PS Volcanic Rifted Margins and Unconventional Delta Systems; Constraining Supply, Sea Level and Slumping*

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Search and Discovery Article #50525 (2011)
Posted December 12, 2011

*Adapted from poster presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

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Abstract

During the late Palaeocene, the rifting event that created the North Atlantic produced significant volumes of lava that erupted on or close to the Faroe Islands. Where lava flows entered the Faroe-Shetland Basin, a number of lava-fed delta systems formed and have been shown to record the early encroachment of the flood basalts into the basin and the position of the palaeo-shoreline (Kiørboe, 1999). Siliciclastic deposition can decrease or cease during volcanism and resume during periods of quiescence. Preservation of these ancient volcanic systems in offshore settings have the potential to record basin development when more conventional depositional systems were absent, including indicators for relative sea level, volcanic sediment supply and available accommodation space.

Mapping of overlapping 2D and 3D seismic surveys within the central Faroe-Shetland Basin has revealed a variety of seismic facies that document the transition of aerial lava flows to marine hyaloclastic breccias. The application of seismic stratigraphic principles delineated a series of discrete, seismically resolvable units with distinct bounding reflectors and internal architectures. The 3D data allowed for the spatial construct of the lava-fed delta front and its depositional processes to be assessed.

The seismic units are taken to represent periods of active volcanism and their stacking patterns has allowed the reconstruction of the gross depositional history. Delta deposition is primarily driven by lava supply, which overwhelmed the basin and caused the system to prograde out into the basin, with later periods of retrogradation as volcanism waned and died. Distinct 3D morphological features have also been identified, including cuspate collapse scarps, lava flow feeder systems and lobate, pahoehoe-like lava flows. These features are directly comparable to those of more recent lava-fed delta systems, including those on Iceland and Hawaii, suggesting that similar

processes may have occurred. This breakthrough allows us to map the development of the delta systems from the lavas that fed them, and ultimately how a paleoshore line was affected by flood volcanism during the breakup of Europe from North America.

Reference

Kiørboe, L.,1999, Stratigraphic relationships of the Lower Tertiary of the Faeroe Basalt Plateau and the Faeroe-Shetland Basin, *in* A.J. Fleet and S.A.R. Boldy (eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Geological Society of London, p. 559-572.

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1. INTRODUCTION

1.1 Research Rationale:

Flood volcanism represent periods within the Earth's history when significant volumes of molten material (commonly basaltic) were emplaced in or on the Earth's surface, through the extrusion of extensive sheets of subaerial lavas via fissure systems, the formation of individual igneous centres and the intrusion of sill complexes.

The growing interest in exploration and production of hydrocarbons from offshore successions with a volcanic component has resulted in the need to understand how such systems have evolved and their inherent complexities. This includes the Faroe-Shetland Basin (UK and Faroes), which is part of the North Atlantic Igneous Province (Fig. 1).

- The Basin is a product of rifting between Greenland and Eurasia during the Mesozoic to early Cenozoic.
- Continental break-up and the onset of seafloor spreading were accompanied by extensive flood basalt volcanism in subaerial to submarine setting.
- In the central Faroe-Shetland Basin, this formed an escarpment of high angle, prograding reflections which have long been interpreted to be formed by lava-fed deltas (Kiørboe, 1999; Spitzer et al., 2008).
- The delta systems have been suggested to record the early encroachment of the flood basalts into the basin and location of the palaeo-shoreline (Wright et al, 2011).

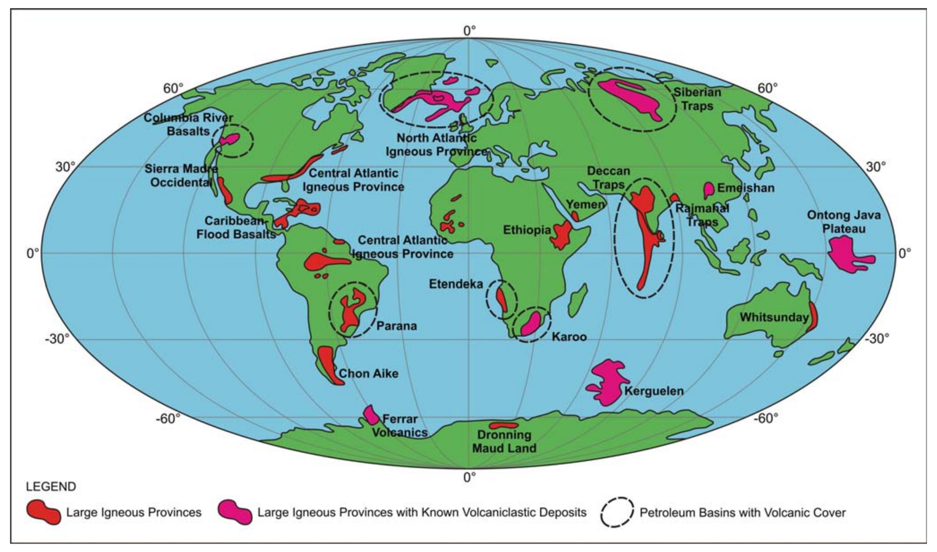

Figure 1. Location map of flood volcanic provinces including those with a known volcaniclastic component, and petroleum basins with volcanic cover that are currently under exploration.

