The facies architecture of large igneous provinces: an integrated geological and geophysical approach to the characterisation of volcanic successions in 3-D

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Richard Single

Abstract

Quantifying the facies architecture of flood volcanic provinces is important as it can be used to understand the physical volcanology and rock property variations throughout the igneous succession. This is very important to the petroleum industry exploration efforts in volcanic rifted margins as volcanic successions commonly mask geophysical images of sub-volcanic petroleum plays. This problem is known as the 'sub-basalt imaging problem' and is caused by factors including the geometrical heterogeneities and elastic velocity and density contrasts through the volcanic pile.

The study of facies architecture is broken down into a series of orders of scale. These scales reflect a systematic approach to the characterisation of the facies architecture, from a centimetre through to kilometre-scale, and incorporates 3D modelling of a range of data types for constructing the 3D structure of the flood volcanic successions.

A system for the characterisation of lava flow scale facies is presented termed the 'intrafacies scheme'. This may be used to assess and interpret the geological facies heterogeneities present on a 'micro-scale' and link the interpretations to geophysical rock properties. The scheme is applied to outcrop-scale case studies in the Talisker Bay area of the Skye Lava Field on the Isle of Skye, Scotland.

On a lava field scale of study ('meso-scale'), the geometrical relationships of several flood basalt provinces are studied, focusing on the Skye Lava Field. This is studied in 1D through to 3D, revealing that the lava field may be divided into architectural sequences based on lava flow facies interpretations. The facies evolve upwards through the volcanic succession from geometrically complex thin, olivine-basaltic compound-braided lava flow facies towards the base, to simple, thick basaltic-andesite tabular lava flows. The lower lavas are interpreted to have formed on the gently dipping flanks of a shield volcano.

The observations and understanding of flood volcanics on a lava field scale of observation and the facies forming the building blocks of lava fields are used to interpret the GFA-99 2D seismic data from the Faeroe-Shetland Basin. The interpretation is developed into 3D and thicknesses of the Faeroes Lava Group are calculated.

The complete study of facies from intrafacies through to basin-scale interpretations reveal that flood volcanic successions contain substantial geometrical and rock property heterogeneities, and that these can be characterised in the 3D modelling environment into geologically realistic geophysical flood basalt facies architectural models.

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To My Family

And the people and places

that have made me who I am

Contents

Chapter 1

1. INTRODUCTION

Flood volcanic provinces represent some of the most voluminous lavas on Earth and cover large areas of continental rifted margins. Associated with these lavas are deep seated intrusive complexes, dykes and sills. Traditionally, such lava successions have been termed continental flood basalts (CFBs), forming a sub-set of much larger volcanic systems that are often termed large igneous provinces (LIPs) (e.g. Mahoney & Coffin 1997). Large igneous provinces encompass CFBs, volcanic rifted margins and also encompass vast areas of ocean floor as oceanic plateaux. Continental flood basalts have historically received much research attention, particularly in the field of geochemical studies, and their potential connection with mantle plumes (e.g. White & McKenzie 1985; Scarrow & Cox 1995; Gibson *et al.* 1996; Graham *et al.* 1998; Takahahshi *et al.* 1998; Larsen *et al.* 1999; Sheth 1999).

Recently, new insights into the genesis, structure and internal architecture of flood volcanic successions has attracted new levels of interest; in particular from the petroleum industry where many new frontier basin exploration areas are associated with igneous rocks (Schutter 2003a&b). Igneous rocks can provide good reservoir qualities, create petroleum trapping structures, stimulate hydrocarbon maturation, and volatile fluids can also assist hydrocarbon migration (Schutter 2003a). In areas affected by igneous activity, particular exploration interest lies in frontier basins that are blanketed by volcanic rocks on continental rifted margins (Menzies *et al.* 2002; Jolley & Bell 2002a). The blanketing effects of the volcanic successions pose new problems to the petroleum industry such as the 'sub-basalt imaging problem' which severely affects the quality of geophysical data acquired through and beneath a volcanic succession (Fig. 1-1). In frontier areas such as the Faeroe-Shetland Basin, or

Vøring Margin (Norway), major petroleum plays are considered to be present in the sub-volcanic stratigraphy causing the sub-basalt imaging problem to be a serious exploration issue. The effect of igneous activity in volcanic rifted margins is also of interest in understanding how dykes and sills may compartmentalise reservoir systems and how the activity may affect the crustal geothermal gradient. These factors can affect hydrocarbon migration, trapping and reservoir quality and also alter the maturation history of hydrocarbon source rocks.

The poignancy of such problems poses the following questions:

- What are the lithologies present in flood volcanic successions?
- What are the 3D geometries present within the volcanic successions?
- How can we characterise the external and internal facies architectures?
- How are rock properties affecting the geophysical imaging?
- How can an understanding of the geological evolution of the igneous system help to solve such issues?
- How can an understanding of the facies architecture of flood basalts improve our understanding of their volcanogenesis and emplacement?

To enable a thorough investigation into the problem of sub-basalt imaging, well-constrained geological information on flood basalts is required; and this must incorporate 3D information, rock properties, geometries and facies architecture.

This thesis aims to address the above problems using a combination of fieldwork, image analysis, geophysical datasets and novel use of 3D modelling software GoCad™. In this advanced 3D modelling environment, multiple datasets of multiple data-types may be combined in one interface, into true 3D. Characterisation and modelling techniques are applied to case-studies of CFBs in three igneous provinces, and concepts drawn together into full volcanic province system models.

The PhD research has been integrated into the European Union (EU) 5th Framework project 'SIMBA' as Work Package 1 (WP1): Geological Modelling. The SIMBA consortium has drawn together expertise from Europe through the areas of geophysics, geology and engineering. SIMBA comprises the industrial partners of Total; Norsk Hydro; ARK Geophysics and Institut Français du Pétrole (IFP); and the academic institutions of University of Cambridge; Université de Bretagne Occidentale (University of Brest); University College, Dublin and University of Durham. The PhD project was initially funded by Elf GRC, before being integrated into the work of SIMBA (Appendix 4). The SIMBA consortium is a research project which aims to solve the problems associated with sub-basalt imaging by integrating areas of technical expertise for improved sub-basalt imaging. As WP1 of the SIMBA consortium research, the work associated with this PhD research provides geological information and interpretations for the partners of SIMBA. This geological information is being integrated into 1D, 2D and 3D geophysical models of volcanic successions, at the time of completing this thesis. These models include a complex 3D model of a volcanic filled basin of $50km^2$ area populated with geologically realistic geometries and rock property distributions; and an integrated geological/geophysical study, which integrates gravity, seismic, geological, magnetotelluric (MT), and borehole data into a high resolution 3D model of an onshore flood basalt succession. Gravity data was acquired as PhD training on behalf of ARK Geophysics, as a contribution to SIMBA WP4. Details of these projects are documented in the SIMBA final report, and in Martini *et al.* (2005 *in press*).

1.1 BACKGROUND TO FLOOD VOLCANIC PROVINCES

Flood basalt provinces have been at the heart of some of the earliest work in igneous successions. The classic works of Judd (1874); Clough and Harker (1904) and Bailey *et al.* (1924) describe the petrology of the lavas of the Islands of Mull and Skye and distinguish different magma types based on their varying petrologies. These early works cite some classic field localities such as the Macculloch's Tree on the west coast of Mull and the prominent Preshal More on Skye (Chapter 4). At this early stage in the evolution of flood basalt research, many of the thick lava successions which we observe today were considered to be thick sill complexes, particularly in the Scottish Hebrides where many of the foundation concepts of igneous petrology, petrogenesis and igneous geochemistry were developed.

During the 1970s and 1980s, great advances were made in the fields of elemental and isotopic geochemistry and in isotopic dating. Progress in these areas, particularly in geochemistry, mean that the bulk of the literature associated with CFBs during this period is dominated by new chemical constraints on the development and source regions of the lavas and intrusions, and new concepts of magmatic plumbing and mantle processes (e.g. Thompson *et al.* 1972; Cox, 1980; Morrison *et al.* 1985).

Over the course of the 1990s and through to the present day, much research has focussed on the styles of volcanism and volcanic facies. Models for CFB emplacement have been developed (e.g. Hon *et al.* 1994; Keszthelyi & Denlinger 1996; Self *et al.* 1997) and facies architectural studies undertaken (e.g. Jerram *et al.* 1999a; Planke *et al.* 2000). These research advances have helped guide some of the ideas behind this thesis.

The terms 'flood basalts' and continental flood basalts (CFBs) have become ingrained in the literature. However it is important to clarify that flood basalts are not simply a suite of basalts. They contain lavas of various compositions (e.g. basalts, basaltic-andesites, rhyolites), and are commonly accompanied by hypabyssal rocks (e.g. sills and dykes), and plutonic rocks (e.g. gabbros and granites). For example, the Paraná-Etendeka CFB province (1.1.2) is >90% tholeiitic basalts and basaltic-andesites (Milner *et al.* 1995); basalt itself forming a low percentage of the total volume.

In the following sections, the three continental flood basalt provinces studied in this thesis are briefly introduced.

1.1.1 North Atlantic Igneous Province (NAIP)

An episode of magmatic activity occurred over the North Atlantic area from the late Cretaceous through to the Eocene, associated with continental breakup and opening of the North Atlantic. As early as the 19^{th} Century, it had been noted that igneous rocks of similar affinity existed in Britain, the Faeroe Islands and in Iceland (Giekie 1880). During the course of continued research, the name of the volcanic province has evolved to its present form: 'North Atlantic Igneous Province' (NAIP) (Saunders *et al.* 1997 and references therein). The NAIP comprises a province of volcanics and associated intrusions covering an area of c.1.3 x 10^6 km^2 (Eldholm & Grue 1994). The large scale of this system means that the province may consequently be divided into six main sub-provinces: the British Tertiary Igneous Province in the Scottish Hebrides/Northern Ireland (see 1.1.1.1); the Faeroes Islands (1.1.1.2); east Greenland; Baffin Bay/west Greenland; the Rockall Plateau; and the Vøring Plateau off NW Norway (Fig. 1-2). The NAIP is considered to have been extruded rapidly in two phases: Phase I is observed in west Greenland, SE Greenland and the British Tertiary Igneous Province and occurred from 62 Ma to 58 Ma, whilst Phase II is seen forming the offshore seaward dipping reflector sequences (SDRS) on the continental margins and in east Greenland and has erupted from 56 Ma. This continues to the present day in the Mid-Atlantic Ridge (Saunders *et al.* 1997). A summary of the geochronology of the NAIP is compiled in Fig. 1-3.

1.1.1.1 The British Tertiary Igneous Province (BTIP)

In the British Isles, the NAIP manifests itself as the British Tertiary Igneous Province (BTIP), occasionally referred to as the British Palaeogene Province by some workers (Fig. 1-2). This sub-province stretches through the Hebrides of Scotland (e.g. Skye, Mull, and the Small Isles of Eigg and Rum), across the Ardnamurchan peninsula and southwards through the Isle of Arran, County Antrim in Northern Ireland, and forms intrusive complexes as far south as the Isle of Lundy in the Bristol Channel (Hitchen *et al.* 1994). The NNW-SSE trend of eruptive volcanism is accompanied by the large intrusive complexes running in the same trend. The Rum and Skye Cuillin igneous complexes contain substantial mafic and ultramafic cumulate sequences (Upton 1988), whilst silicic intrusive centres also lie on this volcanic axis, notably in the granitic Red Hills centres of Skye, the Northern Arran Granite and on the Isle of Lundy. Through the axial zone of the volcanics and main igneous centres are dyke swarms each of which increase in intensity towards the axis of the central igneous complexes.

On Skye and the Small Isles, the lava field covers some 1500km^2 (Preston 1983). The lava sequence on Skye is mainly dominated by the transitional to alkali-basalts of the Skye Main Lava Series (Thompson 1982). Much study has focussed on the onshore areas of the BTIP, particularly in the field of geochemistry (e.g. Thompson *et al.* 1972; Preston *et al.* 1988; Kerr 1993), but the full extent of the offshore sequences to the NW of the Hebrides are still being realised. The offshore sector, where many Cretaceous and Palaeogene seamount volcanic complexes exist (Jones *et al.* 1974), is becoming better understood due to oil company exploration taking place in the Faeroe-Shetland Basin and across the Rockall Plateau and Hatton Bank areas (Jolley & Bell 2002a & references therein).

1.1.1.2 The Faeroe Islands

The Faeroe Islands lie in the North Atlantic between Iceland and Scotland (Fig. 1-2). They comprise onshore remnants of part of the larger NAIP known as the Faeroes Lava Group and extend offshore both SE into the Faeroe-Shetland Basin and NW towards Iceland (Ellis *et al.* 2002 and references therein). The large offshore extent of these volcanics has been a significant factor in stimulating the interest of the petroleum industry in characterising flood basalts successions: the Faeroe-Shetland Basin is known to be a mature petroleum system, however the blanketing of the potential plays by the Faeroes Lava Group makes exploration particularly difficult and expensive. The Faeroes Lava Group is considered to have erupted during Phase II of the NAIP development and as such, may be correlated with volcanics in the east Greenland (Larsen *et al.* 1999).

1.1.2 Paraná-Etendeka

The Paraná lavas of central South America and those of the Etendeka Province of Namibia, together form the Paraná-Etendeka LIP (Peate 1997 and references therein). This extensive system of flood volcanics and large igneous centres is linked to the opening of the South Atlantic and the main phase of magmatism is thought to have occurred between 134-129Ma (Peate 1997). The total preserved volume amounts to over $1x10^6km^3$ dominated by the Paraná lavas of South America (Cordani & Vandoros 1967). The Etendeka Igneous Province (see Fig. 4-1), which is the focus of some of the research presented in this thesis, forms a comparatively small outlier area of volcanics particularly concentrated in the Huab Basin area where the Etendeka Group has been studied in great detail due to the high quality of the exposure (e.g. Milner *et al.* 1995; Jerram *et al.* 1999a; Jerram *et al.* 1999b; Jerram & Robbe 2001).

1.1.3 Rational for case study selection

The Isle of Skye in the BTIP was initially chosen for the focus of this research for several reasons:

I. Skye contains substantial, accessible, well-exposed sections through a CFB sequence; including dykes, sills and a central volcanic complex.
II. Geochronology is well constrained by field relationships and dating techniques (Pearson *et al.* 1996; Jolley 1997; Hamilton *et al.* 1998).
III. The base of the lava sequence is accessible in several parts of the island overlying the basinal Mesozoic sedimentary sequence.
IV. The lava sequence represents an onshore exposure of the more extensive offshore flood volcanics of the Faeroe-Shetland Basin, which is an area of interest for offshore petroleum exploration.

During the field season of 2001, foot and mouth disease struck the UK, rendering the BTIP inaccessible. As result, fieldwork was moved to the Huab area of the Etendeka CFBs of Namibia. This area was selected due to the high quality of exposures in the volcanics, and because the area is stratigraphically well-constrained and 3D modelling work has been previously applied to the succession in the Huab area (e.g. Peate 1997; Jerram *et al.* 1999a; Jerram & Robbe 2001).

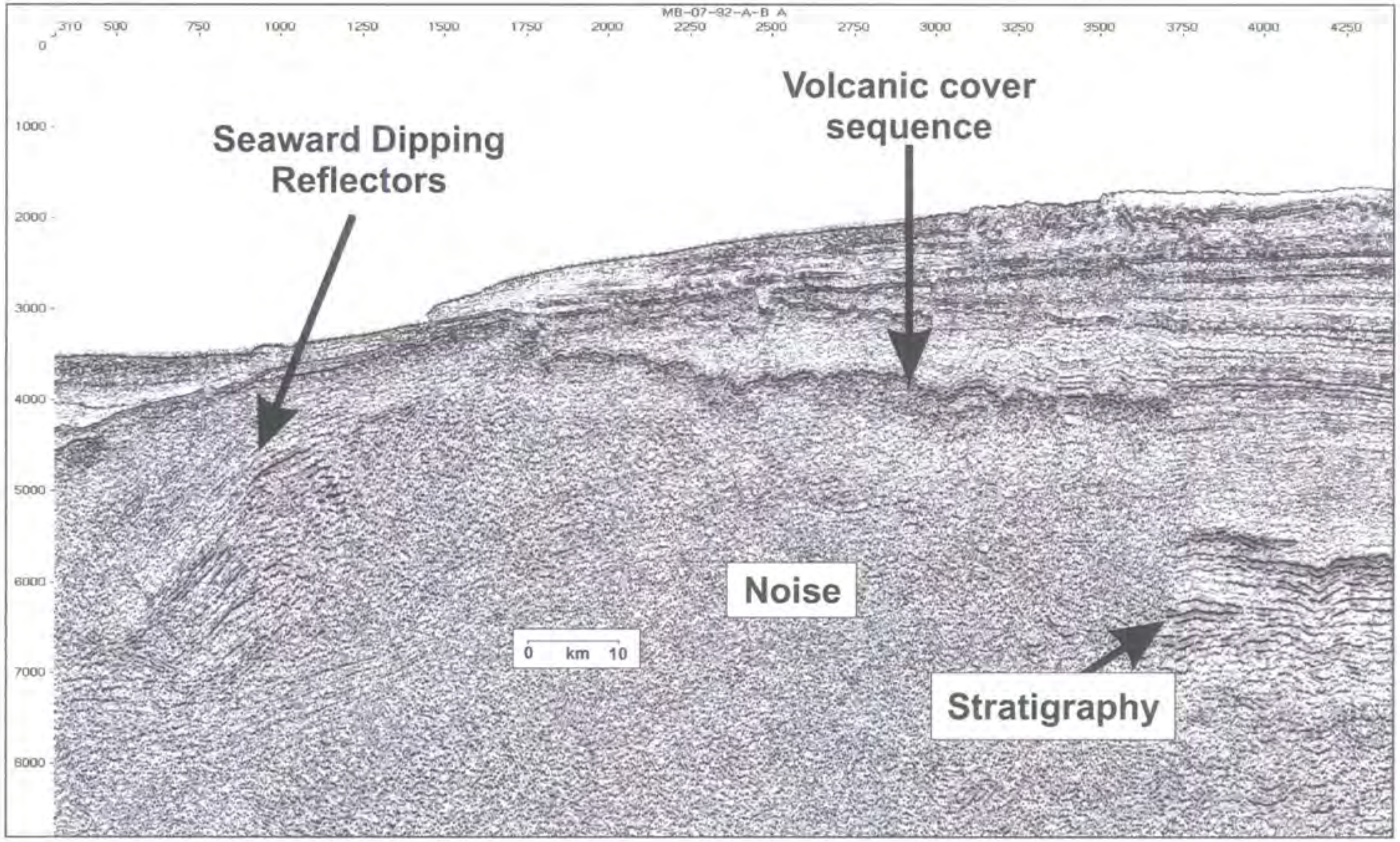


Figure 1-1 Seismic line MB-07-92 from offshore Norway, highlighting the problem of sub-basalt seismic imaging (MB-07-92 NPD is owned by Norwegian Petroleum Directorate [NPD]; image courtesy of Elf Norge) (after Jerram 2002).

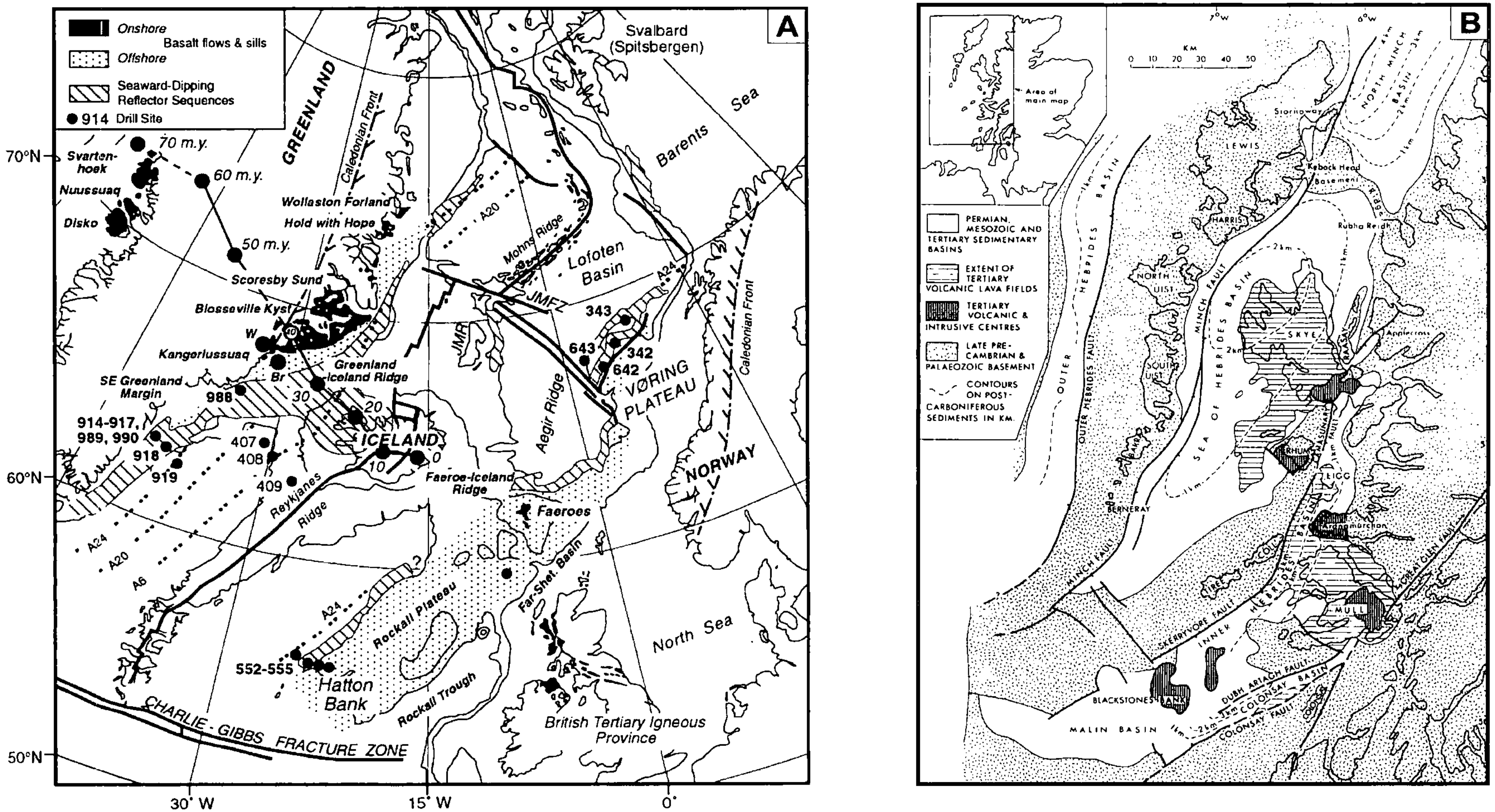


Figure 1-2 Volcanism over the North Atlantic area. **A:** Map of the North Atlantic showing the extent of the North Atlantic Igneous Province. Small filled circles in the indicate drill sites of the ODP and DSDP. Note the estimated track of the ancestral Iceland plume (after Saunders *et al.* 1997); **B:** A sketch map of the main volcanic part of the British Tertiary Igneous Province. Also shown are the offshore sedimentary basins (after Naylor & Shannon 1982).

