

# Seismic Volcanostratigraphy of the Faroe-Shetland Basin

A thesis  
Submitted towards the partial fulfilment of  
BS-MS dual degree programme  
by

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DATE: 31/10/2023

under the guidance of

DR. SUDIPTA SARKAR

IISER PUNE

from May 2022 to Oct 2023

INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH  
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# Certificate

This is to certify that this dissertation entitled "Seismic Volcanostratigraphy of the Faroe-Shetland Basin" submitted towards the partial fulfillment of the BS-MS degree at the Indian Institute of Science Education and Research, Pune, represents original research carried out by "Saksham Rohilla" at "IISER Pune", under the supervision of "Dr. Sudipta Sarkar" during academic year June 2022 to December 2023.

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# Declaration

I, hereby declare that the matter embodied in the report titled “Seismic volcanostratigraphy of the Faroe-Shetland Basin” is the result of the investigations carried out by me at the “IISER Pune” from the period 01-06-2022 to 01-10-2023 under the supervision of Dr. Sudipta Sarkar and the same has not been submitted elsewhere for any other degree.

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# Abstract

The Faroe-Shetland Basin, located in the North Atlantic Ocean, is well known for its complex geological history, with a significant volcanic and tectonic influence shaping its subsurface architecture. The Paleocene continental breakup in the North Atlantic was accompanied by cataclysmic volumes of flood basalt eruption, followed by regional scale intrusion of igneous bodies. The resulting volcanic deposits in the Faroe-Shetland basin hold the key to understand the evolution of a volcanic rifted basin. The thesis presents a comprehensive study of the Paleocene-Eocene volcanic succession using the concepts from seismic volcanostratigraphy to shed light on the paleodepositional environment of different volcanic and volcanoclastic deposits. We use high resolution 3D seismic cubes to classify and interpret different seismic facies, integrated with well log analysis to capture the variations in the physical properties of the intrabasalt units. Our results show the development of a NE prograding lava fed delta system in the central Corona basin during early Paleocene, which is followed by thick deposition of subaerial simple and compound lava flows. We also map the regional Top Basalt reflector and perform RGB spectral blending to delineate different kinds of flow morphologies exhibited by the compound subaerial lava flow during the final stages of flood basalt volcanism in the Brynhild basin. We identify late stage igneous intrusion related gas escape features in the Judd basin that are manifested as narrow vertical zones of amplitude blanking in the seismic data, known as 'seismic chimneys'. We use multi-attribute analysis of the seismic data in order to characterize the 3D geometry, size and fluid flow within in the chimneys.

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# Chapter 1

## Introduction

The Earth’s geologic history is a testament to the relentless forces that shape our planet, and volcanic activity has been a prominent contributor to this ever-evolving narrative. While volcanic eruptions on the Earth’s surface garner immediate attention due to their often cataclysmic and disruptive nature, leading to mass extinctions [Wignall [2001]; Keller et al. [2009]], their deeper intrusive counterparts hold the key to understanding global heat flux into the atmosphere and climate change [Iyer et al. [2013]; Svensen et al. [2006]; Berndt et al. [2023]].

In this pursuit, the Faroe-Shetland Basin (FSB), located in the North Atlantic Ocean, emerges as a remarkable geological setting, where the continental breakup during the Paleocene was accompanied by voluminous continental flood basalt eruption and the intrusion of regionally extensive magma bodies, leading to the formation of the North Atlantic igneous Province (NAIP) (Fig. 1.1) [Saunders [2016]; Meyer et al. [2007]]. The total areal extent of the eruption is estimated to be close to  $1.3 \times 10^6 \text{ km}^2$  with the total volume of extrusive and intrusive volcanic deposition of around  $6.6 \times 10^6 \text{ km}^3$  [Coffin and Eldholm [1994]; Eldholm and Grue [1994]]. These large-scale volcanic deposits make the Faroe-Shetland basin a literal ‘hotspot’ for studying ancient volcanic activity and associated phenomena.

In addition to being a geological marvel, FSB is also one of the last frontiers in hydrocarbon exploration in the North Atlantic, hosting the largest oil field on the UK continental shelf - the Clair field, which was discovered in 1977 [Johnston et al. [1995]]. Further significant discoveries were made in the Cambo-Rosebank regions within the intrabasaltic reservoirs [Hardman et al. [2019]; Schofield and Jolley [2013]; Millett et al. [2021]]. These discoveries in particular exhibited the role of volcanic deposits as barriers and baffles in hydrocarbon systems. At the same time, several studies explored the possible role of igneous intrusions in hydrocarbon maturations and the

development of fluid migration conduits [Senger et al. [2017]; Rateau et al. [2013]]. Therefore, the understanding of the evolution of FSB during periods of extensive volcanic activity is of prime interest in the context of future hydrocarbon explorations.

Volcanic stratigraphy, the study of the layering of volcanic deposits and their geological context, is an indispensable tool in reconstructing the geological history of volcanic provinces [Martí et al. [2018]]. The key to understanding the stratigraphy of volcanic deposits lies in the application of advanced geophysical exploration techniques. Seismic surveys and deep ocean drillings have emerged as powerful tools for probing the subsurface, allowing researchers to generate detailed images of the geological structure and layers beneath the Earth’s surface [Mondol [2010]]. These methods have transformed our ability to study volcanic deposits, enabling us to distinguish between different volcanic units, interpret their age and composition, and reconstruct their spatial distribution within the basin.

Some of the earliest studies related to FSB and the development of NAIP were focused on the development of tectonostratigraphic models for the intracontinent rifting and the initiation of continental breakup in the North Atlantic [Ritchie et al. [2011]; Ellis and Stoker [2014]]. In recent years, with the advent of sophisticated exploration technologies and the extensive network of drilled wells, the focus has shifted to the detailed mapping and analysis of both extrusive and intrusive volcanic successions in the basin. These studies exploited the regional 3D seismic datasets calibrated with well logs and constructed detailed models of depositional environments of various reservoir units [Schofield and Jolley [2013]]. [Wright et al. [2012]] implemented the concepts of seismic volcanostratigraphy and mapped an ancient lava-fed delta system over the Faroe-Shetland Escarpment. Studies related to igneous intrusions focused on their 2D and 3D geometrical characterization and the development of emplacement models [Bell and Butcher [2002]; Schofield].

This thesis embarks on an exploration of the Faroe-Shetland Basin’s volcanic history, using state-of-the-art 2D and 3D seismic technology to map and analyze its subsurface volcanic stratigraphy. Through a comprehensive investigation, we aim to build upon earlier studies and extend their methodologies to the areas within the basin that still remain unexplored. We attempt to provide critical insights into the interplay between magmatism, tectonics, and sedimentation during the overall evolution of a volcanic-rifted basin. We also seek to explore the potential role of igneous intrusions in the development of conduits for fluid migration within the basin.

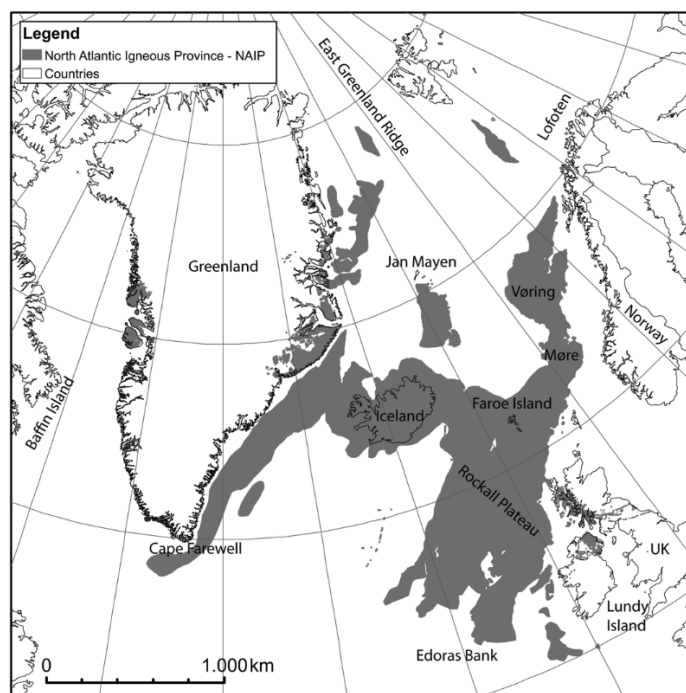


Figure 1.1: Regional extent of the North Atlantic igneous province comprising of both extrusive and intrusive igneous rocks. (Taken from [Horni et al. \[2017\]](#))

## 1.1 Objectives

The study is driven by the recognition that unraveling the seismic volcanostratigraphy of the Faroe-Shetland Basin is not only a valuable endeavor for advancing our understanding of volcanic systems but also holds practical implications, including the assessment of geohazard risks, hydrocarbon exploration, and a more comprehensive understanding of the Earth's dynamic processes. In this context, we define the following objectives for our study -

1. To analyze the paleodepositional environment, geomorphology and internal characteristics of the early Paleocene syn-rift extrusive lava flows in the Faroe-Shetland Basin.
2. To identify the post-rift igneous intrusions and characterize the associated subsurface fluid escape features in the Faroe-Shetland basin.

# Chapter 2

## Geological History

The Faroe-Shetland Basin (FSB) is a composite of several NE-SW trending basement ridges and sub-basins located in the NE Atlantic Ocean between the Faroese margin in the East and the West Shetland platform in the West [Sørensen [2003]] (Fig. 2.1(a)). The northern and southern extents of the FSB are characterized by the Erlend Platform and the Wyville Thomson Ridge, respectively [Mudge and Bujak [2001]]. The overall NE-SW trend of the basin is inherited from the Early Paleozoic Caledonian orogeny, remnants of which are present in East Greenland, Norway, England, and Scotland. Several NW-SE trending transfer lineaments transect the basin and are possibly connected to sediment routing in the basin (Fig. 2.1(a)) [Ellis et al. [2002]; Schofield and Jolley [2013]]. The basin was formed as a result of several episodes of rifting from Permian to Cretaceous that were initiated with the collapse of the Caledonian orogeny and culminated in the breakup of the continent Eurasia [Doré et al. [1999]; Sørensen [2003]]. Early rift and extension formed normal fault-bounded depocentres where deep marine conditions prevailed during the Permo-Triassic [Doré et al. [1999]; Naylor et al. [1999]]. The erosion of the Caledonian highlands in Scotland and East Greenland provided the majority of the sediments that were deposited in the West Orkney and Flannan basins that lie southwest of the Faroe-Shetland basin [Sørensen [2003]].

Due to enhanced rifting and subsidence in the Faroe-Shetland area during Late Jurassic-Early Cretaceous times, the depocentre shifted to FSB [Stoker et al. [1993]; Doré et al. [1999]]. Much of the crystalline basement structure in the FSB was formed during this time. The newly created accommodation space was infilled with hemipelagic sediments and mud, forming the Kimmeridge clay member, a major hydrocarbon source rock in the NE Atlantic [Lundin and Doré [1997]; Sørensen [2003]].

The Paleocene T-sequence stratigraphic framework of the Faroe Shetland

Basin was defined by [Ebdon et al. \[1995\]](#) and the lithostratigraphic units were defined by [Knox et al. \[1997\]](#) (Fig. 2.2).

Early Paleocene (Danian-Selandian) was a time when sedimentation in the Faroe-Shetland Basin was dominated by the deposition of deep marine basin floor fans derived from the West Shetland platform [[Lamers and Carmichael \[1999\]](#)]. These sand-rich fans are denoted by two separate sequences named T10 and T20 that form the Sullom and part of the Vaila formation respectively (Fig. 2.2). T10 sands of the Sullom formation possess good reservoir quality and contain a 175m thick hydrocarbon column named the ‘Marjun’ discovery [[Smallwood and Kirk \[2005\]](#)].

The deepwater sedimentation in the Faroe-Shetland basin continued till the end of Selandian with mud deposition intercalated with coarse-grained sandy fans forming the T32-T35 units of the later part of the Vaila formation (Fig. 2.2). During Thanetian, the basin experienced a regional uplift due to the passing of the proto-Icelandic plume [[Ellis and Stoker \[2014\]](#)]. This led to a major relative sea-level fall in the area and the deposition of prograding T36-T38 sand bodies of the Lamba formation that form the reservoir units for the two major oil field discoveries named Foinaven and Schiehallion [[Ebdon et al. \[1995\]](#); [Smallwood and Kirk \[2005\]](#)]. The base of the Lamba formation is characterized by a thick regional tephra deposit known as the Kettla Tuff member, which was deposited as debris flows due to volcanic flank collapses during the early stages of the development of localized volcanic centres [[Eidesgaard and Ziska](#)] (Fig. 2.2).

By the end of Thanetian, most of the basin was exposed to fluvial erosion leading to the development of the Top Paleocene unconformity [[Smallwood and Maresh \[2002\]](#)]. At the same time, the continental breakup of Eurasia had begun accompanied by the widespread continental flood basalt eruption [[Eldholm and Grue \[1994\]](#); [Doré et al. \[1999\]](#)]. The eruption was led by numerous volcanic centers and localized fissures that were repeatedly activated and led to the deposition of widespread T40-T45 units comprising of extrusive lava flow deposits interbedded with volcanoclastic rocks (e.g., the colsay sandstone member) [[Ebdon et al. \[1995\]](#); [Schofield and Jolley \[2013\]](#)] (Fig. 2.2). The end of Paleocene is marked with the resumption of post-rift subsidence, establishment of marine conditions throughout the basin and the deposition of the T50 clay-rich Balder formation [[Ebdon et al. \[1995\]](#)] (Fig. 2.2).