1.2 Lava-fed Delta Systems:

Lava-fed deltas represent an extreme of hyaloclastic deposition, and preserve the transition from subaerial to submarine strata. They are produced by rapid deposition of quenched and fragmented material, as lava flows enter a standing body of water. The form and structure of the delta system records a number of important factors that occurred during deposition, including;

- The transition from terrestrial lava flows to hyaloclastic breccias denotes the position of relative sea level at the time of deposition, and in doing so are a record of the position of the palaeo-shoreline (Fig. 2).
- The height of the hyaloclastic foresets will indicate the available accommodation space at the time of deposition (Fig. 2).
- Growth of the delta system will be affected by variations in lava supply (Fig. 2).

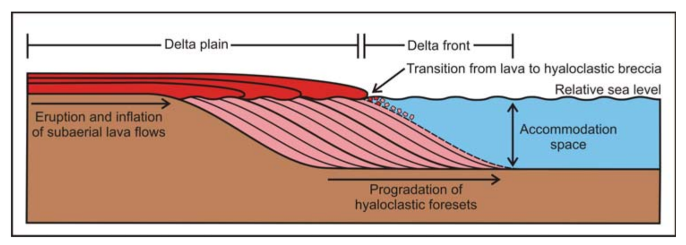

Figure 2. Schematic cross section through a developing lava-fed delta. Based on this study, Fuller (1931), Jones & Nelson (1970).

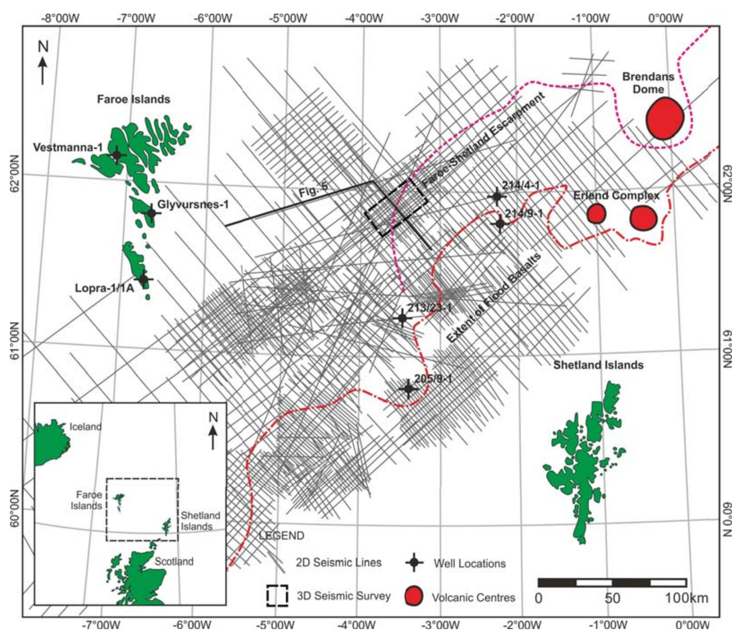

Figure 3. Location map of the Faroe-Shetland basin, with distribution of 2D and 3D seismic datasets, well locations and position the Faroe-Shetland Escarpment.

1.3 Datasets:

This study has used a variety of 2D seismic reflection surveys gathered within the Faroe-Shetland Basin between 1983 and 2005 with large areas of geographical overlap. The greatest concentration of survey lines is located over Faroe-Shetland Escarpment (Fig. 3) and images the flood basalt succession and contemporaneous deeper water strata at an average vertical resolution of 20-30 m. In addition, a 20x40km, recently acquired 3D reflection survey located over the centre of the escarpment and images the whole thickness of the volcanic succession with a similar vertical resolution.

Well control is limited as the majority of wells are located beyond the extent of the Faroe-Shetland Escarpment (Fig. 3). these wells have encountered inter-bedded successions of hyaloclastic breccias, lavas and siliciclastic successions of varying thickness. The onshore volcanic succession is penetrated by 3 boreholes which encountered varying thickness of lava flows and hyaloclastic breccias (Fig. 3).

1.4 Methodology:

This study investigates the reflection geometries of the lava-fed delta system of the Faroe-Shetland Escarpment and the applicability of seismic and sequence stratigraphy to define a series of volcanic units, which can be interpreted in terms of relative sea level, lava supply and available accommodation space.

- The top surface of the flood basalts is identified by a prominent, high amplitude and strongly continuous reflection. A clear offlap break marks a change to inclined, moderate to low amplitude reflections with prograding, sigmoidal geometries.
- The strong reflectivity of the top surface and the internal heterogeneity within the volcanic succession presents a challenge for imaging. Despite this, variations in seismic amplitudes and reflection geometries have been clearly imaged, making it possible to apply seismic stratigraphy to define the gross stratigraphic architecture.
- The recognition of units of relatively conformable reflections, bounded by unconformities is through identification of systematic discordances or reflection terminations against the bounding reflection.