1st Order	DATES (Ma)	NORTH ATLANTIC IGNEOUS PROVINCE (NAIP)						
2nd Order		GREENLAND		FAEROES/VØRING		BRITISH TERTIARY IGNEOUS PROVINCE (BTIP)		
		WEST	EAST	FAEROES	VØRING	SKYE	MULL	RUM, SMALL ISLES
3rd Order	53.0		Tephra 53.8+/-0.3Ma; Ar-Ar (Heister *et al.* 2001)			Eastern Red Hills Granites 53.5+/-0.8Ma; Rb-Sr (Hamilton *et al.* 1998)		
	54.0				Lower Series Lavas 54.3+/-0.5Ma; Ar-Ar (Sinton *et al.* 1998)			
	55.0			MLF/ULF syn-break-up onset >55Ma early Chron C24r (Waagstein *et al.* 2002)			Staffa Lava Group 55-54.5Ma (Jolley & Bell 1997)	
	56.0		Kangerlussuq Sill 56.3+/-0.9Ma; Ar-Ar (Tegner *et al.* 1998)	LLF top 56.4+/-0.5Ma (1Sigma), start of Chron C24r; K-Ar & Ar-Ar (Waagstein *et al.* 2002)				
	57.0							
	58.0					Western Red Hills Granites 58.75+/-1.8Ma; Rb-Sr & 59.3+/-1.4Ma (Hamilton *et al.* 1998)	Mull Central Complex - Loch Ba Felsite, Centre3, 58.5+/-0.1Ma; U-Pb (*pers comm* Emeleus)	
	59.0		East Greenland Lava 58.7+/-1.4Ma; Ar-Ar (Upton *et al.* 1995)	LLF onset 58.8+/-0.5Ma (1Sigma) in Chron C26r; K/Ar (Waagstein *et al.* 2002)		Cuillin gabbros, Preshal More lavas & dykes 58.91+/-0.07Ma; U-Pb (Hamilton *et al.* 1998)		
	60.0	Vaigat Fm. 60.3+/-1.3Ma; Ar-Ar (Storey *et al.* 1998)				Conglomerate underlying Preshal More lavas & sediments within Skye Main Lava Group 58.0-58.25Ma (Bell & Jolley 1997). Sleadale Trachytic Tuff, Skye Main Lava Group below Preshal More Conglomerate Fm. 58.91+/-0.1Ma; Ar-Ar (*pers comm* Emeleus)	Mull Plateaux Lava Fm. 58.66Ma; Ar-Ar (*pers comm* Emeleus)	Canna Lavas & Skye Lava Field after a period of erosion (Hamilton *et al.* 1998) Rum Layered Igneous Complex 60.53+/-0.08Ma; U-Pb (Hamilton *et al.* 1998)
	61.0	Maligat Fm. 60.1+/-2.2Ma; Ar-Ar (Storey *et al.* 1998)						
	62.0							Rum & Small Isles dykes (Hamilton *et al.* 1998) Rum Western Granite (Hamilton *et al.* 1998) Muck & Eigg lavas 62.8+/-0.6Ma; Ar-Ar, K-Feld (Hamilton *et al.* 1998)

Figure 1-3 The geochronology of the NAIP summarised from the work of several sources. Geochronology assembled from Pearson *et al.* 1996; Hamilton *et al.* 1998; Gamble *et al.* 1999; Jolley & Bell 2002 and Jolley *et al.* 2002 and references therein.

1.2 SUMMARY OF THESIS AIMS AND OBJECTIVES

The main aims and objectives of this thesis are to:

I. Better constrain the influence CFBs have on the sedimentary basins into which they erupt.

II. Analyse, interpret and characterise the fine-scale rock property variability at an intra-lava flow scale using detailed fieldwork and image analysis.

III. Build well-constrained 3D geological models of metre to kilometre scale architectures developed within an onshore lava field.

IV. Build 3D geological models from interpretations of offshore geophysical datasets utilising the understanding developed from onshore studies.

V. Suggest future work areas and targets that should be met in flood volcanic province research for further understanding of these igneous systems and to enhance a geological and geophysical collaborative effort to solving sub-basalts imaging problems.

VI. Recommend future ideas for the further development of use and application of 3D modelling to integrated geoscience studies.

1.3 THESIS OUTLINE

This thesis is organised into five major chapters, a concluding summary and four appendices.

Chapter 2 provides an overview of the data available to this study and the methodologies that may be used to address the problems of integrating multiple data types. A brief outline of some of the basic functionality of the GoCad™ 3D geoscience modelling software has been incorporated into this chapter.

Chapters 3 to 5 investigate the flood volcanic successions on three scales of observation. These have been called the micro-, meso- and macro-scales of observation of flood volcanic successions. The purpose of these categories is to provide a framework into which the successions may be investigated and presented as a complete hierarchical study.

In Chapter 3, the *micro-scale* 'intrafacies' architecture is investigated in detail in the Skye Lava Field as a case study area for characterising the building blocks of a typical CFBP lava field. This chapter addresses centimetre to metre-scale heterogeneities within the lava field using small-scale field case studies and image analysis.

In Chapter 4, the thesis investigates how the architectural building blocks are pieced together to form the *meso-scale* scale system of a CFB lava field succession. A geological case study is presented from the Talisker area of Skye in the Minginish District. The focus of this section is on the geometric aspects of the lava field architecture.

Chapter 5 presents data at the igneous sub-province *macro-scale* utilising an offshore seismic dataset from the Faeroes-Shetland Basin, and outcrop analogue data from various CFBs including the onshore Faeroe Islands succession. This chapter addresses how the lava field scale case studies fit into the architecture of a large igneous system and provides geological interpretations of geophysical data.

The upscaling of each level of observation is ultimately combined in Chapter 6, where the issues realised from each scale of investigation are discussed and developed into a complete model of a flood volcanic province.

Conclusions are drawn together from each of the preceding chapters into a bullet-point list of new insights and advancements made in flood volcanic province studies in the light of this work. Some recommendations for future expansion of this field of research are also stipulated.

The appendices contain links to important websites, location data for geophysical data and a simplified system for GoCad™ file storage. A CD is also appended containing some animations of 3D models, and a selection of presentations made throughout the PhD. A final copy of the publication Single & Jerram (2004) is included, and also the papers that are in press and submitted for 2005 and 2006.

Chapter 2

2. METHODOLOGY AND DATA REQUIREMENTS

The data requirements for the 3D modelling of geological sequences fall into three main categories with regard to data collection, analysis and modelling. These categories are based on the scales at which we observe the volcanic system. The following chapter therefore opens with a section which acts as an introduction to these orders of observation. The data is subsequently discussed as it is broken down into each of the scales. The main aim of this chapter is to outline the data used in the present study and how they may be incorporated into a 3D geological Earth model.

Because this study uses a complex 3D modelling package (GoCad™), an introduction to the functionality of the software is also provided, that outlines some of the ways in which it can aid geological and geophysical studies.

2.1 SCALES UNDER INVESTIGATION

In order to build a strategy for characterising the 3D facies architecture of a flood basalt province, it is important to outline the hierarchy of scales of observations. Each of these hierarchial scales are considered in detail in Chapters 3 to 5. Hierarchical scales of observation are ever-present in geological description and interpretation, regardless of the particular type of geological system we are considering. Many geological studies have worked with the concepts of scales within a geological system, and orders of hierarchy mainly within the research area of sedimentology (e.g. Kocurek 1981; Miall 1985 & 1988). In igneous systems, the hierarchy of scales of observation and investigation have not been fully documented, and research has mainly focussed upon a particular scale or level of investigation for example, the basin scale (Planke *et al.* 2000) or the lava flow scale (e.g. Jerram 2002). In these studies, the scales of investigation have focussed on the seismic facies (Planke) and the flow facies and province architecture (Jerram). These important contributions address the characterisation of the geological architecture and facies heterogeneities in flood volcanic systems on scales ranging from metres to tens of kilometres.

The detailed architectural field observations of igneous flood volcanic suites documented in this work provide a basis for the characterisation of heterogeneities on three main scales of observation:

- 'Micro-scale' - millimetres to metres (lava flow scale)
- 'Meso-scale' - metres to kilometres (lava field scale) (e.g. Jerram)
- 'Macro-scale' - kilometres to tens of kilometres (sub-province scale)

The next sections outline the architectural features under investigation at the scales of investigation.

2.1.1 Micro-scale – 'Internal Facies Architecture'

Flood volcanic successions are comprised of a large suite of igneous rocks, both extrusive and intrusive. The micro-scale architecture may be considered to be the internal heterogeneity that exists within the individual igneous units within a lava field at a very small scale: typically the centimetre or metre-scale for example within individual lava flows or intrusions (4^{th} order heterogeneity). These may be studied down to the lowest scale of observation possible without the need for special analytical instrumentation. The 5^{th} order of heterogeneity which is beyond the scope of this research may be considered to be the scale of observation which requires specialist equipment e.g. chemical isotope ratio variations across individual crystals (e.g. Tepley *et al.* 1999; Solovova *et al.* 2002; Bishop *et al.* 2003).

In studying the 4th order of heterogeneity, this work concentrates on the intra-flow scale diagnostics of igneous facies. These are termed *intrafacies* (Single & Jerram 2004) and are discussed in detail in Chapter 3. Diagnostic intrafacies describe specific heterogeneities: e.g. distribution of vesicles within lava flows, the textures of crystals within a flow and the juxtaposition of certain rock unit types within the building blocks of the meso-scale (flow facies scale) architecture of a lava field succession.

The micro-scale architectural building blocks of the igneous succession are studied in detail so as to provide not only an understanding of the metre-scale geometrical (short-wavelength) heterogeneity within the igneous units present, but also an understanding of how geophysical rock property variability is distributed with these geometries. Geophysical rock properties that are very important to the characterisation of volcanic successions for sub-investigation are those of density and compressional (or primary) velocity. The elastic velocity properties of the geology directly relate to the bulk rock densities present, so it is density which has the controlling affect on seismic acquisition. Density is also inherent to gravity modelling. Rock property variations within the igneous succession may affect each of these geophysical variables in particular, leading to the inaccurate geophysical modelling of volcanic successions. These issues are discussed in detail in Chapters 3 and 6.

2.1.2 Meso-scale – 'Flow Facies Architecture'

The 3rd order of heterogeneity in the study of the architecture of large igneous provinces involves the study of the flow facies architectural scale, whilst understanding the variability that exists within the flow-facies due to micro-scale heterogeneities. Meso-scale studies focus upon the vertical stacking patterns of igneous units on a lava field scale. At the meso-scale, it may be possible to make many lateral correlations throughout the lava field by the use of marker beds such as tuffs, tuffaceous sandstones and siltstones, and the basal contacts of prominent lava flows (e.g. Jerram *et al.* 1999a; Jerram & Widdowson 2004 *in press*). The meso-scale architecture concentrates on the geometrical heterogeneities that exist through the lava field succession, such as the distribution and geometries of thick lava flows, the development of ponded lavas and the onlapping and off-lapping relationships present in a lava field system (Jerram 2002).

Meso-scale studies are important to geologists and geophysicists as these are at the scale which is most easily recognised in correlation exercises and seismic surveying; the reservoir-scale or lava field scale of interest. In this work, the onshore lava field in the Talisker area of the Isle of Skye is studied in detail and modelled in 3D in order to capture the 3D geometrical heterogeneity present in a CFB lava field. The area is considered to be analogous in volcanic style and scale to certain petroleum prospected areas in the Faeroes-Shetland Basin and in the Vøring Margin on the eastern north-Atlantic seaboard.

2.1.3 Macro-scale – 'Basin Scale Facies Architecture'

The North Atlantic Igneous Province comprises the British and Faeroes sub-provinces on the east side of the north Atlantic, and the west and east Greenland lava fields on the west seaboard (1.1.1). Correlations across this vast area may be possible by use of borehole data and field studies which lie beyond the scope of this research. Volcanic tuff horizons are laterally extensive and studies cite trans-Atlantic correlations between east Greenland and the Faeroe basalts (e.g. Larsen *et al.* 1999) and also the Paraná-Etendeka Province of South America and Namibia (Milner *et al.* 1995). This Large Igneous Province (LIP) scale must be considered the largest scale of study, where correlations are made across both sides of a volcanic rifted margin. This is therefore described as being the 1st order of heterogeneity.

In this work, the highest level scale of study within the hierarchy of flood volcanic sequences is the study of the external and internal facies architecture at the igneous sub-province level (2nd order heterogeneity): in particular, the Faeroes Lava Group which may be internally correlated and architecturally sub-divided over the tens to hundred kilometre-scale (the basin scale).

Within this volcanic system as a whole, many facies types are present laterally and vertically over metres to kilometres. The facies changes over these distances are important for the overall understanding of the province, but the recognition of facies associations within the basinal architecture are more important at the 2nd order of observation so as to characterise the bulk structure of the sub-province. Such facies associations may be large scale volcanic disconformities that may only be recognised by long distance correlation (e.g. Jerram *et al.* 1999a) or the types of facies variations which occur on the scale visible on seismic sections. Taking into account the wider picture and understanding what is within, for example the seismic scale of investigation (e.g. Planke *et al.* 1999; Planke *et al.* 2000) is very important to interpretations made in geophysical data (Chapter 5).

2.2 THE NEED FOR GEOLOGICAL FIELDWORK – ONSHORE ANALOGUES FOR OFFSHORE PROBLEMS

Most geological 3D modelling is performed within the spheres of the petroleum and mining industries. In the petroleum industry, geological modelling is usually based around a *Voxet* of seismic data (usually 3D seismic) which is geologically constrained by 1D well data. The 1D well data may be utilised from sparse distributions across entire basins in low-resolution basinal correlation exercises, but may equally provide a high resolution of 1D data in close proximities to petroleum reservoirs. The 1D geological information is available through various combinations of data types: Drill cuttings and core samples, petrophysical wireline analysis, and possibly vertical seismic profiles (VSPs) in order to tie important correlations across a large scale basinal sequence or through a reservoir. The steps involved in moving from 1D geological analysis to 3D modelling therefore requires interpolation, but the interpolation is usually constrained by extensive, high resolution seismic surveying: Importantly, the dataset runs through the entire stratigraphy and allows its internal sub-division into a series of units. Lithological unit distributions, juxtapositions of units, their correlations, predicted internal rock properties and stacking patterns may all be constrained with accuracy.

In the mining industry, boreholes provide 1D constraint in a similar way to well data in petroleum exploration and production. Additional information is collected by mine-mapping geologists and integrated into the full dataset.

One approach used in the petroleum industry to aid the construction of detailed 3D models is to use field analogues. Well exposed areas of stratigraphy are chosen which represent similar geological facies to those which are interpreted to occur in the sub-surface. Detailed stratigraphic logs, correlation panels and rock property data are collected and used to construct a picture of the depositional environment and the characteristic geological patterns that are present. These can be used to aid geophysical seismic interpretations and hence the construction of the 3D reservoir model. A classic example of this style of approach has been used to characterise sequence stratigraphic stacking patterns in the shore-face deposits of the Book Cliffs in Utah (e.g. Howell *et al.* 2001). In a recent study, a similar approach was used to construct a 3D model of the Etendeka flood basalts in NW Namibia (Jerram & Robbe 2001).

In the present study, the approach of using detailed onshore analogues will be adopted to aid the construction of 3D geological Earth models of flood basalts, with specific emphasis on the North Atlantic Margin.

2.2.1 Onshore analogue for micro- to meso-scale study

The Minginish district of SW Skye was selected as the source for well-constrained geological information to be integrated into a 3D model of a flood basalt lava field on the micro- and meso-scales of observation (Fig. 2-1). In this area, we can observe eight extrusive lava groups, sedimentary intercalations and dyking in a complex lava field succession. This succession is also further complicated by post-eruptive faulting which consists of an array of several large and many sub-seismic scale faults. The hills of Minginish district rise to over 400m above sea level. A thick igneous succession is therefore available for 3D modelling. Characterising the internal variability is essential to being able to address the geophysical modelling and acquisition problems being currently experienced in offshore exploration.

2.2.2 Offshore dataset for basin-wide macro-scale study

The area selected for the study of macro-scale flood basalt architecture is the Faeroe-Shetland Basin where a large 2D seismic grid was acquired by Geco-Prakla. The GFA-99 dataset is introduced in section 2.5.

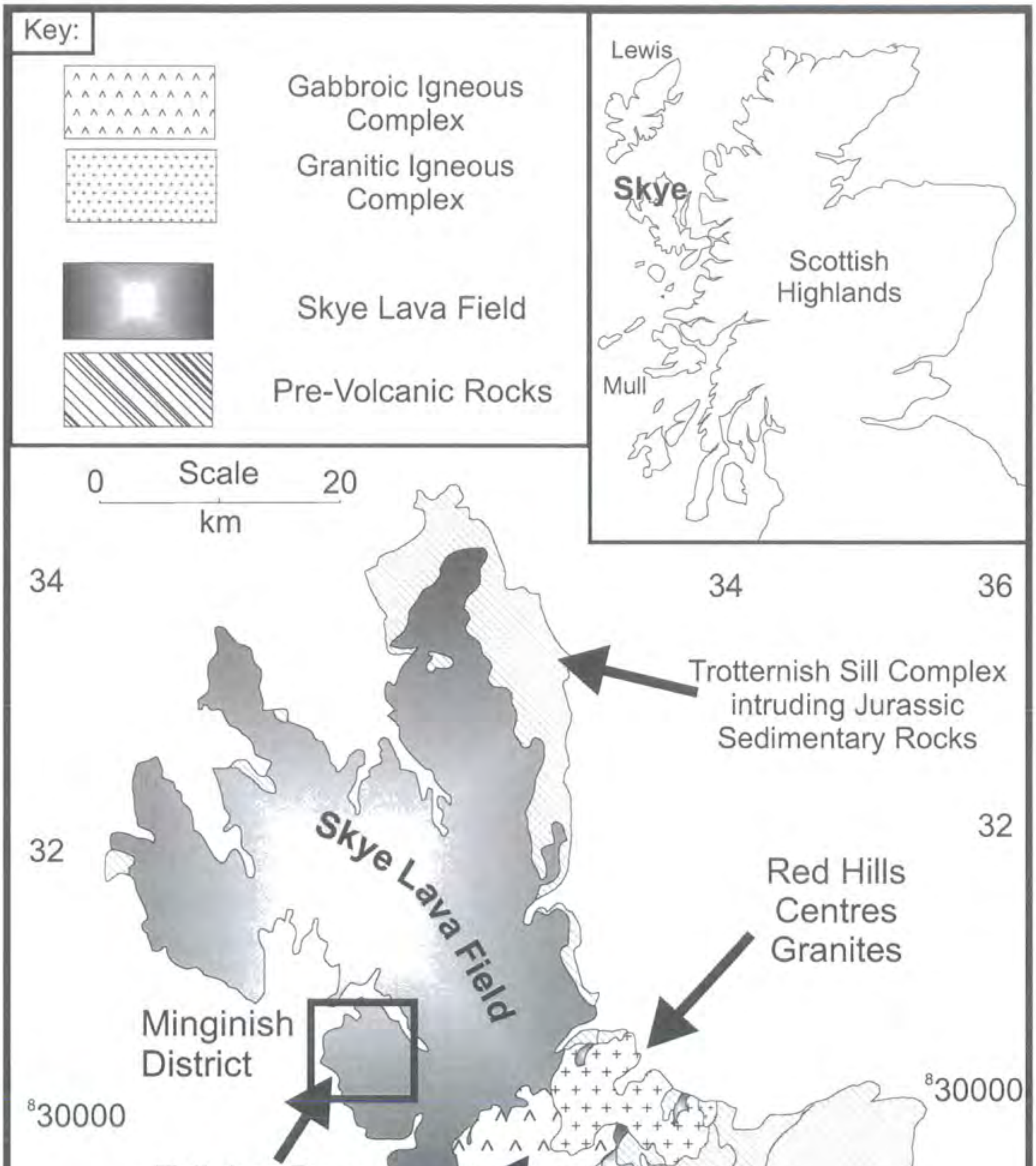


Figure 2-1 Location of the 'meso-' and 'micro-' scales of study within the British Tertiary Igneous Province. On the Isle of Skye, the micro-scale study area lies in Talisker Bay, and the meso-scale study lies over the hills east of Talisker Bay on the north of the Minginish Peninsula.

2.3 MICRO-SCALE STUDY DATA

In this study, micro-scale data are studied in both 1D logs and in 2D cliff sections. The data gathered from these sections provide information about vertical and lateral changes in the lava sequence: Lithological, facies and rock property variations. The data used in this detailed study are from the field, although wireline studies can reveal details of the rock property distributions through boreholes in 1D. Geophysical rock properties are discussed in more detail at the micro-scale in Chapter 3.

2.3.1 Data available

The following section outlines the data types at the micro-scale associated with the field case studies cited in Chapter 3.

2.3.1.1 Fieldwork

In the low lying cliffs of Talisker Bay and the surrounding area, lies a wealth of geological data in the west-central lava field of the Skye Lava Field. The wave-cut platform on the north and south sides of Talisker Bay provide particularly interesting areas to study the physical relationships between different lava types, sedimentary horizons, and the internal organisation of both. Fieldwork data available includes:

- A lava sequence shallowly dissected by a wave-cut platform
- Thinly banded lavas at the base of the cliff sections
- Tuffaceous beds and thick sedimentary units
- Intrusive contacts
- Centimetre-scale description of the building blocks of lava flows

2.3.1.2 Photographs

The cliffs surrounding Talisker Bay form thick 2D sections through the extensive lava pile. These sections show a variable succession of lithotypes and contact relationships. The bases and tops of several sections are accessible at various points through the lava field. The ability to access the thick volcanic succession in several parts of the stratigraphy, mean that the collection of a large photographic dataset is an important way of constraining the lithotypes and lithofacies present. In addition, their lateral and vertical variability can be constrained throughout the lava sequence.

2.3.2 Methodology

The following sections outline some of the methods employed in the fieldwork and data analysis parts of this micro-scale investigation.

2.3.2.1 Sections

Sections in 1D and 2D form an important part of characterising the facies present in the volcanic succession at a centimetre to metre-scale of observation. The sections were constructed close to sea level in Talisker Bay. Using a combination of field sketches and photographic montages, detailed notes of the geometries of the units present were developed in 2D sections. During reconnaissance fieldwork, a large photographic dataset was collated for much of the field area. An emphasis was placed on collecting a photographic dataset which covered volcanic features of various scales within the micro-scale study: Centimetre to metre-scale features were captured as individual photographs taken at several focal lengths; whilst scales of metres through to tens of metres scale were captured as a dataset for cliff section montages for facies evaluation on a grander scale. For each photograph, the location was noted with a GPS, with the orientations of the photograph centre and focal length. During subsequent fieldwork, copies of the photographic dataset were taken into the fieldwork and directly annotated with geological information. Field sketches enhanced the interpretations and developed the ideas from the micro-scale study. In addition to the 2D photographic montages and field sketches recorded, 1D logs were constructed where possible in the base of the cliff sections. The bases of each section were marked with paint in order to allow easy location as the tides heavily influenced the timing and availability of these outcrop log sections. The aim of the small log sections was to develop an understanding of the vertical construction of the igneous sequence, whilst the 2D photographic montage sections developed the 2D data coverage. Wherever possible, data was collected to strengthen and develop our understanding of the concepts of igneous sequence development in 3D. Fig. 2-2 highlights an example of such a photographic montage.

2.3.2.2 Mapping

Over the area of a small isolated wave-cut platform on the south side of Talisker Bay, mapping was undertaken. The mapping of this small area provides a 3D extension to the observations of the 2D cliff sections and so ultimately improves the 3D understanding of the lava sequence present. A series of paint marks were sprayed onto the peninsula and small cairns erected each time the tide retreated. A base map was constructed by using a combination of the GPS, a compass, and the cairns. During this study, the GPS used was a hand-held Garmin model. This provided a location accuracy of +/-5m. All of the GPS locations used in this study were recorded prior the improvement in location resolution which occurred during the Summer of the year 2000, when the navigation scramble (Selective Availability) was removed by the US military.