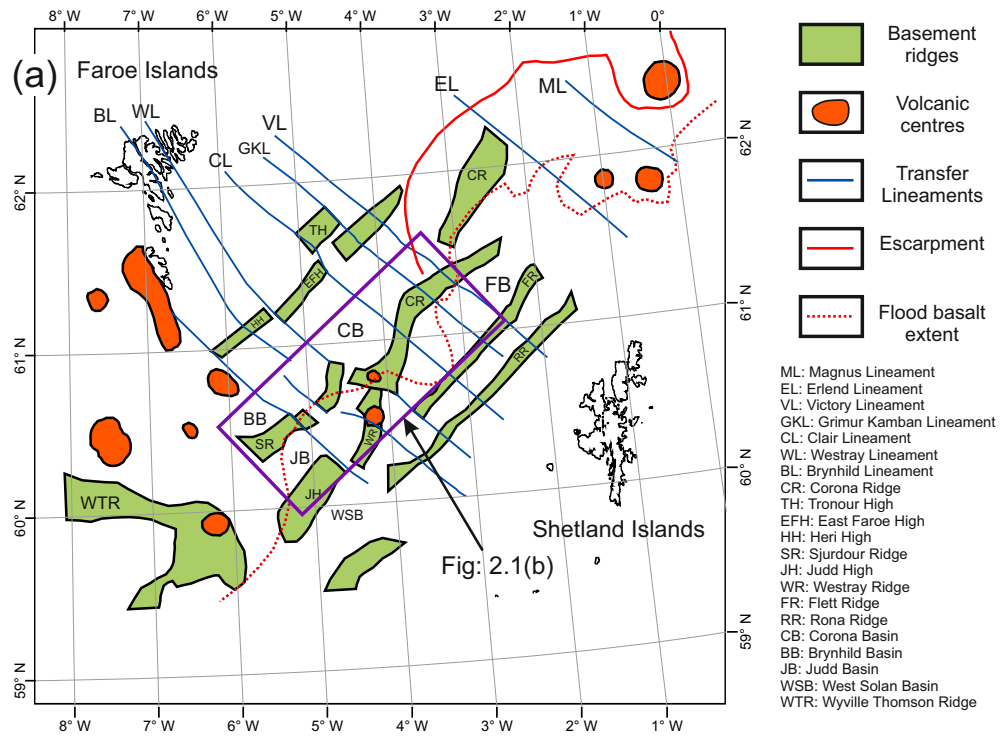
The Faroe-Shetland Basin also underwent renewed post-rift subsidence during the Eocene, with intermittent interruption caused by episodes of Paleogene and Neogene compression [[Ritchie et al. \[2003\]](#); [Smallwood and Kirk \[2005\]](#)]. Additionally, the basin margin experienced regional uplift and tilting at various points in time [[Stoker et al. \[2002\]](#); [Davies et al. \[2004\]](#)].



## 2.1 Onshore stratigraphy of the Faroe Island Basalt group (FIBG)

The products of the Paleogene continental flood basalt eruption are found in Greenland, Ireland, Scotland and the Faroe islands [Larsen et al. [1999]; Naylor et al. [1999]]. The Faroe Island Basalt Group (FIBG), as it is called, contains a  $\sim 6.6$  km thick volcanic succession which is divided on the basis of lithology, geochemistry and flow emplacement style [Ellis et al. [2002]; Passey and Bell [2007]; Passey and Jolley [2008]]. Passey and Jolley [2008] formalised the stratigraphy of the FIBG and divided it into seven major formations (Fig. 2.2).

The Lopra formation is the oldest and includes a thick subaqueous hyaloclastic breccia deposit sandwiched between two thin volcanoclastic sandstone units. This formation overlies the precambrian continental basement [Holm et al. [2001]; Casten [1973]; Bott et al. [1974]], and reflects the initiation of volcanism [Ellis et al. [2002], Passey and Bell [2007]; Passey and Jolley [2008]]. This is followed by the thick simple lava flows of the Beinivord formation, separated by thin beds of volcanoclastics and paleosols [Self et al. [1997]; Passey and Jolley [2008]], indicating extensive volcanism and short periods of quiescence. The Benisvoro Formation is overlain by thin coal rich Prestfjall Formation and pyroclastics rich Hvannhagi Formations, representing periods of significant hiatus and mild volcanism respectively [Rasmussen et al. [1956]; Ellis et al. [2002]; Passey and Bell [2007]]. The resumption in extensive volcanism is captured in the Malinstindur Formation which consists of thin beds of compound lava flow, interbedded with reddened volcanoclastic sandstones and mudstones, and overlain by sedimentary conglomerates of the Sneiss Formation [Passey and Bell [2007]]. Enni Formation marks the final stage of volcanism and consists of both simple and compound lava flows with significant volcanoclastic input [Passey and Jolley [2008]].



(b)

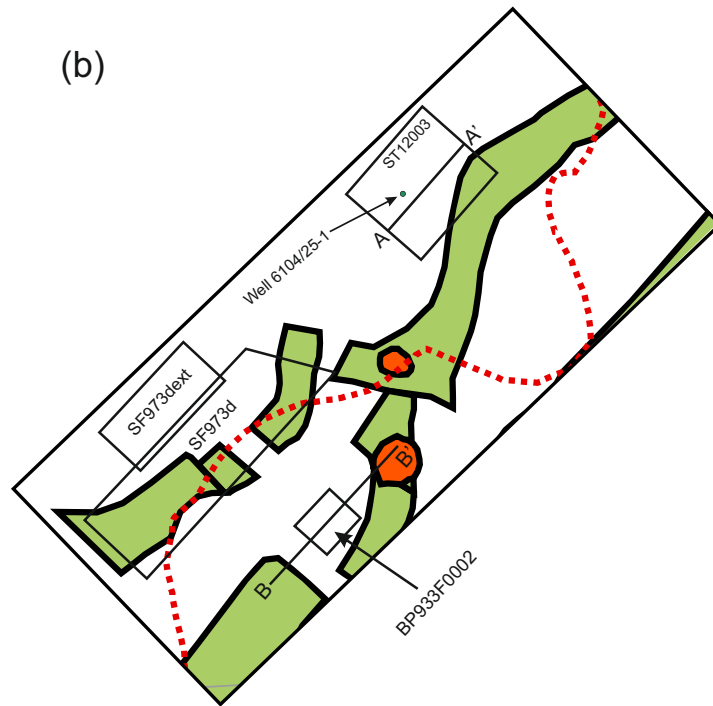


Figure 2.1: (a) Location and major tectonic and magmatic elements of the Faroe-Shetland basin (Modified from [Wright et al. \[2013\]](#)). (b) Location of the 3D seismic cubes and sections interpreted in this study.

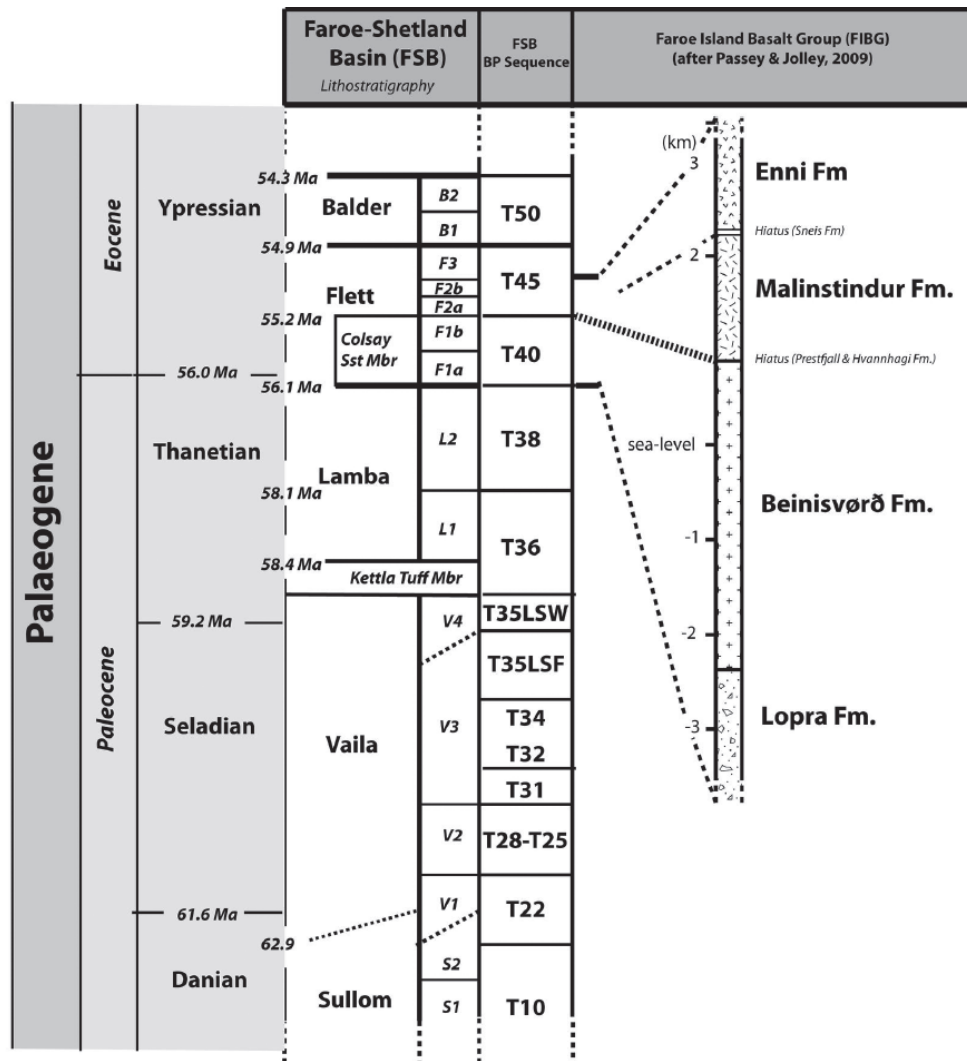


Figure 2.2: Early Paleogene stratigraphy of the Faroe-Shetland Basin along with the correlation with Onshore volcanic stratigraphic units of the Faroe Island Basalt Group (FIBG) (Taken from Schofield and Jolley [2013]).

# Chapter 3

## Data and Methodology

### 3.1 3D seismic reflection method

Seismic reflection is a geophysical technique used to study the subsurface of the Earth, particularly for oil and gas exploration, but also for various geological and environmental investigations. It works by sending acoustic waves into the Earth's subsurface and recording the echoes (reflections) of these waves when they encounter acoustic impedance contrasts between different rock layers or structures beneath the Earth's surface (Fig. 3.1(a)). Acoustic impedance is a characteristic property of rocks defined by the product of the density of the rock material and the velocity at which seismic waves propagate within the rock. These seismic reflections, provide valuable information about the composition, depth, and geometry of subsurface features.

The final processed data is plotted with the two-way travel time of the reflections on the y-axis and the horizontal distance on the x-axis. The two-way travel time of a reflection contains information about the seismic velocity of the subsurface and the actual depth of the acoustic impedance contrast in the subsurface (Fig. 4.1(a)). The amplitude of the reflections is primarily dependent on the acoustic impedance contrast of the geological interface but can be influenced by fracturing, anisotropy, and the presence of fluids.

3D seismic technology is an advanced geophysical technique used to create detailed three-dimensional images of the subsurface of the Earth. It builds upon the principles of traditional 2D seismic reflection by acquiring and processing data from a grid of sources and receivers, allowing for a more comprehensive and accurate representation of subsurface structures (Fig. 3.1). 3D seismic technology provides a higher level of detail and clarity in subsurface imaging compared to 2D methods and the processed data is used to create a 3D volume or cube of the subsurface, which can be sliced and visualized

| Survey ID  | Area ( $km^2$ ) | Inline spacing ( $m$ ) | Crossline spacing ( $m$ ) | Sampling interval ( $s$ ) | Record length ( $s$ ) |
|------------|-----------------|------------------------|---------------------------|---------------------------|-----------------------|
| ST12003    | 838             | 12.5                   | 12.5                      | 0.004                     | 8.5                   |
| SF973D     | 1665            | 18.75                  | 12.5                      | 0.004                     | 8.0                   |
| SF973dext  | 580             | 18.75                  | 12.5                      | 0.004                     | 8.0                   |
| BP933F0002 | 157             | 15                     | 12.5                      | 0.004                     | 4.6                   |

Table 3.1: Table showing the acquisition parameters for different 3D seismic surveys used in this study (See Fig. 2.1(b) for locations).

at different depths and angles. The major advantage of using 3D seismic data over conventional 2D seismic data comes from the concepts of time and horizon slices.

- **Time Slices:** 3D seismic data can be sliced at specific time intervals, allowing geologists and geophysicists to examine the subsurface at different geological epochs. This is especially valuable for studying the temporal evolution of geological features, such as sedimentary layers or fault movement.
- **Horizon Slices:** By visualizing the seismic data at specific horizons or geological interfaces, researchers gain insight into the geometry, continuity, and lateral variations of subsurface structures. This is crucial for understanding reservoir geometries and the presence of potential hydrocarbon traps.