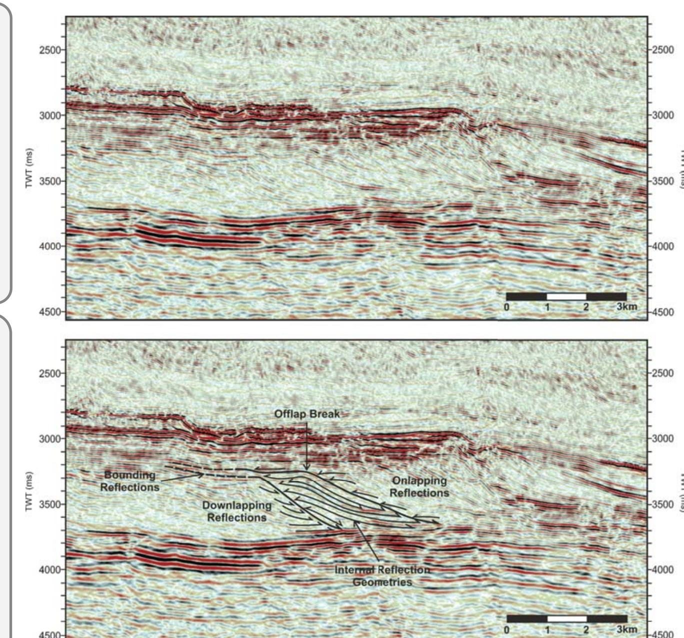

Figure 4. Seismic stratigraphic methodology used to identify seismic reflection units after Vail et al. (1977), Posamentier & Vail (1988) and Kiørboe (1999).

2. 2D SEISMIC ANALYSIS

2.1 Seismic Facies Analysis:

Initial analysis of the 2D seismic data identified five distinct seismic facies, using key observational criteria such as amplitude, continuity and configuration, with each facies named according to their distinctive reflection characteristics (Table 1). They represent the transition from thick, tabular lava flows that have fed the delta to the prograding wedge of submarine hyaloclastic breccias to distal reworked hyaloclastic deposits.

Seismic Facies	Seismic Reflections	Geometry	Top Reflections	Internal Reflections	Base Reflections	Interpretations
Low Amplitude Semi-Continuous (LASC)		Wedge	Moderate amplitude inclined and subparallel reflections.	Low amplitude, inclined, subparallel, varies between semi-continous and disrupted reflections.	Low amplitude, subhorizontal, subparallel reflections.	Reworked and remobilised deposits of lava and hyaloclastic material due to the collapse of the delta front.
High Amplitude Continuous (HAC)		Sheet-like	High amplitude, horizontal to subhorizontal. Parallel largely continuous with a irregular or undulating reflections.	High to moderate amplitude, horizontal to subhorizontal Parallel to subparallel, continuous reflections.	Moderate amplitude, subhorizontal, parallell. Varies from continuous to disrupted reflections.	Topsets composed of subaerial lava flows that supplied the hyaloclastic foresets.
Moderate Amplitude Continuous (MAC)		Wedge	Moderate amplitude, subhorizontal, parallel to subparallel reflections.	Moderate to low amplitude, inclined, parallel to subparallel, continuous to semi-continuous reflections.	Low amplitude,parallel to subparallel, semi-continuous reflections.	Foresets composed of hyaloclastic breccias from the fragmentation of lava flows.
Moderate Amplitude Semi-Continuous (MASC)		Sheet-like to wedge	High amplitude, horizontal to subhorizontal. Parallel to subparallel, occasionally rugose reflections.	High to moderate amplitude, horizontal to subhorizontal. Parallel to subparallel, semi-continuous, hummocky reflections.	Moderate to low amplitude, subhorizontal, parallel. Varies from semi-continuous to disrupted reflections.	Interbedded lava flows and hyaloclastic breccias, most likely from an earlier, easterly volcanic source.
High Amplitude Semi-Continuous (HASC)		Sheet-like?	High amplitude, horizontal to subhorizontal, largely continuous reflections.	High to moderate amplitude, parallel to subparallel, varying continuity with strong layered reflections.	Moderate to low amplitude, parallel to subparallel, semi-continuous reflections, difficult to identify.	Underlying basin fill prior to the onset of delta deposition, may contain subaerially eroded volcanic material or minor volcanic intrusions.

Table 1. Description of seismic facies, including observational criteria, external geometry and typical reflection configurations.

2.2 Seismic Stratigraphic Analysis:

Analysis of the reflection configurations and facies distributions has identified 13 seismic reflection units, with each unit characterized on the basis of bounding reflections and internal reflection configurations (Fig. 5).

- Units 1-11 display a progradational trend, with an increasingly aggradational element shown in units 6-11 (Fig. 5). The inclination of the sigmoidal reflections vary, becoming shallower within the deeper parts of the delta body.
- Units 12-13 display a retrogradational trend, with both units run largely parallel to the delta front.The units mimic the geometry of the reflections within units 1-11 although the angle of the inclined reflections is much shallower (Fig. 5).
- Each unit is interpreted to have a stratigraphic significance and represent a individual period of active volcanism followed by a hiatus of little or no volcanic activity. Therefore, we propose the bounding reflections are erosional surfaces produced during such hiatuses.