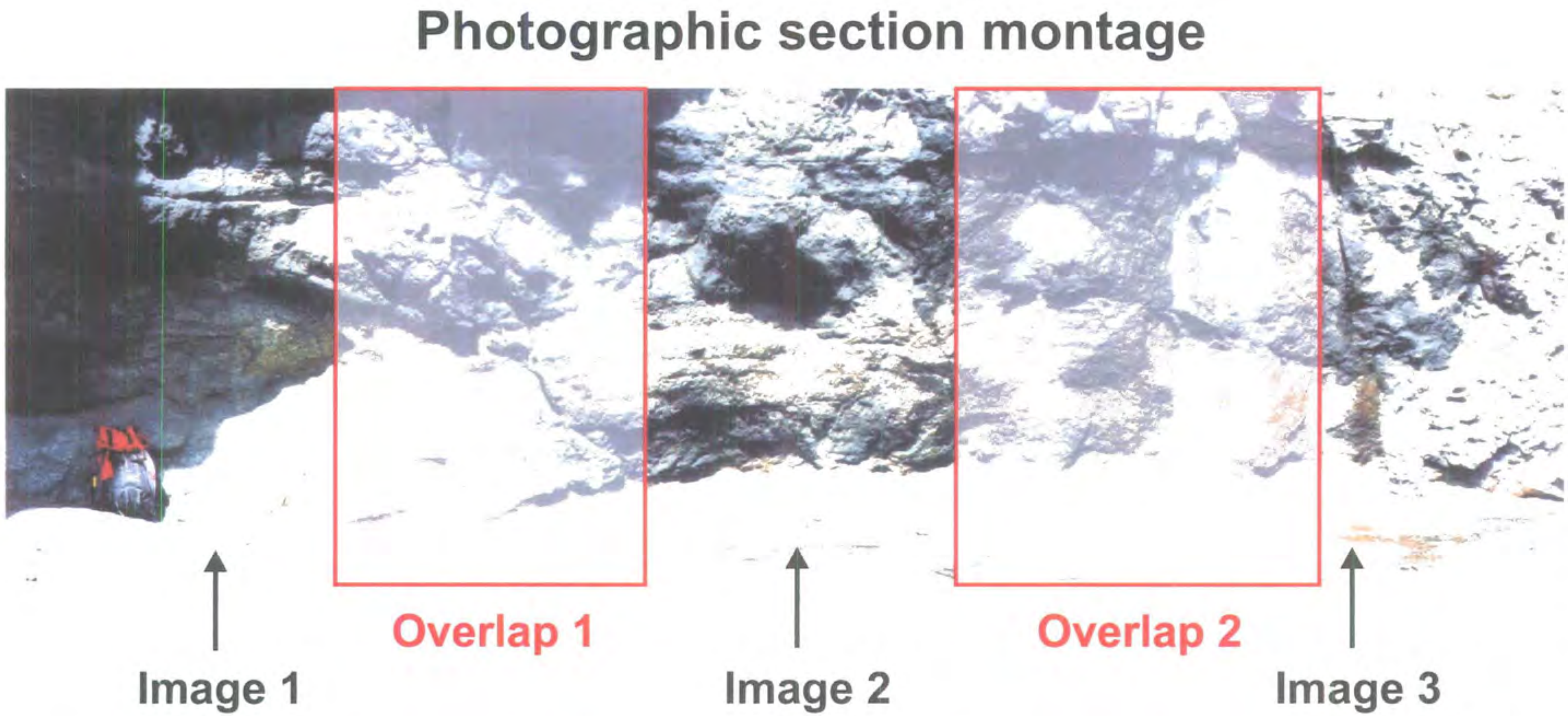


Figure 2-2 Example of a photographic 2-D section montage of a cliff section containing a series of stacked pahoehoe lava lobes in YZ-plane section. The photographs are stitched together either manually in Corel Draw, or by use of stitching applications such as 'Quickstitch', or 'The Panarama Factory' (Appendix 1). A fixed focal length, consistent image size and c.35% overlap are required for successful image montaging.

2.3.2.3 Image Analysis

The photographic dataset has allowed detailed investigations into the structure of the lava sequence to be performed by the use of image analysis software. The software primarily used in the studies of Chapter 3, is the package *UTHSCSA Image Tool* which is available on the internet via the University of Texas (Appendix 1). This package was developed as a tool for use in the University of Texas hospital for analysing biogenic materials; however can also be used as a tool for geological analysis.

In the centimetre to metre-scale of study, image analysis methodology was applied to photographic sections in order to constrain amygdale densities in lava flows. The amygdaloidal sections of igneous units give a measure of the vesicle population of the unit. The variations in both the vesicular and non-vesicular characters create lava flow heterogeneities vertically and laterally through the lava pile; image analysis provides a method by which the degree of vesiculation may be quantified. The analysis of an amygdaloidal section of olivine-phyric basalt is shown in Figs. 2-3 & 2-4. The technique requires a crisp photographic resolution of 150dpi or above, UTHSCA Image Tool and a spreadsheet application such as Microsoft Excel. Six steps provide a quantitative analysis of the photographic section and a measure of vesiculation as percentage of bulk rock area (Figs. 2-3 & 2-4). Such estimates of vesicle distributions are very important when considering rock property heterogeneities in Chapter 3. In addition to centimetre to metre-scale studies, Image Tool may also been used for the quantification of intrafacies present in 2D cliff sections.

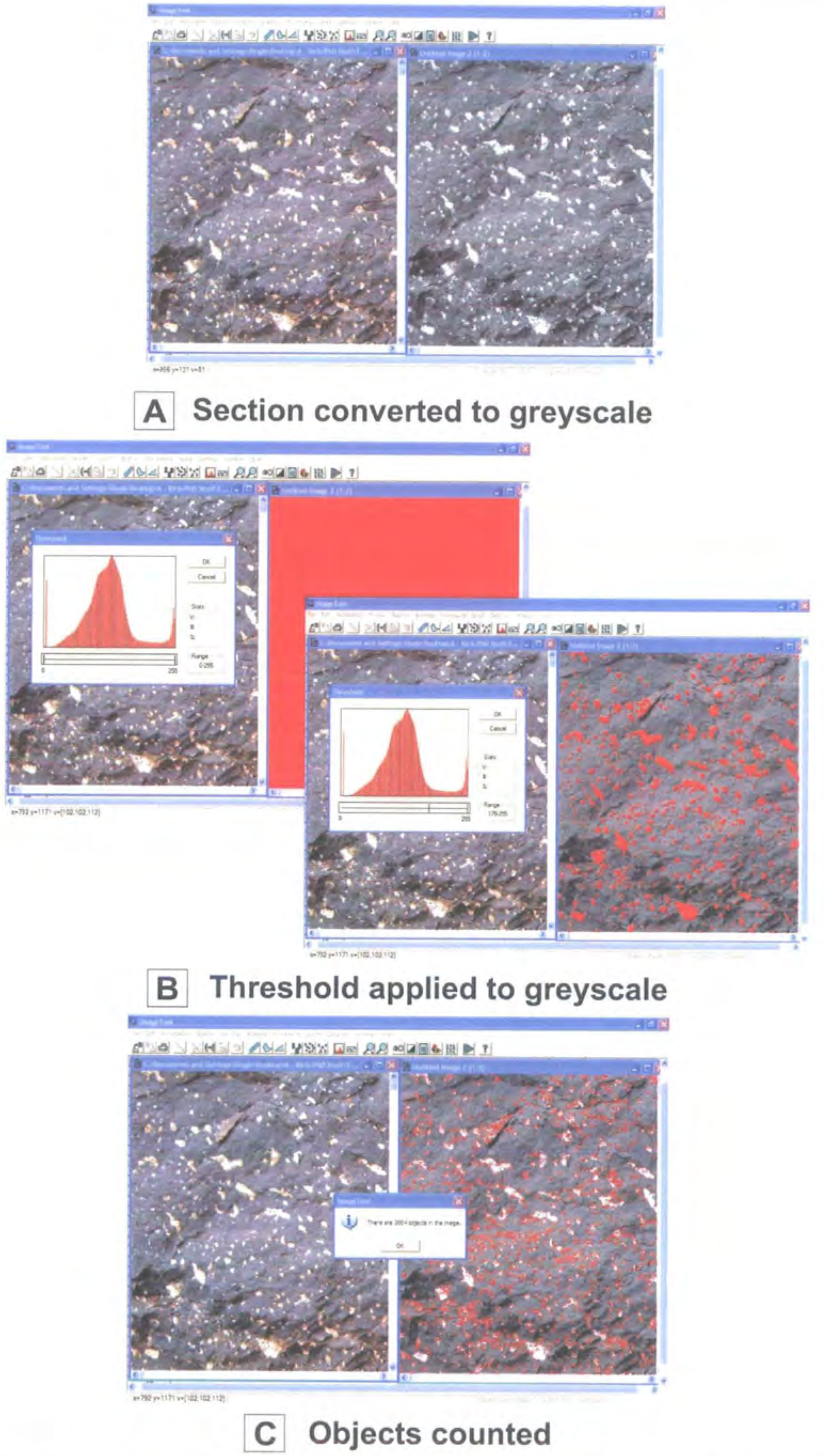


Figure 2-3 Object analysis in a section of vesiculated basalt - the aim is to calculate the percentage of vesiculation exists as % of bulk rock area. **A:** Photograph imported into UTHSCSA Image Tool and processed colour-to-greyscale; **B:** Vesicles are thresholded (red) by use of a threshold histogram; **C:**The thresholding creates a number of objects that can be statistically analysed.

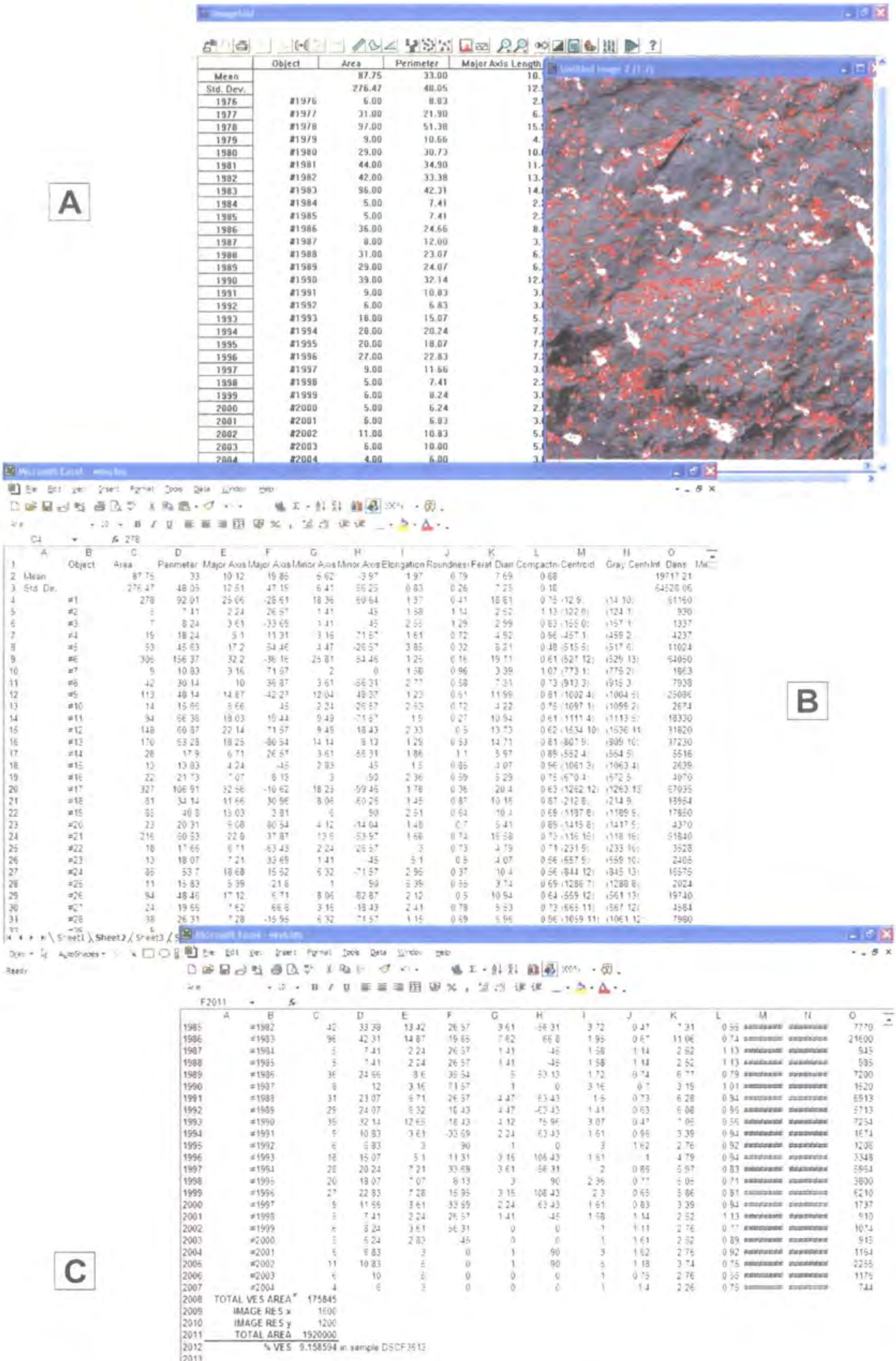


Figure 2-4 Object analysis in a section of vesiculated basalt. **A:** Objects are analysed in order to find their total area in the photograph. Many other statistics are available providing information such as vesicle centroids and axial lengths; **B:** Data are transferred into Microsoft Excel; **C:** Percentage vesicle area is calculated using the object analysis and image resolution information.

2.4 MESO-SCALE STUDY DATA

2.4.1 Data available

Field data comprise much of the dataset for meso-scale studies, but at this scale of investigation, more data options are available for integration into the research; particularly in the Minginish district which was selected for modelling due to the high volume of existing data.

2.4.1.1 Digital Terrain Models (DTMs)

Digital Terrain Models are now freely available on the internet for academic institutions via the Edina homepage (Appendix 1). The data for the case study area has 50m horizontal (XY plane) and 1m vertical resolution. Files are downloaded in *.dxf or *.ntf format and are sourced in conjunction with landscape and infrastructure data such as *Landline* data. The map tiles used in this research were downloaded in *.dxf format and converted to Ascii using as conversion utility (Appendix 1). The primary focus lies on the Minginish district tile [NG22].

2.4.1.2 Geological maps

The UK is geologically extremely well surveyed. The British Geological Survey (BGS) has covered Great Britain in considerable detail (generally at 1:10,000 scale); therefore well-constrained data readily available for this project. Geological maps covering the whole of the UK have been constantly updated on many scales and much effort has been channelled into constraining relationships present within the British Tertiary Igneous Province (BTIP). Geological maps may also be combined with other data types within GoCad™.

2.4.1.3 Photographs

A large photographic dataset was collected and developed for fieldwork as in the micro-scale study. Aerial photographs are also available for NW Scotland, but were not used in this study: The relevant photographs are now old and a new survey of Britain was expected to be available online during the project, although that is still being finalised. Due to the quality of the dataset, it was decided to utilise the host of other data which has been readily available.

2.4.1.4 Satellite data

LandSat-7 satellite data are available for download from the internet (Appendix 1) and may be used in two formats: colour 25m resolution, and greyscale 15m resolutions. These may be downloaded and geo-referenced as shape files or integrated into the GoCad™ interface by use of Voxet (2.6.2.4).

2.4.2 Methodology

Detailed lithological sections were logged around the north of the Minginish district, working through the lava succession from the micro-scale study are of Talisker Bay (Chapter 3). Lithological logs were developed to note the main contacts through the lava sequence; particularly the basal contacts of sedimentary units, bole beds, tuffs and the bases of prominent, thick lava flows. These contacts were considered as essential marker horizons for kilometre-scale correlation across the lava field. Correlations between the marker horizons were developed into correlation panels that create a second dimension to the 1D log data as a series of hypothetical cross sections through the faulted lava sequence (Fig. 2-5A). The log sections were imported into GoCad™ for integration into the 3D environment and draped onto the DTM data which was downloaded from the internet. Until mid-2002, all models developed within GoCad™ were built around a DTM which had been constructed through a nine-stage process which involved the hand-tracing of a 1:25,000 Ordnance Survey map of the field are. The accuracy has improved substantially with the addition of the imported satellite DTM data, which became freely available during the later stages of the project.

Within GoCad™, individual data points were added to the project, and the BGS geological maps integrated with the DTM data. Faults were picked using the high resolution DTM, field data, by the use of photographs and geological maps. By integrating the understanding of the lava field from the field work and the correlations stipulated by the lithological logging, GoCad™ was used to interpolate between data points to give a 3D surface visualisation of interpretations of the interior of the lava field. Architectural sequences were consequently converted to volumes in GoCad™ for volume calculations.

The steps required to move from fieldwork data collection, to building a 3D model of a lava sequence are summarised in Fig. 2-5. Essentially, we need to move from a 1D dataset to a 3D model via 2D surface interpolations, so it is important to consider the errors and assumptions involved in making this dimensional leap both during the course of the description of methodology and whilst considering the results (Chapters 3 to 5).

2.5 MACRO-SCALE STUDY DATA

The extrapolation of architectural studies onto a macro-scale may be best attained through use of multiple log sections correlated over tens of kilometres (e.g. Jerram *et al.* 1999a) or the use of photogrammetry. Long distance correlations have been made through use of marker horizons that link west and east Greenland (Larsen *et al.* 1999), across the Paraná-Etendeka igneous province (Milner *et al.* 1995) and also between the Paraná and the Kwanza Basin in western Angola (Marzoli *et al.* 1999). The methods employed reflect the offshore nature of the study and concentrate on 2D seismic and 2D gravity data.

2.5.1 Data available

Due to the scale of observation, different data types and procedures are required in order to develop realistic geological models. This study focuses on offshore data from the Faeroe-Shetland Basin.

2.5.1.1 2D Seismic

The investigation of flood basalt architecture over macro-scales made use of the GFA-99 2D seismic dataset which covers seven lines about 60km SE of the Faeroes (Fig. 2-6). Across the grid of this survey lies the FLARE line GFTL98-10 which was acquired in 1998 by Schlumberger Geco-Prakla for Amerada-Hess in the White Zone acquisition blocks of 6005/6/7 and 6105/6104 (Appendix 2). The lines are spaced on a 20km grid. The longest line is the north-south line 201 which is 122 km in length.

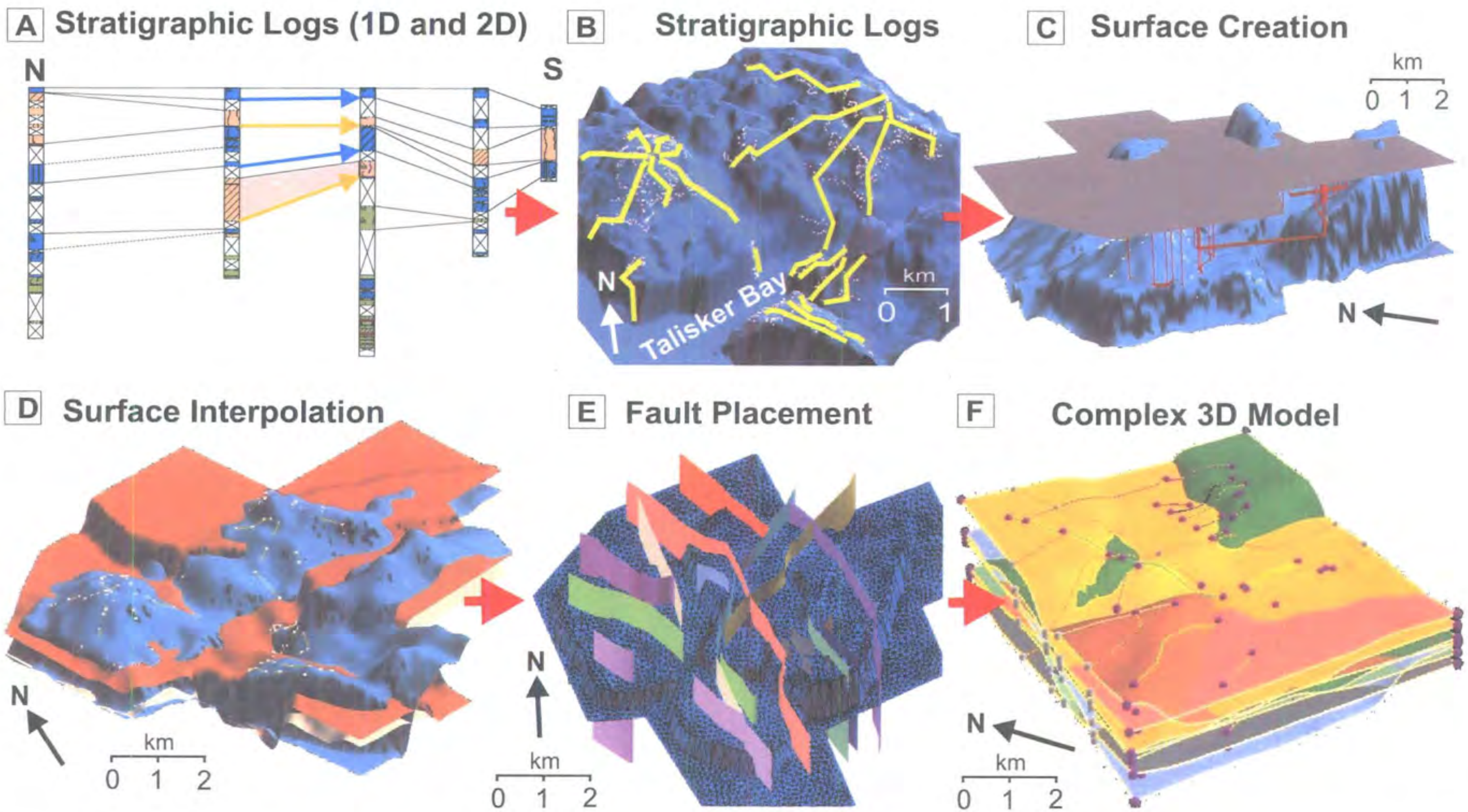


Figure 2-5 Building a 3D model of a volcanic sequence. **A:** 1D log section data are collected through the lava field and correlated in 2D panels; **B:** Log section data (1D) located on a 2D DTM of the field case study area; **C:** Precise locations of correlatable data points marked as *Property Control Points*; **D:** Correlatable points interpolated as a 2D surface - interpolation reveals eroded lava sequence material; **E:** Faults added to the 2D surface model; **F:** Complex 3D model of lava field developed incorporating multiple flows, correlations and faulting. Problems associated with upscaling from 1D to 3D are discussed in Chapter 6.