In our study, we use four 3D seismic cubes spread over different regions of the Faroe-Shetland basin with the details given in Table:3.1.

### 3.1.1 Spectral blending

Spectral blending is an advanced seismic processing and interpretation technique that utilizes three different frequency-filtered data and blends them together to form a composite RGB image of the subsurface [Chopra and Marfurt [2007]; Brown [2011]]. It is based on the principle that different frequencies present in the dataset enhance different lithological or structural variations in the data. For example, an increment in the higher frequency content of the reflection signals can indicate the thinning of the particular

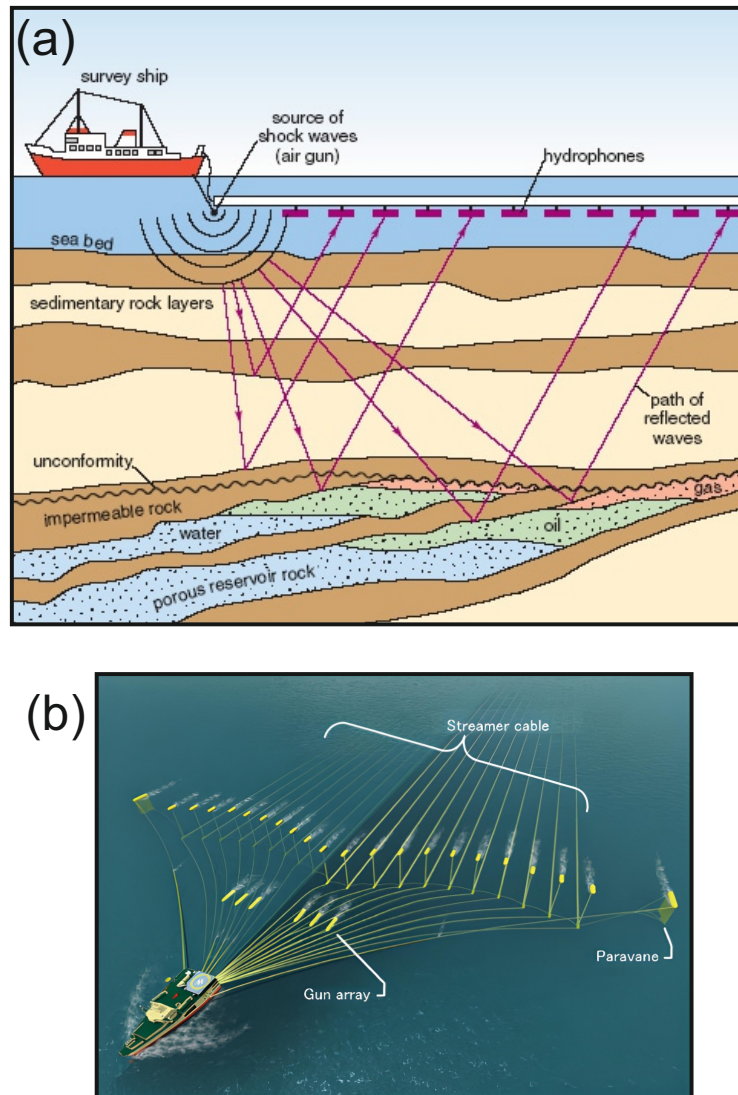


Figure 3.1: (a) A schematic representation of the acquisition of seismic data to image acoustic impedance contrasts in the subsurface (taken from <http://geologylearn.blogspot.com/2015/06/marine-and-land-seismic-aquisition.html>). (b) General configuration of the vessel and connected receivers (streamers) in a 3D seismic survey. (Courtesy: PGS)

lithological unit due to the interference of the reflections coming from the top and base of the unit. Similarly, enhanced lower frequencies can indicate thickening of a lithological unit [Brown [2011]]. However, this could also be due to the presence of fluid which absorbs the high-frequency content of the incoming wavefield, thereby acting as a low-pass filter.

We use spectral blending of horizon slices in order to map the morphology and extent of different lava flow units, and to characterize the geometry of fluid escape features in 3D.

### 3.1.2 Seismic attributes

Seismic attributes are quantitative measures that are derived from the variations in amplitude, two way time, frequency and phase of seismic reflections [Brown [2011]]. These measures are related to the certain geological features and allow us to condition the data for a regional stratigraphic and structural interpretations. Analysis of multiple independant attributes is important to highlight different uncorrelated physical properties of the region of interest. The catalogue of Seismic attributes has become enormous over the years with the advent of efficient computational algorithms. In the context of our study, we will describe two attributes that we have analysed using the proprietary GeoTeric<sup>®</sup> software -

- *Dip*: The volumetric dip attribute is a measure of the direction of maximum dip in the data. It is used to aid structural interpretation of faults, fractures, folds, diapirs, and chimneys. Mathematically, the dip is nothing but the dominant eigenvector of what is known as the Gradient structure tensor ( $\mathbf{T}_{GS}$ ), defined as the covariance matrix of the three directional derivatives of seismic amplitude  $\left(\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}\right)$  within a specified analysis window [Chopra and Marfurt [2007]]-

$$\mathbf{T}_{GS} = \begin{bmatrix} \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial x} \frac{\partial u_{jk}}{\partial x} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial x} \frac{\partial u_{jk}}{\partial y} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial x} \frac{\partial u_{jk}}{\partial z} \\ \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial y} \frac{\partial u_{jk}}{\partial x} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial y} \frac{\partial u_{jk}}{\partial y} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial y} \frac{\partial u_{jk}}{\partial z} \\ \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial z} \frac{\partial u_{jk}}{\partial x} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial z} \frac{\partial u_{jk}}{\partial y} & \sum_{k=-K}^K \sum_{j=1}^J \frac{\partial u_{jk}}{\partial z} \frac{\partial u_{jk}}{\partial z} \end{bmatrix} \quad (3.1)$$

where,  $\pm K$  is the number of samples and  $J$  is the number of traces in the analysis window.

- *Envelope*: The mathematical definition of signal envelope comes from the analysis of complex trace defined as a function of time  $t$  -

$$C(t) = T(t) + iH(t), \quad (3.2)$$

where  $C(t)$  is the Complex trace,  $T(t)$  refers to the original trace and  $H(t)$  is the Hilbert transform of the original trace computed by convoluting the original trace with  $\frac{1}{\pi t}$ , representing a  $\pm 90^\circ$  phase shift in the original trace.

The signal envelope ( $E$ ) is then defined as the absolute value of  $C(t)$  -

$$E = \sqrt{T(t)^2 + H(t)^2} \quad (3.3)$$

Since the envelope attribute directly captures the reflection strength, it is sensitive to variations in acoustic impedance and therefore, helps in stratigraphic interpretation such as lithology, hydrocarbons, and porosity.

## 3.2 Well logging

Well logging is a crucial technique used in the field of geology, petroleum engineering, and environmental science to obtain detailed information about the subsurface properties of a borehole or well. It involves meter scale measurement and recording of various physical properties of rocks and fluids encountered during drilling, and these measurements help geoscientists to better understand the composition and structure of the Earth's subsurface at a single location that complements and calibrates the regional picture supplied by 3D seismic data. Various tools and instruments are used for well logging, each designed to measure specific properties of the subsurface. Some common logging tools include (Rider [2000]) :

- **Gamma Ray**: Gamma ray logging relies on the natural radioactive decay of certain elements found in rocks. Elements like uranium, thorium, and potassium are naturally present in many geological formations. As these radioactive elements decay, they emit gamma rays. The energy and intensity of these gamma rays can be measured, and this information is used to assess the composition and lithology of the surrounding rock. Lithologies such as shale that are rich in radioactive content are



characterized by high gamma ray values in the range of 60-150 API whereas radioactive poor rocks like sandstone and limestones produced low gamma ray values in the range of 15-30 API and 10-40 API respectively. Igneous rocks are known to have extremely low quantities of radioactive elements, producing gamma ray values below 30 API.

- **Resistivity:** Measures the electrical resistance of the formation, which can help in determining the rock's porosity and water saturation. Clay-rich shales exhibit low resistivity values from 1 to 5 ohm-m. Sandstones display resistivities in the range of 5-100 ohm-m. Igneous rocks are characterized by extremely high resistivities that can go upto 1000 ohm-m due to the absence of conductive materials. However, resistivity values in any lithology can come down due to the presence of conductive fluid filled fractures or pores.
- **Density:** Measures the density of the formation, which is used to identify different types of rocks. Density log is sensitive to the contrast in lithologies, fracturing, presence of fluids, compaction and metamorphism. In the context of our study, combined with the gamma ray log, it is an important element for distinguishing igneous and volcanoclastic rocks from pure siliciclastic rocks. It can also be used to further derive the acoustic impedance values of the formation which is useful in characterizing different basaltic units. Sandstone rocks typically have low density values from 2.1 to 2.4 g/cc due to high porosity and the presence of fluids compared to highly compacted shale that can have density in the range of 2.4 to 2.7 g/cc. Igneous rocks have slightly higher density from 2.6 to 2.9 g/cc.
- **Sonic:** Measures the compressive ( $V_p$ ) and shear wave ( $V_s$ ) velocities through the formation to determine the rock's mechanical properties. Typical  $V_p$  values for clay rich shale rocks vary from 1.5 km/s to 5 km/s (compacted) whereas compacted sandstones have higher  $V_p$  values of around 5.5 to 6 km/s. Velocities in hard igneous rocks can go upto 7-8 km/s.

For our study, we use the well logs from the Statoil Sula Stelkur 6104/25-1 well (See Fig:2.1(b) for location), which was aimed to drill two late Paleocene to early Eocene hydrocarbon prospects - (1) The Sula prospect at T45 colsay sandstone member (Fig:2.2) of the Flett Formation, northwest of the Rosebank discovery at the same stratigraphic level, and (2) The Stelkur prospect at the late T45 Hildasay sandstone member of the Flett Formation (Fig:2.2). The well was drilled upto a total depth of 2984 m.

### 3.3 Seismic volcanostratigraphy

Seismic volcanostratigraphy refers to the application of the concepts of traditional seismic stratigraphy in volcanic rifted basins to understand the depositional history and emplacement environments of different volcanic rocks - both intrusive and extrusive. It relies on the characterization of seismic facies on the basis of their amplitude, frequency, continuity, and geometry. These characteristics are then correlated with lithological variations observed in drilled boreholes.

[Planke et al. [2000]] divided a complete regional volcanic succession into 6 seismic units going from landward to seaward direction: Outer SDRs, Outer high, Inner SDRs, Landward Flows, Lava Delta and Inner Flows (Fig:3.2). Each of these units provide substantial information about the emplacement environment and tectonic setting. It is important to note that not all units are consistently present along single margin transect. In the context of our study, we will discuss two of these units that are mapped consistently throughout our study region.

1. *The Landward Flow unit*: It is identified as a set of subparallel, disrupted reflections topped by a smooth high amplitude event (Fig:3.2). In the North Atlantic Ocean, the base of landward flows is mapped along a regional escarpment or a local land-sea margin [Planke et al. [2000]]. Borehole data suggests that the unit is composed of subaerially erupted laterally extensive lava flows interbedded with thin clastic or volcanoclastic beds [Eldholm et al. [1989]; Larsen et al. [1999]], representing the topset part of a lava-fed delta system [Wright et al. [2012]] (Fig:3.2). The characteristics of the constituent internal reflectors are sensitive to physical properties such as porosity, pore aspect ratio and degree of alteration [Wilkens et al. [1991]].
2. *The Lava Delta front unit*: It is composed of disrupted, inclined and progradational internal reflections topped by a change in reflection configuration from flat-laying to inclined (Fig:3.2). The base is identified with the terminations of the internal reflections. Borehole and outcrop analogues shows that the lithology is dominated by hyaloclastic breccias that are formed as a result of rapid quenching of hot lava flow during an explosive lava-sea/lake interactions (e.g., Hawaii lava delta) (Fig:3.2). The unit, therefore, constitutes to the delta front part of the lava-fed delta system [Wright et al. [2012]].

