure 8c. The extent of the thick non-volcanic section separating the lower and upper pre-breakup volcanic successions is inferred, similarly the interdigitating geometry of the interaction between the syn-breakup volcanic and the non-volcanic successions.

Profile C
Profile C (Fig. 9a–c) extends southeastwards from the Brynhild Sub-basin into the Judd Sub-basin where it ties the Svinoy well. The entire Paleogene section in the well is sedimentary, which on the seismic data is seen as a section that is well resolved with many continuous reflections with little noise.

The Base Basalt interpretation, which is tied to a regional interpretation, is defined by a series of discontinuous strong reflections. The interpretation stops where the internal seismic reflection of the overlying unit changes from being chaotic to being dominantly plane parallel with discrete upward curved reflections, interpreted to represent igneous sills intruded into a sedimentary succession.

The Kettla member and ‘lower tuff’ are seen as a pair of strong continuous reflections towards the SE. When these reach the area under the syn-breakup volcanic succession, they both loose reflection strength. The lower tuff is currently interpreted to be contemporaneous with the base of the second time the pre-breakup volcanic succession extends into the study area (Fig. 9b, c). It is not possible to follow the Kettla member under the syn-breakup volcanic succession.

The noisy section, which is interpreted to be pre-breakup volcanic units, above the interpreted base basalt reflection, terminates abruptly towards the SE. The older part of the pre-breakup volcanic succession extends towards the SE before receding prior to a new advancement towards the SE. No dipping reflections are seen towards the front of the pre-breakup volcanic succession, suggesting that the entire succession consists of either weathered volcanic units or volcanioclastic sediments.

Base syn-breakup volcanics is interpreted as a continuous reflection separating the discontinuous chaotic reflections below from the plane-parallel reflections above. The termination into the Judd Sub-basin is based on a slight change in reflection character of the overlying unit. Top basalt is seen as a strong continuous reflection, which in a similar manner to base syn-breakup volcanics, ends where the reflection character of the section between those two horizons changes character.

Figure 9c shows a schematic representation of the interpreted interaction between the volcanic and non-volcanic succession. The schematic is constrained by the Svinoy well. The intra-volcanic characteristics is based on seismic interpretations described above.

Profile D
Profile D (Fig. 10a–c) extends from the Svinoy well in the Judd Sub-basin northeastwards onto the Mid Faroe High, where it ties the Anne Marie well (3.8 km offset). Near the location of the well the deeper section is dominated by the Mid Faroe High structure. The Anne Marie well drilled into a siliciclastic section at the base. This is used to interpret base basalt across the Mid Faroe High area. The base basalt reflection ties into the reflection of the ‘lower tuff’ drilled by the Svinoy well, indicating absence of the older pre-breakup lavas drilled by the Longan well. The interpreted top pre-breakup volcanics horizon extends from the mound at the crest of the Anne Marie into the northeastern part of the Judd Sub-basin where it ties the top Kettla member drilled in the Svinoy well.

The base syn-breakup volcanics reflection has not been interpreted as a separate unit. It coincides with the top pre-breakup volcanics horizon across the mound, where it separates discontinuous reflections below from plane-parallel reflections above. The plane-parallel syn-breakup reflections onlap the mounded pre-breakup section. Towards the SW it has not been possibly to confidently interpret basesSyn-breakup volcanics due to the interaction of the continuous reflections of the onlapping syn-
breakup lavas and the continuous reflections of the Lamba Formation siliciclastic sandstones drilled in the Svinoy well.

Top basalt is seen as a strong continuous reflection from the crest of the Mid Faroe High and into the Judd Sub-basin. The Svinoy well did not drill through any lava flows. The available 2D seismic data do not suggest a precise location for the termination of the top basalt reflection.

Figure 10c shows a schematic representation of the interpreted section at the same scale. The interaction between the volcanic and non-volcanic successions is partly based on the interpretation of the seismic data but is augmented with inferred details. Improved seismic data quality is a requirement for mapping these units in greater detail.

Geological evolution

Correlation of well analyses and seismic data shows how the volcanic units entered different parts of the Judd Sub-basin area at different times.