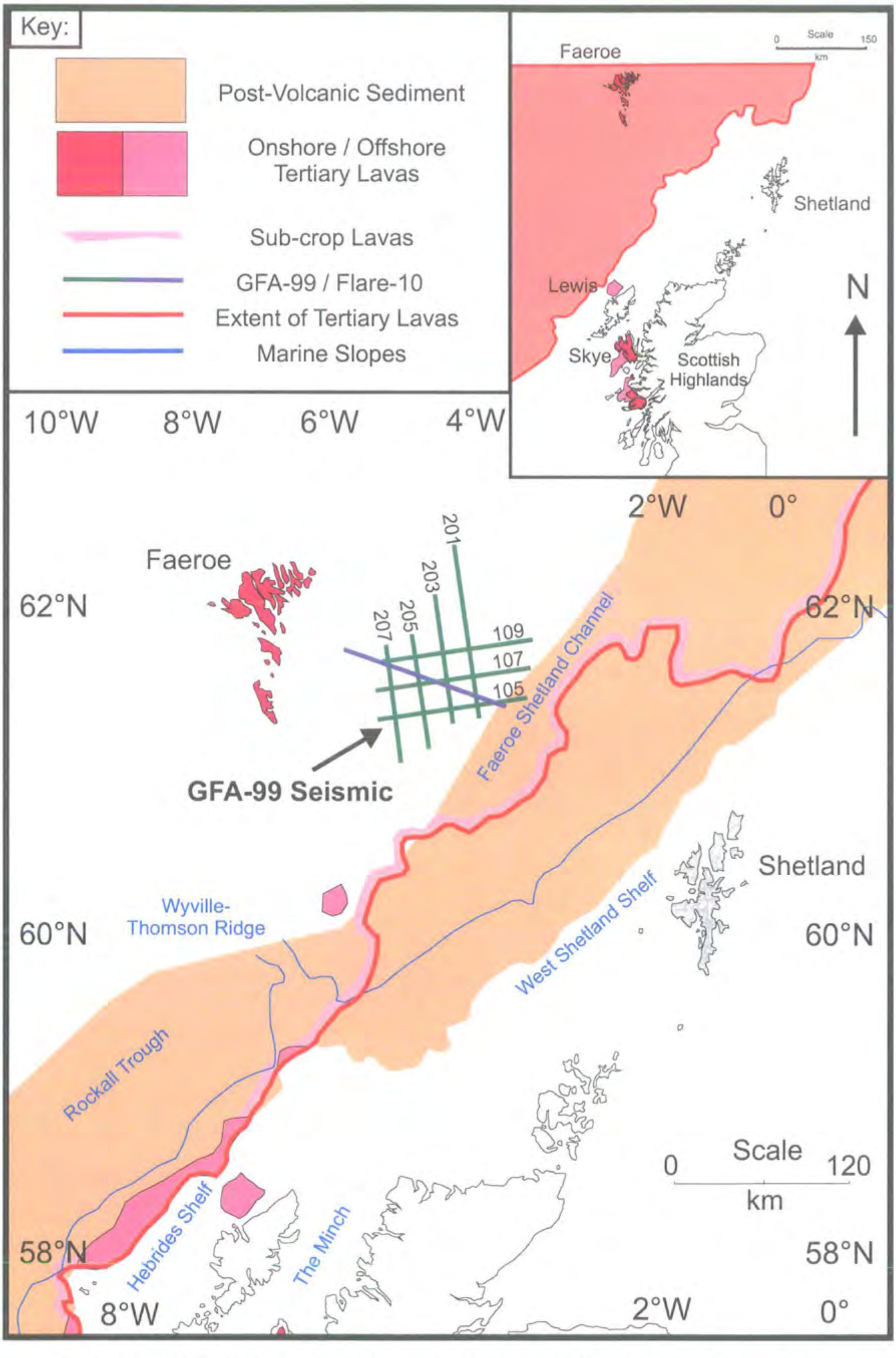


Figure 2-6 Location of the GFA-99 seismic data in the context of the British Tertiary Igneous Province. Great thicknesses of onshore lavas occur on the Faeroe Islands and on the Isles of Skye and Mull in the Inner Hebrides of Scotland. The offshore lavas in the Faeroe-Shetland Basin are a continuation of the large onshore succession of the Faeroe sequence.

2.5.1.2 Potential field data (Gravity / Magnetics)

In this study, gravity data were employed as the most useful potential field tool for ratifying the various contrasts in geological facies observed within the GFA-99 seismic offshore sequences. The data falls into two categories of 2D format:

- Vertical plane surveys along the 2D seismic lines of GFA-99
- Horizontal plane Sandwell satellite data (Appendix 2).

Horizontal plane data are useful for picking out large scale structural trends in the basin morphology – particularly the structures present within the basement. Vertical plane gravity which is usually shot in conjunction with seismic surveys, provides a way of testing interpretations within the seismic

2.5.2 Methodology

All work was performed within GoCad™ software for the full integration of geological and geophysical data types. The GFA-99 dataset was imported into GoCad™ from *.jpg pictures as Voxet sections: this allowed for high quality visualisation combined with simple data manipulation. The 2D lines were manually located by using the shot point data from the survey and key horizons picked from the Voxets as Curves and PointSets (2.6.2). All interpretations were picked in Two-Way-Time (TWT) and 2D Surfaces interpolated through the seismic grid. All interpolations were subsequently depth-converted using Voxet depth-conversion cubes (utilising average velocity) and built into Stratigraphic Grid volumes for volume calculations (2.6.2).

2.6 BUILDING 3D MODELS IN GOCAD™

GoCad™ 3D modelling software is at the forefront of the 3D modelling software market. The main industrial applications are petroleum systems modelling related and the major users of GoCad™ are Total, Chevron-Texaco, Shell and BP as well as a number of other industrial and academic sponsors. The stand-alone version used in this research provides full true 3D functionality. Plug-ins are available that allow more accurate, in-depth analysis of oil systems (Appendix 1). GIS applications such as ArcMap that are used in the geosciences are capable of 3D visualisation, however they are not capable of utilising multiple [Z] values. Therefore they are not true 3D; they are toolboxes for 3D visualisation of 2D surfaces. For example, geological maps may be draped accurately on an eroded, landscape topography in order to visualise the spatial character of the lithological boundaries. GoCad™ easily integrates multiple Z_value points for true 3D volume building.

2.6.1 Software overview

During the course of this research, the functionality, stability and ease of use of GoCad™ has improved substantially. As the package is one of the petroleum industry standards for 3D modelling and visualisation, it is a large package which hosts a multitude of features for data handling and manipulation. As such, most users are unlikely to use all of the object options as each type is specific for certain tasks or data types. An extensive menu system follows the same logic regardless of the object type being manipulated. The recent addition of wizards and workflows has made the operation more accessible to the beginner; however the work in this study uses only the menu system. Large file sizes are generated as output due to their simple Ascii format. File storage methodology is an integral part of learning the software and new storage methods have been developed to both make the best use of the user interface and allow for easy file retrieval (Appendix 3). For maximum efficiency within GoCad™, file editing is best performed in both Microsoft Notepad and Excel.

The methods by which datasets are created for use in GoCad™ have now changed significantly since work began. For example, the DTM used for the Talisker Bay case study area (4.3) was created through a nine step process, but now is available on the internet for immediate integration in the 3D environment. Fig. 2-7 provides an overview of the concepts of dimensions within GoCad™ from a point in [X,Y,Z] space, to a volume. These concepts are important when considering the manipulation and modelling of data types in the 3D environment. The next section acts as a guide to some of the most useful data types in terms of what they are, how they may be used and how they are integrated into 3D visualisation models.

2.6.2 Data types

GoCad™ handles data as a series of 'objects'. Objects that are being manipulated and accessed regularly together are grouped into a GoCad™ 'project'. In total there are 15 object types. These are made of 'atoms' or 'nodes' that are inter-related by physical links or by way of their 'properties'. At its simplest level, the property of an atom is its [X,Y,Z] location; further properties may be added to an atom at that location in space. Each object is divided into 'parts' and the parts in turn, may be divided into object 'regions'. Operations may be performed on any constituent piece of an object or its borders. In this section, the main data types are introduced and explained in terms of their applications in 3D modelling.

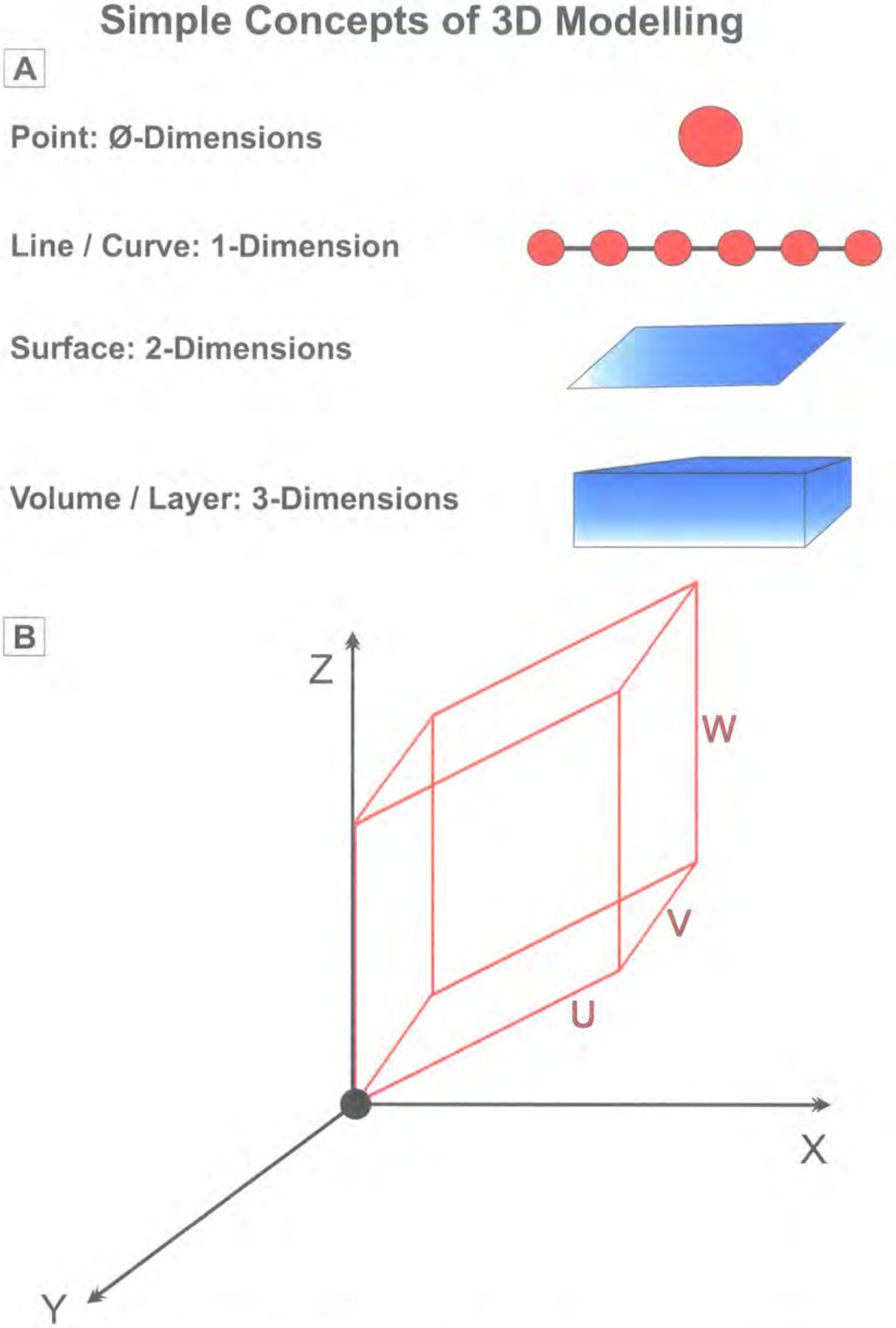


Figure 2-7 Dimensional concepts in 3D modelling. **A:** Several data types may lie in [X,Y,Z] space and may have properties attributed to locational data. Points are dimensionless but may have a property tagged to a location denoted by [X,Y,Z] coordinates; lines are 1D, surfaces 2D and volumes 3D, but all may have complex morphologies in 3D space. Adding a time constraint to any of these object types adds one dimension; **B:** Axial concepts in GoCad™ objects; [U,V,W] represents a system of denoting object axial dimensions in [X,Y,Z] space. Property modelling can make full advantage of this versatile system, as [U,V,W] axes need not be orthogonal, so complex boundaries and property distributions are not constrained by the rigid [X,Y,Z] grid like many geophysical modelling applications.

2.6.2.1 PointSet / VSet

The PointSet or VSet (Vertex Set) represents the most basic data type and is used for location-specific data points. Individual atoms are located in 3D space by their [X,Y,Z] coordinates. PointSets may consist of groups of points that are grouped as a PointSet part (SubVSet). The PointSet is input by clicking on-screen, or by importing a data file. Data files which can be imported cover a huge range of software output types, but the simplest format for the import of a PointSet is a space delimited 3-column Ascii file. An example of a common PointSet data type is a DTM consisting of a grid of atoms with properties of [X,Y,Z]. Each point may be assigned further properties such as density, elastic velocity or porosity. PointSets are extremely versatile as they are the building blocks of the curve and surface object types – they are utilised to both create more complex object types, and are also created from more complex objects in order to simplify complex structures and borders.

A simple example of PointSet manipulation is shown in Fig. 2-8. A PointSet of 25 atoms is imported as a 2D grid, regions are created within the PointSet and each region is assigned new [Z] values. The result is a PointSet which is has its data points distributed through 3D space.

2.6.2.2 Curve / PLine

A Curve is a polygonal line (PLine) which consists of segments that connect a series of atoms. Curves may be open or closed. A closed curve ends at the first atom, whilst an open curve has two extremities per segment. Curve files define the vertices and the links between the vertices. Curves are often created from the borders of an object, and if closed, may be used for surface creation (2.6.2.3). These are functional in different ways to the simpler PointSet: PointSets can be created as a grid of vertices from a surface or from a Voxet (2.6.2.4), Curves cannot be created in this way, but they can provide boundaries to any PointSet and be used for well and channel construction. It is rare to apply properties to Curves – property application functionality is best catered for by applying and transferring properties to and between PointSets, Surfaces, Voxets and SGrids.

An example of the use of a Curve is the creation of a closed Curve around the convex hull of a PointSet (Fig. 2-8D). This may subsequently be densified to create atoms with specific distances between them. The strength of densifying Curves lies in the ability to tightly fit Curve paths to distributions of PointSet vertices, and also to define triangle edge length in Surface creation (2.6.3.4).

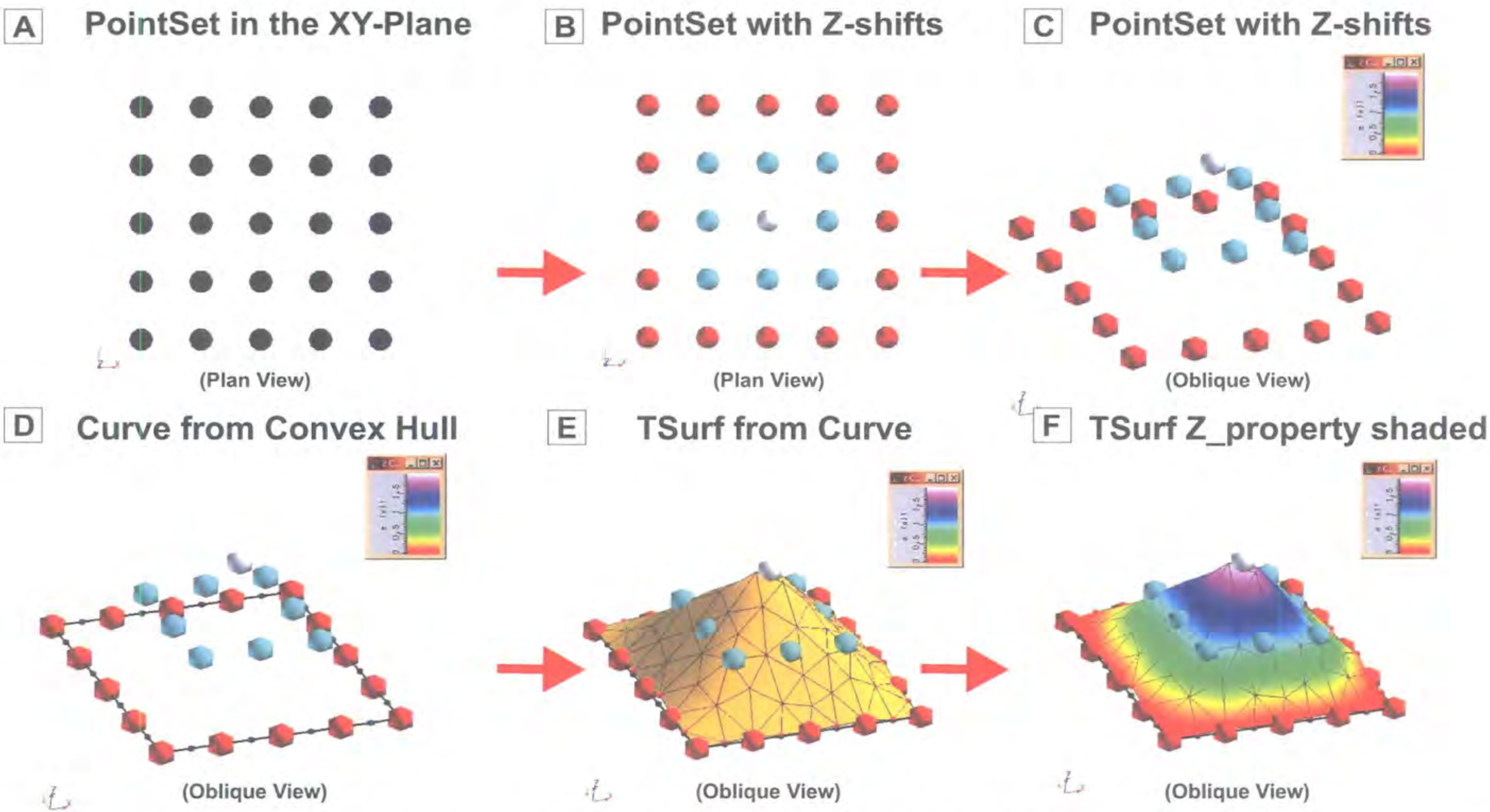


Figure 2-8 A simple visual demonstration of the relationships of three of the most important data types in GoCad™. **A:** A *PointSet (VSet)* displayed in plan view consisting of 25 *nodes* spaced 1unit length apart lying in the XY-plane; **B:** The PointSet is divided into three *Parts* and a Z-shifts applied of +1 unit (blue) and +2 units (grey); **C:** The Z-shifts visualised from an oblique viewing angle; **D:** A *Curve* is created from the convex hull of the PointSet and densified to 0.5 unit length; **E:** A *Surface (TSurf)* is mapped onto the PointSet using the densified Curve to constrain the triangle border length; **F:** The Surface displaying the property of [Z] by property shading the object.

2.6.2.3 Surface / TSurf

Surfaces consist of an arrangement of triangles (TFaces) that lie as 2D planes between atoms, creating a tessellated 2D surface. A border bounds a surface and needs to remain simple for successful modelling. Surfaces are used to create realistic DTMs, and to interpolate between data points in 3D space. They may be open or closed; completely closed surfaces that are bounded by simple borders can be converted into surfaces that bound layers for 3D volume creation.

A simple Surface is created from the PointSet data and densified basal bounding curve as an example of the data format (Fig. 2-8E). As with all GoCad™ object types, the Surface may be painted with discrete properties from a property server or with a simple property such a Z_value (Fig. 2-8F).

2.6.2.4 Voxet / Voxel Set

The Voxet is a 3D data box-volume which sits in the space domain of [X,Y,Z], but has its axes parallel to the non-orthogonal axial system of [U,V,W]. A Voxet contains Voxel (volume elements) or Cells that have cell-centred nodes (Fig. 2-9A). Voxets have the advantage of being able to deal with both volumes and properties associated with those volumes. A Voxet may house the property of 3D seismic through its volume, or may be painted with one or more property sections; for example when importing a picture file into a project.

2.6.2.5 Stratigraphic Grid / SGrid

Stratigraphic Grid is a set of Voxel volume elements that may be formed from and manipulated into more sophisticated shapes than Voxets. The geometry of an SGrid has axes following the [U, V, W] system in [X,Y,Z] space as in the Voxet, however the Voxels in a SGrid delimited by nodes in the corners of the cells instead of cell centres. This object type is ideal for making volume calculations and for modelling facies distributions in an Earth model (Fig. 2-9C&D). For successful facies population within a SGrid, strong 3D control is required for both the facies analysis and distribution internally with the stratigraphy.

2.6.3 GoCad™ Tasks

This section outlines some of the common tasks that may be performed in GoCad™ when working on geological and geophysical datasets. The section introduces data integration and manipulation, but does not delve into the details of menu operation. Due to the growth in information sources available, methodology that was employed in the early stages of this work have since been made obsolete, however some of the procedures undertaken are described, as they provide a good understanding of how the different elements of the software are used and combined in order to create robust geological models.

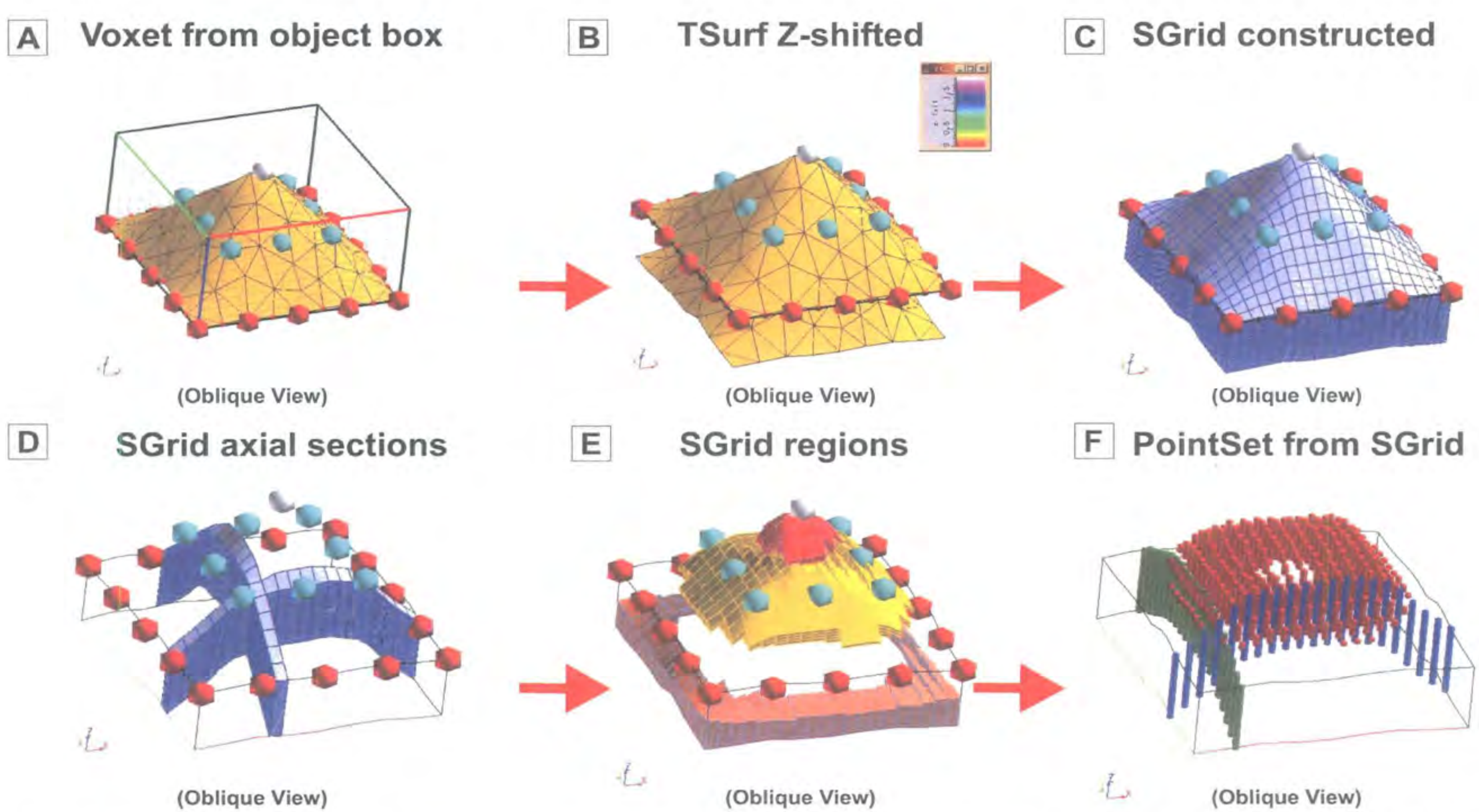


Figure 2-9 The Surface and PointSet data are used to create further important GoCad™ data types. **A:** A *Voxet* is built from the objects box of the PointSet and Surface. The objects box directly incorporates the PointSet data but does not extend beyond the PointSet limits. The Voxet contains 1000 *voxel volume elements* that surround cell-centred nodes. i.e. The Voxet is a 10*10*10 grid; **B:** The Surface is copied and a Z-shift of -1 unit is applied to the copy i.e. {Z = Z - 1 ; }; **C:** A *Stratigraphic Grid (SGrid)* is constructed between the two Surfaces. Note that although the SGrid also consists of Voxels, in this case, the cells are node-bounded which allows for the flexibility of the SGrid volume geometry; **D:** Sections are cut through the SGrid volume; **E:** Selected regions from the SGrid displayed; **F:** PointSets created from SGrid region (red), from U-axis and V-axis sections (green/blue).

