Understanding Lava–Sediment Interaction during Basaltic Plains Volcanism – Final Report

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Understanding Lava-Sediment Interaction during Basaltic Plains Volcanism

Final Report

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Abstract

This study integrates the results of a field visits and subsequent laboratory analysis of volcanic and sedimentary rocks in the Malinstindur and Enni formations, Faroe Islands Basalt Group. Field mapping of stratigraphical sections allied to petrographic analysis has identified two competing shield volcano sourced flow fields in the Enni Formation. These shields are thought to be around 45 km in diameter, and were centred around Sandoy in the southwest, and around Svinoy and Fugloy in the northeast. A single, contemporary central fissure flow field was also mapped on the east of Streymoy. The northeast and southwest shields are repeated in the upper part of the Argir Beds, indicating long term persistence of magmatic plumbing systems. The sedimentary rocks of the Argir Beds are preserved in the accommodation space between the eruptive products of the two large shield volcanoes, against the edge of the central fissure flow field. This is important, in that it demonstrates the creation of accommodation space by the interaction of separate constructional lava fields.

Analysis of the sedimentary interbeds in the Enni Formation has enabled them to be broadly categorised into two different groups. Mass flow deposits, conglomerates, lacustrine sediments and thin red sandstones occur in the areas to the northeast and southwest of the central fissure field, having a western limit at the edge of the western shield volcano. These were deposited by mass wasting processes in an active volcanic landscape, while ephemeral drainage systems and lava dammed lakes were developed in longer hiatuses in shield eruption history. Between these two shield volcano lava fields was a south-easterly sloping surface. This surface hosted a drainage system which deposited the fluvial sandstones and mudstones of the Argir Beds. This braided fluvial system was the longest lived and best developed of the sedimentary interbeds.

Comparison of the Enni Formation low angle shield volcano structures with that of the Erlend volcanic centre, highlights a closely comparable size and development history. These 45 km diameter structures are also comparable with recent examples from the Afar Rift valley, east Africa. This suggests that shield development across the NAIP may be on a broadly predictable scale. Similar shields are thought to have played a part in constraining drainage systems in the Late Paleocene to Early Eocene of the Corona Ridge, Faroe-Shetland Basin. Comparison of the scale of the Faroe Islands central fissure flow field with one previously identified from seismic data on the Corona Ridge suggests similarity.

Correlation of available MgO and the successional status of lava field vegetation were used to highlight the correlation between the time interval between volcanic episodes, and the
complexity of the sedimentary drainage system. Interbeds of the FIBG Enni Formation exhibit early to early-middle seral succession palynofloras and high residual MgO values. Comparison with Hawaii models suggest a duration of <2000 years for many of these interbed units. Interbeds of this character occur in the ‘Rosebank Upper Volcanics’, which postdate the Rosebank Field reservoir. Interbeds with late seral succession status and depleted MgO are not found in the Enni Formation, because of the short intermissions between volcanic episodes proximal to the proto rift. However, interbeds of this character form the thick reservoir sections of the Rosebank Field. Here, comparison to Hawaii data suggests interbed durations of 2000 to >8000 years. Although the interbedded drainage systems on the Corona Ridge are proximal to local, FIBG contemporary volcanic shields and fissures, activity is punctuated by longer time periods than in the core of the FIBG. It is noteworthy that in peripheral parts of the NAIP lava field, intra lava field drainage systems are controlled by the creation and destruction of accommodation space, just as recorded in the rift proximal basalt plains sequences of the Enni Formation.
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1 Introduction

1.1 Objectives

The discovery of the Rosebank field in the mid 2000’s has focussed attention on intra-lava plays, with an emphasis on Sequence T40 (Ebdon et al. 1995) depositional systems. Interest in the Sequence T45 strata of the Cambo Field has subsequently expanded the area of interest. This project was undertaken to establish a model which characterises the lava fields and intra-volcanic deposits of this younger sequence. In the Rosebank and Cambo field areas, these lava fields occur beneath and influence the distribution geometries of the Hildasay Member sandstones. They also pass laterally into wholly siliciclastic facies of the Sequence T45 Flett Formation in the Flett and Judd Sub-Basins of the Faroe-Shetland Basin. Similarly, our understanding of what appears to be basaltic plains volcanism of the Enni Formation, Faroe Islands Basalt Group (FIBG) is also limited. Enhancing our knowledge of the interaction of sedimentary and volcanic depositional systems in this part of the FIBG would allow the use of this well exposed onshore example as an analogy for the younger lava fields of the Flett Formation. The overall objectives can be identified as:

1. Understanding the volcanic and sedimentary evolution of basaltic plains volcanism
2. Categorise the interaction between sedimentation and lava flow emplacement
3. Constraining the depositional system of the different lava flows and sedimentary units
4. Understanding the structural influence involved in the development of basaltic plains volcanism
5. Discuss the potential implications of basaltic plains volcanism on hydrocarbon exploration in the volcanic-affected region of the Faroe-Shetland Basin

1.2 Overview

The Enni Formation is typical of the basaltic plains style of volcanism that is characterised by topography forming low shield volcanoes composed of compound lava flows (Passey & Bell 2007). The areas between the compound lava flows are filled with sediments and simple lava flows (cf. sheet lobes) that drown the landscape and maintain regionally planar surfaces and it is in these areas, between the shield volcanoes, that potential hydrocarbon reservoirs may exist. This project will obtain a better understanding of basaltic plains volcanism as a direct analogue for offshore settings in the Faroe-Shetland Basin.
The Faroe-Shetland Basin is a NE-SW orientated rift basin in the NE Atlantic Ocean that has a prolonged sedimentary history from the Devonian to recent (e.g. Doré et al. 1999). In the western part of the basin the Devonian-Palaeocene sedimentary succession is overlain by the Palaeocene-Eocene Faroe Islands Basalt Group (FIBG), locally consisting of up to 5 km of hyaloclastite deltas, subaerial basalt lava flows and interlava sedimentary units (Passey & Hitchen 2011). Within the FIBG lava field the lava flows are intercalated with sedimentary rock units deposited by rivers and in shallow marine environments (Ellis et al. 2002). Probably the best known of these is the Rosebank hydrocarbon discovery (Helland-Hansen 2009), which has highlighted interlava hydrocarbon plays in Sequence T40. Younger Sequence T45 lava flows are intercalated with thick, mixed siliciclastic and volcaniclastic sedimentary units in wells offshore the Faroe Islands. This succession includes the Hildasay Member sandstones, whose sandstones are included in the Cambo Field area.

The FIBG is subdivided into seven lithostratigraphic formations dominated by subaerial lava flows intercalated with volcaniclastic lithologies (Fig. 1.1; Passey & Jolley 2009). The Beinisvørð Formation is a c. 3.2 km thick sequence composed primarily of <70 m thick sheet lobes (lava flows with widths that are significantly greater than their thicknesses). The Beinisvørð Formation is overlain by the Prestfjall and Hvannhagi formations composed of sedimentary units marking a hiatus in the lava flow volcanism (Passey & Jolley 2009). Lava flow volcanism resumed with the emplacement of the maximum 1.4 km thick Malinstindur Formation composed of locally erupted compound lava flows (Passey & Bell 2007; Passey & Jolley 2009). This is followed by another hiatus in the emplacement of the lava flows marked by the deposition of the Sneis Formation, a mass flow sequence up to 30 m thick and consisting of hyperconcentrated flow sandstones and debris flow conglomerates (Passey 2009; Passey & Jolley 2009; 2010). The final phase of lava flow volcanism on the Faroe Islands is represented by the >900 m thick Enni Formation that is characterised by so-called basaltic plains volcanism, where compound lava flows are intercalated with laterally extensive sheet lobes (Passey & Bell 2007; Passey & Jolley 2009). This mixture of lava flow morphologies implies that two different styles of eruption mechanism were operating at the same time and this is reinforced by contrasting olivine-phyric and plagioclase-phyric petrologies of the lava flows (Passey & Bell 2007; Passey & Jolley 2009).
Although the Enni Formation forms the youngest part of the stratigraphy only the lower 300 m has been investigated with a focus on the inter-bedded sedimentary units (Ellis et al. 2009; Passey 2009; Passey & Jolley 2009; 2010). These investigations have shown that the interaction between the different lava flow morphologies and petrologies is very complex, but the distribution of the different flow-types is beginning to resolve source directions and structural control on their emplacement. In addition, the Enni Formation is punctuated by abundant volcaniclastic interlava units, which become increasingly frequent up section. One of the most noticeable is the Argir Beds, a <6 m thick dominantly arenaceous unit of fluvial and floodplain facies (Passey 2009; Passey & Jolley 2009; 2010). The >600 m thick stratigraphy above the Argir Beds has been largely neglected, primarily due to the isolation of exposures occurring on the outer islands of the Faroese archipelago. However, the completed SINDRI project C46-38-01 (Jolley & Passey 2012) investigated the lower part of Nólsoy, part of the Enni Formation above the Argir Beds, and demonstrated the presence of up to 40 m of sedimentary interlava units (maximum unit c. 15 m thick) intercalated between the lava flows in a 150 m thick interval. Some of these younger units on Sandoy contain marine palynofloras indicating the flooding of valleys in the latest stage of volcanism (Ellis et al. 2009).