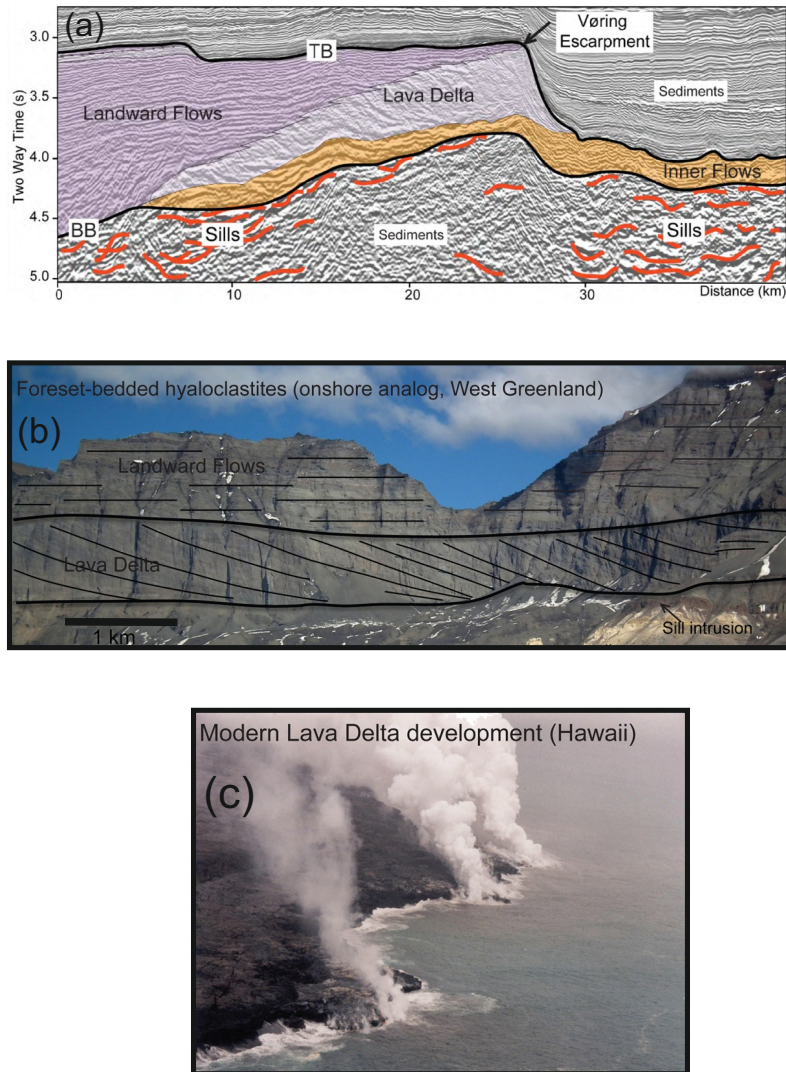


Figure 3.2: (a) Seismic facies classification in the Voring Basin using seismic volcanostratigraphy. (b) Outcrop example of a volcanic sequence in West Greenland composed of prograding hyaloclastic lava delta topped by parallel beddings of Landward flows. (c) An example of the modern Lava delta development in Hawaii. (All images are taken from [Abdelmalak et al. \[2016\]](#))

# Chapter 4

## Observations and Interpretations

### 4.1 2D Seismic Interpretation

We perform a detailed 2D seismic interpretation on the cube ST12003, using concepts from seismic volcano stratigraphy and conventional seismic stratigraphy. Reflector configurations are used to characterize 6 seismic units - Unit 1 to Unit 6, on the basis of reflection amplitude, continuity and geometry. Lithological interpretation is aided by analyzing well log data corresponding to each unit using the Statoil Sula Stelkur well 6104/25-1 (Fig. 4.1). Spectral blending of the horizon slice for the top of unit 3 (Top Hildasay member) is constructed in order to capture a key transition in the depositional environment during the deposition of hildasay sands (Fig. 4.2).

#### 4.1.1 Unit 1

Seismic unit 1 is characterized by low amplitude, north-easterly dipping, moderately continuous, and parallel to sub-parallel reflector configurations. The base of Unit 1 is constructed by connecting the lower terminations of the dipping reflectors. The top of Unit 1 is marked by connecting points where a change from horizontal to dipping reflections can be observed and is correlated with a sharp rise from 12.8 API below to 120 API above in the gamma ray log (Fig. 4.3). Within the unit, the gamma ray response varies in a small range between 11 API to 17 API and the resistivity log ranges from 4.5 ohm-m to 25 ohm-m, similar to a general volcanoclastic rock response as described by [Andersen et al. [2009]]. Thin section analysis of cutting samples describes the dominant lithology as devitrified glass fragments or hyaloclastites. The Unit 1 is interpreted as the prograding foresets part of a lava delta.



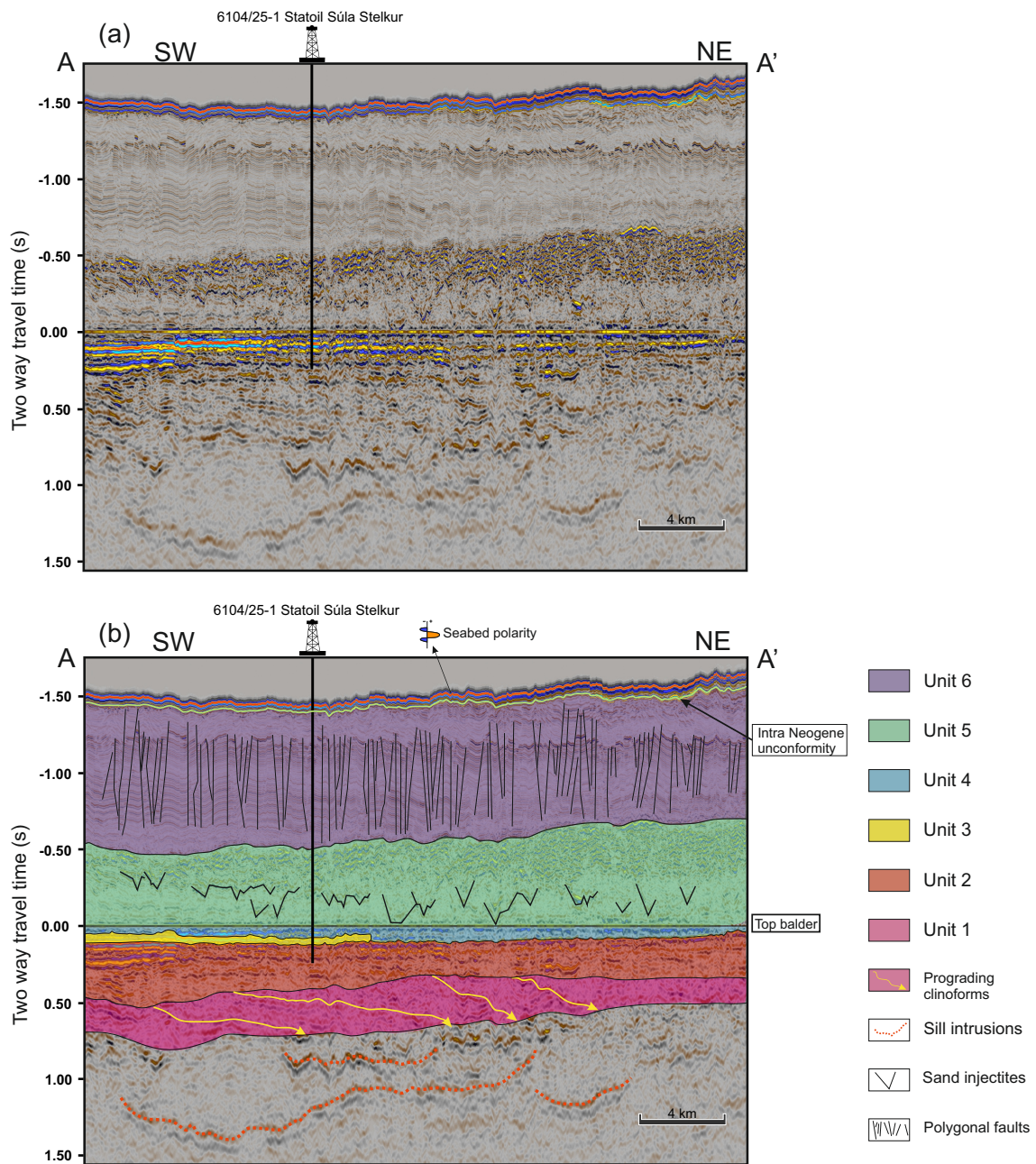


Figure 4.1: (a) Uninterpreted Line 3077 of the seismic survey ST12003 flattened at Top Balder (see Fig. 2.1(b) for location). (b) Interpreted Line 3077 of the seismic survey ST12003 showing the classification of different seismic facies using conventional seismic stratigraphy and seismic volcanostratigraphy.

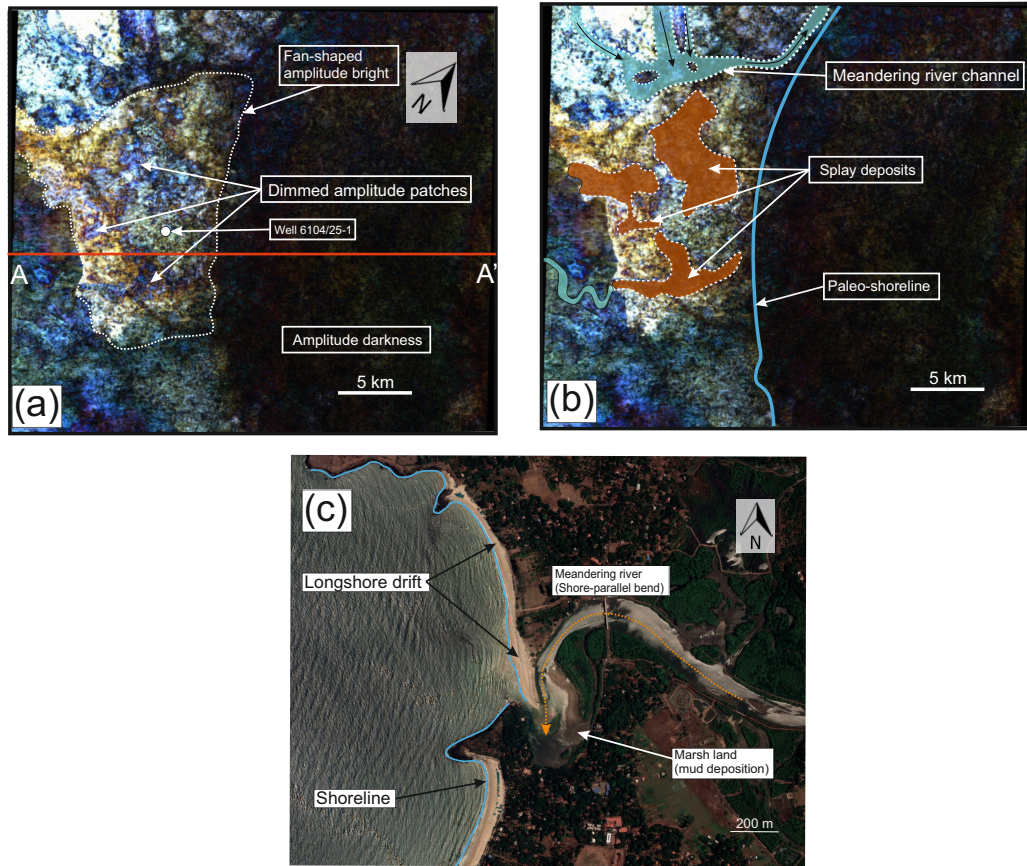


Figure 4.2: (a)-(b) Interpreted RGB spectral blend (24Hz, 31Hz and 45Hz) of Horizon slice of the Top of Unit 3 indicating a low fluvial energy estuarine environment (See Fig. 2.1(b) for location). (c) Modern analogue of an estuary in Malvan, Maharashtra (Courtsey: Google Earth).

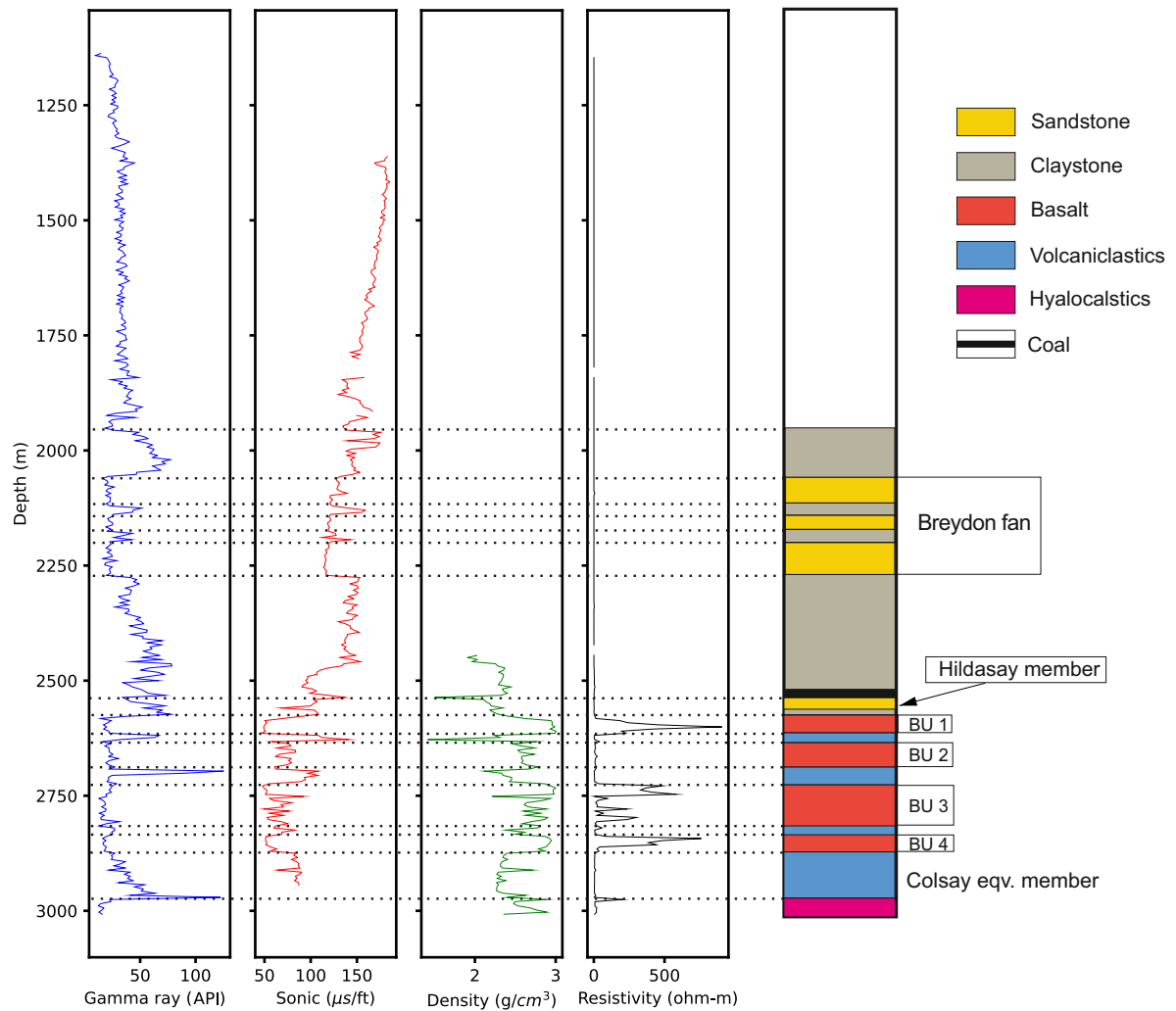


Figure 4.3: Correlated Statoil Sula Stelkur 6104/25-1 well logs along with interpreted lithologies and basaltic subunits (BU1-BU4). See Fig. 2.1(b) for location.