2.6.3.1 Import

The import functionality in GoCad™ has grown rapidly during the course of this study. This is predominantly attributed to the following reasons:

- The expansion of the internet
- Growth in user usage of GIS software applications
- Competition with other 3D modelling software packages
- The requirement to integrate multiple datasets of multiple data types

The internet has become a large source for many data types and related software applications. DTMs, satellite data, aerial photographs, data-conversion utilities, 3D viewers and image analysis packages are just a few of the ever increasing number of materials available online. During this study, more than ten separate applications have been utilised for data manipulation and conversion exercises; and more than 7 websites used as data sources (Appendix 1 details an up-to-date list of the most useful software products).

Most of the import functions in GoCad™ are data filters for various types of reservoir modelling software and for integration of seismic data, however several functions import DTM data such as *.dxf formatted elevation data. The failsafe method for importing most [X,Y,Z] datasets other than seismic, is to convert the data to three simple data columns in a spreadsheet and then import the data as an [X,Y,Z] PointSet. Although this may involve the use of several steps and conversion utilities, this format bypasses many of the problems associated with the GoCad™ internal filters. Although file sizes may seem large to import, GoCad™ objects are saved in Ascii format, so even relatively small *.dxf files inflate when saved as GoCad™ objects or as part of a GoCad™ project.

2.6.3.2 Input

Data may be directly input into GoCad™ by the use of on-screen icon-driven digitisation, or by adding points using precise values entered into data windows opened from the menu system. Direct input has the advantage of seeing exactly where the data points lie in the 3D environment; the disadvantage is that input is very slow for large sets of data values. Input is most valuable for digitisation – creating new objects on a pre-existing dataset is a powerful tool as it provides a way of moving into the data: For example, interpreting fault Curves on an aerial photograph or tight-grid DTM creates a Curve-stick dataset. Between these Curve-sticks, we may be able to interpret fault Surfaces and the relationships between them. Similarly, within a seismic Voxet, picking marker horizons by digitising with the 'New PointSet Digitiser' may allow the 1D picks to be developed into 3D volume models after Surface interpolation.

2.6.3.3 Creating a DTM

The Original Talisker Bay DTM:

The first DTM which was built for the Talisker Bay area of the Minginish district was built before DTM data were available for download off the internet data sources highlighted above. The data available for the construction of the DTM was Ordnance Survey 1:50,000 Landranger Map 32. This was used in preference to the 1:25,000 Pathfinder Series maps, so that the data format could be consistently metric in the [X,Y,Z] dimensions. The procedure for the construction of the DTM required scanned images of hand-tracings of the Landranger map. These were accurately imported and locating tracing in GoCad™ as Voxet sections. A PointSet was built from the Voxet properties, followed by individual contour Curves and finally as Surface interpolation.

This produced a gridded DTM with an ultimate Surface triangle border segment length of 50m resolution. Interpolation was constrained by the contour spacing in the [X,Y], and contour interval in the [Z] direction. Since 2002, the most standard procedure for the import of a DTM into GoCad™ has been simplified: The DTM is downloaded *.dxf format from Digimap. The file is pushed through the application *Dxf2xyz* and subsequently imported into GoCad™ as an [X,Y,Z] located and geo-referenced PointSet file.

The imported data is a PointSet DTM containing a data resolution of 50m in the XY plane, and 1m in the [Z] axis. A 2D Surface DTM must be created over and interpolated from the PointSet, if interpretations and digitisation are not to be limited by the spacing of the PointSet. A general procedure for the construction of a DTM is covered in Figs. 2-10 to 2-12.

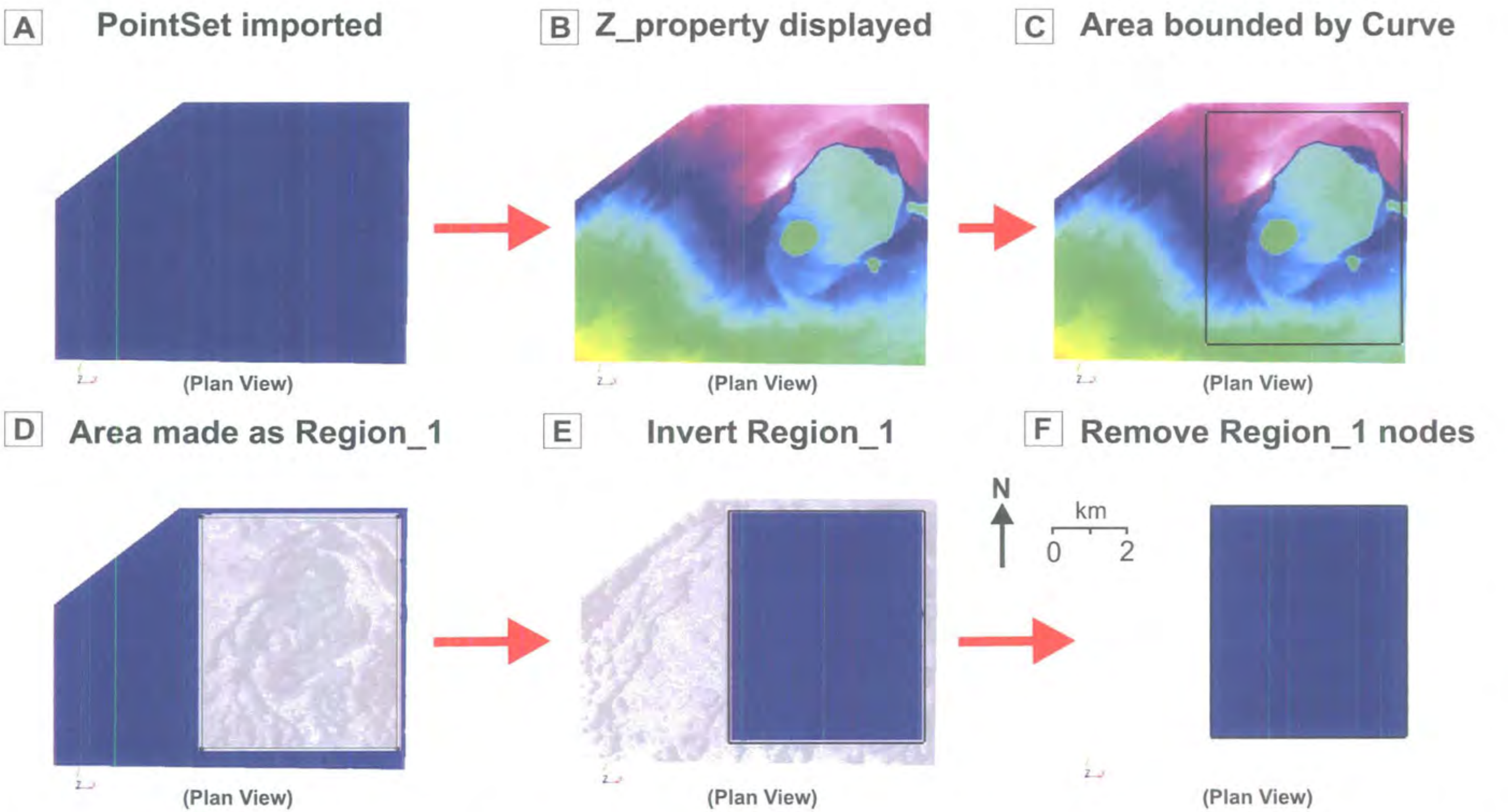


Figure 2-10 Stages of creating a realistic DTM 2D Surface. **A:** PointSet is imported as a raw [X,Y,Z] file in Ascii format; **B:** Z_property is displayed in order to see the area in which a DTM surface is required; **C:** A Curve is created surrounding the area of interest for Region creation; **D:** After deselecting the Z_property paint, Region_1 is built over the area of the Curve in order to include all PointSet points within the area; **E:** To crop this Region_1 area, the region is inverted, and then the nodes in the new Region_1 are removed; **F:** The area of interest now remains as a PointSet.

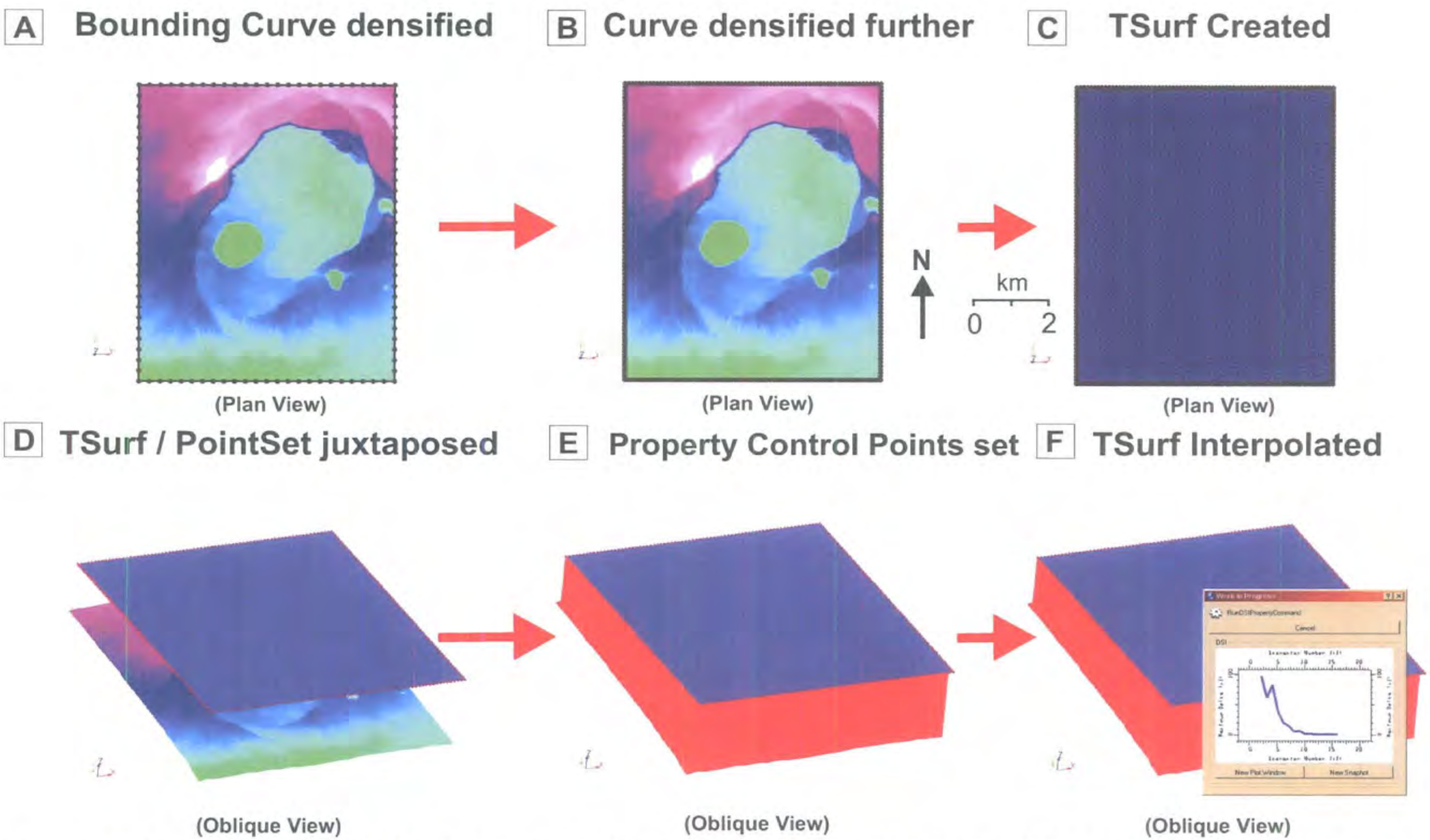


Figure 2-11 Stages of creating a realistic DTM 2D Surface (continued). **A:** The bounding Curve is densified to 250m; **B:** For a higher resolution DTM, the densification is increased (iterative process) to 100m; **C:** Surface created from the densified Closed Curve. Each triangle border is 100m in length as the Surface is flat; **D:** Properties copied from Z to ZZ. The ZZ_property is therefore created; **E:** *Property Control Points* are set as *Constraints* for the Surface which is to be mapped onto the PointSet (AtomSet); **F:** ZZ_property is initialised and interpolated for the Surface.

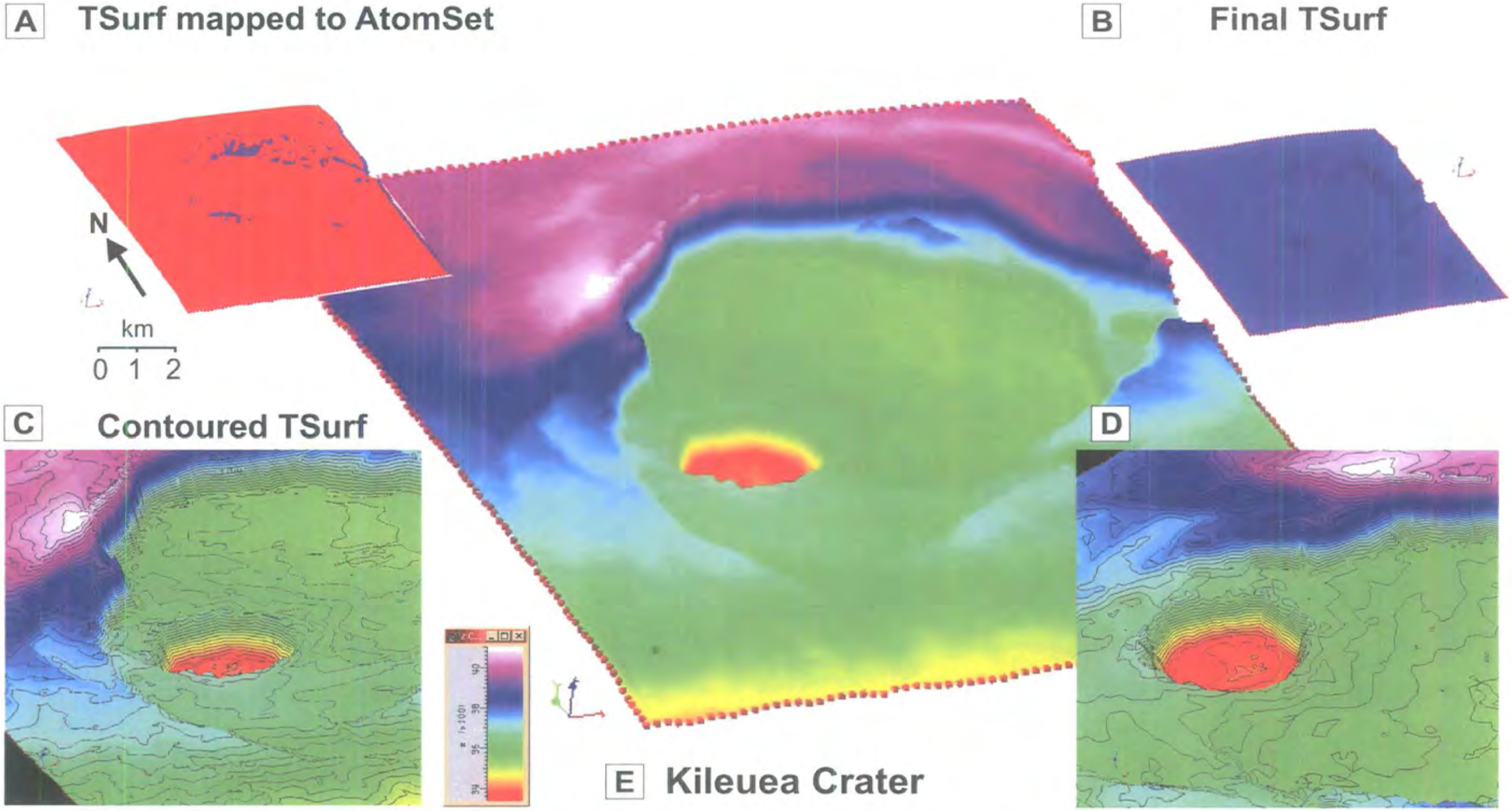


Figure 2-12 Stages of creating a realistic DTM 2D Surface (continued). **A:** Surface is mapped to the AtomSet points of the PointSet. Property Control Points are shown on the top of the DTM Surface; **B:** Constraints removed from the Surface. Note the lack of clarity in morphology; **C:** Z_property painted onto DTM and contours added at 20m and 100m increments. View looks towards the NE; **D:** Looking NW over contoured DTM; **E:** The full area selected for the Surface DTM - Kileuea Crater, Hawaii.

2.6.3.4 Building Surfaces

Surfaces are most commonly constructed from PointSets, Curves, from Voxets and combinations of the above. The method which provides the most satisfactory and accurate 2D Surface between data points is by using the *interpolation* method across a dataset. Several triangulation and interpolation methods exist as wizards within the software interface, however the finest interpolation is worked via the main command menu system and requires the steps covered Figs. 2-10 to 2-12.

The Surface produced is the most accurate interpolation of the data points into a 2D Surface. Note that the interpolation of a 1D or 2D dataset suffers heavily from data scarcity, and artefacts develop in the resulting Surfaces that may not be geologically reasonable, given the data area. Problems associated with upscaling, data interpolation and artefact development during modelling are discussed in Chapter 6.

2.6.3.5 Texture mapping a Surface

Texture mapping provides the capability of painting complex objects with the properties of another object via vertical projection or [U,V,W] texture mapping. The advantage of this technique is that data may be superimposed onto, for example, one plane which combine valuable information. The process of texture mapping is described in Fig. 2-13 which displays an example of texture mapping a topographic map onto a DTM.

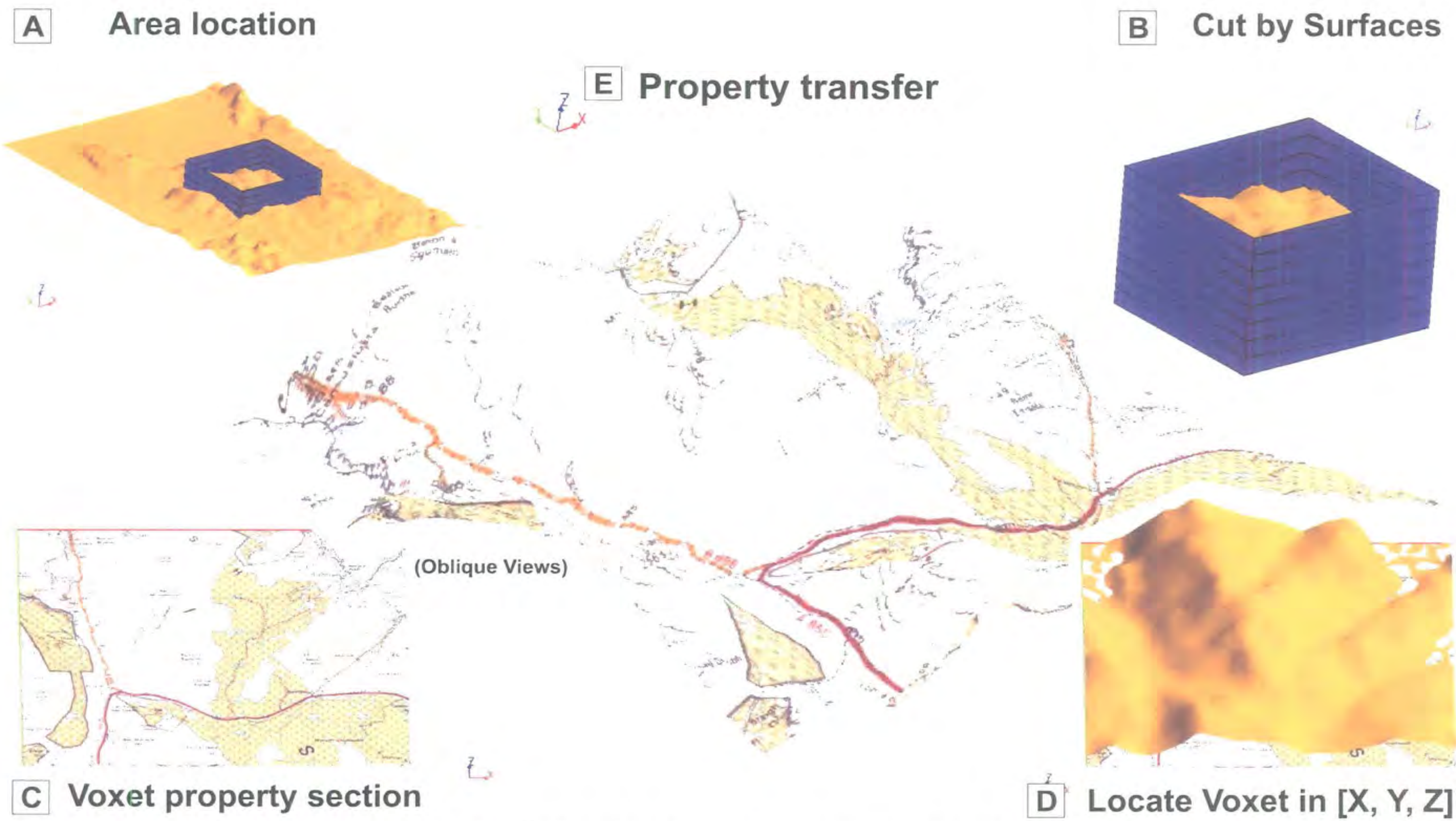


Figure 2-13 The creation of a property texture mapped Surface. **A:** The area on which the property texture is to be applied is selected from the DTM. A cutting Surface is built as a *Tube* through the topography; **B:** The DTM is reduced to the cut area; **C:** A Voxet property W-axis section is imported; **D:** The Voxet section is located precisely beneath the topographic Surface; **E:** The property section of the Voxet is transferred by vertical projection onto the DTM.

2.7 SUMMARY

GoCad™ provides us with the extensive tool-box for making geological and geophysical interpretations from multiple data types, integrated in one, 3D environment. GoCad™ is a modern way of integrating and analysing and data over infinite scales. Controlling and manipulating geoscience data in a Universe hosting the dimensions [X,Y,Z,$property_1$,$property_2$...,...] means that we can develop Earth models which incorporate more data types than ever before, and upscale and downscale as necessary in order to provide the most accurate description of the sub-surface possible. By modelling in true 3D, the aspects of volumes are fully considered in the models created therefore geological 'space problems' are lost and 2D cross sections may be ratified. There are many problems associated with 3D modelling however for example: limited data control can cause severe interpolation artefact development creating over-simplified models; model over-complexity equally, may severely hamper the user interface and make both manipulation and model analysis extremely difficult.