This increase in sedimentary interlava units reflects either the waning of lava flow volcanism or the eruptive nature of basaltic plains volcanism. It has been demonstrated in other basaltic plains volcanism regions that the compound lava flows typically build-up to form low shield volcanoes dominating the local landscape (Fig. 1.2; Greeley 1977; 1982). In between the shield volcanoes, sediments and sheet lobes can be deposited and emplaced that drown the pre-existing topography and maintain a regionally planar land surface (Greeley 1977; 1982). Therefore, by understanding basaltic plains volcanism from onshore Faroe Islands can help constrain volcano-seismic interpretations offshore and potentially identify plays between the compound lava flow shield volcanoes.
Fig. 1.1. Simplified geological map and gross stratigraphic column for the Faroe Islands Basalt Group. The geological map and stratigraphic column are modified after Rasmussen & Noe-Nygaard (1970) and Passey & Jolley (2009), respectively.

Fig. 1.2. Block diagram showing the relationship of low shield volcanoes, major lava tube flows, and fissure flows within Basaltic Plains volcanic provinces. Modified after Greeley (1977; 1982).
2 Methodology

2.1 Experimental Design and Dataset

To underpin this project, detailed lithostratigraphic logs for the youngest exposed sections of the Faroe Islands Basalt Group were collected in four field visits (2009 – 2011). This has been integrated with data already collected by the investigators during the previous 10 years. In all sections, details of both volcanic and sedimentary lithologies were recorded and incorporated into stratigraphical cross sections. Fieldwork was undertaken on the following islands:

- Sandoy; Stóra Dímun; Fugloy; Svínøy; Nólsoy; Skúgvoy, with further work conducted on both Streymoy and Eysturoy.

The methodology used in this study incorporated the following techniques:

1. Construction of lithostratigraphic logs to provide the basis for the stratigraphical and palaeoenvironmental reconstruction.

2. Macroscopic characterisation of the lava flows (sheet lobes and compound flows) to establish 3D geometries.

3. Microscopic (thin section) description of selected sedimentary units to identify source and compositional character.

4. XRF analysis of interbed sedimentary rocks to provide data on depositional system and profile maturity.

5. Palynological analysis of sedimentary units to establish stratigraphical relationships to siliciclastic sequences in the Faroe-Shetland Basin and to establish an environmental system model to constrain the basalt and sedimentary geometries

2.2 Terminology

2.2.1 Volcaniclastic Rocks

A volcaniclastic rock is an umbrella term that covers a variety of lithologies in predominantly volcanic environments. In simplistic terms, a volcaniclastic rock is a clastic rock that contains volcanic debris (Fisher 1961; 1966; Fisher & Smith 1991). This is a very broad
definition and subsequent researchers have attempted to quantify the amount of volcanic debris that such a rock should contain, for example, >10% by Gillespie & Styles (1999) and more recently >60% by the Shipboard Scientific Party (2002). There has also been much debate about how to categorise the volcanic debris and whether the rock is primary, i.e. formed directly by volcanic activity or secondary, e.g. formed by sedimentary processes (e.g. Schmid 1981; Cas & Wright 1987; McPhie et al. 1993; Gillespie & Styles 1999; Shipboard Scientific Party 2002; White & Houghton 2006). Following the guidelines of Cas & Wright (1987) this study considers secondary debris to be derived from the reworking of unconsolidated primary volcanic deposits (e.g. tephra) as well as from the erosion of pre-existing volcanic rocks (e.g. lava flows, tuffs). This scheme places the emphasis on the final mode of deposition rather than the debris forming mechanism (cf. Cas & Wright 1987). The specific volcaniclastic rock name, for example, volcaniclastic sandstone, is a first order descriptive term that does not imply any mode of genesis. Although this appears to be semantic, it has become increasingly important to carefully examine volcaniclastic rocks in rift margins where they can be interbedded and mixed with, for example, siliciclastic components (e.g. Wickens & McLachlan 1990; Cas et al. 2001).

2.2.2 Lava Flows

This report uses the terminology of Self et al. (1997) that has been used in the Faroe Islands by Passey & Bell (2007), Passey (2009) and Passey & Jolley (2009) to describe the gross morphological features of the subaerial lava flows. A flow lobe is an individual package of lava surrounded by a chilled crust and a lava flow is the product of a single, more or less, continuous outpouring of lava that may be composed of one or more flow lobes. Individual lava flows are typically separated by weathering surfaces and/or clastic (typically volcaniclastic) lithologies. If a lava flow consists of a single flow lobe, it is referred to as a simple lava flow (Walker 1971). Conversely, a compound lava flow (Walker 1971) consists of two or more flow lobes of any geometry or size that typically overlap, meander and anastomose. Flow lobes that are significantly wider than they are thick and have a sheet-like/tabular geometry are classified as sheet lobes (Self et al. 1997). On the Faroe Islands, sheet lobes and simple flows have been regarded as synonymous (Passey & Bell 2007).
2.3 Analytical Techniques

2.3.1 Palynology

Sedimentary interbed samples (>650 samples) were crushed to small fragments and the silicates dissolved in 40% hydrofluoric acid until all the grittiness was removed. The neutralized sample was then sieved using a 5 μm mesh nylon sieve, and the resultant residue treated with dilute 40% nitric acid for <5 minutes to remove any pyrite. Neutralized residues were then pipetted onto glass coverslips using dilute PVA and mounted on glass slides as permanent strew mounts using a two-part epoxy medium. Slides were examined under a transmitted light microscope, with counts of up to 250 specimens being undertaken where the abundance of the palynomorphs allowed. Data was added to an Excel spreadsheet and graphical presentations created in the ‘C2’ data analysis program (version 1.6.9, S. Juggins – University of Newcastle). Further analysis of palynofloral data was undertaken using the MVSP (Multi Variate Statistical Package) software (Kovach 2007).
3 Facies of Basaltic Plains Volcanism

3.1 Overview

Passey & Varming (2010) suggested, using the spline surface for the base of the Argir Beds, that c. 770 m of the uppermost Enni Formation remains exposed on Sandoy. The correlation presented in Fig. 3.1 confirms this estimate, covering the uppermost c. 760 m of the Enni Formation to the top of Stórafjall, Sandoy (the youngest point on the islands as suggested by Passey & Varming 2010). The thirty-three logged sections are arranged on a theoretical line from SW-NE, orthogonal to the general south-easterly dip of the strata. The sections are flattened to the base of the Argir Beds, a ubiquitous and conspicuous stratigraphic marker unit between Stóra Dímun and southern Eysturoy (Ellis et al. 2009; Passey 2009; Passey & Jolley 2009; 2010; Passey & Varming 2010). To the N and NE however, the Argir Beds are generally poorly developed or absent and their basal surface is recognised by a perceptible change between mainly pale weathering, plagioclase-phyric to brown weathering, aphyric basalt lava flows (Ellis et al. 2009; Passey 2009; Passey & Jolley 2009; 2010; Passey & Varming 2010). It should be noted that the base of the Argir Beds identified on Fugloy by Passey & Jolley (2010), contradicting the original surface picked by Passey & Varming (2010), has, following additional fieldwork on Svinoy, led to the latter horizon to be reinstated whilst strengthening correlations across the north-eastern islands (Fig. 3.1).

Passey & Bell (2007) in their examination of lava flow morphologies of the Faroe Islands attributed the simple lava flows/sheet lobes to having been erupted over laterally extensive areas from fissure systems. This contrasts with the tube-fed compound flows which were erupted in a gradual, piecemeal manner from point-sourced, low-angle shield volcanoes with diameters a few tens of kilometres across. Following this scheme it appears that the lower 250 m of the volcanic succession above the Argir Beds is dominated by two shield volcanoes situated to the NE and SW of the central islands (i.e. Streymoy and Eysturoy). The area between the shield volcanoes is characterised by laterally extensive sheet lobes (cf. simple flows) fed by fissures. The upper 500 m of the Enni Formation is poorly constrained due to the lack of exposure either due to erosion or the strata being submerged beneath sea level. The SW and NE sides of the correlation nevertheless, appears to consist of contrasting compound lava flow sequences erupted from opposing shield volcanoes. The distribution of the different eruptive sequences is modelled in Fig. 3.2 and each sequence is described below.
3.2 Argir Beds, Eystnes Flow and Ovarafjall Flows

The Argir Beds and associated Eystnes Flow and Ovarafjall Flows have been described in detail by Passey & Jolley (2010) and are briefly summarised here. The Argir Beds are found c. 250 m above the base of the Enni Formation. The Argir Beds are relatively easy to identify across the central islands from southern Streymoy and Eysturoy to Stóra Dímun due to their pronounced thickness (>1.8 m) in a sequence dominated by plagioclase-phyric compound and simple flows. Across southern Eysturoy the Argir Beds are however, intercalated with brown weathering, aphyric to olivine-phyric flow lobes belonging to a distinctive compound flow named by Passey & Jolley (2010) as the Eystnes Flow. Moving northwards and to the north-eastern islands it becomes increasingly difficult to recognise the disconformity surface that the Argir Beds rest upon because they are poorly developed or absent. The surface is however, overlain by at least one, locally three, distinct brown weathering, aphyric to olivine-phyric simple flows between 4 and 20 m thick, named collectively as the Ovarafjall Flows (Passey & Jolley 2010). Volcanism during and immediately following the deposition of the Argir Beds is restricted to the islands NE of Sundini and Tangafjørður that separate Streymoy from Eysturoy.