Vaila formation (T25–T35)

The first occurrence of volcanism in this area is in the T32–T34 during middle Vaila formation times (Figs 2 and 11a). The volcanic units transgressed on three occasions from the west/NW into a shallow marine environment in the western part of the study area, where it on each occasion deposited a sequence of hyaloclastites.
overlain by sub arial basalt. These volcanic units have a distinct pre-breakup geochemical signature (Fig. 4), demonstrating that that pre-breakup volcanism started no later than c. 60 Ma (timescale by Gradstein et al. 2020). This is considerably earlier than the age model for FIBG volcanism proposed by e.g. Ellis et al. (2002); Jolley (2009) and Hardman et al. (2019), who argue that the entire pre-breakup lava section is part of the Flett Formation on the basis of palynological correlations across the NE Atlantic. The combined evidence of seismic interpretations, cuttings, and geochemical analyses, presented here, firmly places extrusive pre-breakup volcanism in the T32–34, negating the need to introduce a new volcanic province as proposed by Watson et al. (2017), or a new abnormally large igneous centre underneath the Faroe Islands as proposed by Jolley et al. (2021).

Evolved geochemical signatures are seen in two of the six samples in the pre-breakup volcanic succession in Longan (Fig. 4). Such signatures are only seen in volcanic centres in the region, both in the Erlend Volcano (Kanaris-Sotiriou et al. 1993; Jolley and Bell 2002) and in well 163/6-1A (Darwin) (Morton et al. 1988), where dacitic compositions with highly enriched in LREE signatures are documented. For magmas to evolve signatures like these, sustained magmatic differentiation in magma chambers is needed coupled
with crustal contamination. The only volcanic complex in the vicinity of Longan is Frænir, situated some 50 km to the WNW (Fig. 1). In comparison, the most evolved samples of the series are comparable in both major element compositions and REE-trends to the Lamba formation Kettla member tuffs (Fig. 4).

The collective well data and seismic interpretation presented here, corroborate with the age model for the NAIP that, based on radiometric age determinations (Waagstein et al. 2002; Storey et al. 2007), terrestrial magnetostratigraphy of the flood basalt on the Faroe Islands (Abrahamsen et al. 1984; Riisager et al. 2002), as well

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**Fig. 10.** Seismic profile D, see Figure 1 for location. Top: un-interpreted seismic section. Middle: seismic section with interpretations. Bottom: geoseismic interpretation of the seismic section at the same scale. JSB, Judd Sub-basin; MHF, Mid Faroe High (data courtesy of TGS). See main text for introduction to the interpreted seismic horizons.
as trans-Atlantic correlations (Larsen et al. 1999), demonstrates that the pre-breakup volcanism initiated at 62–60 Ma and is thus contemporaneous with the lower Vaila formation in the study area.

Volcanic transport systems fed lava flows into the western part of the area (Fig. 8), where they advanced at least three times. The latter two flowing into a shallow water environment, leading to formation of progradational lava deltas with infill hyaloclastite aprons eventually overrun by subaerial basalt lava flows (Figs 6–8). The sediments deposited on top of the oldest and youngest drilled pre-breakup subaerial basalts are siliciclastic (Fig. 7), while those that cover the middle section of subaerial basalts are volcaniclastic. The latter suggests the emergence of elevated volcanic terranes as source material for volcaniclastic deposits during pre-breakup volcanism. The extent of these subaerial basalts reached further into the Judd Sub-basin in comparison to the overlying syn-breakup succession that is commonly used to define the edge of the basalt. The lack of sufficient quality 3D data over the northern and eastern part of the area prevents detailed mapping. However, 2D data indicates that the pre-breakup lavas did not flow as far into the northeastern part of the basin (Fig. 9), which could suggest a less shallow marine environment in the northeastern part of the basin at this time.

Fan deposits sourced from the SE were prograding into the Judd Sub-basin during upper Vaila Formation times (Ebdon et al. 1995; Lamers and Carmichael 1999). Seismic data suggests that the volcanic and non-volcanic depositional systems both infill the basin at similar rates as demonstrated by the near identical thicknesses of the succession between top basalt and its non-volcanic equivalent to base basalt and its non-volcanic equivalent (Fig. 5).