In Chapter 3, image analysis is applied to micro-scale studies and in Chapters 4 and 5, the GoCad™ tool-box is used and applied to the modelling problems of flood volcanics. In Chapter 4, field data are integrated into 3D case studies on a meso-scale in the Talisker Bay area of Skye; in Chapter 5, the understanding of the development of flood basalt sequences onshore is applied to the offshore seismic data from the Faeroe-Shetland Basin.

Chapter 3

3. MICRO-SCALE ARCHITECTURE – A CASE STUDY FROM TALISKER BAY

Global studies of the micro-scale architecture of flood basalt provinces are represented onshore by geological field case studies on modern lava fields such as those on Hawaii (e.g. Anderson *et al.* 1999), the ancient successions of the Columbia River, Etendeka of Namibia (e.g. Hooper 1997; Jerram 2002) and the Deccan (e.g. Duraiswami *et al.* 2001), and in global studies of basaltic rocks from multiple sampling locations (e.g. Caroff *et al.* 2000). The huge cliff sections of Greenland have also enhanced our understanding of the early evolution and internal structure of a host of volcanic succession types present both onshore and offshore in the North Atlantic Igneous Province (NAIP) (e.g. Pedersen *et al.* 1998; Heister *et al.* 2001).

Although the vast majority of studies concentrate on geological aspects of the volcanic systems, some field studies are combined with geophysical investigations in order to constrain rock property variability within volcanological lithofacies (e.g. Riisager & Abrahamsen 1999; Cañón-Tapia & Coe 2002). Offshore studies in areas such as the Vøring Margin of Norway contain supplementary micro-scale data by core sampling and the acquisition of wireline log suites (e.g. Planke & Eldholm 1994; Planke & Cambray 1998; Bücker *et al.* 1999). These provide valuable rock property data for studies of the geophysical structure of the volcanic successions.

In this section, geological examples of the igneous succession internal architecture are presented, with a focus on the Talisker Bay area of SW Skye [NG 131 830] (Fig. 3-1). The basaltic cliff sections in Talisker Bay reveal a superb variety of metre-scale lava field structural relationships and facies types for use in detailed studies. In much of the landscape however, these details are masked in areas of no exposure as the basaltic sequence is easily weathered, forming featureless topography (Fig. 3-2).

Firstly, the internal facies architectural styles are discussed and classified according to the '*intrafacies scheme*' which has been developed in this study to characterise the heterogeneities present within an igneous rock unit. Field outcrops from the Skye Lava Field are cited as examples of these intrafacies. Subsequently, intrafacies distributions are presented at a number of locations. These outcrops are interpreted in terms of their volcanological evolution and implications for distributions of heterogeneities. Finally a volcanological setting of the Talisker Bay area is presented, based on the micro-scale data, and a model for the evolution of the lava pile is proposed.

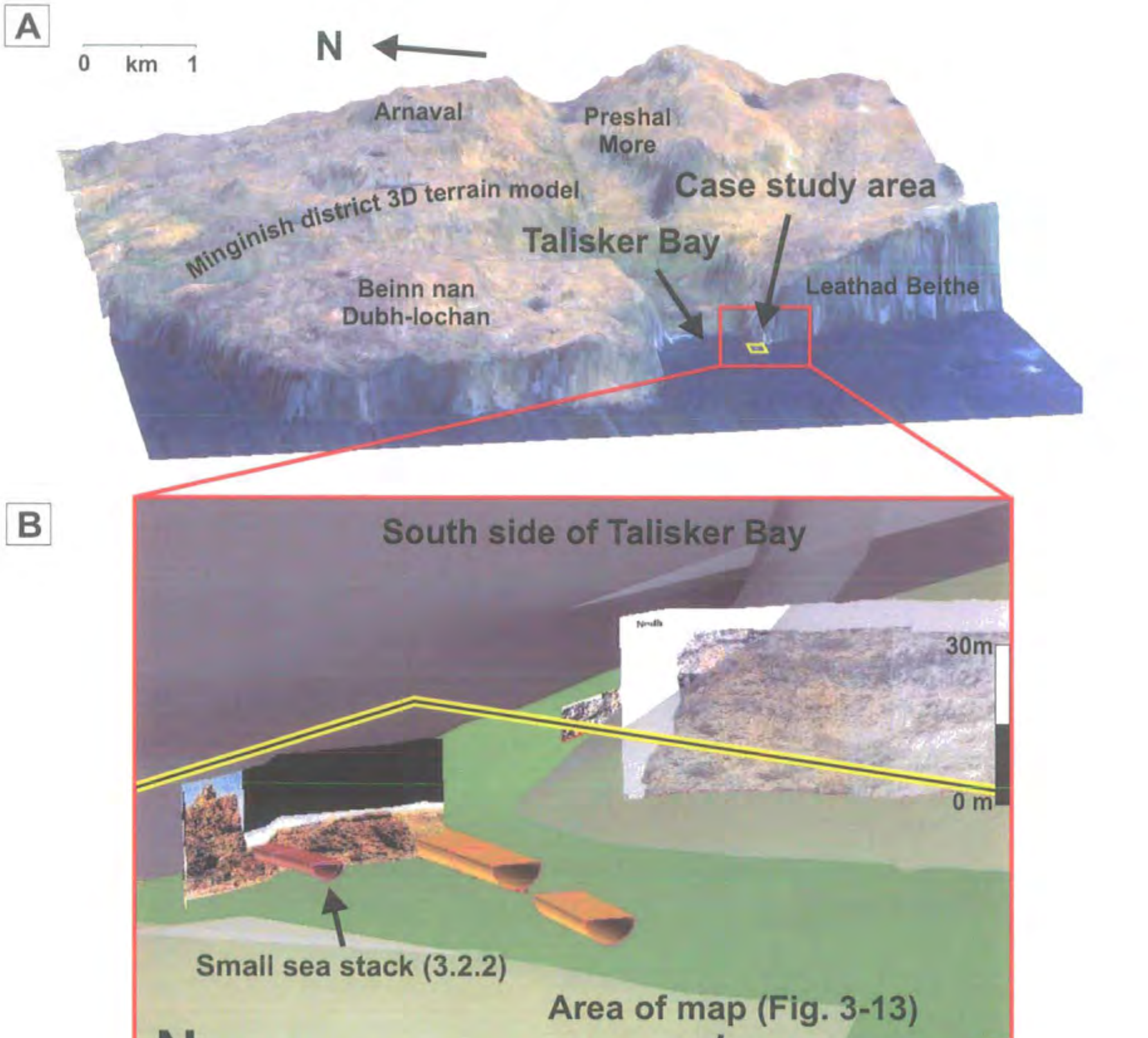


Figure 3-1 **A:** The Talisker Bay area [NG 1311 8299] micro-scale case study, located on the north Minginish district Digital Terrain Model (DTM); **B:** Zoom-in to the south side of Talisker Bay showing 3D data incorporation on the foreshore area; **C:** Location of geological map (Fig. 3-13).

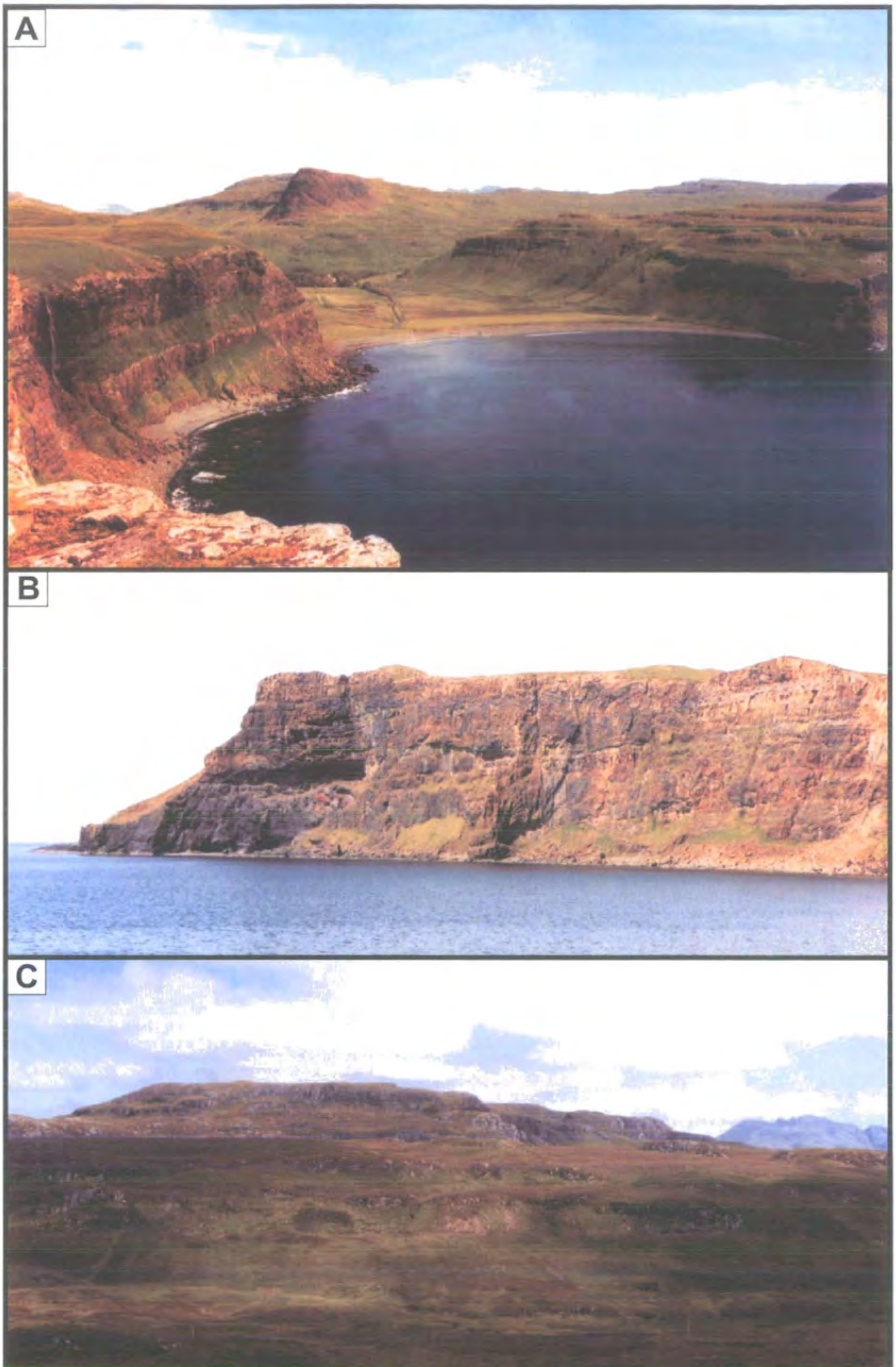


Figure 3-2 Levels of field exposure in the Talisker Bay area of the Minginish district. **A:** Looking SE into Talisker Bay from the top of the northern cliffs; **B:** Looking north at the south-facing cliffs of Talisker Bay; **C:** Looking east towards Arnaval at the lower level of exposure seen inland.

3.1 THE KEY GEOLOGICAL INTRAFACIES OF THE TALISKER BAY LAVA SEQUENCE

The key geological intrafacies are now discussed on the centimetre to metre-scale with examples taken from the good quality outcrop sections in the Talisker Bay cliff sections.

3.1.1 Classification of flow heterogeneities: The Intrafacies Scheme

The facies observed in flood basalts have been considered on a lava field scale by Jerram (2002) and on a seismic scale by Planke *et al.* (2000). Architecture and sequence relationships at these scales include features such as shield volcanoes, volcanic disconformities over tens of kilometres, seaward dipping reflectors and lava deltas. It is crucial to include architectural features and facies on these scales in 3D models of volcanic successions. It is of equal importance to understand what these kilometre-scale features comprise of, on the scale of the individual lava flow; both architecturally and in terms of geophysical rock properties. Below, we discuss the building blocks of the larger architectural features and provide a classification of the geological heterogeneity; the 'intrafacies scheme' which can be used to estimate geophysical rock property distributions in lava field successions.

Shorthand descriptive classification schemes in sedimentary sequences are in common use and have been developed from studies of fluvial systems (e.g. Allen 1983; Miall 1985 & 1988). These schemes provide a method by which a field or well-site geologist (who may be studying core samples/drill cuttings) can interpret sedimentary facies by studying how descriptive architectural elements are associated in a series of rock units. In the classification for fluvial systems for example, centimetre-scale lithofacies are described and allocated a 'lithofacies code'.

Subsequently, the associations of the lithofacies in the geological record are used to interprete the architectural elements and facies evolution of the succession (Fig. 3-3).

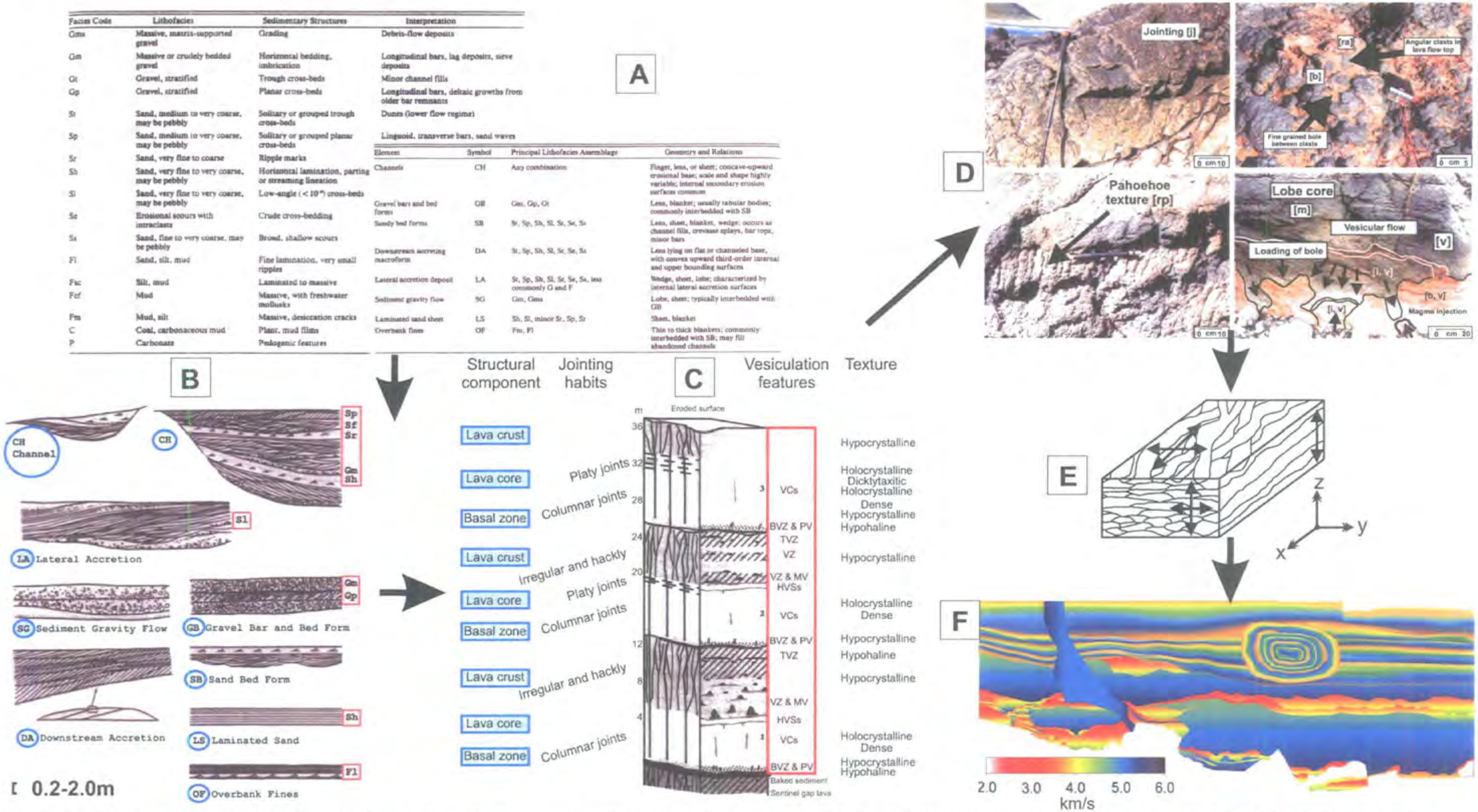
In igneous sequences large textural variations, and subsequently rock property variations exist within the individual facies units themselves, caused by, for example the organisation of distributions of vesicles within lava flow units. We can use the term 'intrafacies' to describe these variations within individual igneous structures, both intrusive and extrusive. Classification schemes for igneous architectural facies are uncommon, although Jerram (2002) and Planke *et al.* (1999; 2000) have provided systems of architectural sub-divisions on the scales of kilometres to tens of kilometres, respectively. Self *et al.* (1997) have discussed several internal features of lava flows such as mega-vesicles (MV); vesicle sheets (VS) and pipe vesicles (PV). The associations of many of the observations of Self *et al.* (1997) have been used to invoke lava sequence development models, but are limited in their ability to predict heterogeneities in the geophysical properties of rocks.

The intrafacies scheme is useful as it provides a systematic shorthand notation for describing features in lava sequences. The work incorporates some of the concepts of Self *et al.* (1997), but aims to build a system which can provide a rapid interpretation tool for the field and well-site geologist as an aid to interpretation of igneous facies, which can be based solely on field or borehole observations. The system aspires to provide a distinct classification for rock property analysis in order that petrophysicists or geophysicists may improve the characterisation of igneous sequences in both seismic and potential field data (gravity and magnetic studies). Small-scale components of the classification characterises the most basic level of lava sequence heterogeneity, typically at the centimetre to metre-scale. Subsequently, the associations of these components are discussed as the intrafacies of igneous successions, along with their geophysical implications for sub-volcanic investigation.

3.1.2 Intrafacies Components of Flood Basalt Architecture

A series of intrafacies components have been recognised from observations made in the case study area of Talisker Bay. The components are the most fundamental level of field observation and form the constituent elements of intrafacies and the larger scale architecture of flood basalts (Table 3-1). The emphasis lies in description of architectural styles and textures at this smallest scale of investigation, noting features such as vesiculation, fracturing, presence of palaeosol beds (boles) and an account of the shape of the features and how they are juxtaposed. Interpretation of the intrafacies or geophysical rock properties is not essential at this stage in the characterisation. An architectural intrafacies component is denoted by a letter within square brackets. For example, [v] denotes vesiculation and [j] indicates the descriptive component of regular jointing. At any particular part of an outcrop, several components will be present. The combination and association of the components are subsequently used to help constrain the metre-scale intrafacies interpretation.

Each of the intrafacies components displayed in Table 3-1 may be observed without the use of specialist equipment at the outcrop or field specimen scale. Our classification aims to maintain consistency in scale, such that these intrafacies components may be integrated to form larger, lava flow scale intrafacies associations as discussed below.



Facies Code	Lithofacies	Sedimentary Structures	Interpretation
Gms	Massive, matrix-supported gravel	Grading	Debris-flow deposits
Gm	Massive or crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bars, lag deposits, sieve deposits
Gt	Gravel, stratified	Trough cross-beds	Minor channel fills
Gp	Gravel, stratified	Planar cross-beds	Longitudinal bars, deltaic growths from older bar remnants
St	Sand, medium to very coarse, may be pebbly	Solitary or grouped trough cross-beds	Dunes (lower flow regime)
Sp	Sand, medium to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Linguoid, transverse bars, sand waves
Sr	Sand, very fine to coarse	Ripple marks	
Sh	Sand, very fine to very coarse, may be pebbly	Horizontal lamination, parting or streaming lineation	
Sl	Sand, very fine to very coarse, may be pebbly	Low-angle (< 10°) cross-beds	
Se	Erosional scours with intraclasts	Crude cross-bedding	
Ss	Sand, fine to very coarse, may be pebbly	Broad, shallow scours	
Fl	Sand, silt, mud	Fine lamination, very small ripples	
Fsc	Silt, mud	Laminated to massive	
Fcf	Mud	Massive, with freshwater mollusks	
Fm	Mud, silt	Massive, desiccation cracks	
C	Coal, carbonaceous mud	Plant, mud films	
P	Carbonate	Pedogenic features	

Element	Symbol	Principal Lithofacies Assemblage	Geometry and Relations
Channels	CH	Any combination	Finger, lens, or sheet; concave-upward erosional base; scale and shape highly variable; internal secondary erosion surfaces common
Gravel bars and bed forms	GB	Gm, Gp, Gt	Lens, blanket; usually tabular bodies; commonly interbedded with SB
Sandy bed forms	SB	St, Sp, Sh, Sl, Sr, Se, Ss	Lens, sheet, blanket, wedge; occurs as channel fills, crevasse splays, bar tops, minor bars
Downstream accreting macroform	DA	St, Sp, Sh, Sl, Sr, Se, Ss	Lens lying on flat or channeled base, with convex upward third-order internal and upper bounding surfaces
Lateral accretion deposit	LA	St, Sp, Sh, Sl, Sr, Se, Ss, less commonly G and F	Wedge, sheet, lobe; characterized by internal lateral accretion surfaces
Sediment gravity flow	SG	Gm, Gms	Lobe, sheet; typically interbedded with GB
Laminated sand sheet	LS	Sh, Sl, minor St, Sp, Sr	Sheet, blanket
Overbank fines	OF	Fm, Fl	Thin to thick blankets; commonly interbedded with SB; may fill abandoned channels

Figure 3-3 The concept of the Intrafacies Scheme. **A:** Lithofacies and architectural elements tables of shorthand notation of descriptive elements (Miall 1985; 1988); **B:** These are pieced together into sedimentary facies interpretations; **C:** Self *et al.* (1997) sub-divide lava flow units on internal facies analysis; **D:** Intrafacies scheme classifies igneous descriptive components on the cm-scale; **E:** Geological intrafacies heterogeneity interpretations constructed from component associations; **F:** Geophysical interpretation of igneous facies, given the intrafacies present in outcrop.

3.1.3 The Intrafacies of Flood Basalt Architecture

Intrafacies may be interpreted, to a large extent, on the basis of the natural association of the architectural intrafacies components outlined above (Table 3-2). These are similar in scale to the features described as architectural elements by Miall (1985), and are of the same scale as the subdivision of lava flows by Self *et al.* (1997). Although several of the intrafacies in Table 3-2 contain similar intrafacies components, they are usually distinguished by a combination of the components within the geometries observed. In the following section, field examples of flood basalt intrafacies are cited from Talisker Bay.

3.1.4 Intrafacies Examples in the sequence of Talisker Bay

In the flood basalt sequence of Talisker Bay, we can observe most of the intrafacies listed in Table 3-2. Heterogeneities in the distribution of rock properties through such igneous sequences may heavily affect the performance of geophysical remote sensing techniques due to the variability in their rock properties over centimetre to metre-scales (Planke & Cambray 1998). The key geological intrafacies that affect the ability of geophysical methods to image through igneous successions are highlighted in Table 3-2, but particular facies to note are:

I. Boles –high attenuation (Qs & Qp) in seismic surveying
II. Flow tops / bases – low velocity, low density zones
III. Flow cores/massive sheets – high velocity, high density zones
IV. Sills – thick high velocity zones with high bulk density
V. Dykes – vertical high velocity, high density sheets

It is important to recognise how the varied geological intrafacies of the volcanic sequence may affect remote sensing techniques, as they are volcanic sequence geophysical heterogeneities. These invariably cause seismic waveform scattering and degeneration due to factors such as surface geometry (rugosity) and acoustic impedance contrasts through the lavas. These heterogeneities reduce the quality and resolution seismic and also affect gravity modelling. The major intrafacies features of the Talisker Bay rocks are now discussed, together with their geophysical implications. A field outcrop intrafacies summary (Fig. 3-4) is accompanied by some more detailed field outcrop examples. The locations of these are indicated on a location map (Fig. 3-5).