3.3 Lower South-western Shield Volcano

The lower south-western shield volcano of Sandoy consists of plagioclase-phyric compound lava flows resting upon the Argir Beds. The volcano is at least 100 m thick in the Stórhøvd Section of NE Sandoy, but is potentially as thick as 200 m towards the centre of the island. Similar lava flows are not observed overlying the Argir Beds on Hestur or Streymoy, but comparable flows are intercalated with the simple lavas of the central fissure flow field (see below). The compound flows consist of meandering, anastomosing and overlapping flow lobes generally 2-5 m thick. The flow lobes comprise aphyric to plagioclase-phyric basalt with 10-30 % laths commonly up to 1 cm in length. Due to the high plagioclase feldspar contents the flows appear pale greyish-white in the field. This helps to distinguish them from the brown-weathering flows comprising the north-eastern shield volcano. The flow lobes resting directly upon the Argir Beds commonly contain tree moulds along their bases.

3.4 Lower North-eastern Shield Volcano

The lower north-eastern shield volcano is up to 300 m thick across Svínøy and Fugloy where it comprises brown weathering, aphyric to olivine-phyric basalt compound lava flows that rest directly upon sub-Argir Beds pale-weathering, plagioclase-phyric compound flows. The compound flows of the shield volcano are also found across the remaining NE islands and NE Eysturoy, but is no more than 100 m thick and
commonly includes sparsely porphyritic plagioclase-phyric basalt compound lava flows. The flows belonging to the lower volcano have only been observed as far SW as a hypothetical NW-SE trending demarcation line running through Skálafjörður. This also coincides with the south-western extent of the underling 5-50 m thick plagioclase-phyric simple and compound lava flow sequence and the Ovarafjall Flows.

Individual compound flows are difficult to identify due to the scarcity of well-developed intervening sedimentary units, but flows are most likely decametres thick. The flow lobes are generally blocky and consist of meandering, anastomosing and overlapping flow lobes. The flow lobes tend to have features characteristic of inflated pahoehoe flow lobes better defined than those of the pale weathering compound flows of the south-western shield volcano; for example, well defined vesicle cylinders, horizontal vesicle sheets and horizontal vesicle zones. The highly vesicular upper crusts generally weather back forming steep gradients unlike the underlying near-vertical faces of the massive lava cores. The flow lobes vary greatly in thickness from a few decimetres to several metres. The thinness of the flow lobes means they are generally grass covered and poorly exposed and form very monotonous sequences.

3.5 Central Fissure Flow Field

The central fissure flow field is at least 180 m thick on Streymoy, but is generally about 140 m and appears to onlap the lower south-western and north-eastern shield volcanoes. Between Skopunarfjörður and Skálafjörður the flow field rests directly upon the Argir Beds and is dominated by pale weathering plagioclase-phyric basalt simple flows that range in thickness from 6 to 32 m (mode: 10 m; average: 17 m). To the SW of Skopunarfjörður these flows are intercalated with pale weathering, plagioclase-phyric compound flows that presumably emanated from the lower south-western shield volcano. To the NE of Skálafjörður the plagioclase-phyric simple flows have reduced modal and average thicknesses of 5 and 8 m, respectively (range: 3-17 m) and are underlain by up to 100 m of brown weathering, aphyric to olivine-phyric simple flows. This configuration and the reduced flow thicknesses gives the impression that the plagioclase-phyric simple flows are thinning to the NE. On the NE side of Skálafjörður and on southern Borðoy the flow field is locally overlain by pale weathering, plagioclase-phyric compound flows of unknown origin. In the area between Viðoy and Svinoy the flow field thins considerably and has tentatively been correlated to minor simple flows within the north-eastern shield volcano. The central fissure flow field is also conspicuous when compared to the adjacent shield volcanoes by containing up to 16 m thick volcanioclastic conglomerates and other well-developed, typically reddened, volcanioclastic sandstones.
3.6 Upper North-eastern Shield Volcano

The upper north-eastern shield volcano is exposed on the highest mountains of the NE islands, although the thickest sequences are found on Svinoy and Fugloy due to being situated further down the regional dip. The base of the volcano consists of 25-60 m thick sequence of dominantly brown weathering, aphyric to olivine-phyric basalt compound lava flows comparable to those from the lower north-eastern shield volcano. The overlying 200 m consists of brown weathering, aphyric to olivine-phyric basalt simple lava flows intercalated with volcaniclastic conglomerates up to 10 m thick. The simple flows range in thickness from c. 3 to 20 m and have a modal and average thickness of 10 and 9 m, respectively.

The relationship between the upper north-eastern shield volcano and the brown weathering, aphyric to olivine-phyric basalt compound and simple lava flows of Nólsøy and southern Streymoy is unclear, but may be distal flows erupted from the same volcanic system. The lack of exposure through this section of the stratigraphy between Nólsøy and the NE islands means that this correlation cannot be elucidated upon.

3.7 Upper South-western Shield Volcano

The upper south-western shield volcano is exposed on Sandoy and Nólsøy and is a monotonous sequence at least 600 m thick. The compound flows are non-descript and are neither particularly pale weathering nor brown weathering in character. The flows are typically comprise aphyric to sparsely plagioclase-phyric basalt and the meandering, anastomosing and overlapping flow lobes are generally several metres thick. The flow lobes locally exhibit well-developed to curvi-columnar jointing suggesting that some of the flow lobes have ponded in depressions. This is most noticeable in southern Sandoy, particularly in the Dalur Section. In this area, oblique, but poorly exposed, road cuts suggest the presence of multi-tiered and hyaloclastite flows. The lower 250 m is also conspicuous for containing numerous volcaniclastic sedimentary units locally up to 10 m thick in addition to a localised spatter vent deposit exposed along the coastline SE of Dalur village.

3.8 Nólsøy Depositional System

Borehole data and field mapping of the Nólsøy by Jolley & Passey (2012) showed that the area was dominated by an ephemeral freshwater lake. The corresponding sedimentary and lava flow facies record episodes of northwards transgression and southwards regression of the lake shoreline. The Tjørnunes Flow, for example, records the south-eastwards progradation of the flow from a subaerial to subaqueous environment. There is a natural progression from massive through multi-tiered to hyaloclastite foreset-
bedded lava flow facies. Other lava flows on Nólsoy also show a general thickening trend to the SE, for example, the compound flow above the Høsmøl Beds thickens by 40 m over 4 km.

This south-eastwards progradation or strong NW-SE alignment of facies is recorded through the volcanic sequence above the Argir Beds, although on a smaller scale. On Svínoy, for example a c. 4 m thick volcaniclastic sandstone in the Ryssugjógv Section is observed along the south-eastern coastline, but within a distance of c. 2 km to the NW the sandstone has pinched-out inland. A similar pattern is also seen on Sandoy between the Lítlavatn and Mataráin sections where a volcaniclastic sequence thickens and coarsens from c. 3 m thick sandstones to a c. 8 m thick conglomerate and sandstone couplet.
Fig. 3.1. SW-NE correlation between Sandoy and Fugloy, Faroe Islands. The correlation is flattened to the base of the Argir Beds and covers the upper c. 750 m of stratigraphy of the Enni Formation. Where the base of the Argir Beds is not observed the base is inferred from the spatial surface modelled by Passey & Varming (2010). The summit of Stórafjall, Dalur, Sandoy has tentatively been suggested by Passey & Varming (2010) to be the youngest point of the FIBG on the islands and this is supported by this correlation. The correlation between sections has been idealised, but generally reflects the dominant weathering colour (brown vs. pale), petrography (aphyric, olivine-phyric and plagioclase-phyric) and morphology (simple vs. compound) of the constituent lava flows and is aided by the presence of stratigraphic marker units (e.g. Argir Beds, Høsmøl Beds). The correlation will be aided by geochemical analyses, as shown on Nólsoy by changing geochemical signatures with height (Jolley & Passey 2012).