### 4.1.2 Unit 2

Unit 2 contains high to moderate amplitude, horizontal, continuous and parallel reflectors. The base coincides with the top of Unit 2, and the top is marked with a sudden rise in gamma ray log from 14.3 API to 67 API and a drop in resistivity from 320 ohm-m to 18.7 ohm-m (Fig. 4.3). The corresponding sonic and density logs report sharp changes from 49  $\mu$ s/ft to 107  $\mu$ s/ft and from 2.97 g/cc to 2.22 g/cc, respectively (Fig. 4.3). The lithology consists of thick flood basalt deposits interbedded with volcanoclastic siltstone as observed in sidewall cores. We interpret this unit as subaerial lava flows built during multiple episodes of volcanic activity and erosion during periods of no activity.

To further characterize the intrabasalt well response, we identify four basaltic subunits - BU1, BU2, BU3 and BU4 going from top to bottom in the stratigraphic successions and separated by volcanoclastic sediments. BU1 is a ~40 m thick flow showing a consistent blocky response on gamma, sonic, and density logs with minimal oscillations and sharp boundaries, and a triangular peak in the resistivity log. BU2 is a 60 m thick package with a very similar Gamma ray response as BU1 but the sonic and density logs show lower values with high frequency chaotic oscillations. The resistivity response of BU2 is consistent and considerably reduced as compared to BU1. These significant changes could be due to heavy fracturing in the basalt and the presence of conductive fluid in between the pores and fractures. Porosity calculations by using the sonic log show porosities in the range of 8-40% for BU2 and 2-15% for BU1. BU3 represents a thick 100 m package on the gamma ray log but can be divided into two different sections with the help of sonic and density log. The upper 30 m section has a consistent blocky response similar to BU1 possibly the lightly fractured part of the succession and the remaining sections behave similar to the highly fractured subunit BU2. The porosity in BU3 varies within a range of 3-40%. Finally, BU4 is a 40 m thick subunit characterized by an overall blocky response on sonic and density logs with a small dip in the middle. This subunit could be a composite of two different flow units separated by the low velocity fractured crust of the older flow. The porosity ranges from 2% to 25%.

### 4.1.3 Unit 3

Unit 3 consists of high amplitude, parallel, and continuous reflectors. The top is a bright positive reflection correlated on the well logs as a drop in



| Unit        | Depth (m) | Gamma ray (API) | Sonic ( $\mu s/ft$ ) | Density (g/cc) | Resistivity ( $\Omega m$ ) | Porosity |
|-------------|-----------|-----------------|----------------------|----------------|----------------------------|----------|
| BU1         | 2580-2615 | 14.3-64.8       | 45.7-109.3           | 2.2-3.0        | 1.9-1130.0                 | 2-15%    |
| BU2         | 2630-2695 | 8.9-38.8        | 54.9.7-121.2         | 1.9-2.8        | 1.5-92.0                   | 8-40%    |
| BU3         | 2705-2820 | 11.4-45.6       | 47.2-114.7           | 2.0-3.0        | 2.7-2250.7                 | 3-40%    |
| BU4         | 2835-2875 | 11.6-48.7       | 46.4-97.8            | 2.3-3.0        | 5.2-928.8                  | 2-25%    |
| Colsay eqv. | 2875-2971 | 16.3-126.7      | 58.4-128.1           | 1.8-2.8        | 2.9-22.3                   | -NA-     |

Table 4.1: Summary of well log responses and porosity estimation of different basaltic subunits.

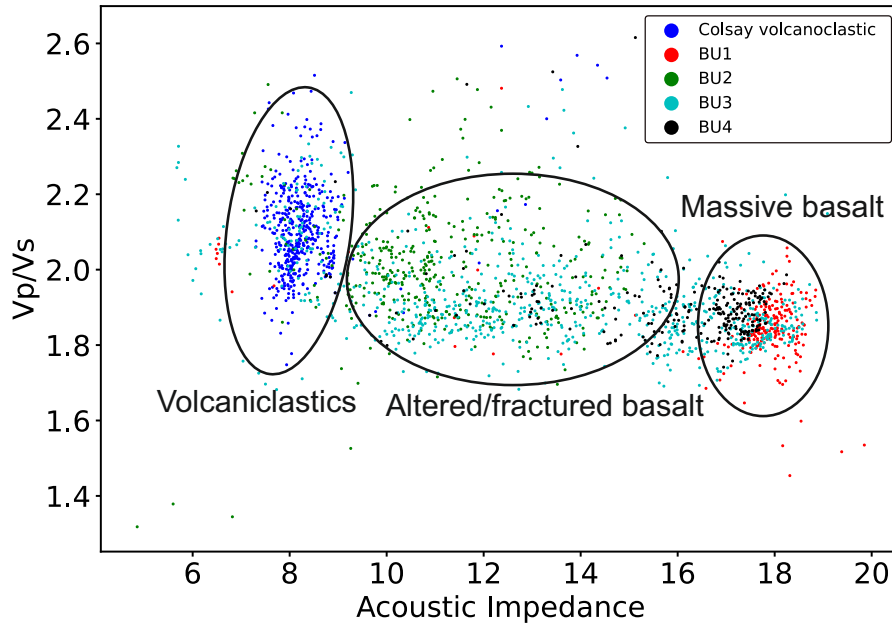


Figure 4.4: Cross-plot of well-logs derived acoustic impedance and Vp/Vs ratio within 2580 m-2971 m vertical depth. Identification of different clusters is done manually and interpretation of each cluster is done in accordance to [Bhardwaj et al. \[2021\]](#)

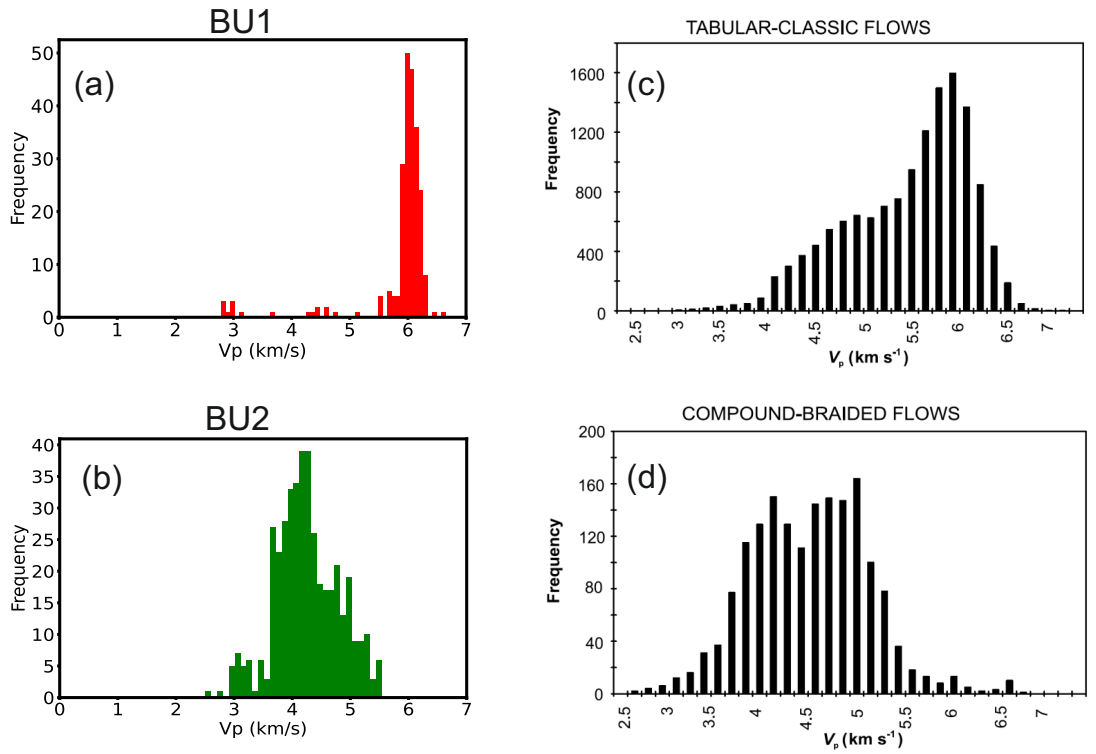


Figure 4.5: (a)-(b) Frequency distributions of the P-wave velocity( $V_p$ ) of the two basaltic subunits BU1 and BU2 identified from the Statoil well 6104/25-1. (c)-(d) Comparison with the P-wave velocity histograms of tabular and compound lava flows as interpreted in [Nelson et al. \[2009\]](#).

gamma ray and density from 59.4 API to 27.8 API and from 2.2 g/cc to 1.5 g/cc as we move to Unit 4 above (Fig. 4.3). This unit is composed of medium to fine-grained sand and clay with occasional limestone stringers. The top surface is interpreted as an interface between fine grained siliciclastics below to a thin coal unit above, indicating that the entirety of Unit 3 was deposited in a low-energy paralic depositional environment.

We also examine the RGB spectral blend of the 3D horizon slice of the top of unit 3 using frequencies - 24Hz, 31Hz, 45Hz in order to substantiate our interpretation of the paleo depositional environment (Fig. 4.2(a),(b)). In the spectral blend map, we observe a high-amplitude fan-shaped structure opening up towards the northeast, reaching a maximum width of around 16km and ending abruptly at around 13 km from its probable narrower origin. We also observe two low amplitude meandering channel-like features - one seems to be coming from the southwest and ending where it meets the fan and the other one possibly coming from the northwest and deflecting towards the northeast parallel to the sharp boundary of the fan. Within the fan shaped body, we observe three irregular shaped low amplitude high frequency anomalies that are interpreted as thin fine grained mud dominated splay deposits that are found near river mouths (Fig. 4.2(c)).

These features are typical of a low fluvial energy transgressive estuarine environment where rivers bring in medium to fine-grained clastics and sometimes deflect due to shoreline parallel wave action in a wave-dominated setting (Fig. 4.2(c)).

#### 4.1.4 Unit 4

Unit 4 is characterized by low amplitude, parallel, and discontinuous reflectors with the top showing an increase in the gamma ray response from 66.8 API to 91.6 API (Fig. 4.3). The top of unit 4 is a regional positive polarity reflection representing the top of the balder formation [Smallwood and Gill [2002]]. The unit entirely consists of fine grained clay rich in tephra deposits and is considered to be a regional marker of the complete cessation of volcanic activity and establishment of deep marine conditions.

#### 4.1.5 Unit 5

Unit 5 is a thick package characterized by predominantly high amplitude, discontinuous chaotic facies overburdened on low amplitude continuous parallel reflectors (Fig. 4.1). The basal unit has a gradational gamma ray response indicating a coarsening up sequence while the upper unit has a blocky low gamma response with localized high blocks indicative of a predominantly

coarse-grained unit interbedded with thin finer-grained materials (Fig. 4.3). We interpret this to be a sand rich fan deposited over marine claystones. Unit 5 is heavily influenced by high amplitude crosscutting conical-shaped facies that are ubiquitous of injection of overpressured sands into overburden layers. These are known as sand injectites [Bureau et al. [2013]; Shoulders et al. [2007]].

#### 4.1.6 Unit 6

Unit 6 is a thick succession entirely built up from low amplitude, continuous, and parallel seismic reflectors topped by the regional intra-Neogene unconformity (Fig. 4.1). This unit extensively features an intricate network of sub-vertical faults that travel down to the top of Unit 5. We interpret this unit as deep marine clay deposits polygonally faulted possibly from the expulsion of fluids.

## 4.2 Seismic Geomorphology of the Top basalt surface

The high amplitude top basalt reflector represents the upper end of basaltic deposits that can be easily mapped in regional datasets. The surface can be correlated with the top of last stage retrograding unit 12 of [Wright et al. [2012]] and the top basalt surface within the Corona basin as discussed in [Schofield and Jolley [2013]]. We extend their interpretation of the top basalt surface over Sjourdour high and Brynhild sub-basin. We perform spectral blending of the top basalt surface using three frequencies - 12 Hz, 22 Hz and 40 Hz. As a result, we discover distinct flow morphologies of the latest stage of flood basalt eruption (Fig. 4.6, 4.7, 4.8).