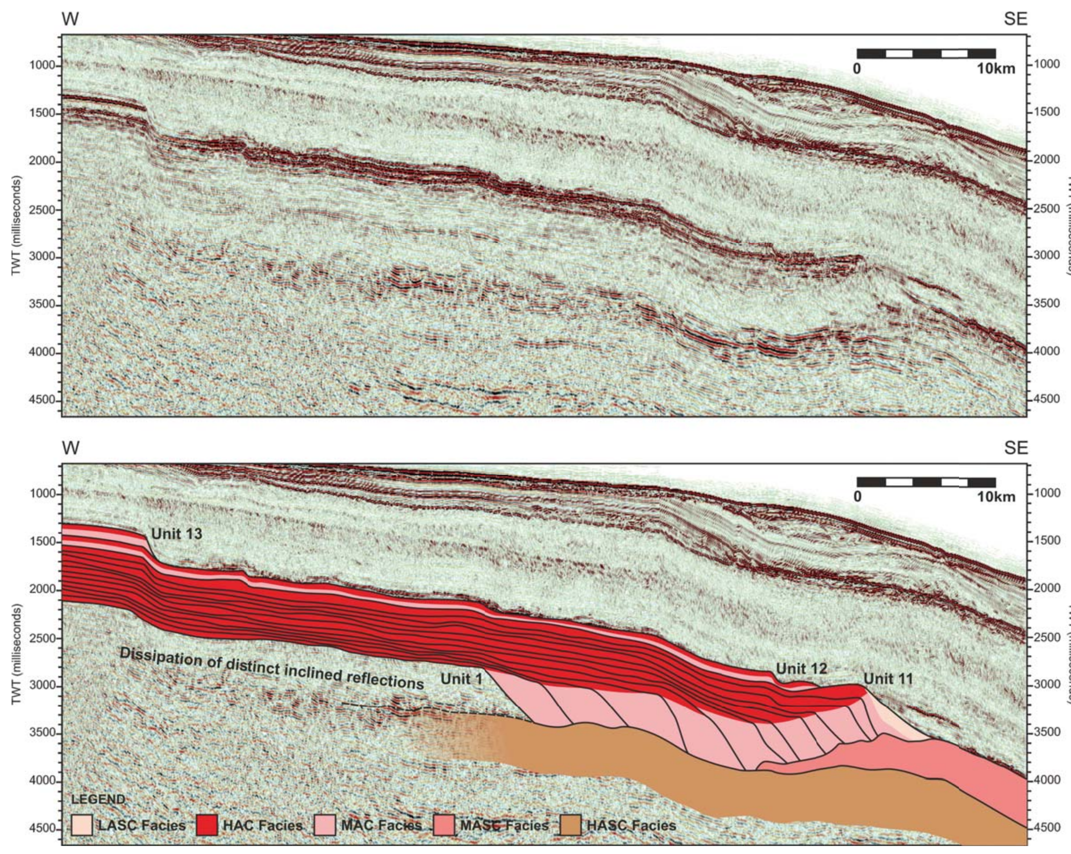

Figure 5. (A) Uninterpreted seismic sections through the Faroe-Shetland Escarpment. (B) Interpreted seismic section through the Faroe-Shetland Escarpment, displaying bounding reflections of the seismic reflection units and distribution of seismic facies (see Fig. 3. for location).

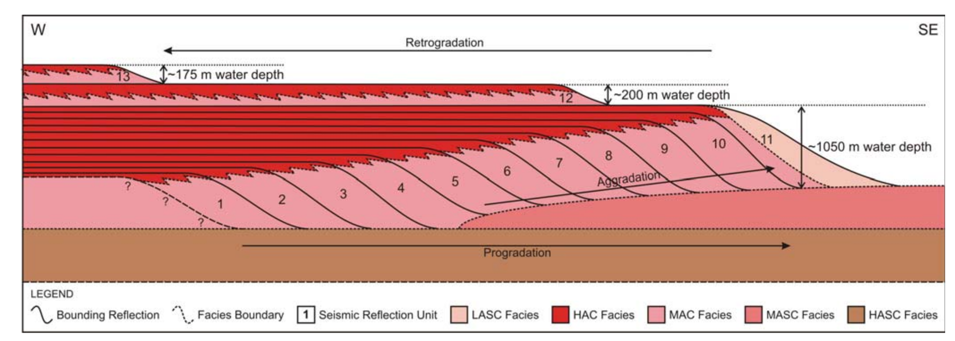

Figure 6. Schematic cross section through the lava-fed delta based on figure 5, including seismic reflection units and distribution of seismic facies (not to scale).

2.3 Delta Development:

The seismic reflection units appear to have been deposited sequentially, with the gross stacking pattern revealing variations in the available accommodation space, relative sea level rise and the supply of volcanic material.

- Seismic reflection units 1-11 display a progradational trend (Fig. 6) due to high volumes of lava entering the basin and infilling the available accommodation space. The height of the units indicate absolute water depth at the time of deposition, with variations interpreted to be a product of syn-volcanic subsidence.
- Seismic reflection unit 11 displays localised collapse scarps (Fig. 6) and is interpreted to resulted from a prolonged hiatus or decrease in the supply of new material, which left the delta front prone to erosion and reworking by tides, waves and storms.
- Seismic reflection unit 12 and 13 display a retrogradational trend (Fig. 6) during lower volcanic flux and a syn-volcanic sea level rise. The units were likely deposited after a volcanic hiatus when the delta system was no longer actively depositing and subsiding, suggesting the units record a more significant relative sea level rise.
- During progradation, the delta front gradually rotated anticlockwise from NE-SW to N-S, caused by variations in the volume of material filling the available accommodation space (Fig. 7). During retrogradation, the delta front rapidly rotated clockwise to NE-SW (Fig. 7) as volcanism was waning and becoming more sporadic, likely with less volcanic sources.