A1 VERSION CAN BE FOUND ON THE SUPPORTING DVD.
Fig. 3.2. Generalised distribution maps for lava flow packages, from oldest to youngest, recognised from the SW-NE correlation above the base of the Argir Beds. Lack of exposure means these maps should be regarded as models based on all available field, geochemical, palynological, etc. data. Despite these limitations, there appears to be a strong NW-SE trending corridor contained between opposing shield volcanoes.
Age of the Malinstindur and Enni Formations

The first comprehensive published studies considering the age dating of the geology of the islands include those of Waagstein (1988). Waagstein (1988) determined the presence of short intervals of normal polarity in the exposed Beinisvørð Formation. In combination with isotopic dates, mainly based on whole rock K/Ar analyses, this information was used to suggest a Late Palaeocene age for the Faroe Islands lava pile based on correlations to Chrons 25n and 26n (Waagstein et al. 2002). More recent isotopic dating studies have been limited by the availability of suitable material and by the necessity of relying on whole rock dating techniques. This has led to imprecision in dating the lava field.

The Malinstindur and Enni formations has been subjected to recent Ar/Ar isotope dating by Storey et al. (2007), who reported dates within the Malinstindur Formation (54.9+0.7 Ma) and near the top of the Enni Formation (55.2+0.7 Ma) that are within errors of each other. These dates are corroborated by ages derived from the Milne Land Formation of Kangerlussuaq, East Greenland (Hansen et al. 2002), strata geochemically comparable to the Malinstindur and Enni formations (Larsen et al. 1999). Together, these dates indicate that this Early Eocene part of the Faroe Islands Basalt Group was erupted over a period of time <1my. This conclusion is reinforced by the cooling history of the Skaergaard intrusion, East Greenland, one of a series of magma chambers that erupted coeval basaltic rocks over a period of <300 ky (Larsen & Tegner 2006).
5 Sedimentary Rocks of the Enni Formation

5.1 Introduction

In the context of this report, the term ‘interbed’ is used to describe both sedimentary rocks and weathering horizons/palaeosols. Interbeds are of primary importance in assessing the style and rate of eruption within a lava field. Flows and flow fields represent a fraction of the time in which the lava field was active. Interbeds can record hiatuses in eruption of a thousand years, to over a million years. They also preserve climatic proxy data and define sedimentary environments and flow field architecture.

Within the Malinstindur and Enni formations, eruption of >2 km of lava in c. 300 ky in the temperate Early Eocene climate would be expected to result in a continued patchwork of flow fields of varying age. This would mitigate against establishment of an integrated drainage system on the flow fields. Instead, disconnected, often unconstrained or ephemeral drainage systems would be expected. Rapid changes in lava field geomorphology would also be expected to result in mass wasting episodes, and localised thicknesses of volcaniclastic deposits derived from mass transport processes.

5.2 Interbed characteristics

The interbeds of the Enni Formation follow on from a succession of interbeds in the older Malinstindur Formation. As they represent a continuation in overall depositional system, it is important to consider the interbeds of the Malinstindur and Enni formations together.

Between the base of the Malinstindur Formation and the Kvívík Beds, interbedded sedimentary rocks and soils (interbeds) are rare. The lava field is characterised by inflated compound lavas, which erupted quickly and cover a wide area (Passey & Jolley 2009). The Kvívík Beds are a sequence of volcaniclastic sandstones and mudstones, locally with conglomerates, c. 780 m above the base of the Malinstindur Formation (Passey & Jolley 2009). Above the Kvívík Beds, interbeds occur more frequently. In this interval, thicker, often tabular lavas are separated by geographically persistent, thicker interbeds, with complex lithofacies.

The boundary between the Malinstindur Formation and Enni Formation is marked by the Sneis Formation, a prominent and widespread palaeosurface that has been used to correlate lavas and interbeds across the FIBG (Passey & Jolley 2009). The Sneis Formation comprises a sequence of sandstones overlain by basaltic conglomerates, deposited in stream and hyper-concentrated flow with individual beds (> 1 m) stacked to a total thickness of up to 40 m. As a part of the stratigraphical analysis of the lava field, it became necessary to give interbeds, or co-occurring groups of interbeds. The base of
the Sneis Formation (almost synonymous with the earlier ‘C horizon’ of Rasmussen & Noe-Nygaard 1970) represents a good stratigraphical horizon, the interbed successions were referred to by their position relative to the ‘C Horizon’.

Immediately overlying the Sneis Formation of Streymoy and Eysturoy are a succession of interbed units and weathered flow tops (interbeds C+0.5). These were deposited by ephemeral braided fluvial systems and debris flows during a period of active, localised eruption and so are difficult to correlate laterally. Above these interbeds (C+0.5) is a thick and laterally continuous interbed (C+1), but termed the Argir Beds by Passey & Jolley (2009). The exposure at Argir, the strato-type of the Argir Beds, comprises c. 2.7 m of coarsening-upwards coarse sandstones in shallow channels overlain by an upwards fining unit. Similar temporary exposures occur to the NW where multiple, stacked, low amplitude channels of <1 m thickness are developed. These complex fluvial deposits represent a longer hiatus in lava field activity, but are succeeded by more geographically restricted interbeds that vary from conglomerates to channel bedded sandstones.

Above the Argir Beds, the interbeds show geographical characters. In the northeast, Enni Formation interbeds are typically thin (<0.5 m), except for coarse grained fluvial sandstones and thicker conglomeratic beds from debris flows. Some more massive bedded lacustrine deposits are also recorded. On Streymoy and west Eysturoy, red and red-brown fluvial sandstones occur in this interval. These are thicker (up to 1.5 m), and were deposited in a shallow braided fluvial system. On Nólsoy and Sandoy, the interbeds of the post Argir Beds interval are of a third, different character. These comprise thin (<1 m) fluvial sandstones with low angle foresets, and laminated (on a cm scale) or massive-bedded lacustrine deposits. Thick (>5 m) conglomeratic beds occur on Sandoy, and probably represent localised mass wasting deposits. These are distributed though the upper part of the Enni Formation succession in the southwest, but are not common seen because of the lack of exposure.
6 Palynology

6.1 Interbed Ecology

Overall, the palynoflora recovered from interbeds within the Malinstindur and Enni formations are of low diversity and frequency and in general terms, the palynofloras of the two formations show little variation, except for a notable increase in chestnut type pollen (Cupuliferoipollenites cingulum subspecies) recorded in the Enni Formation interbeds. This distribution is not an example of stratigraphical control, but rather a reflection of the ecological conditions. To interpret the ecological controls on lava field vegetation, palynofloral data recovered from >650 Malinstindur and Enni formation samples was synthesised into two common data sets, one for Sandoy, Nólsöy and Skúgvoy, the other for Streymoy, Eysturoy and the NE islands. These data were then subjected to correspondence analysis with rare taxa downweighted (MVSP programme, Kovach 2007).

Analysis of the Streymoy, Eysturoy and NE islands data encompassed 36% of the overall compositional variation in first two axes. These were plotted as a scatter plot (Fig. 6.1), and show a continuum from early to mid successional vegetation ecology. In this diagram, one axis reflecting increasing succession state, the Y axis reflecting moisture availability. This indicates that the substrate water saturation and frequency of disturbance by volcanism are the two primary controls on the vegetation ecology of the central and NE area Malinstindur – Enni formations interbeds.

Frequency of disturbance as a factor in controlling vegetation ecology on lava fields has been detailed by Jolley et al. (2008) for the Columbia River Basalt Group, similar controls with comparable results are seen here for the Early Eocene portion of the FIBG. Because of the relatively high precipitation in the Early Eocene, it is intuitive that the palynofloras would reflect a high degree of substrate saturation. This extends from intra lava field lakes supporting chlorophycean algae, through saturated floodplain soils to dryer raised areas dominated by pines.

Nutrient availability is a third factor controlling vegetation ecology in the lava field (Jolley et al. 2008). Comparison of nutrient availability and substrate maturity data with palynological data from the Sneis Formation and younger interbeds around Slættaratindur and Kaldbaksfjørður was undertaken. This was achieved using canonical correspondence analysis (Kovach 2007). Scatter plots resulting from this analysis (Fig. 6.2) show a slight positive relationship between higher base levels (MgO) and chlorophycean algae, often associated with eutrophic lakes (Tappan 1980) and primary colonist fern spores which growing on newly formed soils that have not suffered base loss. A second grouping shows
a relationship between macronutrient depletion and taxa associated with drier, base poor soils. Here these include relatives of pines, myrtles (Myricaceae), *Ginkgo* and planes/sycamores (Plantanaceae), all taxa with known links to these environments (Jolley *et al.* 2009).

Within Streymoy, Eysturoy and the NE islands, Malinstindur Formation sediments yield low diversity palynofloras. These palynofloras are best preserved in the Kvívík Beds sections exposed along the west side of Eysturoy from Eiði and Svinoy in the north to Selatrað and Morskranes in the south (Fig. 6.3). These sediments contain *Inaperturopollenites hiatus* (*Metasequoia*)-dominated floras, some with common occurrences of *Cupuliferopollenites cingulum* subspecies (*Fagaceae*), *Caryapollenites circulus* (*Juglandaceae*) and *Deltoidospora adriennis* (cyathacean fern). This assemblage is suggestive of weathered flow tops with base rich poorly drained soils supporting a predominantly taxodiaceous vegetation, similar to mid-successional communities recorded from older Faroe Islands sediments (Lund 1989; Ellis *et al.* 2002).