Table 3-1 The essential intrafacies components of flood basalt architecture. Scheme based on field data from the Skye Lava Field.

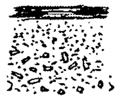
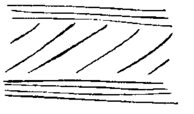
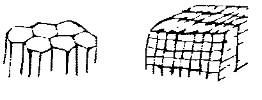
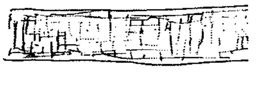
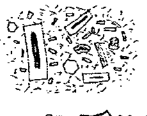
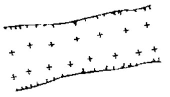
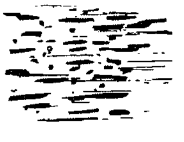
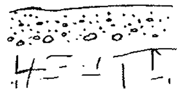
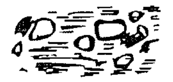
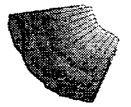
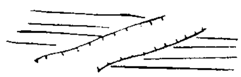
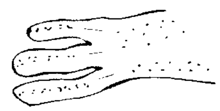
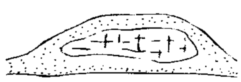
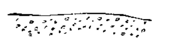
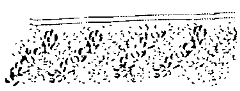
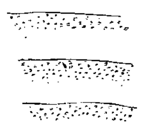
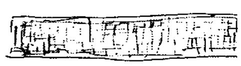
Notation	Component	Diagnostics	Schematic Structure	Interpretations
[a]	Aphanitic margin	Very fine crystal size at margins of structure, no phenocrysts, glassy		Chilled margin
[b]	Bole material	Red-grey fine loamy matrix, usually slickensided and often contains rubble		Fossil soil material, sedimentary horizon
[c]	Concentric banding	Concentrically layered, often striated, ovate, signs of thermal erosion		Lava feeder tube, lava channel, flow foliation banding, pillow structure, lobe breakout
[f]	Foreset bedding	Steeply dipping foresets, hyaline angular clasts		Hyaloclastite breccia, extrusion of lava into water body, lava delta
[i]	Injection structure	Injection of lava tongues, alteration, veining		Invasion of lava into sediment / lava, vein invasion from a zone of high heat flux
[l]	Loading structure	Grey / reddened horizons below lava, 'flame' structures, alteration, folding		Loading of lava onto sediment
[j]	Jointed (regularly)	Regular joint pattern present		Jointing pattern is heavily dependent on the structures cooling history
[m]	Massive	Fractured, low vesiculation density, holocrystalline (90-100% crystals) often low SiO_2 lava		Degassed lava lobe core, lava conduit, tabular flow, degassed horizons in inflated lavas
[p]	Porphyritic texture	Phaneritic phenocrysts reside amongst groundmass		Slower cooling of igneous body, magma mixing
[ra]	Rubbly surface	Rubble, striated angular lava clasts, rounded cobble like clasts		A'a type lava flow top surface, intra-lava sedimentary horizon, bole
[rp]	Ropy surface	Rope-like texture		Pahoehoe type lava flow top, cast of lava top in sedimentary horizon
[si]	Inclined sheet	Intrusive sheet, concordant or discordant, ≥2 chilled zones		Mainly discordant: dyke; mainly concordant: sill. Simple, composite, sheeted, layered types
[t]	Tuffaceous material	Volcaniclastic material, fine grained well sorted matrix to poorly sorted mixed clast size, finely laminated, reddened, often fissile, crushed clasts, fiamme, high temperature clasts e.g. sanidine, CPX		Explosive volcanic product, clasts may be lengthened parallel to bedding due to compaction
[v]	Vesiculated	Frothy vesiculated lava, often amygdaloidal, <1mm to >100mm		Frothy lava flow top surface, product of inflation process (degassing exercise), lava flow base
[xl]	Medium to coarsely crystalline	Groundmass is 1-5mm crystal size		Towards centre of body, zone has experienced slow cooling history

Table 3-2 Geological intrafacies considered to be of importance to geophysical modelling studies of a 'basaltic' lava field.

Geological Intrafacies	Intrafacies Components Present	Schematic Diagram of Intrafacies	Description	Size of Feature	Vp (kms^{-1})	RHOB (gcm^{-3})
Bole (Weathered lava top surface)	[b, i, l, m, ra, t, v]		Weathered soil surface	1cm-5m thick	2.2-4.3	2.01-2.88
Conduit /Lava Feeder Tube	[c, m, i, j, v, xl]		Magma feeder conduit. Open and covered 'pipe' types. Striated margins, often picritic lithology	2m-<10m diameter	3.3-5.3	1.86-2.92
Dyke / Compound Dyking	[a, i, j, p, si]		Mainly discordant inclined sheets. 2+ chilled margins. Form sheeted complexes in proximity to central volcanic complexes	10cm-50m wide	4.5-5.8	2.79-3.02
Flow Base	[a, i, l, ra, v]		Vesiculated often piped, may be rubbly, show magma injection structures & evidence of sediment loading & induration	<2m thick	2.7-4.4	2.56-2.72
Flow Breakout	[a, c, i, l, m, v]		Tongue / finger like projections from lava flow lobe	30cm-0m wide, 20cm-1m thick	3.3-5.3	1.86-2.92
Flow Core	[i, j, m, p, xl]		Massive region at flow lobe core, fractured, may be injected, often medium grained	1m-10m wide, 1m-5m thick	4.5-5.8	2.72-2.84
Flow Top (unweathered)	[a, ra, rp, v]		Frothy and vesiculated, may be rubbly	<10m thick	2.7-4.4	2.56-2.72
Hyaloclastite Breccia	[a, b, f, ra]		Foreset-bedded, contains sharp angular glass fragments and small volcanic clasts, may contain organic matter	10cm->10m	2.6-4.7	2.03-2.87
Inflated Sheet Flow	[a, i, j, l, m, v]		Sheet flows that show alternating horizons of high and low vesiculation densities	10cm-30cm thick	3.3-5.3	1.86-2.92
Massive Sheet	[a, j, m, p, xl]		Fractured, structure less with low vesiculation densities	>10m wide, 1m-5m thick	4.5-5.8	2.79-3.02
Pillow Lava	[a, c, i, m, v]		Bulbous pillow-like vesiculated structures, concentrically banded	<1m diameter	3.3-5.3	1.86-2.92
Sill	[a, i, j, p, si, xl]		Mainly concordant sheet, 2+ chilled margins	1m-100m thick	4.5-5.8	2.79-3.02
Volcaniclastic	[b, i, l, p, t]		Broken volcanic debris, fine ash, flattened clasts, organic debris	1cm-3m thick	2.2-4.3	2.01-2.88

The geological intrafacies which have the most important implications for geophysics are underlined and in italics. Examples of the relationship between geological intrafacies and geophysical properties are also presented: columns 6 and 7 show the range of compressional wave velocity (Vp) and density (RHOB) predicted for each of the geological intrafacies. Note that sedimentary horizons (denoted as boles) and vesiculated zones will dramatically reduce the overall Vp and RHOB through a volcanic succession. Sample rock property data collated from the SIMBA rock property database and from Planke (1994) & Planke *et al.* (1999 & 2000).

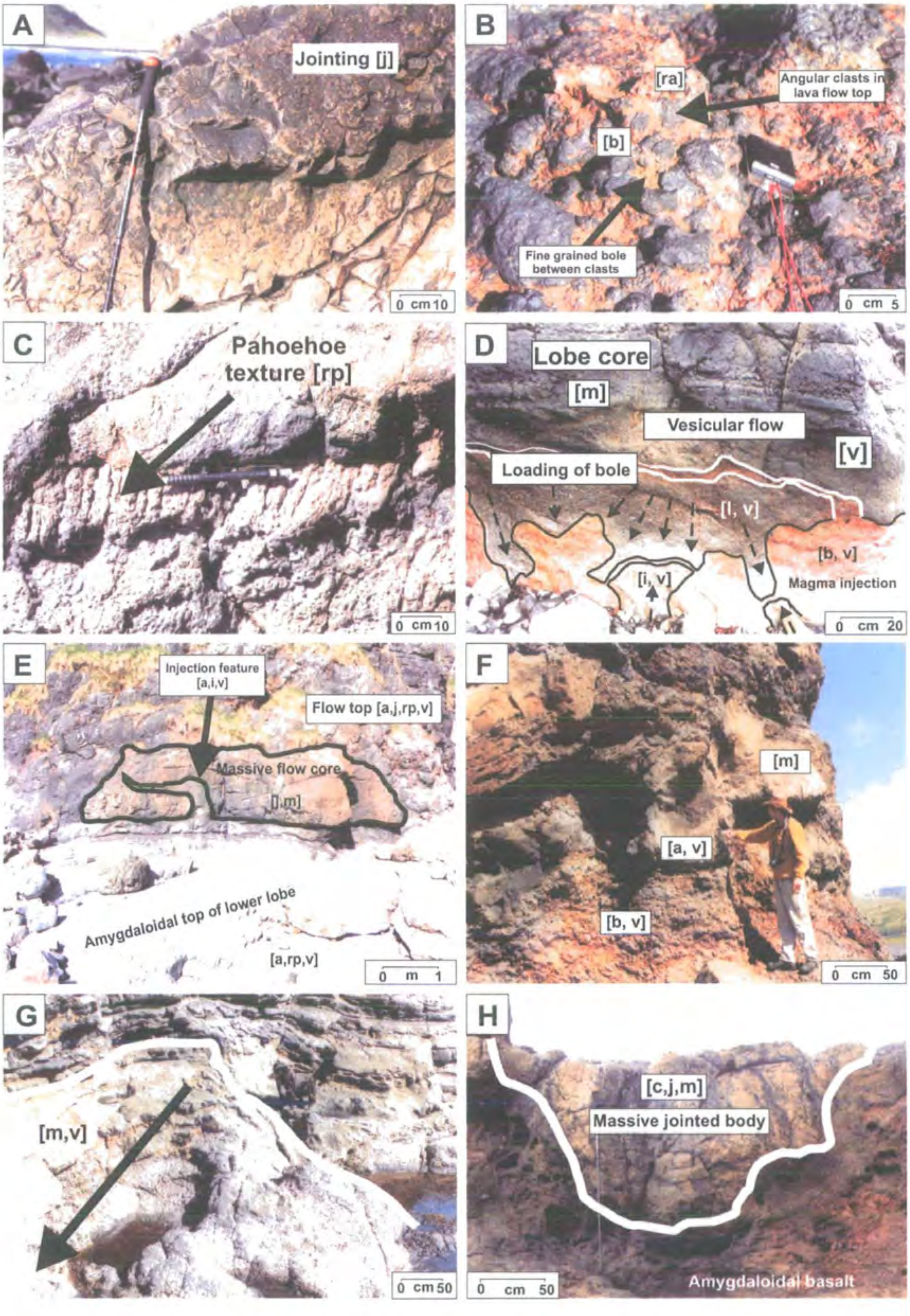


Figure 3-4 Field examples of intrafacies from the British Tertiary Igneous Province (BTIP). Intrafacies components are described and denoted in square brackets. **A:** Composite dyke; **B:** Rubbly weathered lava top; **C:** Pahoehoe texture developed on top of an olivine-phyric basalt; **D:** Magma injection structures through a bole; **E:** Massive core and vesiculated top of picritic lava lobe; **F:** Thick sedimentary horizon or bole; **G:** Lava lobe breakout; **H:** Massive picritic feeder tube in pahoehoe lava sequence.

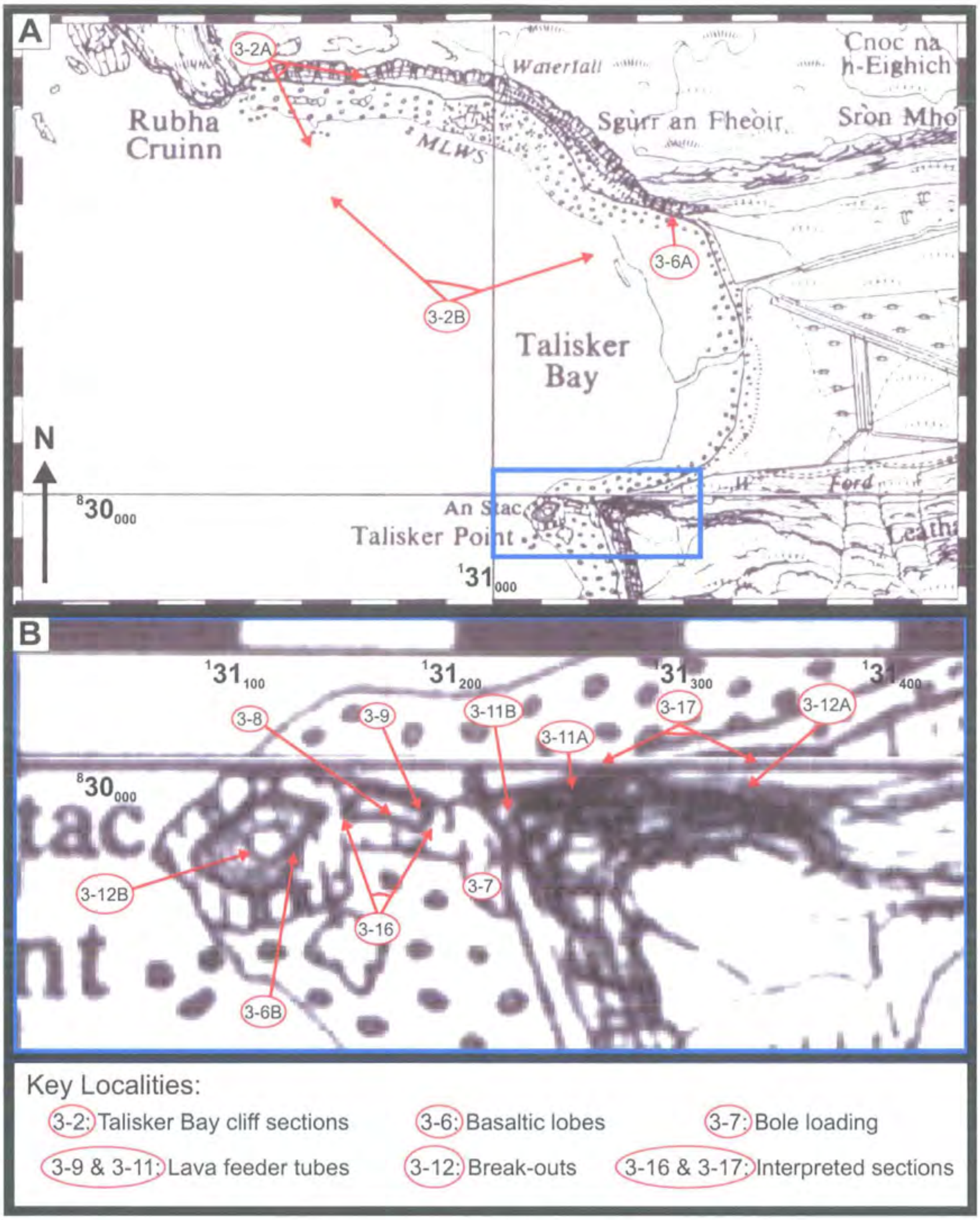


Figure 3-5 Localities of importance in Talisker Bay [NG 131 830]. Numbers correspond to those of figures associated with this chapter. **A:** The Talisker Bay grid squares showing the complete bay area. Map B lies within the blue box marked on the south side of the bay; **B:** Individual localities located accurately on the south side of Talisker Bay.

3.1.4.1 Dykes and Sills

Although Talisker Bay is 8-9km SW of the axis of the most intense dyking seen in the Skye swarm of the British Tertiary Igneous Province (BTIP), several dykes are exposed in the sea cliffs and the surrounding hillsides (Fig. 3-4A). The dykes assume the common BTIP strike of NW-SE and cut through the entire igneous succession. A compound dyke cuts the north-facing cliff section containing evidence of multiple injection episodes. The walls are columnar jointed and aphanitic and internally the massive core is texturally zoned. The geophysical rock properties of the dyke are interpreted to be similar to that of a massive degassed sheet flow or sill; however the steeply dipping orientation of dykes severely affects acquisition of seismic data.

Sills form an important geological facies of flood basalt igneous successions such as the Trotternish sill complex of NE Skye (Gibson 1990) and the huge Huab sill complex of the Etendeka flood basalts of Namibia (Jerram 2002) however these are introduced in Chapters 4 and 5 due to the large scale of these particular features.

3.1.4.2 Rubbly Lava Flow Tops

Rubbly lava flow tops are uncommon in the lower parts of the succession in Talisker Bay; however, a very angular, poorly sorted a'a flow top sits on the toe of a massive sheet flow close to sea-level. In the rubbly top, is a very fine-grained, slickensided, clay-rich matrix (Fig. 3-4B). The presence of the angular a'a lava flow top suggests a rapid eruption rate in this particular flow of $>20m^3s^{-1}$ (Walker 1993). Geophysically, such flow tops are noted as attenuated low velocity zones on wireline logs due to the clast-supported nature of the intrafacies and, often as in this case, the presence of low density bole material (Planke & Cambray 1998). This rugose, clastridden intrafacies will also cause reduction of seismic bandwidth due to scattering of the high frequencies.

3.1.4.3 Inflated Pahoehoe

Alternating sheeted bands of vesicular and non-vesicular material (0.1–0.2m thick) are observed in the pahoehoes at the base of the succession. The vesicles are often piped ('PV' notation of Self *et al.* 1997) and their orientation indicates the lavas flowed towards the west (e.g. 3°/278°). This is consistent with the flow indications in the ropy lava tops (Figs. 3-4C & 3-9C). The pipe vesicles are developed in the basal zones of pahoehoe flow lobe units, but most of the dense vesiculation in the succession is represented by sub-parallel vesiculation bands. These are inferred to have formed by reducing the internal pressure and degassing the inflating pahoehoes. This may occur when breakouts escape from the semi-solid flow carapace (Hon *et al.* 1994; Self *et al.* 1998). Within these thinner lavas at the base of the exposed igneous succession, massive and vesiculated zones are always present and this alternating banding supports the notion of passive flow inflation.

3.1.4.4 Injection and Loading Structures

The injection and loading observed in this part of the lava system provides direct evidence of pahoehoe inflation from beneath, and also for country rock assimilation processes on a centimetre-scale (Fig. 3-4D): several flow base zones sit directly on reddened vesicular bole material developed on the frothy top of the subjacent lava. The bole hosts complex structures where the upper basaltic lobe has loaded and contorted the bole layer. Several zones of detached bole have also been amalgamated into the basaltic lava lobe. These have been detached into rafts by magma injection from below. Reaction rims are noted at the contacts between the boles and the basalts (Fig. 3-7).

3.1.4.5 Massive Lobes Cores / Frothy Lava Flow Tops

High compressional wave velocity (primary velocity), high density lava flow core regions occur on two scales: As laterally impersistent core zones in pahoehoe flows (0.5–2m thick), or as laterally persistent zones in thicker tabular-type flows (>5m thick). On the north side of Talisker Bay is an example of an inflated pahoehoe core region beneath a heavily vesiculated flow top (Fig. 3-4E). The massive core region has been injected by a subsequent batch of magma, which adds to the complexity of its inflation; however, the core is essentially geophysically isotropic (Fig. 3-6). Flow core zones in the Talisker Bay olivine-phyric lavas are a maximum of 2.5m in thickness, but the mean thickness is less than 1m. The massive core zones display more regular jointing than the heavily fractured lava flow lobe bases and tops. During the pahoehoe inflation process described by Hon *et al.* (1994), the core zones may develop into tubes that transport molten basalt to small pahoehoe lobes at the toe of the advancing lava field (Keszthelyi & Denlinger 1996). Massive core zones grade upwards into a zone of more profuse vesiculation (<25%) with an overall large vesicle size (mean of c.5mm). As lobe tops are approached, the density of vesiculation increases and the size of the vesicles reduces as a common observation. As the top is reached, a zone of vesicles generally <0.1m thick is often noted where the vesiculation density may be as high as 80%. This zone is usually capped by an aphanitic, glassy top which represents the quenched flow top. Both the vesiculated zones and the lobe cores are laterally discontinuous (Fig. 3-6).

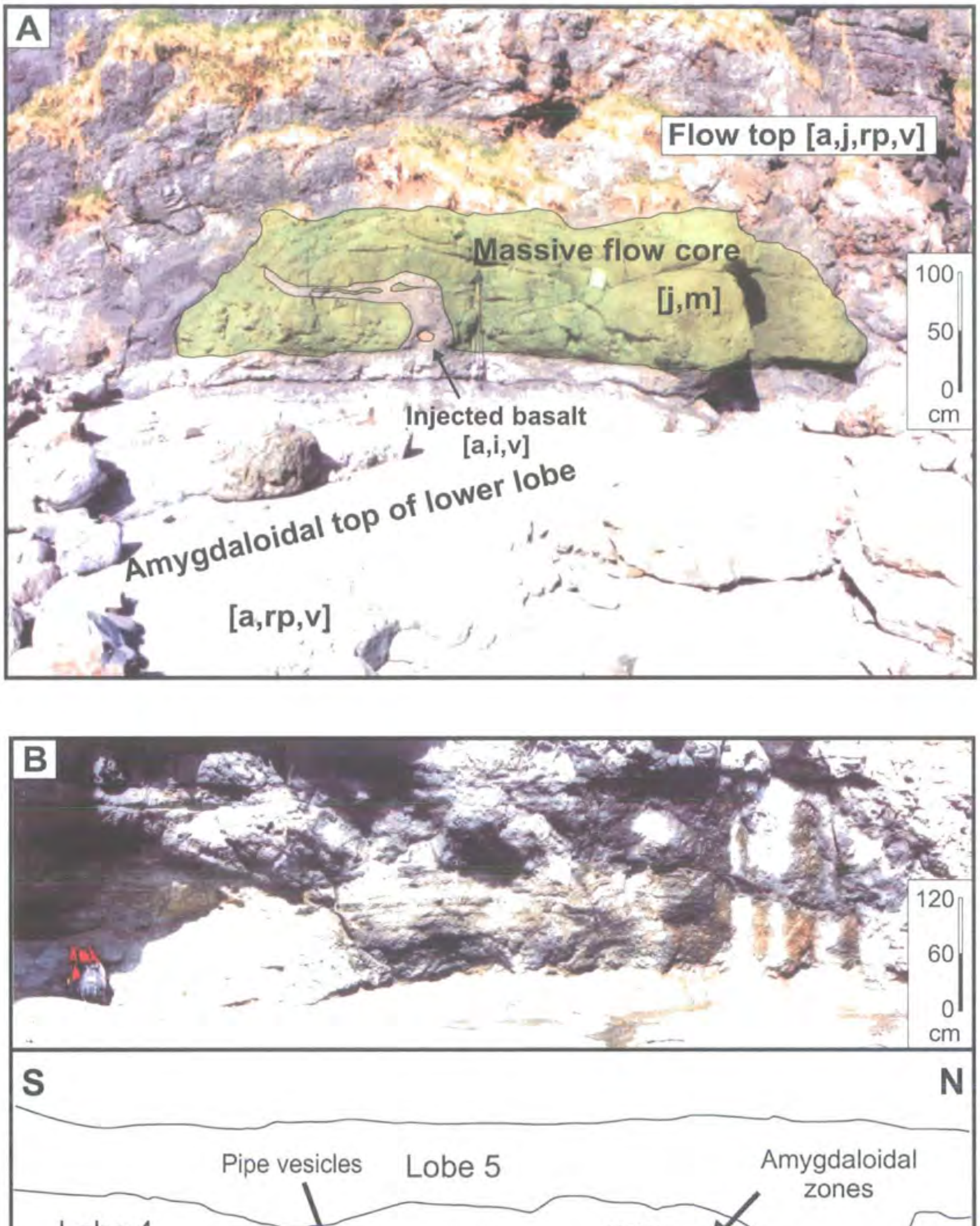


Figure 3-6 Olivine-basalts of Talisker Bay. **A:** A well-defined flow lobe core revealed in the south-facing cliffs [NG 13135 83060]. The walking stick is extended to 1m in the centre of the figure. Above the core is a thick, highly amygdaloidal rubbly zone up to 1.5m thick. The lobe core is injected by basalt which contains a rounded cobble of foreign amygdaloidal basalt; **B:** A stack of pahoehoe lobes at the base of An Stac [NG 13113 82997]. Lobe numbers correspond to the stacking order of the units, flow 1 being the oldest. Thin boles lie on parts of the lower lobes. Sub-parallel amygdaloidal bands run across the basalt lobe sections, indicating the flows to be inflated. (a = aphanitic margin; i = injection structure; j = jointing; m = massive; rp = pahoehoe surface; v = vesiculated).