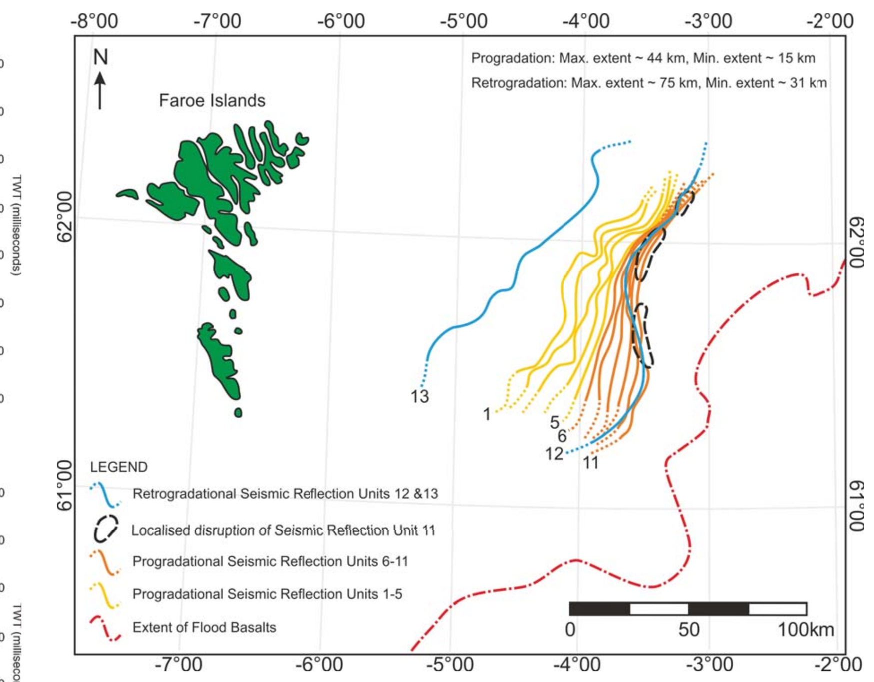

Figure 7. Map of the extent of seismic reflection units, with the position of the offlap break for the most easterly lying clinoform within each unit identified.

2.4 Delta Duration:

Relative and absolute dating between eruptions can be difficult and relies on the preservation of erosional surfaces, deposition of non volcanic units, palynology and geochemical fingerprinting of different eruptive units. In offshore settings, it can be extremely difficult to obtain this information, especially if the volcanic succession is undrilled. Delta deposition has been previously associated with the Beinisvørð Formation of the Faroe Islands, which is the longest and more sustained period of volcanism.

Using an empirical equation $t = 164.8\,C^2$ by Hon et al. (1994), we calculated the minimum the length of time the lava flows for each seismic reflection unit took to inflate and cool based on the thickness of the flow crust (Table 2).

- The equation states $t = 164.8\,C^2$ where t is time in hours, 164.8 is an empirically determined constant and C is the thickness of the flow crust in metres.
- We calculated the average lava flow thickness flows from TWT and velocities suggested by borehole data and the core to crust ratios of 60/40 from Nelson et al. (2009) which are constrained by Faroese borehole data.
- The sum of t for all the units (1-13) gives a value of 2,617.75 years of active delta deposition. This estimate is a minimum and does not include any periods of volcanic quiescence which can vary from 10 - 10^4 years.

Seismic Reflection Unit	Average Total Flow Thickness (m)	C (m)	t (hrs)	$t/24$ = days	$t/24/365$ = yrs
1-11	275	110	1994080	83086.67	227.63
12 & 13	137.5	55	498520	20771.67	56.91

Table 2. Average thickness for lava flows feeding the seismic reflections units and the calculated time taken to inflate to the total flow thickness (to 2 decimal places).

3. 3D SEISMIC ANALYSIS

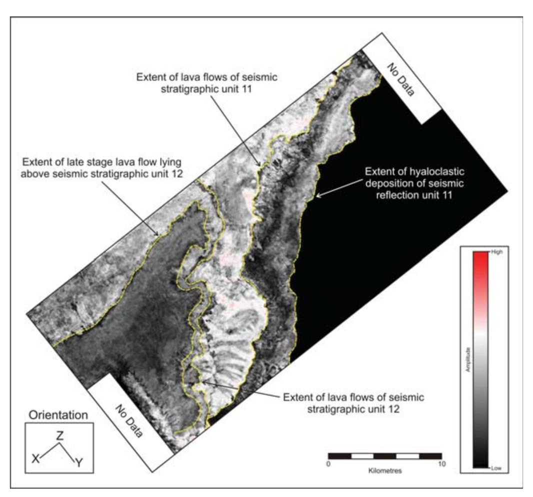

Figure 8. RMS amplitude of the top surface of the lava-fed delta system, including seismic reflection unit 11, unit 12 and an apparently late stage lava flow feature.

3.1 Geomorphology:

The top of the delta system is delineated by the top bounding reflection of seismic reflection units 11, which is the most easterly progradation of the delta into the basin, seismic reflection unit 12, which is the first retrogression of the delta front and a late stage lava flow that lies directly on top of unit 12. This composite top surface is well imaged (Fig. 8) and displays a number of morphological features that are comparable with those seen in outcrop.

Seismic Unit 12

- Seismic reflection unit 12 displays the regression of the delta front during syn-voclanic subsidence and decreased volcanic activity, with a smooth and lobateintact delta front and small, inclined reflections which mimic those of th main delta body. This feature is interpreted to be a perched delta front that formed during a short-lived eruption (Fig. 10).
- Lying above unit 12 is a late stage flow which did not reach the extent of unit 12 and therefore, did not deposit hyaloclastic breccias. This is identified as a lava flow feeder system with a number of individual branches and incised edges, which may have possibly fed unit 12 (Fig. 10).

Seismic Unit 11

- Seismic Reflection Unit 11 displays the furthest extent of delta progradation into the basin, with the majority of the delta front intact with inclined, sigmodial internal reflections. The top of the unit has a smooth and lobate shape from the inflation and coalesing of lava flows, with furrows which may have formed between the individual flows during inflation and were later infilled by eroded volcanic material from subsequent volcanism (Fig. 9).
- Unit 11 also displays a highly concave delta front, with the internal reflections changes from steeply inclined to shallowly dipping. This feature is interpreted to be a series of collapse scarps with propagated along the delta front, most likely during a time of decreased delta deposition (Fig. 9).