To the NE on Viðoy, bedded volcaniclastic conglomerates and sandstones are exposed between compound lava flows of the Malinstindur Fm at Viðareiði (Passey & Bell 2007), and are here included within horizon C-2. Note that all interbed horizons in the Malistindur Formation and lower Enni Formation are referred to relative to their position in respect to the ‘C Horizon’ now known as the Sneis Formation. Negative numbers indicate interbeds older than the Sneis Formation, positive numbers, those younger.

Although no pollen is recorded at the Viðareiði C-2 interbeds, these strata contain abundant aseptate fungal mycellae, characteristic of a substrate containing rotting vegetation. This implies rapid deposition in a catchment with a low biomass vegetation, possibly mainly *Equisetum*. Evidence of this type of disturbance-tolerant early successional vegetation is also seen in the coarse volcaniclastic sandstones near the upper limit of the Malinstindur Formation at í Bugum (C-2 interbeds, 275-295 m below the Sneis Formation) on the eastern side of Streymoy. Here, trough cross-bedded sandstones cut down into laminated finer sandstones with commonly occurring macrofossils of *Equisetum*. These coarse-grained sediments provide evidence of an active fluvial system cutting through the lava field. Evidence for primary colonization of C-2 interbed fluvial systems by *Equisetum* is also seen in the Malinstindur Formation C-2 interbeds on Borðoy, Kalsoy and at Sneis on Streymoy. Similar evidence is also provided by the thin interbed sandstone exposed at Eiðisvatn on north Eysturoy. It is evident from the unstable nature of these fluvial systems, and the short interbed duration, that only a low biomass vegetation dominated by disturbance tolerant (ruderal) species could colonise these surfaces.
In one location, Lokkafelli on Eysturoy, there is evidence of early mid-successional vegetation. Here a C-2 interbed yielded the acritarch *Micryhstridium* and the pollen grain *Alnippollenites verus*. These fossils indicate a lacustrine or estuarine environment, with wet soils on the marginal floodplain. The occurrence of the *Alnippollenites* grains are possibly indicative of N-fixing plants dominating an early mid-successional, nutrient deficient ecosystem (Chapin *et al.* 1994; Jolley *et al.* 2008).

Support for the presence of low salinity facies in Kalsoyarfjørður has been recovered from samples taken from this horizon during the cutting of the Eysturoy-Borðoy tunnel. Here fragments of *Apectodinium* sp were recorded. This dinocyst is characteristic of brackish water facies in the earliest Eocene of the region (Jolley & Spinner 1989). These remain the only records of this facies in the Malinstindur Formation. This suggests that the Kalsoyarfjørður area experienced low salinity lacustrine conditions, with the flanking areas to the northeast and southwest continuing to erode actively, and provides direct evidence of a complex landscape.

Further evidence of disturbed environments in C-2 interbeds are recorded from Syðradalur on Streymoy. Here, large scale volcaniclastic conglomerate foreset beds dip to the east and are overlain by volcaniclastic sandstones, and tabular lavas. This is a localised feature, possibly near to a fissure eruption source, but it emphasises the localised nature of topographic slope prior to C-1 Interbeds.

The high-energy disturbed environments prevalent during the deposition of C-2 interbeds contrast sharply with C-1 horizon sites in west Eysturoy, where higher biomass, mid to late successional communities developed. They were dominated by *Metasequoia* and by juglandaceous and fagaceous trees or shrubs, implying greater environmental stability. Of particular note are the common occurrences of *Cupuliferopollenites cingulum*, This species is recorded in C-2 and C-1 interbeds, and indicates later succession vegetation. In the Eysturoy profile it occurs in an interval of plagioclase phryic compound flows round Morskranes and Selatrað which are interleaved with thin interbeds representing irregular eruptions rather than a prolonged hiatus. To the north, the area between Múlatindur and Slættaratindur, lava facies around the C-1 horizon is dominated by aphyric compound flows with few interbeds. These lavas represent inflation and more extended effusion of magma with consequently lesser chance for the development of interbeds. However, around Middagsfjall, the C-1 interbeds contains the floodplain marginal species *Tricolpites hians*. This distribution of species suggests that the C-1 interbeds were deposited as a floodplain fluvial sequence in the north of Eysturoy, with relatively short interbed durations between eruptions. Further south, down the drainage system, lakes and wetland soils were deposited in an area where eruption rates were slower and of different character.
Exposures of the C-1 interbeds on the western face of Sneis have also yielded palynomorphs. Here, an early successional community is suggested by the frequent occurrence of *Deltoidospora adriennis* and *Inaperturopollenites hiatus*. The latter is most probably derived from *Metasequoia* vegetated flow tops marginal to the immediate site of deposition, while the fern spore *D. adriennis* is typical of better drained early successional sites.

Exposures of the C-1 interbeds on the islands of Kunoy and Borðoy are of fundamentally different character to comparable units seen in eastern Eysturoy. The channelised sandstones and thin conglomerates of Eysturoy are replaced by thick conglomerates with underlying sandstones up to 1 m thick. The character of these units is closely similar to that of the younger Sneis Formation. The C-1 interbeds in the northeast are probably debris flow deposits, again with later sill intrusion into the conglomerates making a resistant feature in the landscape.

The Sneis Formation basal units comprise sandstones of the Sund Bed, which was deposited under hyperconcentrated flow conditions, and characterised by charred branchwood. This transported wood is replaced by a zeolitic mineral which has preserved little of the original cell structure. Despite this, we can conclude that the interbed duration was limited for the Sneis Formation as the branchwood diameters rarely exceed 40 cm. There is little accompanying pollen in these coarse grained sediments. However, sampling of the horizon at the distal margin of the deposits on Hestur (Fig. 6.3), yielded an assemblage from a succession of medium grained sandstones. These green-grey sandstones are analogous to the Sund Bed, but appear to have been deposited in a lacustrine environment as evidenced by occurrences of the algae *Botryococcus braunii*. Other species recorded in this assemblage include common *Inaperturopollenites hiatus* and a possible record of *Platyca ryapollenties platycaryoides*. These taxa are characteristic of mid-successional floras in the Faroese lava field and suggest that while the constructional lava field on Streymoy, Eysturoy and the NE islands was dominated by mass flow processes depositing the Sneis Formation, the lower reaches of the drainage basin were in a fluvio-lacustrine floodplain setting.

Of unusual character, but equal significance are the records of palynomorphs from high in the drainage basin of the Sneis Formation, were the Sund Bed is exposed on the north slope of Vaðhorn. They contain an abundant dinoflagellate cysts reworked from Campanian clastic facies rocks, that were deposited in a shelf marine environment. Their significance lies in their indication of Late Cretaceous source sediments exposed to the north or northwest. This source may be on an upthrown fault scarp, or associated with the eruptive fissures that produced the volcaniclastic material that comprises the Sneis Formation.
6.2 Palynoflora of the Enni Formation

6.2.1 Streymoy, Eysturoy and the northeastern islands

At Sundshálsur to the NW of Tórshavn, thick reddened sandstones are exposed, attributed to interbed horizon C+0.5. The exposed sandstone at Sundshálsur is approximately 1 m thick, and shows colour mottling which is attributable to oxidation of in situ rootlet structures. The evidence for high biomass vegetation in this exposure is confirmed by the occurrence of a branchwood mould in the base of the overlying lava. In addition, plant macrofossils collected during building work on Húsareyn (Rasmussen 1990), show that *Metasequoia occidentalis* (Newberry) Chaney 1951 continued to form a dominant part of the vegetation. This is seen in other NAIP lava fields, for example Skye (Jolley 1997) where these plants formed the climax vegetation on weathered lava profiles away from the main fluvial system channels. In west Eysturoy at Morskranes, a similar flora is recovered from C+0.5 interbeds. Here common *Inaperturopollenites hiatus* are accompanied by *Pityosporites* spp, and these high biomass conifers suggest a longer interflow duration.

Primarily because of the grain-size, recovery of palynomorphs from the stratotype of the Argir Beds is poor. The most commonly occurring species is *Inaperturopollenites hiatus* together with rare *Pityosporites* spp. and *Tricolpites* cf. *hians*. This pollen flora is comparable with those recovered from streamside vegetation dominated by Fagaceae and Platanaceae, with the surrounding weathered flow top vegetated by a *Metasequoia* forest (cf. Allt Mhor interbeds, Skye Lava Field, Jolley 1997).

Further outcrops of the Argir Beds are seen at Sandur, Sandoy and on Súgvoey. In the latter exposure a rich palynoflora is recovered from the fine-medium sandstones. This flora includes frequent *Deltoidospora addriennis*, frequent *Retitricolpites retiformis*, *Laevigatosporites haardtii* and, *Triatriopollenties subtriangulus*. These are derived from ferns and angiosperms which are characteristic of mid-successional floodplain facies, supporting the evidence from the Argir palynoflora that this interbed was deposited during a more prolonged hiatus in the eruption of the lava field.