We observe a set of complex overlapping elongated bodies with lobate ends terminating eastwards in the southeast corner of the Sjourdour ridge (Fig. 4.7(a)). The width of individual units is in the range of  $\sim 1.5$  to  $2.5$  km with a total areal extent of around  $35 \text{ km}^2$ . The elongated regions are dominated by mid to high frequencies, while the lobate ends show localized lower frequency contributions. We interpret this body as a compound flow emanating from the west and composed of multiple flow lobes emplaced either during a single eruption event with varying effusion rates or during multiple eruption events. Lower frequency regions towards the lobe terminations can be interpreted as thickening due to continuous effusion of lava after the flow terminus has cooled.

The central part of the Sjourdour ridge consists of an extensive tabular structure with irregular lobate margins covering an area of around 200  $km^2$  and dominated by mid-frequencies (Fig. 4.6). These characteristics are similar to large sheet lava flows that are formed due to the coalescence of multiple flow lobes in a setting with a high rate of lava effusion. The northern section contains anastomosing high frequency, high amplitude features with dimmer voids in between (Fig. 4.7(b)). We infer these features to be associated with braided lava streams flowing around paleo-topographic high areas, also known as kipukas.

Another sheet flow is encountered near the north-eastern end with irregular lobate terminating towards the west and a truncated linear margin in the east (Fig. 4.6). The elevated lower frequencies indicate a thick flow field. This flow is accompanied by a smaller tabular structure punctuated by multiple low-amplitude circular pits and opening up southwards into an elongated terminus. This could be a separate flow field emerging from a source situated northwards.

We also observe a 40 km long dimmed amplitude meandering channel-like feature with a width in the range of 100-400 m, following a mounded topography in the seismic cross-section (Fig. 4.6). We infer this to be a lava tube formed after the lava channel top solidifies and forms an insulated roof under which the molten core flows through larger distances.

In the central part of the ridge, broad, high amplitude low-frequency lobate units can be seen breaking away from the southern edge of the lava tube and propagating in the southwest direction as a wide channel (Fig. 4.6). The same lava tube could be a possible source of the thin finger-shaped flow field at the eastern end of the ridge (Fig. 4.7(c)).

We follow our interpretation of the top basalt surface into the Brynhild basin northwestward to the Sjourdour ridge. We find that the sheet flow in the central part of the Sjourdour ridge extends into the Brynhild basin with minor breakouts on the eastern margin and a larger channelized breakout possibly originating from the northwest (Fig. 4.8). Mid to high frequencies dominate the sheet flow, while the channelized flow contains higher contributions from lower frequencies, indicating a higher thickness.

### 4.3 Sill intrusions and fluid escape features

We also identify several extremely high-amplitude cross-cutting reflections with abrupt terminations below the base of Unit 1 (Fig. 4.1). In three dimensions, these reflections are “saucer-shaped,” implying a flat or concave upwards concordant base and inclined discordant edges, typical of sill intru-

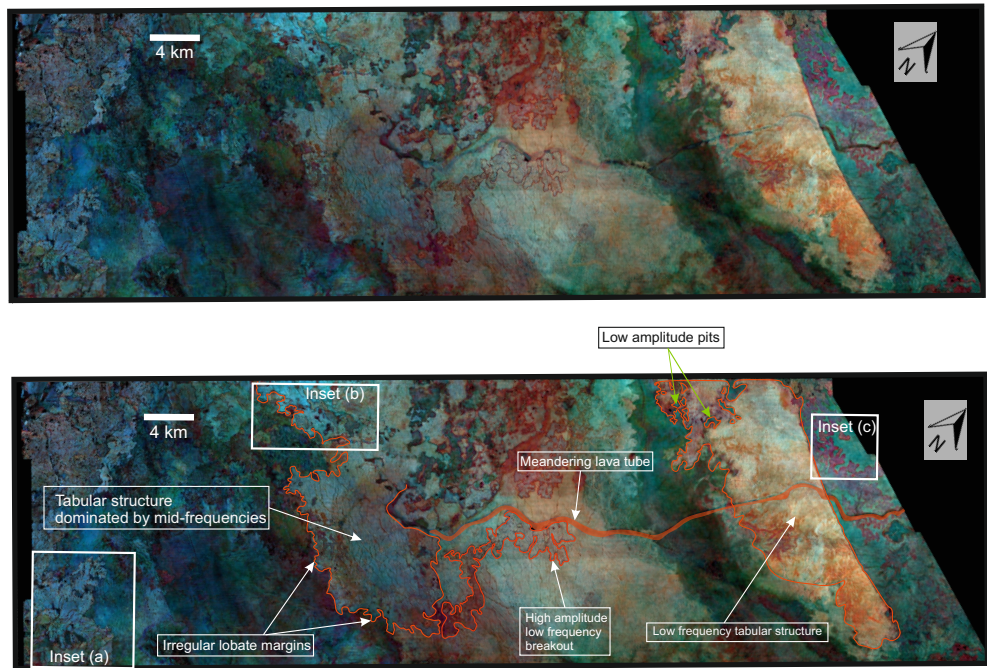


Figure 4.6: Uninterpreted (above) and interpreted (below) RGB spectral blend (12Hz, 22Hz, 40Hz) of the Top Basalt horizon slice in the 3D seismic cube SF973d (See Fig. 2.1(b) for location) showing different kinds of lava flow morphologies during the wanning stage of flood basalt volcanism.



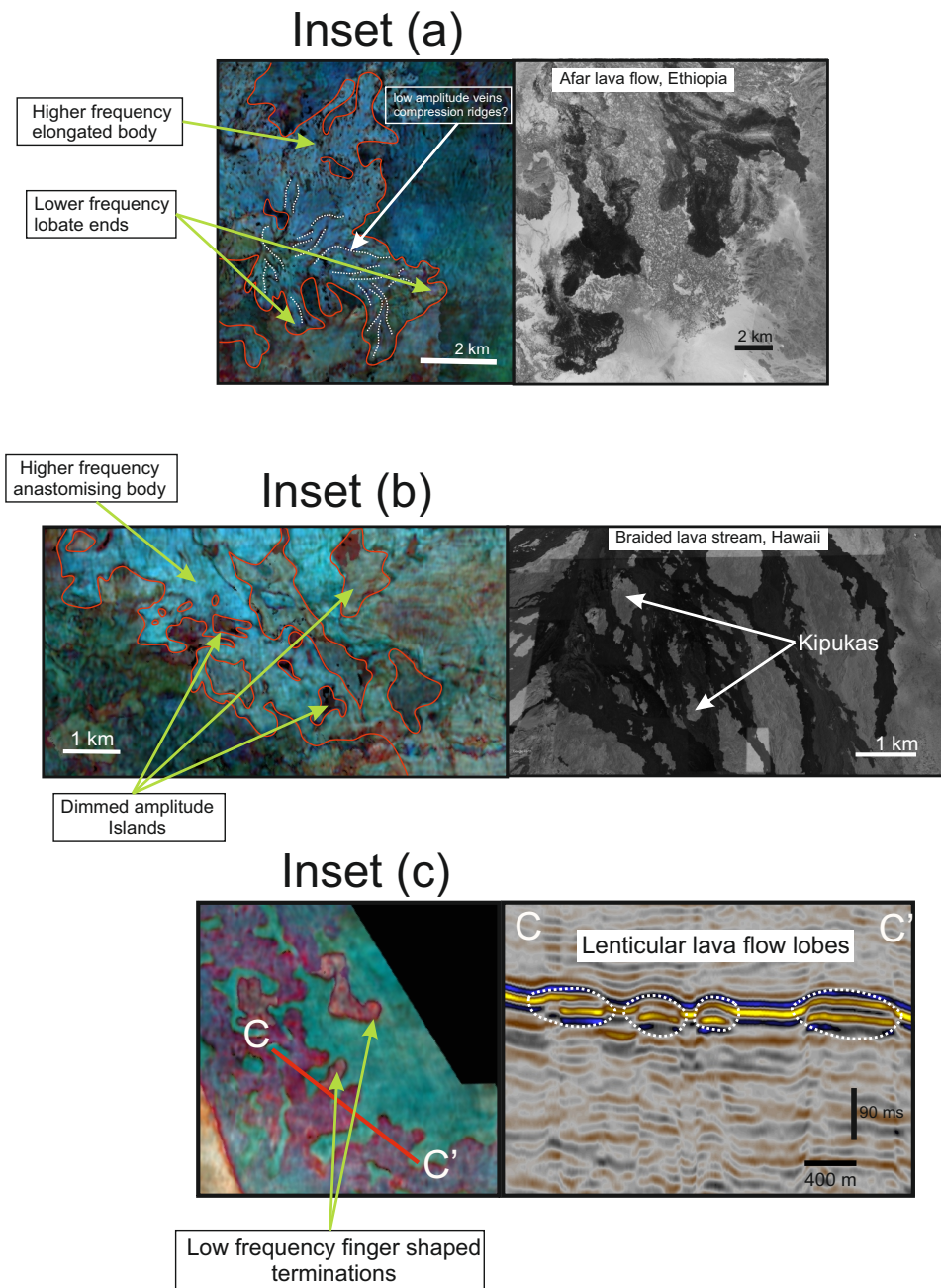


Figure 4.7: Insets from Fig. 4.6 showing the geomorphology of different lava flows and their corresponding modern analogues (a)-(b) (Courtesy: Google Earth). Inset (c) shows the lenticular geometry of flow lobes in a 2D seismic cross-section.

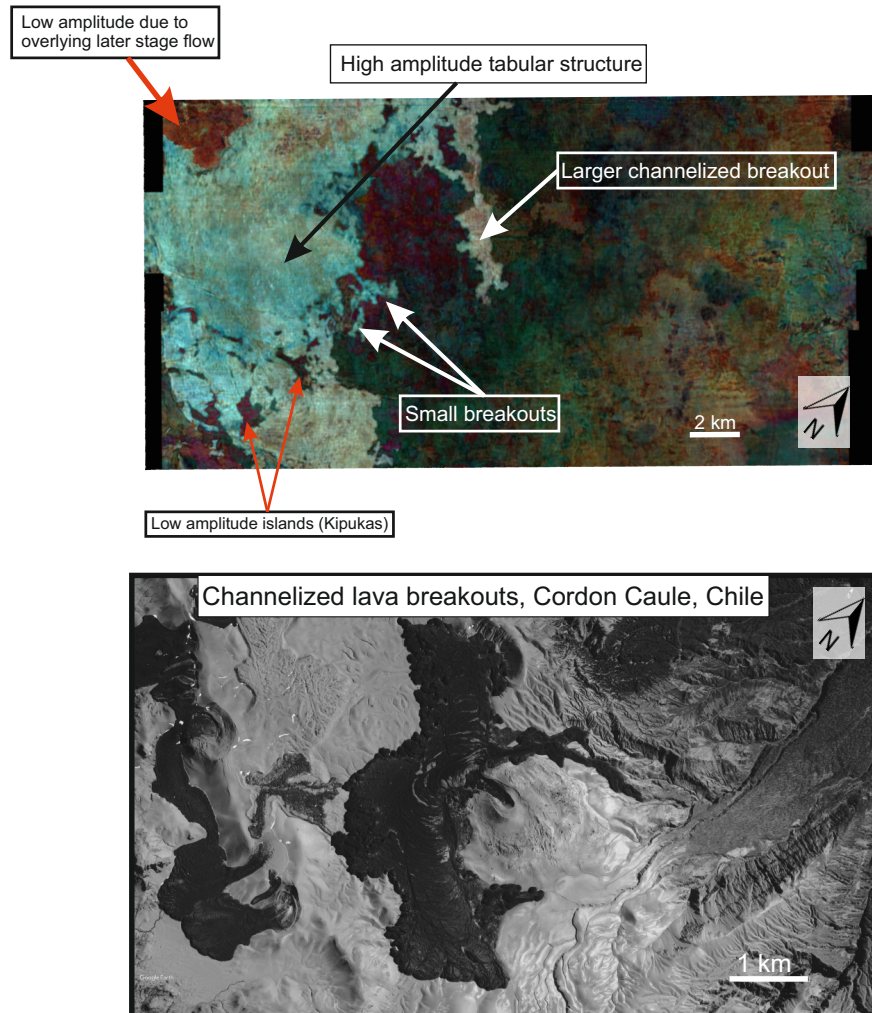


Figure 4.8: Interpreted RGB spectral blend (16Hz, 25Hz, 34Hz) of the Top Basalt horizon slice in the 3D seismic cube SF973dext (See Fig. 2.1(b) for location) showing different lava flow morphologies in the Brynhild basin and their modern analogue in the Cordon Caule lava flow in Chile (Courtesy: Google Earth).



sions in sedimentary basins [Hansen et al. [2004]].