Seismic Unit 10

- Seismic reflection unit 10 appears to interact with unit 11, with the highly concave delta front of unit 11 coming into contact with the delta front of unit 10. It also shows the transition from the steeply dipping internal reflections of unit 10 to the shallow and disrupted internal reflections of unit 11. It is interpreted that during the deposition and subsequent erosion of unit 11, contact was made with the underlying unit 10, which potentially limited the collapse of unit 11 (Fig. 11)

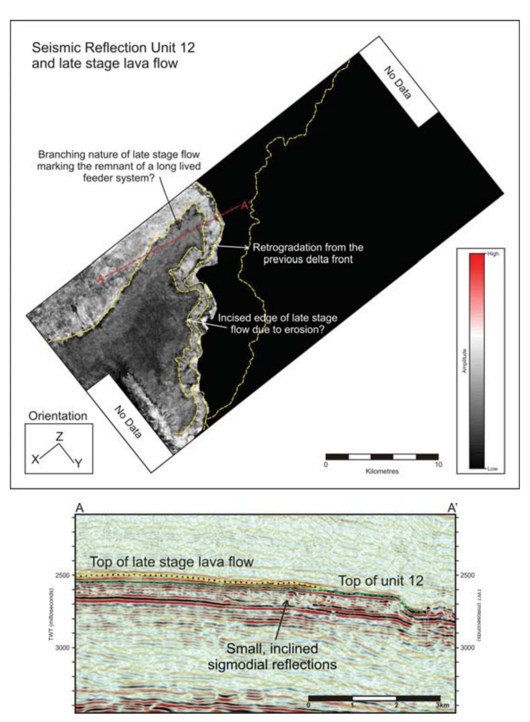

Figure 9. RMS amplitude map of the top of seismic reflection unit 12 and a overlying late stage flows and corresponding cross section A-A'.

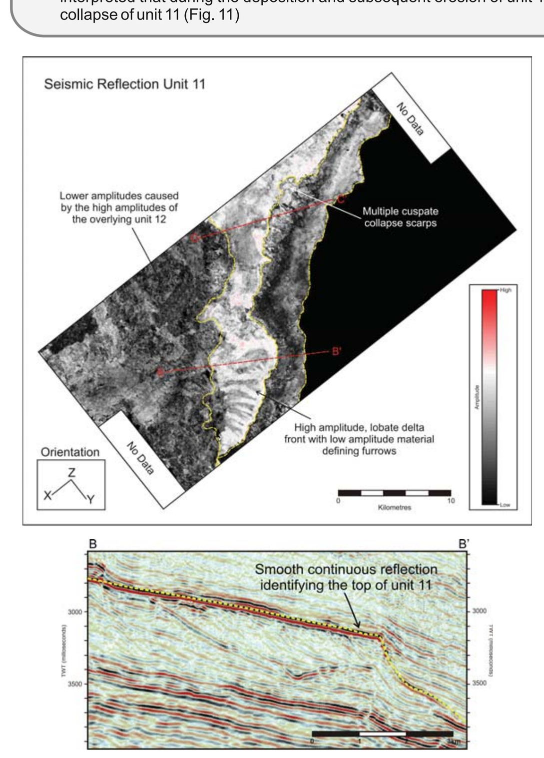

Figure 10. RMS amplitude map of the top of seismic reflection unit 11, with corresponding cross sections B-B'.

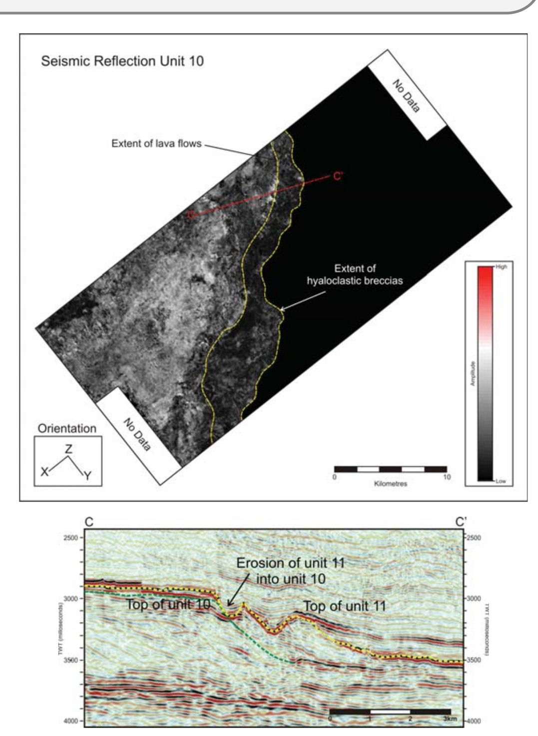

Figure 11. RMS amplitude map of the top of seismic reflection unit 10 and corresponding cross section C-C'.