In the east of the islands, the Argir Beds are exposed as deeply weathered soil profiles in the Stórafjall area. These pass into thin conglomeratic sequences in the area around Múlatindur and Middagsfjall. To the north of these on Slaettaratindur, the Argir Beds are exposed as a sequence of coarse sandstones and gritstones in a bed over 1 m in thickness. This yielded a mid-successional flora with the primary colonising fern *Laevigatosporites haardtii* and the early symbiotic N-fixing colonist *Alnipollenites verus* present. This pattern of vegetation community succession suggests that the longer inter eruption hiatus of
the Argir Beds allowed establishment of mid-successional vegetation in some areas, but continued to
instigate mass flow deposits adjacent to Kalsoyarfjörður.

These interbeds are variably developed in the small north-eastern islands of Kunoy, Kalsoy, Viðoy and
Borðoy, often either being absent, or only represented as a thin sandstone unit. The succession of Argir
Beds to C+2 interbeds on Kunoy (at approximately 500-780m elevation, south of Middagsfjall) has
yielded a palynoflora dominated by Inaperturopollenites hiatus, and including Cupuliferoipollenites
cingulum (Fagaceae) and Deltoidospora adriennis. This indicates that vegetation succession never
progressed beyond early mid successional status in this area.

The C+2.5 interbeds are a group of sandstones best represented in Eysturoy and south Streymoy. Here
they occur as thick sandstones in temporary exposures round Tórhavn and in western Eysturoy.
Elsewhere, these sediments are thin sandstone units with no palynofloral recovery. They are locally
absent in Kunoy and Borðoy, suggesting more rapid effusion of brown-weathering lava flows to the east
of Kalsoyarfjörður. They are not readily detected elsewhere in Streymoy because of the regional dip and
lack of exposure.

The palynology shows early to mid successional palynoflora and the primary controls on this ecology
within the Malinstindur and Enni formations are the substrate saturation and the frequency of volcanic
disturbance. In particular, palynofloras from the area of the NE shield volcano are impoverished and
usually of early seral successions status. This reflects the frequent disruption of the area by volcanic
effusion and the restriction of ecological niches to temporary drainage systems or dammed lacustrine
zones. With reference to the XRF data presented in Chapter 7 below, the ecology of these florals shows
little dependence on the nutrient state of the substrate

6.2.2 Nólsoy, Sandoy and Skúgvoy

Results from the analysis of 230 samples from the islands of Nólsoy, Sandoy and Skúgvoy were
amalgamated into a single data set and then subjected to data reduction, eliminating rare species and
barren samples. The resultant data set was then analysed using detrended correspondence analysis
which yielded a plot of the first two axes on which four ecological groupings could be identified (Fig. 6.4).
These groups demonstrate that the range of ecological groups in the south-eastern islands is more
restricted than in Streymoy and Eysturoy. Lacustrine and early successional groupings dominate the
palynofloras with some input from flow top and dryer substrate groups. The diversity of the lacustrine
facies is of interest, the abundance and diversity of fungal spores and hyphae supporting the
interpretation of these lakes as being the sink of rotting vegetation derived from disturbed flow tops (Jolley & Passey 2012).

The coincidence of lacustrine facies on one palaeosurface (Skúvfjall Beds, Nólsoy and Dalur Beds, Sandoy) suggests either large lacustrine zones, or a surface covered with smaller lacustrine water bodies. The current data is not enough for us to resolve this because of the isolated exposures. However, the persistence of hyaloclastite facies along the SE coast of Sandoy from Dalur village indicates the presence of a large water body at this horizon.

6.3 Summary

The most complex ecosystems identified in the Enni Formation were recorded from the Argir and post Argir Beds interbeds in south Streymoy and east Eysturoy. These are associated with braided fluvial floodplain facies and are interpreted as dominantly mid successional vegetation in streamside, overbank and weathered flow top communities. To the northeast, the thinner coarser sandstone interbeds and conglomerates are often barren, indicating dominantly high depositional energies. Some minor localised lacustrine deposits are recorded such as the Argir Beds on Slættaratindur and on Kunoy, but these are isolated occurrences correlative with ephemeral fluvial deposits and soils over the NE islands. These data indicate that a central lowland floodplain area in south Streymoy and west Eysturoy was flanked to the NE by a constructional flow field, here identified as the NE shield volcano (Fig. 6.5).

The NE shield volcano and the central Eysturoy fissure flow fields prevented the expansion of the Argir Beds braided floodplain towards the NE. However, the flow fields from the SW shield volcano did not erupt thick lavas in the Sandoy-Skúgvoy-Nólsoy area allowing the Argir Beds braidplain to expand to the south and southwest. This is reflected in the often mid successional vegetation preserved in the finer grained deposits of the Argir Beds in that area. Subsequently the SW shield volcano erupted aphyric compound lavas over the south western extent of the Argir Beds braidplain. Large scale mass wasting and lacustrine deposits indicate that any post Argir Beds integrated drainage system would have been forced further to the NE by this constructional flow field. Unfortunately, evidence for this drainage system is missing, the deposits of the upper Enni Formation having been eroded off most of the central Faroe Islands.
Fig. 6.1. Detrended correspondence analysis plot of palynofloral data from the Malinstindur and Enni Formation interbeds of Streymoy and Esturoy. Botanical affinities of the taxa included in this plot identify Axis 1 as representing a proxy for successional status. Similarly, Axis 2 is a proxy for substrate saturation or moisture availability.
Fig. 6.2. Canonical correspondence analysis plot of palynofloral data from the Malinstindur and Enni formations with selected major element oxides plotted as the environmental variable. There is a weak correlation between the eutrophic chlorophycean algae Botryococcus braunii and MgO, a proxy for nutrient availability.
Fig. 6.3. Map of the Faroe Islands showing the estimated thickness of pre Paleogene strata at subcrop after White et al. (2003). The names locations are some of the sample localities discussed in the text.
Fig. 6.4. Detrended correspondence analysis plot of data from the Enni Formation above the Argir Beds in Nólsoy, Sandoy and Skúgvøy. There is a strong component from a lacustrine facies (Group A) with components from disturbed, early successional vegetation in the catchments (Groups B and C). A small element from more mature vegetation is present in Group D. Much of the pine (*Pityosporites* spp) and Swamp Cypress pollen (*I. hiatus*) is probably derived from vegetated flow top rather than the drainage systems. These pollen are from families which are known to overproduce pollen, and hence are well represented in the record. In addition, both these taxa are prone to wind and fluvial transportation, often resulting in high frequencies in the lower parts of catchments and lakes.
Fig. 6.5. Map showing the volcanic facies and biofacies ‘zones’. In this simplified distribution map, the compound flows from the NE shield volcano restrict the NE edge of the Argir Beds fluvial braidplain shown by the heavy dashed line. To the SW, the later development and NE migration of the SW shield volcano allows the Argir Beds braidplain to extend southwards. Subsequent growth of the SW shield volcano converts the area of Sandoy and Nólsoy from within the braidplain zone to a zone of mass wasting and lacustrine facies similar to that persisting in the NE.
7 Interbed Geochemistry

7.1 Interbed chemistry: determining hiatus duration

Standard XRF techniques have been used to analyses the full range of major oxides and trace elements (see Chapter 1 Methods). Of particular use in determining the interbed duration are the following key proxies.

7.1.1 Al:base-K ratio

The Al:base-k ratio (base=MgO + CaO characterises changes in metal oxides likely to show depletions because of their mobility in the substrate. This ratio does not include K₂O as it has an unpredictable behaviour, with losses from leaching and macronutrient uptake and also additions to the system. It is also susceptible to diagenetic changes, to an extent far greater than the other more mobile cations. This ratio is used as an indicator of the sediment maturity, with increasing maturity bases are lost by weathering and uptake of these oxides by the ecosystem resulting in higher Al:base-K ratios (see Jolley et al. 2008).

7.1.2 Chemical Index of Alteration

The Chemical Index of Alteration (CIA-K of (Harnois 1988; Maynard 1992), is the CIA of Nesbitt & Young (1982), calculated without K₂O, and so is restricted to elements with consistent behaviour during weathering (Harnois 1988). This index of alteration records the loss of the more mobile elements with increasing chemical alteration of the sediments and is largely recording the replacement of feldspars by clay minerals (Nesbitt & Young 1984; Fedo et al. 1995).

7.1.3 % MgO depletion

Depletion of MgO relative to the parent material is used to indicate interbed duration. Immature interbeds have limited depletion of MgO as the weathered MgO from the parent material is still present in the sediment. In more mature interbeds the % residual MgO decreases as the MgO is lost from the system due to uptake by plants and leaching from the system. This % residual MgO (and other cations) have been shown to vary with the length of time of soil formation in Hawaiian chronosequence studies over 4 My (Vitousek & Farrington 1997; Chadwick et al. 1999; Vitousek 2004), while application of these proxies to a deep time study was undertaken in the interbed sequences of the Colombia River Basalt Group (Jolley et al. 2008).
7.2 Macronutrient Availability – Ecosystem impacts

7.2.1 P, Mg, Ca availability

Observations from Hawai’i have provided evidence (Vitousek 2004) that P becomes bioavailable as $P_4O_{10}$, being deposited downwind of active eruptions in a manner similar to that suggested by Yamagata (1991). P availability is contributed to by lava flows which reach the sea, causing further fluxes, making it an important contributor to nutrient flow in early succession sites. Many sites in volcanic terrains are rich in P, derived from these sources and contributed to by weathering and breakdown of soil minerals. With increasing age and biomass, P becomes depleted on volcanic terrains and eventually presents the major limitation to plant growth (Vitousek 2004).