Within the southern end of the Judd basin, between the Judd high and the Westeray ridge, we encounter a deep-seated complex network of compound sill intrusions associated with vertical columns of amplitude anomalies with widths ranging from a few tens of meters to a few kilometers across the Eocene strata (Fig. 4.9). These features are similar to gas escape conduits or seismic chimneys reported in sedimentary basins that are associated with extensive subsurface fluid flow. In the case of the wide chimneys, the margins are identified as discontinuities in the horizontally stacked strata manifested as amplitude blankings similar to those caused by vertically propagating fractures and are associated with a significant up-bending of the reflectors (Fig. 4.10(a)). On the other hand, the margins in the narrower chimneys are difficult to identify due to the resolution constraints of seismic data (Fig. 4.10(b)). In these particular cases, the two margins could merge together and form a single discontinuity with little to no disruptions in the reflector geometry.

The identification of root zones is also challenging due to fluid-induced seismic attenuations within the chimneys. In the case of wide chimneys, root zones can be identified more confidently as the downward extent of the up-bending reflectors beneath which we also observe chaotic seismic facies going deeper and merging with the tips of sill intrusions (Fig. 4.9). This could have critical implications for the source of overpressure in the fluidized sediments as the relationship between sill intrusions and hydrothermal circulation is well reported in other volcanic basins such as the More and Voring basin in the NE Atlantic [Planke et al. [2005]]. We also find rootless wide chimneys with abrupt lower terminations within the Paleocene-Eocene strata (Fig. 4.10(b)). These could have formed due to lateral fluid transport from the adjacent chimneys that have well-defined root zones.

Chimney tops are identified on the top Middle Eocene age reflectors and within the Lower to Mid-Eocene succession (age reflectors correlated from [Ritchie et al. [2008]]) and show a variety of geometrical features (Fig. 4.10(a),(b)). Amplitude-brightened mounds can be observed where the up-going fluid pressure is not able to overcome the overburden pressure forming convex up features containing high concentrations of fluid. Whereas, dimmed amplitude depressions are observed, possibly emerging from grain liquefaction due to high-pressure fluid [Cathles et al. [2010]] or hydraulic fracturing of the overburden layer [Løseth et al. [2009]]. We observed some chimneys devoid of any seismically resolvable top structure. These are topped by horizontal continuous reflectors with minor brightened spots (Fig. 4.10(b)). With the identification of chimney tops and bottom, we can ascribe the height of the chimney to the length between the root zones and the chimney tops.

These heights vary from 400-900 ms in two-way travel time, corresponding to 340-760 m, assuming a constant velocity of 1700 m/s [Hustoft et al. [2010]].

The internal configuration of reflectors within the chimneys varies from highly disrupted stacks of mounds and craters to marginally affected narrow-stacked amplitude anomalies (Fig. 4.10(a),(b)). Within wider chimneys, amplitude blanking is dominant but thick brights can be seen in certain reflectors indicating localized fluid accumulations or long-lived gas venting systems.

We also examine a 2D time slice at 1.6s two way travel time to get more insights into the 3D geometry and horizontal extent, and distribution of the seismic chimneys. Fig. 4.11(a) shows three distinct disrupted and brightened amplitude anomalies with respect to the background response. These anomalies are narrow, elongated, and follow a NW-SE trend. The length of the major axis varies from 2.8 km to around 6 km while the width of the anomalies ranges within 300 m to 1.1 km. The geometries and dimensions of individual anomalies are similar to those reported in offshore west Svalbard due to the seepage of subsurface methane as a result of ocean temperature controlled warming of gas hydrates [peterson et al., 2010; plaza-faverola et al., 2015].

These anomalies contain two circular features (mean radius = 215 m) which show a conical geometry in 3D. These are interpreted as possible gas escape vents that are one of the ubiquitous features of many volcanic-rifted basins. Fig. 4.11(b) shows the RGB blending of the time slice at three different frequencies - 18 Hz (red), 24 Hz (red), and 30 Hz (blue). We observe that the margins of the anomalous regions are sharp and dominated by low amplitudes and low frequencies. Fig. 4.11(c) shows that the margins are characterized by high dip values due to the up-bending of reflectors and the presence of vertical fractures. The peripheries of the anomalies are diffused and show consistent brightening in the RGB blend with high envelope magnitudes in some cases (Fig. 4.11(d)). This could be due to the lateral fluid migration outward from the chimney center.

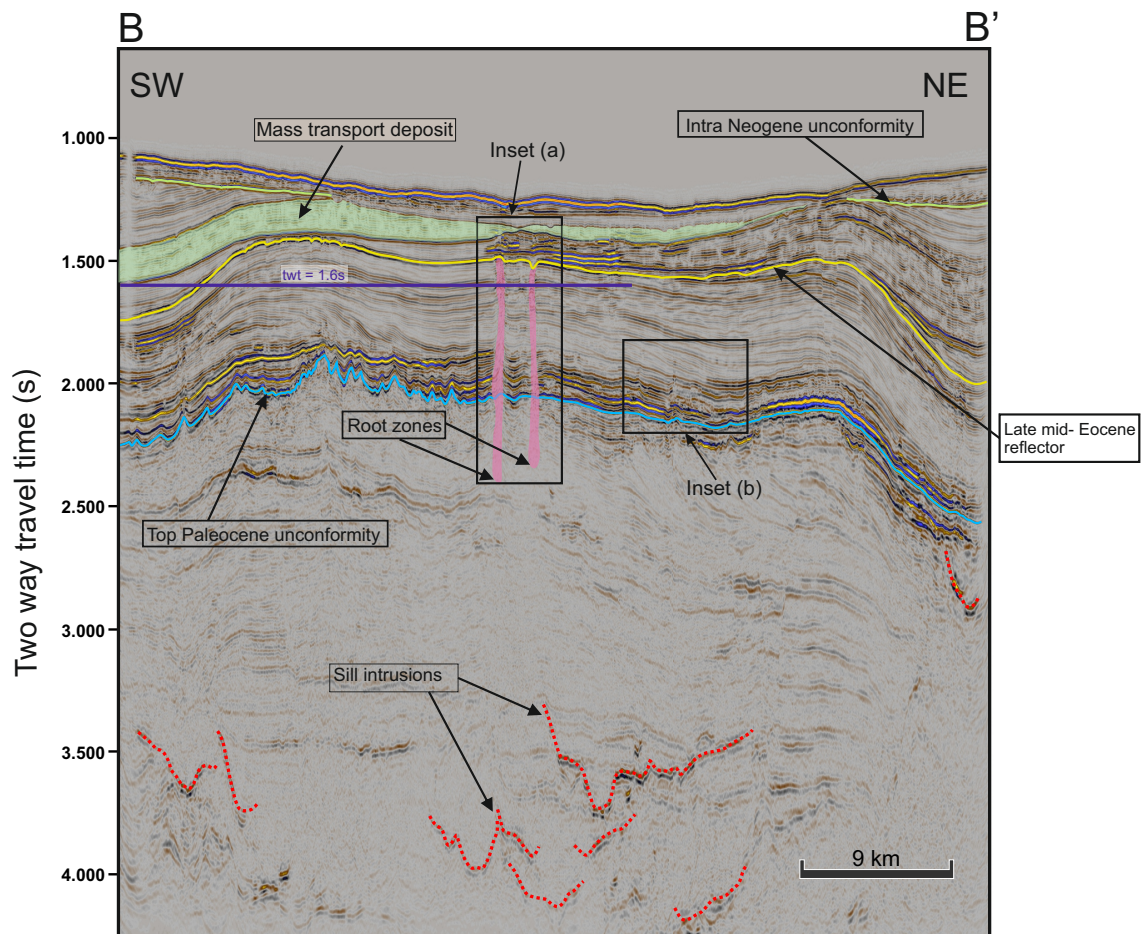


Figure 4.9: Interpreted Line 2356 of the 3D seismic survey BP933F0002 (See Fig. 2.1(b) for location) showing vertical zones of seismic disturbance in the Eocene strata (light pink) and their possible connection to the tips of deep seated sill intrusions. See Fig. 4.10 for insets.

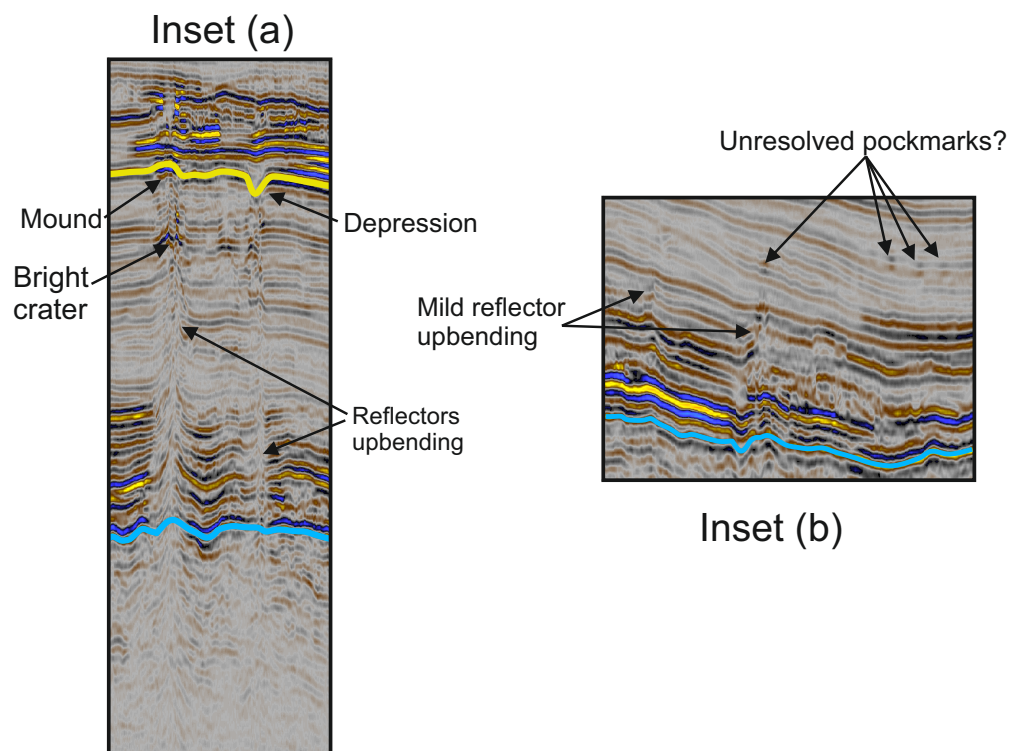


Figure 4.10: Insets from Fig. 4.9 showing the internal characteristics of reflectors and the geometry of the top bounding reflector of different seismic chimneys.



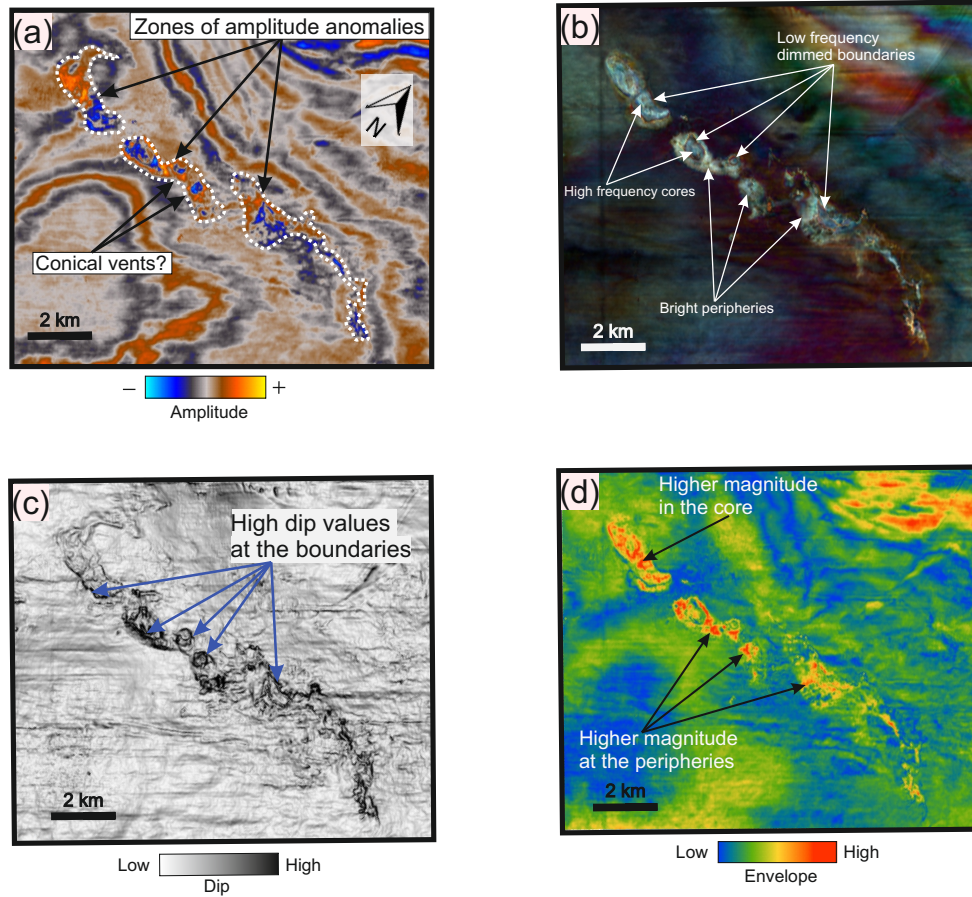


Figure 4.11: Seismic attribute analysis of the time slice at 1.6s of the 3D seismic survey BP933F0002 (See Fig. 2.1(b) for location). (a) Amplitude map (b) RGB Spectral blending using frequencies - 18Hz (red), 24Hz (green), 30Hz (blue), (c) Dip map, and (d) Envelope map.