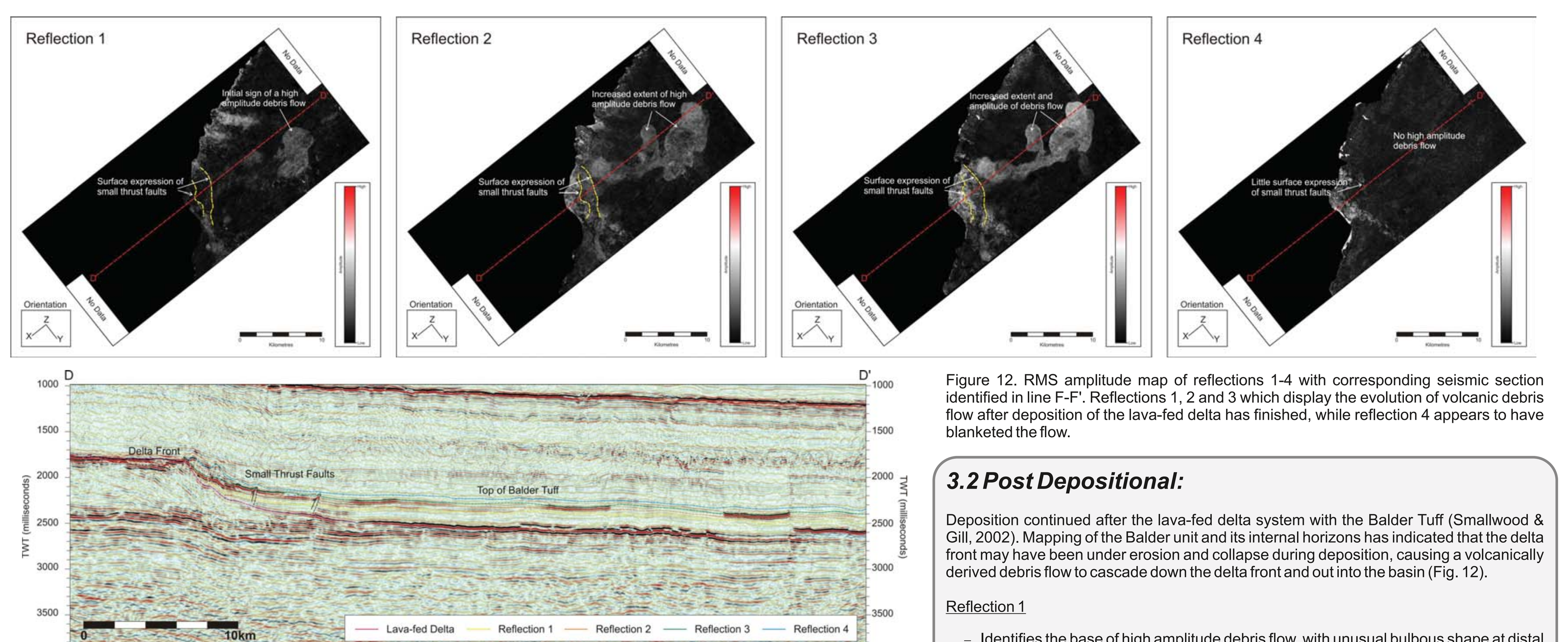

Figure 12. RMS amplitude map of reflections 1-4 with corresponding seismic section identified in line F-F'. Reflections 1, 2 and 3 which display the evolution of volcanic debris flow after deposition of the lava-fed delta has finished, while reflection 4 appears to have blanketed the flow.

3.2 Post Depositional:

Deposition continued after the lava-fed delta system with the Balder Tuff (Smallwood & Gill, 2002). Mapping of the Balder unit and its internal horizons has indicated that the delta front may have been under erosion and collapse during deposition, causing a volcanically derived debris flow to cascade down the delta front and out into the basin (Fig. 12).

Reflection 1

- Identifies the base of high amplitude debris flow, with unusual bulbous shape at distal extent, with slight ridges formed by small thrust faults.

Reflection 2

- Displays an increase in extent and amplitude of debris flow, with ridges formed by small thrust faults.

Reflection 3

- Reveals the full extent of debris flow, with multiple, distinct bulbous edges and obvious ridges formed by thrust faulting during delta front collapse.

Reflection 4

- Shows no indication of debris flow, some possible sign of underlying thrust faults close to delta front.

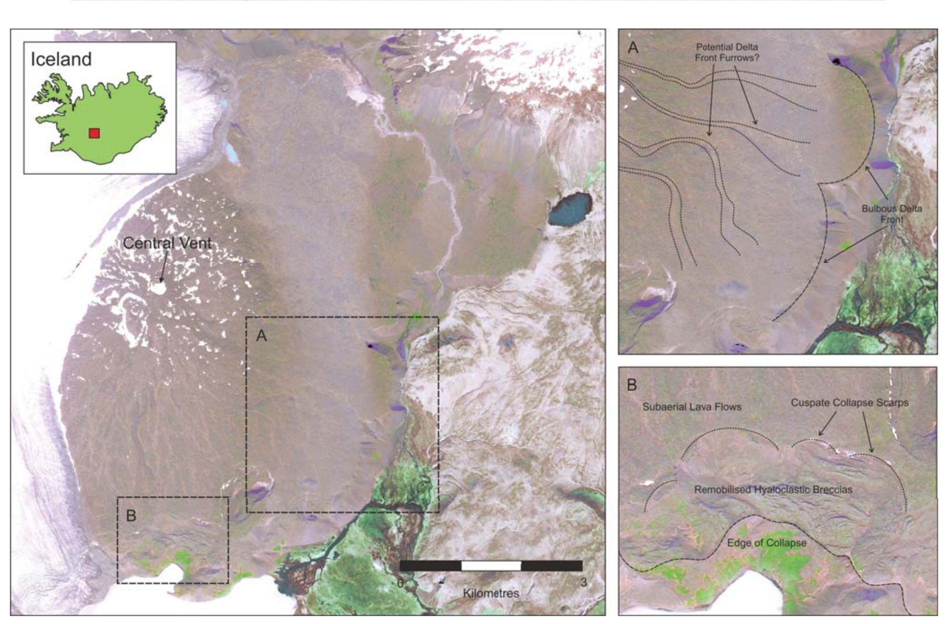

Figure 13. Aerial view of the Sølkatla lava delta, southwest central Iceland. (A) Displays lobated shaped delta front. (B) Displays cuspate collapse scarps and remobilised hyaloclastic material (image from Google Earth).