While P, Mg and Ca are all readily available as products from the breakdown of basaltic lava and ash, it is the long term loss of these macronutrients from developing ecosystems that is of principle interest to studies of LIP’s. In Hawaiian systems, these elements are depleted over time, as they are used by the biomass and leached out of soil profiles into the hydrological system. Losses from the biomass and soil profile prevent total nutrient cycling, resulting in the reduction of these macronutrient to insignificant levels by approximately 100,000 years (Vitousek 2004). After this, plant communities, mainly mature forest on Hawai’i, are dependent on airborne dust in a manner comparable to tropical rain forest on the same latitude. These nutrient depleted climax communities and associated soils are common in the oldest Hawaiian profiles, where Sr depletion can be used as a proxy for the availability of Ca, Mg and P. In this system, almost total removal of volcanogenic Sr isotopes is achieved by 100,000 years, forcing ecosystem reliance on atmospheric P deposition.

7.2.2 N availability

Studies of early colonisation by plants on lava fields have identified the crucial role played by low N availability (e.g. Walker & Aplet 1994). N is available in the initial phases of re-colonization from aerial plankton (Harrison et al. 2001) or by decomposition and burning of already established biomass (Debano & Conrad 1978). Early successional plants growing on lava fields could therefore be expected to have low N demands, or to be symbiotic N-fixers. However, an alternative source of N in primary volcanic landscapes has recently been identified. Working on active volcanoes, Mather et al. (2004) demonstrated NO$_3^-$ production at the interface between hot lava and the atmosphere, the NO$_3^-$ subsequently being oxidized to Nox. The authors of this paper used SO$_2$ production as a proxy for measuring the production of nitric acid, but could not readily quantify the Nox volumes produced. Working in a different area, Huebert et al. (1999) and Heath & Heubert (1999) had previously identified thermal fixing of NO$_3^-$ as a
method of vectoring and enhancing N availability to lava field plant communities. Measurements taken on Hawaii in ‘volcanic fog clouds’ (vog) recorded NO$_3$ levels at 220 ppb, orders of magnitude above background levels (Huebert et al. 1999). Over a time frame of hours to days, this NO$_3$ oxidizes to NO$_2$ and HNO$_3$, species that are easily deposited as either cloudwater, or later by dry deposition. This amounts to a contribution of 2.4 kg N ha$^{-1}$ yr$^{-1}$ into a N depauperate environment. On Hawai’i, the distribution and efficiency of Nox deposition is controlled by local wind directions. Observations by Vitousek (2004) and co-workers, that this N deposition is unusual because Kilauea has been active nearly continuously since 1983, is regarded as not being of concern in the LIP context where volcanism would have been on a larger scale and also similarly long-lived.

Analysis of gases from recent volcanic fog (vog) episodes and from gas samples taken round active vents and lava flows, has shown that atmospheric N is thermally fixed as HNO$_3$ by the contact of hot igneous rocks with the atmosphere (Heath & Huebert 1999; Mather et al. 2004; Vitousek 2004). This process thus provides a source of N, vital to the primary colonization of lava flows by plants.

7.2.3 Estimating N$_{ox}$ flux from LIP lava field eruption

A numerical relationship relating the quantity of SO$_2$ release in a volcanic plume to that of Nox has been established (Mather et al. 2004). Fixing of Nox occurs as an extrinsic process, through thermal effects, either through the interaction between atmosphere and magma lakes, hot ejecta plumes, or by lava surface cooling. Its efficiency is highly T-dependant, and a high temperature lava- or magma-atmosphere interface is required for significant HNO$_3$ production (Mather et al. 2004). Accordingly, Nox fixation is more probable in instances of hotter eruption products.

7.3 Interbed Geochemistry of the Malinstindur & Enni formations

Both the Al:base-K ratios and CIA-K values for the Malinstindur interbeds suggest immature interbeds with little loss of base cations. Al:base-K ratios for the C-2 interbeds are between 0.75 and 1.75, a wider range than within the C-1 interbeds (0.8 to 1.2). The CIA-K values are between 40 and 60 for the C-1 interbed, with a wider range in the C-2 interbed (an average of 52). The Al:base-K ratios increase through the interbeds of the Enni Formation, from an average of 1.13 in C+0.5, to an average of 1.77 in C-2.5. The CIA-K also increases up the stratigraphy and the higher Ba:Sr ratios within the Enni Formation interbeds also suggest increased weathering and losses. The low levels of base loss in the Malinstindur Formation interbeds is also reflected in the % MgO loss relative to the parental composition, they record
average losses of c. 10% in C-2 and c. 15% in C-1. The % losses increase through the Enni Formation interbeds, with C+2.5 showing an average loss of c. 30% MgO (Fig. 7.1).

As well as changes between the different interbed horizons, changes can be seen within some of the horizons. Within the C+0.5 interbed at Kaldbaksfjörður, the thick sedimentary sequence shows a pattern of depletion over time. This sequence shows depletions not only in MgO and other major element oxides, but also in elements such as TiO₂ and Zn suggesting either prolonged depletion, or a variation in the origin of the parent volcanic or volcaniclastic rock.

### 7.4 Macronutrient Availability

The analytical geochemistry from the interbeds demonstrates that they remain moderately immature (Fig. 7.1), with relatively low Al:base ratios and a high percentage of residual MgO. Comparison of these data to the profiles obtained from comparable sedimentary sequences in the Columbia River Basalt Group (Jolley et al. 2008) indicate a shorter duration of formation for individual interbeds, the FIBG interbeds corresponding to the proximal to median zone of the CRBG. However, some, e.g. the Argir beds of Slættaratindur show low Al:base ratios, suggesting that flux of volcaniclastic material into the system as either ash or regolith was a contributory process during interbed deposition. Approximations of interbed duration based on residual MgO (Chadwick et al. 1999; Vitousek 2004) are likely to be affected by the same process, but suggest eruptive hiatuses of between 0.1 My and 0.4 My.

Comparison between the availability of macronutrients in the interbeds and the composition of the palynoflora can be used to demonstrate ecological succession, and in conjunction with MgO levels test further indications of interbed duration. Canonical correspondence analysis of the palynological data against an environmental data set comprising a macronutrient (MgO), and macronutrient depletion proxies (Al₂O₃, Ba:Sr), identifies two major ecological groups (Fig. 6.2). A nutrient sufficient community comprises the chlorophcean algae *Botryococcus braunii*, derived from mildly eutrophic lakes, which is accompanied by the primary succession fern spore *Laevigatosporites haardtii* and the fagaceous angiosperm grain *Cupuliferoipollenties cingulum*. This early succession community contrasts with the lower nutrient status group, which also contains probable arborescent forms. This grouping is dominated by *Pityosporites*, and includes the angioperms *Triporopollenites coryloides* and *T robustus*, both characteristic of lower nutrient status soils. These taxa are accompanied by *Monocolpopollenites tranquilus*, again characteristic of lower nutrient status soils, the relationship with the plane type grain *Tricolpites hians* indicating a riparian habitat. An outlier, comprising Stereisporites (a moss) shows no
relationship to the nutrient vectors, and can be interpreted as an early primary successional species, a role adopted by many moss species today.

### 7.5 Estimation of duration

By comparison to the % residual bases in the Hawaiian profiles of (Vitousek & Farrington 1997; Chadwick et al. 1999), a loss of less than 50% MgO relative to the parent material would suggest interbed durations of less than 10Ka (4-8 ky). Most sections have much lower levels of loss than this suggesting even shorter durations of 1-6 ky. The average % residual MgO of -10-15% as seen in the Malinstindur Formation interbeds and the similar levels seen in the C+0.5 and Argir Beds interbeds suggest durations of 1-4 ky (Vitousek & Farrington 1997). The greater % loss of MgO seen in the C+2 and C+2.5 interbeds, suggest longer durations of these interbeds, up to 6-7Ka (up to -30% MgO loss and an average of ~25% for C+2.5).

The chemical data indicate the increasing duration of the interbeds within the Enni Formation, from short duration/immature interbeds in the Malinstindur Formation and the Sneis Formation to increasing duration of interbeds in the Enni Formation. This is shown by the increasing Al:base-K and CIA-K ratios and the increasing loss of MgO. These changes in the MgO depletion suggest the interbed duration increasing from very short duration interbeds, (1-6 ky) to slightly longer duration interbeds (4-8 ky).