# Chapter 5

## Discussion

### 5.1 Paleocene to Eocene evolution of the Central Corona Basin

The Faroe-Shetland basin experienced a regional uplift during the Early Paleocene, which was responsible for the rapid sea-level fall and the development of NW prograding T38-T40 siliciclastic bodies in the southwestern part of the basin [Smallwood and Maresh [2002]]. [Ziska et al. [2022]] found a coarsening up T38 succession in the mid-faroese high, going from marine claystones to volcanoclastic sandstones. Going further northeast, our results indicate that coastal conditions were established in the central corona basin during T38 times. Lava erupted from localized fissures, and vents flowed towards the northeast, forming a lava delta after encountering the ocean (Fig. 5.1). As the accommodation space got infilled with the episodic supply of volcanic material, the lava delta prograded in the NE direction, and the hyaloclastite foresets were overlain by subaerial lava flows. Other contemporaneous lava deltas have been reported in different parts of the basin. [Wright et al. [2012]] analyzed an ESE prograding lava delta in the northeastern part of the basin over the Faroe-Shetland Escarpment. Although their study does not mention the specific timing of the formation of the lava delta, a regional correlation of the top basalt horizon indicates that the lava delta over the Faroe-Shetland escarpment also developed during T38 time. In the Brynhild sub-basin, located in the western part of the basin, [Ziska et al. [2022]] reported a pre-breakup SE prograding lava delta, which also developed during T38 times. We combine these studies to approximate the geometry of the paleo-coastline that developed in the FSB as a result of the plume uplift. We find that the trend of the paleo coastline was along NE-SW in the Brynhild subbasin in the west, turning anti-clockwise towards NNE-SSW in the central

corona basin and following a similar trend in the FSB escarpment region.

The FSB underwent post-break-up subsidence in the late paleocene-early Eocene, leading to relative sea-level rise and flooding regions with subaerial lava flow deposits. [Wright et al. [2012]] recognized two retrograding units that lie above and post-date the landward flow units of the lava delta in the NE part of the FSB. They related these units to the northwest propagation of the coastline during relative sea-level rise. The top of their latest retrograding unit correlates with the base of unit 3 (refer to Section 4.1) in the central corona basin, which signifies a transition from volcanic deposits of the T40-T45 Flett formation to the coastal siliciclastic deposits of the Hildasay sandstone member of the uppermost Flett formation. 3D seismic geomorphological interpretation of the top surface of unit 3 shows the development of an estuarine environment confined by barrier bars where rivers flowing from the west and north-west deposit organic-rich medium to fine-grained siliciclastics in a low-energy environment. It has been argued that a 5-8 °C rise in global temperatures during the Paleocene-Eocene Thermal Maximum (PETM) led to humid conditions in the FSB and the deposition of the Hildasay sandstones during early Eocene, which is an excellent quality reservoir unit of the Cambo oil field located slightly south-east of our study area [Purvis et al. [2020]].

Continual subsidence during the Eocene established marine conditions throughout the basin, marked by the regional Balder formation composed of marine claystone, coal, and tephra deposits from late-stage volcanism. Deposition of marine claystone continued throughout the Eocene, accompanied by episodes of coarse-grained basin floor fan deposition during the middle Eocene, sourced from the west shetland platform [Shoulders et al. [2007]]. The presence of an extensive network of sand injectites within the Breydon fan in our study area signifies the role of fluid flow in the post-breakup evolution of the FSB. Previous studies have reported kilometer-scale conical sandstone intrusions of late Miocene age in the mid-faroe ridge region with the middle Eocene Strachan and Caledonian fans as their major source [Shoulders et al. [2007]; Bureau et al. [2013]]. In our study area, we encounter a completely different class of sand injectites, both conical and saucer-shaped, that can be seen originating primarily from the top of the Balder formation. These injectites intrude the overlying fan unit and form secondary sources for smaller injectites. Since the balder formation is entirely composed of tuffaceous claystones, the sand must come from the underlying Hildasay sandstone via small fractures/cracks in the balder claystone. Forced folds and subsequent onlaps on the intra-fan and top-fan reflectors suggest that the clastic intrusion activity ceased by the end of the middle Eocene. Overpressure buildup in the Hildasay sands would require higher amounts of water re-



tention during deposition and the rapid burial of overlying balder formation. Subsequently, a trigger event such as an earthquake, tectonic compression, or igneous intrusion is necessary to induce stress and initiate intrusion activity. Late Miocene sand injectites are believed to be triggered by early to mid-Miocene inversion events. However, we do not find any evidence of regional tectonic activity during the middle Eocene. Although late-stage sill intrusion activity could be a plausible trigger mechanism, the age of igneous intrusions in the central corona basin is uncertain. Therefore, the mechanism of middle to late Eocene clastic intrusions in the central corona basin remains unclear.

## 5.2 Paleocene Flood basalt emplacement

Significant erosion and reworking of the subaerial basalt deposits in the central corona ridge region are evident in unit 2 with the absence of the tabular flows of the Rosebank lower volcanics and the presence of thick volcanoclastic units within the Rosebank upper volcanics equivalent basalt.

The variation in porosity in different basaltic sub units indicates variations in the amount of weathering and the period of hiatus, assuming fractures induced due to weathering to be a major source of porosity. Similar results from offshore kutch basin have reported the presence of a volcanic succession consisting of fractured and massive basalts [Bhardwaj et al. [2021]]. However, the difference in the characteristic acoustic velocity history of different basaltic sub units can also be correlated with the classification scheme proposed by [Nelson et al. [2009]]. According to this, the units BU1, BU4, and upper BU3 relate to tabular classic lava flows whereas BU2 and lower BU3 consist of braided compound lava flows. Correlation with onshore stratigraphy of the Faroe Island basalt group (FISB), this type of succession is consistent with the lithology of the Enni formation which consists of both inflated sheet flows that are associated with terraced terrains and compound flows [Passey and Jolley [2008]].

This correlation with the onshore Enni formation is also reflected in the different kinds of lava flow morphologies identified at the same stratigraphic level in the Brynhild Basin. Here, we observe overlapping, anastomosing flow patterns generally associated with compound lava flow as well as regionally extensive tabular sheets of lava deposits associated with simple lava flows [Walker [1991]]. The emplacement order of different lava flows is difficult to examine as they are present in the same horizon slice as time averaged structures. It is evident that different flow characteristics primarily reflect variations in the rate of lava effusion, lava viscosity and paleo topography during the emplacement.

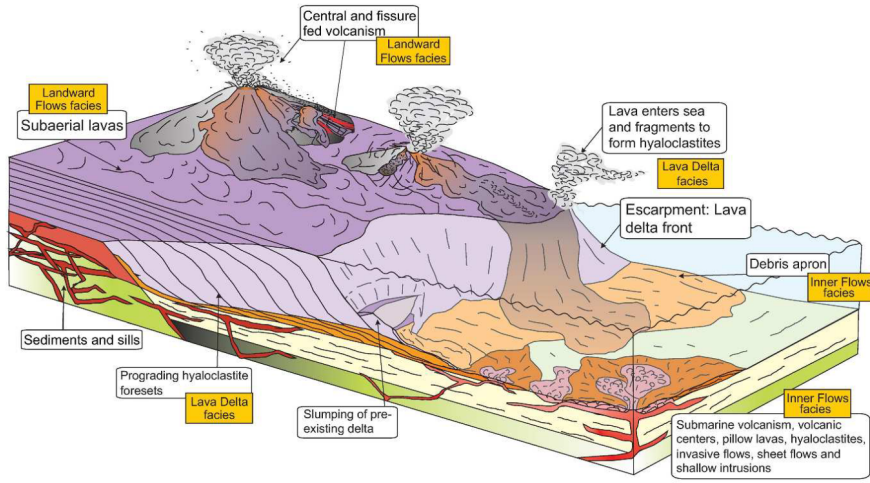


Figure 5.1: A conceptual illustration showing the flood basaltic eruption through volcanic fissures and vents, and the subsequent development of different parts of a lava delta. Picture taken from [Abdelmalak et al. \[2016\]](#)

### 5.3 Late-stage intrusion activities and fluid flow

Igneous sill and dyke intrusions are ubiquitous features in volcanic rifted sedimentary basins. The Faroe-Shetland Sill complex (FSSC) is an extensive suite of both discrete and connected igneous sills intruding the mesozoic and lower paleocene sediments of the Faroe-Shetland Basin. Previous studies on FSSC concentrated on its seismic geomorphological characterisation, emplacement style, age of intrusion and potential role in hydrocarbon migration. The current most reliable age estimate of the FSSC places it between 55 Ma and 52 M, post dating the main phase of flood basalt eruption in the North Atlantic Igneous Province [Passey Hitchen, 2011]. However, [\[Schofield et al. \[2017\]\]](#) found older (61.6 Ma) sill intrusions beneath the Rona ridge based on the forced folds and subsequent onlaps in the stratigraphy. In our data, we do not observe any such forced fold due to sill intrusions in the stratigraphy, which makes it difficult to constrain the relative ages of sill intrusions near Judd High and in the West Solan basin. We, therefore, acknowledge the proximity of our study area with the regional study done by [\[Schofield et al. \[2017\]\]](#) and attribute similar ages (61.6-52 Ma) to the sill intrusions in our study area.

Our results also indicate the widespread presence of focused fluid flow pathways in the Paleocene-Eocene strata. The mere existence of these fea-

tures is indicative of - (1) the presence of a fluidized source, (2) the building of overpressure in the fluid, and (3) the construction of conduits transporting the overpressured fluids into the overburdened host rock. We will now discuss each of these points in detail.

1. *Fluidized source*: Most of the wide chimneys have their root zones located below the Paleocene age Top Flett unconformity which means that the source of fluid lies either within the prograding Lamba formation of middle Paleocene age or the deepwater sand bodies of the Vaila and Sullom formations of Early Paleocene age. Some of the oldest and most prominent hydrocarbon-producing fields in the Faroe-Shetland Basin, i.e. The Foinaven, Marjun, and Schiehallion fields have sand units of the Vaila and Sullom formations as their primary reservoir. The good reservoir properties, therefore, make the Vaila and Sullom formations the likely contenders of the source rock of the seismic chimneys.
2. *Overpressure trigger*: The connection of the root zones with the tips of sill intrusions is not unprecedented. [Planke et al. [2005]] identified similar connections in the More and Voring basins, where several buried hydrothermal vent complexes were shown to be formed as a result of sill intrusion activities. [Hansen et al. [2005]] followed with a regional study spanning the NE Atlantic margin and used the intrusion-related vent complexes to constrain the ages of the discrete phases of sill intrusions. These studies suggest that the boiling and degassing of aqueous pore fluid in the host rock is responsible for the building of overpressure in the source rock. The presence of low permeability overburdened layers is also important to ensure that pressure release does not exceed the pressure buildup due to sill intrusion.
3. *Fluid transport*: The transport of fluid within the overburdened low permeability layers can be explained with the help of two different mechanisms - fracture failure or capillary failure [Cathles et al. [2010]; Løseth et al. [2009]]. Fracture failure occurs when the overpressure in the pores increases beyond the least compressive stress and tensile strength of the overburden leading to the propagation of hydraulic fractures in the direction normal to the minimum stress. On the other hand, capillary failure takes place when the pore overpressure exceeds the capillary entry pressure, leading to the migration of gas through the water-saturated sediments in the overburden in a piston like geometry.

The timing of the cessation of fluid flow activities can be estimated by the age of terminal reflectors of the chimneys, which, in our data, corresponds

to Lower to Mid-Eocene. It is important to note that this age is prone to be overestimated due to the inability of our data to resolve extremely thin pipes that may be present in more recent sedimentary successions. However, this would only be applicable to small-scale features that may only represent a small fraction of the regional fluid flow events. The Lower to Mid-Eocene ages of the chimney terminations are more recent compared to the other estimates in the NE Atlantic margin that encountered intrusion-related hydrothermal vents within the Upper Paleocene strata. A recent study done in the mid-norwegian margin suggested that the Late Paleocene-Early Eocene dated hydrothermal vents in the NE Atlantic margin played a key role in the Paleocene Eocene Thermal maximum (PETM) [Berndt et al. [2023]]. In the context of our results, these events could indicate that intrusion related fluid flow was responsible for the initial development of seismic chimneys during late paleocene to early eocene. These chimneys then became conduits for later stages of fluid flow within the lower to mid-eocene strata.

# Chapter 6

## Conclusions

In the context of our study, we performed combined analysis of 3D seismic and well log datasets in order to get a deeper understanding of the volcanic process that were active in the Faroe-Shetland basin during and after the continental breakup in the North Atlantic during early to late Paleocene. Our study led to the following conclusions:

1. Early Paleocene in the Faroe-Shetland basin was marked with voluminous eruption of basaltic lava that led to the development of a NE prograding lava delta in the central Corona basin, which was followed by subaerial lava flows. Well log analysis results indicate that the subaerial lava flow was composed of both simple and compound lava flows with varying degrees of fracture induced porosity.
2. Seismic geomorphological analysis of the Top basalt surface indicate that the lava flow was primarily compound in the Brynhild basin during the last stages of eruptions.
3. Post-rift intrusive igneous activities in the basin led to the development of conduits for focused flow in the Judd basin during Eocene.

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