3.3 Outcrop Analogues:

Volcaniclastic units in flood basalt provinces are not as well studied as the more distinct lava flow units, but recent work has shown that they can occur in a number of settings and are particularly important at and near the onset of flood volcanism (Jerram & Stollhofen 2002; Ross et al., 2005). Iceland, Hawaii, Greenland and Antarctica all have outcrops of lava fed delta systems similar in thickness and geometry to the one presented in this study.

In Iceland, the Sølkatla volcano at Langjökull erupted against a glacier, with a lava-fed delta deposited in the resulting melt water lake (Rossi, 1996). Although the depositional environment differs from this study, the Sølkatla lava delta displays comparable structures on similar scales (Fig. 13);

- The eastern edge of the delta front is lobate, although later stage erosion and collapse has eaten away at the delta front (A).
- The south extent of the delta front shows cuspate collapse scarps, with curved ridges of hyaloclastic material formed when material of the delta front became remobilised and travelled down slope (B).

4. SUMMARY

4.1 Conclusions:

This study demonstrates the utility in using seismic and sequence stratigraphic concepts to reconstruct the volcanic sediment basin-fill history of rifted margins. It highlights how the preservation of ancient volcanic systems in offshore settings has the potential to record key aspects of basin development, including the histories of relative sea level, volcanic sediment supply and available accommodation space, when more conventional depositional systems were absent.

- Detailed 2D seismic analysis of reflection geometries has identified a series of 13 seismic reflection units that record the evolution of the Faroe-Shetland Escarpment during discrete periods of volcanism, with the bounding reflectors interpreted to represent submarine erosional surfaces.
- Through successive phases of volcanism, the lava-fed delta system developed with the resulting stacking pattern directly related to the interaction of relative sea level, lava supply and available accommodation space (which itself is influenced by synvolcanic subsidence of the delta system).
- The lava-fed delta system underwent a major period of progradation due to high volcanic flux. The aggradation and apparent rise in relative sea level seen in the later deposited units is interpreted to be a product of the loading and syn-volcanic subsidence of the growing delta system.
- The later stages of delta deposition were dominated by retrogradation. This was due to reduced volcanic input after periods of volcanic inactivity, when the delta system was no longer actively depositing and subsiding. Coupled with a basinwide relative sea level rise, delta deposition records a far more significant rise in relative sea level and the creation of new accommodation space.
- Active delta deposition/emplacement of lava flows has been calculated to have lasted ~2,600 years. However, the total duration of the lava-fed delta system, including pauses between eruptions, is likely to have been much longer but without well constraints this is difficult to estimate.
- Detailed 3D seismic analysis has revealed the complex geomorphology of the delta system, which are indicative of active deposition processes and subsequent mass transport. These features appear to be comparable to outcrop examples.

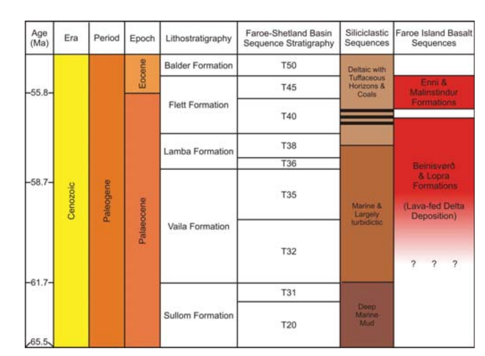

Figure 14. Sequence stratigraphic frame work of the Faroe-Shetland Basin and equivalent basalt sequences.

4.2 Future Work:

Analysis of the 3D seismic reflection survey to;

- Relate the volcanic geomorphology of the lava-fed delta system, its depositional processes and post depositional products to futher outcrop analogues, with emphasis on how the morphological features observed compare in size and frequency with field examples.
- Investigate if and how the morphology of the delta front evolved through time during deposition of the individual seismic reflection units and assess any potential drainage systems that became established during periods of volcanic quiescence.

Understand the syn-volcanic subsidence the delta system underwent during delta deposition and how it affected the distribution of the depositing units.

Combining the insights gained in both the 2D and 3D seismic analysis to;

- Understand how the record of the development of the Faroe-Shetland Escarpment compares to the regional evolution of the Faroe-Shetland Basin.
- Investigate any correlation between events recorded by delta deposition and events recorded during the Beinisvørð Formation of the Faroe Islands (Fig. 14).

Acknowledgements:

Seismic data shown with permission from Fugro Multi Client Services, CGGVeritas and Statoil UK. We gratefully acknowledge the Landmark Universities software grant program. We thank Dave Stevenson & Gary Wilkinson for data loading, software & hardware support. K.A. Wright is grateful to Statoil for funding this research as part of a PhD project within the Volcanic Margin Research Consortium. Also to David Ellis, Richard Brown and Tim Watton for useful discussions.

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