Although there are variations in the nutrient depletions between the interbeds, they all show short durations and immature interbed sediments. The patterns shown by elements such as Ti and Nb and the Ba:Sr ratios are the same as those shown by the base oxides (mainly MgO) and this suggests that the patterns within and between the interbeds are due not only to differences in floras. These show the effects of leaching of elements as well the effects of macronutrient uptake by plants.
Fig. 7.1. Major element oxide geochemistry of interbeds from the Malinstindur and Enni formations of Streymoy, Eysturoy and the NE Islands. A number of geochemical ratios are also plotted, reflecting weathering intensity and overall base depletion (e.g. Al:base). Data for the Malinstindur and Sneis formations is derived from multiple sites and is not subdivided below the interbed succession where they occur. It is of value here in demonstrating the overall values of metals present in this part of the succession. A single large interbed (C0.5) at Kaldbaksfjørður shows a long term depletion in MgO and P$_2$O$_5$. Profiles of this nature have not been recorded from within or below the Sneis Formation. Further evidence of increased interflow duration is recorded by the falling values of MgO and P$_2$O$_5$ (and in consequence base and Al-base ratio) within the mid Enni Formation (interbeds C2 - C2.5).
8 Comparison to the Faroe-Shetland Basin

The shield and fissure eruption fields of the Enni Formation show a clear relationship to the contemporaneous sedimentary interbeds:

- The low angle slope of the shield volcanoes (c. 3°) and their relatively flat flow field amalgamation surfaces led to unconstrained, ephemeral drainage systems. These deposited volcaniclastic sandstones in thin (<1 m thick) beds which sometimes exhibit low angle cross stratification.

- Although the Eystnes fissure flow acted as a barrier to the distal flow fields of the NE shield volcano, the interaction of the NE and SW shields created the most important topographic feature in the Enni Formation. This provided a linear NNW–SSE axis which was exploited by the Argir Beds drainage system. In the south, the Argir Beds drainage system was composed of channels up to 10’s of metres in width, which were shallow and often braided. This is the closest to an integrated drainage system preserved in this stratigraphical interval.

- Within the shield volcano flow fields, topographic irregularities contributed to the development of lacustrine facies. These accumulated organic material from flow top vegetation, but were essentially ephemeral.

8.1 Comparison with Faroe-Shetland Basin lava fields

It is of interest to compare the nature and scale of the volcanic and sedimentary rock units identified in the Enni Formation with those from similar aged deposits in the Faroe-Shetland Basin. The area around the Rosebank Field (Fig. 8.1) is appropriate in this context, because it contains interdigitations of volcanic and sedimentary rock strata. Much of the data from the Rosebank Field is held to be confidential, however, there are volcanic and sedimentary rock units in this area and within the wider Faroe-Shetland Basin that bear comparison to the basalt plains of the Enni Formation.

1. Around 30-40 km to the NW of the Rosebank Field, a seismic amplitude extraction of the top lava surface identified a late-stage, Enni Formation equivalent flow field (Fig. 8.2b; Jolley et al. 2010). Although only partly imaged because of the edge limits of the PGS Megasurvey data available, the NE–SW elongation of the flow field axis and its down dip dendritic structure suggests that this was a fissure-fed flow field. It is therefore of interest to compare this to the extent of the Eystnes Flow, from the Faroe Islands (Fig. 8.2a). This comparison suggests that the exposed part of the Eystnes flow is smaller than its full extent. In particular, the limits of the exposure and the lack of any exposure to the SE control our understanding of its overall morphology. This may also
account for the apparently slightly smaller overall size of the Eystnes flow in comparison to the Corona Ridge example.

2. Although the Eystnes Flow played an important role in defining the edge of the Argir Beds drainage system, and preventing the SW expansion of the NE shield volcano flow field, the shields play a more significant role. The presence of a shield to the SW was primarily responsible for constraining the Argir Beds drainage system, resulting in an integrated drainage network that can be traced over the south of Streymoy, Eysturoy and on Sandoy. Comparison of the size of the Enni Formation NE shield with the low angle shield of the Erlend Complex suggests similarity (Fig. 8.3). The 40-50 km overall diameter of these shields is similar to those currently exposed in the Afar Rift Valley, east Africa, a factor probably related to the rate of extrusion and the viscosity of the basaltic melt. Comparison between the Erlend Complex shield and the SW Enni Formation shield suggests that there is a degree of inaccuracy in the projection of the Enni Formation shield forced by the lack of exposure outside the islands. The extent of the SW shield plotted on Fig. 8.2 is of the late-stage aphyric compound flow field. This overlies the plagioclase phytic, earlier part of the flow field which is smaller and exposed to the SW. It is possible that the later stage aphyric compound flows erupted from a vent that had migrated NE from the earlier vent zone.

8.2 Comparison with Faroe-Shetland Basin drainage systems

Physical comparison of the drainage systems present in the Enni Formation, with those of the Faroe-Shetland Basin are limited by the lack of available data. Little is currently known of Faroe-Shetland Basin fluvial drainage systems outside the Rosebank Field. Much of these data is also confidential. However, it is possible to draw some comparisons where well data is available.

1. Calibration of base element depletion with the biostratigraphical data has been discussed in Chapter 7. These data can be tabulated and compared with the broad facies character of the sediments to draw inferences regarding the depositional environment. As a primary observation it is of importance that the accumulations of siliciclastic sediment recorded in the Rosebank Field are not seen in the FIBG interbeds. This is indicative of a extra lava field sediment source, and potentially a more mature depositional system. This inference is supported by a comparison of integrated siliciclastic (or mixed siliciclastic/volcaniclastic) drainage systems with palynofloral succession and metal oxide depletion data (Fig. 8.4). This shows a clear separation of weakly constrained, ephemeral and volcaniclastic drainage systems from integrated, mixed or siliciclastic
drainage systems. From this relationship, all of the FIBG interbed data can be inferred to be <5 ky depositional duration, either in lava field lakes or in ephemeral fluvial systems.

2. In contrast, Colsay 1 in both Sequence T40 and T45 (Ebdon et al. 1995), Colsay 3 equivalent in a Quadrant UK214 well, and Colsay 3 in Rosebank Field all show late-mid or late succession floras with durations =>4Ky. Residual MgO values >60% in Colsay 3 and some Columbia River Basalt Group interbeds (Fig. 8.4) which were deposited by a more mature drainage system are thought to be a result of additional clastic inputs of MgO from extra volcanic sediment sources.

3. Finally, it is of interest to note that the volcaniclastic interbeds of the Rosebank Field, Upper Volcanics of Sequence T45 contain >90% residual MgO. This indicates that the lava field and drainage system that postdates the Paleocene Colsay Rosebank reservoir, and predates the Flett Delta deposits of the Cambo Field area was deposited by a locally derived lava field sourced ephemeral fluvial system.
Fig. 8.1. Regional map showing the extent of volcanic extrusive facies in the Faroe-Shetland Basin. The location of the Faroe Islands and well 205/1-1 at the SW end of the Rosebank field are illustrated. Map modified after Jolley et al. (2010).
EARLY SUCCESSION AND LACUSTRINE FACIES
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POST ARGIR BEDS LACUSTRINE FACIES

Fig. 8.2. Maps showing the comparative sizes of the two main shield volcano structures which erupted much of the FIBG Enni Formation (A) and the late stage, Enni Formation equivalent flow field to the NW of the Rosebank Field (amplitude extraction B, after Jolley et al. 2010). Also illustrated is the Eystnes Fllow on Eysturoy. Although mapping of the outline of the Eystnes Flow is limited by the exposure, it appears to be only slightly smaller than the fissure fed flows to the NW of Rosebank Field (B).
Fig. 8.3. Map of the shield and fissure volcano systems of the Enni Formation, FIBG (A), with an interpreted seismic section (B) through the Erlend Volcanic complex showing the vent area. The extent of the Erlend Volcanic Complex is shown at C, with a best fit circle for Erlend superimposed on the NE islands FIBG Enni Formation flow field in A. This demonstrates the comparability of size between the Enni Formation NE islands shield, and Erlend. It also suggests that the size or shape of the SW Enni Formation shield may be inaccurate. Given the lack of exposure this is reasonable, but it is also possible that the shield is not symmetrical (B and C after Jolley et al. 2010).
Fig. 8.4. Plot of the percentage residual MgO from sedimentary interbeds against plant community seral succession status. The MgO percentage is derived from XRF data and calibrated against the MgO values of the potential parent volcanic rock. The seral succession status is derived from the DCA plant community analysis, using the axis 1 sample data calibrated by the axis 1 & 2 seral succession groupings. The interbed age is derived from Chadwick et al. (1999), based on data from the Hawaii island chain. Three separate data sets are plotted, Columbia River Basalt Group, FIBG Malinstindur and Enni formations and Faroe-Shetland Basin sediments. The Faroe-Shetland Basin interbeds are: T40-C1, Colsay 1, Sequence T40, Rosebank Field; T40-214, Colsay 3 equivalent 214 Quad; T45-C1, Colsay 1, Sequence T45, Rosebank Field; C3, Colsay 3, Rosebank Field; UV, Upper Volcanics, Sequence T45, Rosebank Field.
9 References