The Marjun well documents a continued supply of westerly sourced sediments throughout Vaila formation times (Morton and Hallsworth 2002), which shows that pre-breakup volcanism did not sever the link to these provenance areas during this time. Highly angular siliciclastic and volcaniclastic grains in the upper Vaila formation in the Svinoy well (Fig. 3b in Friis et al. 2014) do indicate a limited transport distance, which leaves the adjacent Munkagrunnur Ridge the most likely provenance area (Fig. 1) as previously proposed by Ziska and Andersen (2005). The absence of westerly sourced sands in the Longan well located nearer the Munkagrunnur Ridge, does however highlight the need for further work to understand provenance and the most likely transport direction of the westerly sourced sands.

**Lamba formation (T36–T38)**

In the northeastern part of the Judd Sub-basin area a large mound NE of the Westrey Lineament, mapped by Schofield and Jolley (2013), extends from the NW towards the SE without reaching the

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*Fig. 11. Synthesis of observations from the Judd sub-basin area in the early Paleogene presented as a series of conceptual geological block-diagrams. Stratigraphic T-sequences are used as age intervals. See Figure 2 for absolute ages. The figure is based on well analysis and seismic interpretations.*
The primary cause of failure in early exploration on the Faroese Continental Shelf, which was centred in the greater Judd Sub-basin area, was the abundance of siliciclastic sands, and consequently the lack of potential seal (Varming 2009). A thick oil column in the Marjun well, a thin gas column in the Svinoy well and oil shows in the Longan well did however prove the presence of an active hydrocarbon system in the area (Varming 2009). The failure to find hydrocarbon accumulations in commercial quantities led to a re-focus of the exploration effort being changed to searching for large four-way dip closed sub basin structures (Goodwin et al. 2009; Varming 2009). The effort to drill four-way dip closed structures on the FoCS were unsuccessful in finding any viable reservoirs, with all the drilled targets being wholly volcanic. The Anne Marie well drilled through a total of 365.5 m of significant gas shows within the volcanic succession. There was less than 5 m of pay due to the volcanic succession having very low permeability to being tight, based on core analyses and formation pressure tests (Alkanshi et al. 2011).

Analyses of the Rosebank discovery using state of the art seismic data (Duncan et al. 2020; Poppitt et al. 2021), and integrating these and other data with well results (Millett et al. 2021), supported by analogues (Hole et al. 2013; Larsen et al. 2018; Vosgerau et al. 2021), has increased the understanding of how volcanic units affect charge, reservoir distribution, connectivity and quality as well as provide competent seals for hydrocarbon accumulations (Helland Hansen 2009; Larsen et al. 2018). A comprehensive breakdown of potential play types in a volcanic setting can be seen in Millett et al. (2020).

Our work has shown that volcanic units have at different times extended into a dominantly siliciclastic succession in the study area, and thus potentially providing the seal, which was the key cause of failure in the first wells drilled in the area. It is therefore relevant to re-evaluate potential trap configurations based on our work.

Figure 12 shows a schematic cross section illustrating a transition from a purely volcanic succession on the left (blue and purple units) to a dominantly non-volcanic succession on the right (yellow unit). The interaction between the volcanic and non-volcanic units in the figure is based on the findings in previous sections. The overall risks associated with the interaction varies depending on the relative thickness of the volcanic v. non-volcanic units, with top seal becoming more competent when the volcanic succession becomes thicker, while reservoir thickness and connectivity decrease with increasing thickness of the volcanic succession (Larsen et al. 2018).
The volcanostratigraphy is shown to the left of the figure, while the non-volcanic stratigraphy is shown to the right. The diachronous nature of the transgression of volcanic units into the basin prevents a cross figure correlation of stratigraphic units.

The earliest proven incursion of basaltic material in the Judd Sub-basin area was during middle Vaila formation (1 on Fig. 12), where episodic southeastward advances by a lava transport system occurred (Figs 6 and 7), which led to interdigitation with siliciclastic sandstones (Fig. 2). Oil shows were found within the siliciclastic sands separating the two lowermost transgressions of subaerial lavas into the western part of the study area (Varming 2009). These sands most likely pinch out northwestern towards the continuous, thicker stack of the pre-breakup volcanic section (Figs 5c and 6c) thereby potentially constituting a stratigraphic trap. In addition, detailed mapping of the subaerial basalts identified in Figures 7 and 8, especially the middle unit, which overlies siliciclastic sandstones, could reveal four-way dip closed structures that potentially could constitute hydrocarbons traps.

The second major incursion of volcanic units into the Judd Sub-basin area occurred towards the top of the Vaila formation (2 on Fig. 12). The Longan and Marimas wells drilled a volcaniclastic unit, which can be correlated with the base of the volcanic succession in the Mid Faroe High area is seismically correlated with the Kettla member, which Lamers and Carmichael (1999) suggested acts as a regional seal. The Kettla member can be mapped in the eastern part of the Judd Sub-basin area. Both volcaniclastic units (lower tuff and Kettla member) rest on siliciclastic sands, which means that positive structures could provide exploration targets (Fig. 12), although the Marjun well did penetrate this unit without finding any hydrocarbons at this level (Varming 2009). The Figures 5, 6, 9, and 10 show how the siliciclastic units pinch out when they meet the front of the pre-breakup volcanic units. There is thus scope for both structural and stratigraphic traps in the eastern and northeastern part of the area. It is currently unclear if the play is present towards the SW, where a volcanic incursion (Fig. 5) seems to have occurred contemporaneously with the pre-breakup succession in the Mid Faroe high area (Fig. 10).

The syn-breakup lavas constitute the third large scale incursion of volcanic material into the basin (3 on Fig. 12). These lavas can act as top seal in stratigraphic traps around the edge of the basin, as well as in currently unmapped structural traps. Thick siliciclastic sands of the Lamba and Flett formations separate the pre-breakup volcanic units from the syn-breakup volcanic units (Fig. 12). Detailed mapping of the base of the syn-breakup volcanic succession would show if there are any significant structures that could be explored. Similarly, mapping of the pinchout of the Lamba and Flett formation sands the latter infilling the erosional landscape created by the Flett formation unconformity, towards the NE, north and west could reveal potential three-way dip closed structures with an up-dip seal provided by the dominantly very low permeability of volcanic units as demonstrated by Alkanshi et al. (2011) and Ólavsdóttir et al. (2015).

**Conclusions**

The temporal development of the greater Judd Sub-basin area of the Faroe–Shetland Basin during the middle to late Paleocene was complex and highly dynamic due to frequent and transient changes in the depositional environment and provenance. These changes were to a large extent caused by changes in the volcanic and tectonic regimes. Existing source regions and siliciclastic sediment transport systems were obstructed and diverted, new volcaniclastic sources emerged, volcanic transport systems prograded into the basin where deposits interdigitated with those of competing siliciclastic transport systems, while transient uplift led to rapid changes in water depths thereby causing depositional shifts to shallow-marine facies, shelf bypass and erosion.

Incursions of volcanic material varied across the Judd Sub-basin area, with the first proven incursion, consisting of volcanic units within the T32 sequence of the Vaila formation, emplaced in a shallow marine to subaerial environment in the western part of the study area. The earliest indication of volcanism in the Mid Faroe High area is latest Vaila to early Lamba formation (T35–T36), which is seismically correlated to a volcaniclastic unit (Lower Tuff) in the Svinoy and Marimas wells, while the top pre-breakup volcanic succession in the Mid Faroe High area is seismically correlated to the Kettla member within the lower Lamba formation in the central part of the Judd Sub-basin area.

A siliciclastic delta system dominated the Judd sub-basin area during upper Lamba Formation and was penecontemporaneous with the Prestfjall Formation that separates pre-breakup and syn-breakup volcanic successions onshore Faroe Islands.

The syn-breakup volcanic units encroach upon the Judd Sub-basin area from west, north and NE, where they in parts of the study area rest on an erosional unconformity that represents a hiatus, that spans most of the Flett formation (T40).

The employed methodology of integrating new interpretations of cuttings from boreholes, performing geochemical analysis of these, and correlating the results with seismic interpretations has enabled a better understanding of the geological evolution in the study area during the mid-Paleocene to early Eocene.

This study demonstrates that in several areas of the greater Judd sub-basin, siliciclastic sands of Vaila to Flett formation age are overlain by or wedged between volcanic units, which opens up for