3.1.4.6 Boles and sedimentary beds

Boles indicate prolonged periods of sub-aerial exposure and are often associated with volcaniclastic material such as tuffaceous beds from explosive silic eruption events (Bell *et al.* 1996; Widdowson *et al.* 1997; Bryan *et al.* 2002) and deltaic and laccustrine sedimentary units such as conglomerates, sandstones, mudstones and coals. Sedimentary beds and weathered zones in igneous successions of the BTIP are generally <5m thick (Figs. 3-4F & 3-7). In other parts of the NAIP however, some beds are much thicker. For example on the Faeroe Islands and in the offshore Faeroes Lava Group, a 10-20m thick coal-bearing sequence caps the Lower Lava Formation (Chapter 5; Ellis *et al.* 2002) and in Antrim, parts of the Interbasaltic Formation are up to 28m in thickness where acid volcanics have been heavily weathered to laterite or bauxite (Preston 2001). Many such beds are high quality, laterally persistent 'marker horizons' for lava sequence correlation, and are used to divide the lava succession and for dating (e.g. Anderson & Dunham 1966; Williamson & Bell 1994; Milner *et al.* 1995; Bell & Jolley 1997; Bell & Williamson 2002). The rock property characteristics of these beds attenuate propagation of high seismic frequencies, reduce bandwidth, and reduce the density of the overall lava succession. In the upper tabular-type architectural sequence of lavas in the Talisker Bay area, boles form up to 15% of the succession: major lava flows of 8–15m thick are capped by boles of up to 3m thickness. This has the effect of substantially reducing the specific gravity of the overall sequence which is an important consideration for gravity models being built in areas that contain such lava sequence types.

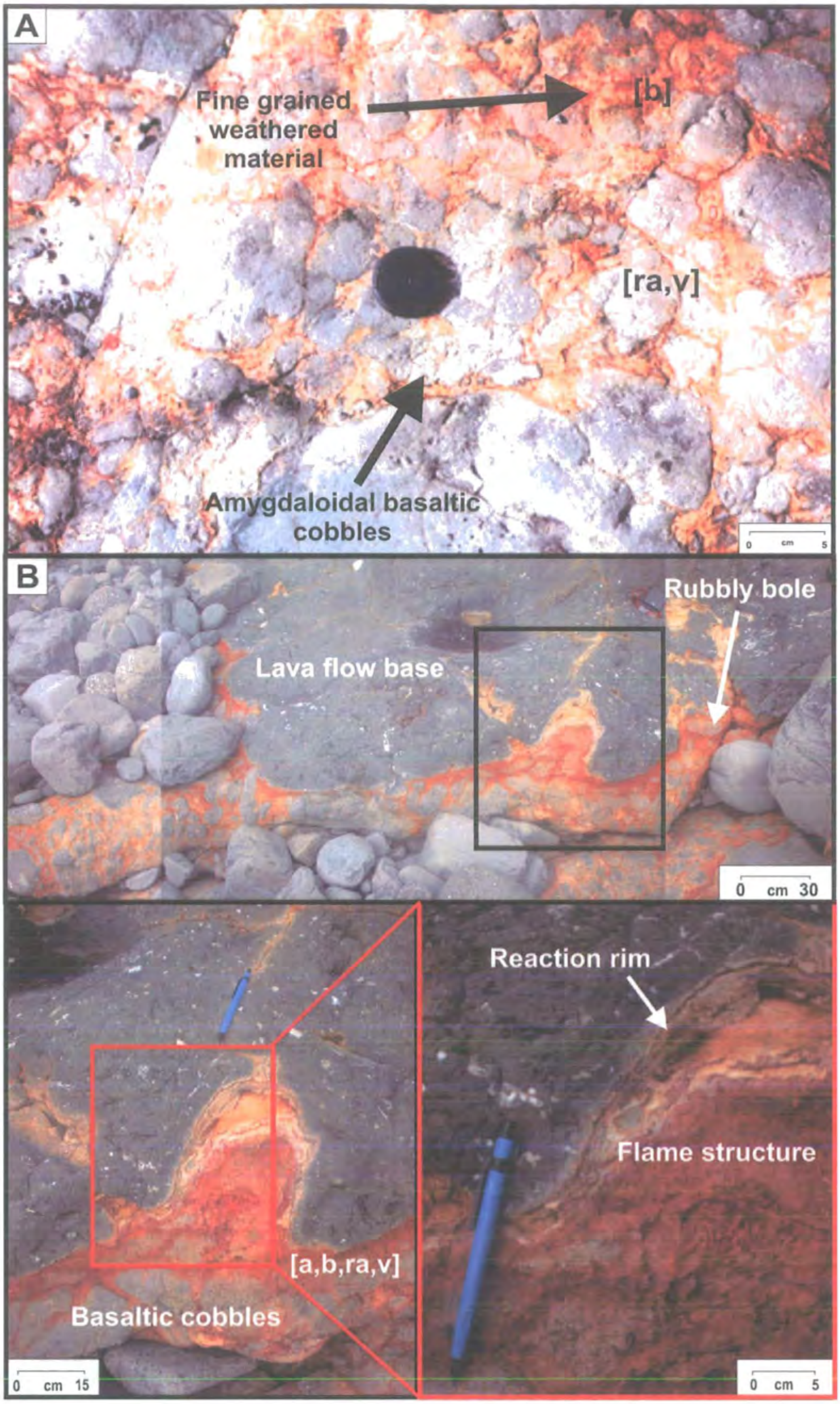


Figure 3-7 Sections through bole on the south side of Talisker Bay [NG 13122 82995]. **A:** A rubbly, vesiculated olivine-basalt surface is weathered and bole material is resident between the degenerated basaltic cobbles; **B:** A complex bole / basalt contact. Close-ups show the bole contact to be heavily altered by the low grade thermal metamorphic effects of the basalt enveloping the soft sediment. Vesicles radiate around the flame structure in the basalt due to micro-scale phreatic interactions. (a = aphanitic; b = bole; ra = rubbly surface; v = vesiculated).

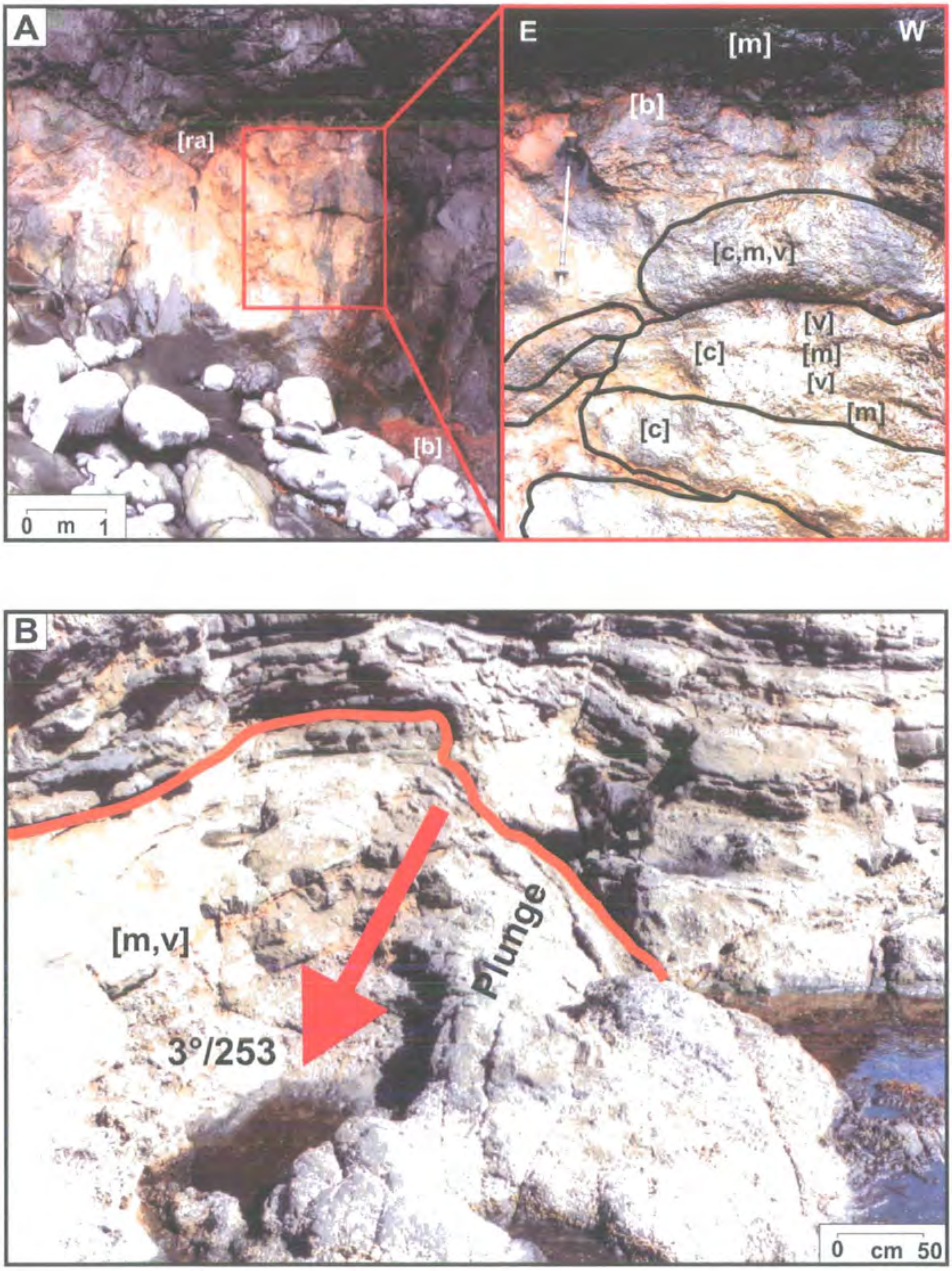


Figure 3-8 Pahoehoe lava lobe breakouts. **A:** A series of breakouts filling a depression in the lava sequence. The small breakouts are shown in elevation section and consist of a series of concentrically banded lobes which have alternating internal amygdaloidal and structureless bands [NG 13134 82998]; **B:** Large pahoehoe breakout on the west side of An Stac which plunges gently towards the SW [NG 13110 82996]. (b = bole; c = concentric banding; m = massive; ra = rubbly surface; v = vesiculation).

3.1.4.7 Breakouts

Lava flow breakouts are interpreted to occur at the toe of advancing lavas when basalts escape the cooled carapace. Breakouts are externally characterised by finger-like or lobe-like geometries. Internally, these are observed to be highly vesicular in slim sub-parallel zones and have aphyric margins. In vertical sections, breakouts may represent independent pillow-like features that have concentrically banded structure (Figs. 3-4G & 3-8). Breakouts are an essential part of the pahoehoe inflation system; and are considered to be geophysically similar to inflated pahoehoes or pillow lavas. Thin alternating massive and vesicular zones typify each of these intrafacies types, as noted by their intrafacies components. Breakouts in Talisker Bay pahoehoe flows are observed to verge to the SW (Fig. 3-8).

3.1.4.8 Lava feeder tubes and pipes

Typical, rhythmically banded and inflated basalts are cross-cut, and intruded by large, concentrically banded lava structures in several parts of the bay area [NG 13125 82998]. These are interpreted to be lava flow feeder tubes that sub-horizontally fed lava to the developing lava field from within (Fig. 3-4H). To the south of Loch Eynort, structures similar to those described below are also observed in cliff sections. Systems of such feeders exist in present-day persistently volcanic environments such as on Hawaii (Fig. 3-10; Halliday 2003; Kempe *et al.* 2003) and also in more sporadically volcanic areas such as those of Mount St. Helens in the Cascades volcanoes of west U.S.A. and in Japan (Miyamoto *et al.* 2003). They are also documented to a limited extent, in ancient flood basalt provinces such as the huge system seen in the Deccan Traps where lava tubes and channels have been indentified in over two hundred localities in a study area of c.120,000km^2 (Misra 2002).

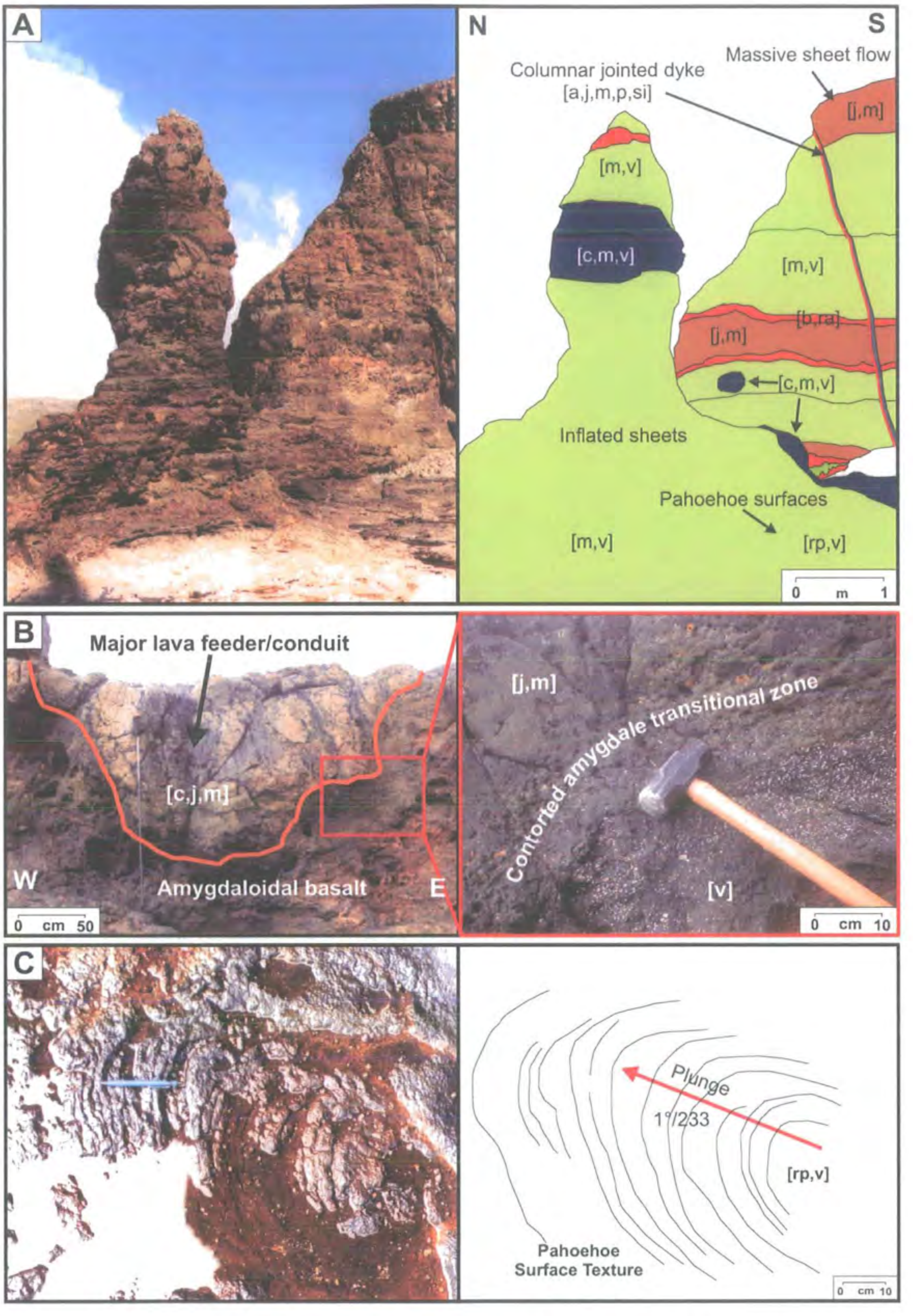


Figure 3-9 Structures in inflated pahoehoe near An Stac [NG 13117 82997]. **A:** The small sea stack from the west. The interpretation of the lavas in this stack reveal inflated pahoehoes invaded by lava feeders both in the stack, and in the distant cliff section; **B:** A structureless picritic lava feeder tube/conduit cuts across the base of the small stack and contorts the surrounding lavas. This indicates that the lavas surrounding the feeder were hot enough to be plastically deformed by the structure; **C:** Pahoehoe surfaces at the foot of the stack plunge gently towards the SW. (b = bole; c = concentric banding; j = jointing; m = massive; ra = rubbly surface; rp = pahoehoe surface; v = vesicular).

Four distinct lava tubes are observed in the intrafacies of the Talisker Bay section. These are divided into two simple categories:

- Passively-emplaced type
- Channel-like (erosive) type (Fig. 3-11).

3.1.4.8.1 Passive-type lava feeder tubes/pipes

Several such structures sit passively within the inflated basalts (Fig. 3-9 & 3-11A). They are olivine-rich, laterally impersistent; forming a low percentage of the bulk rock volume and are interpreted to be high heat flux lava pipes or tubes feeding the toe of the lava field. At the west end of the north-facing cliffs, a pipe-like feeder consists of concentric layers of holocrystalline, olivine-basalt. The massive core region is c.1.5x2.2m and the body plunges gently towards the SW. Inflated pahoehoe sheet flows are passively intruded and folded around this pipe-like feature. This suggests that the sheet flows into which the structure was intruding were still hot and able to deform plastically. The feeders plunge shallowly towards the SW which is consistent with flow directions indicated by pahoehoe textures, lava breakouts and flow overlap directions.

3.1.4.8.2 Channel-like erosive lava feeder tubes

The most prominent channel-like lava feeder tube (Fig. 3-11B) lies in the sea stack section [NG 13119 82997]. The body truncates the surrounding lavas and invades them with basaltic veins. Strong striations on the tube walls plunge at the same attitude as the tube indicating these to be a product of the magma movement (Fig. 3-12). Concentric banding also contains vesicles that are sheared in the direction of striation plunge.

The presence of a large number of tube-like lava feeders suggests that there was a well established, high heat flux plumbing system active at the base and within the lava fields' inflating basaltic sheet flows. The dimensions of the feeders imply that the Talisker Bay section may be quite proximal to a magma source which was erupting relatively small volumes from the direction of Loch Harport. The volcanic system may be considered to be analogous to those of modern day Hawaii or Iceland, where the slow eruption rates ($<20m^3s^{-1}$) and volumes allow good preservation of detailed lava field features (Walker 1993). The Hawaiian lava field near the Kilauea vent displays extremely similar features to those seen in the Talisker Bay area of Skye: well-preserved inflated pahoehoe basalts are fed at the present day, by a well established plumbing system of lava feeder tubes – this configuration of volcanic system is common to both locations (Fig. 3-10).

Basaltic lava field development

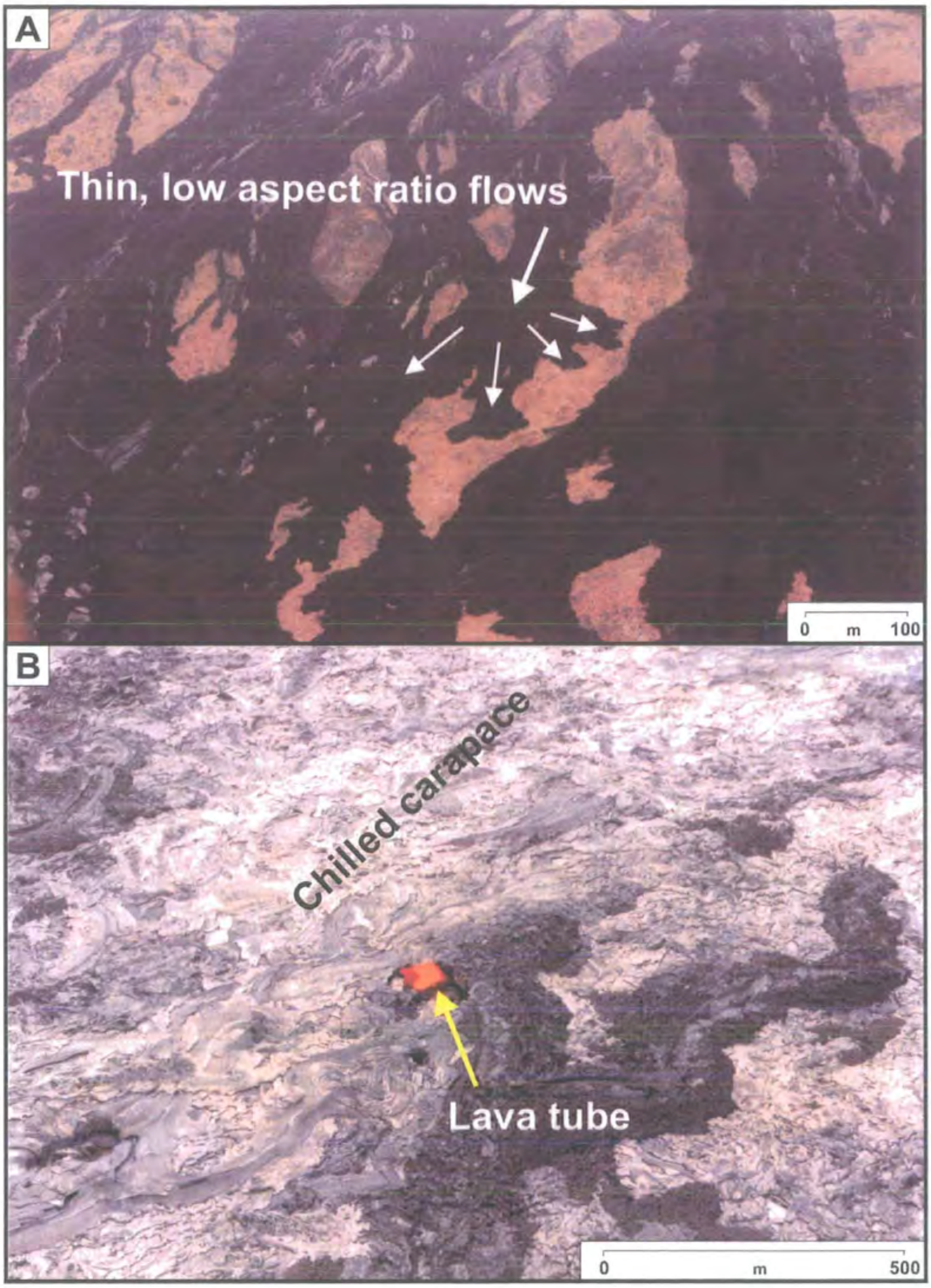


Figure 3-10 The development of a basaltic lava field in a typical shield volcanic setting. These photographic examples are from the Kilauea volcano on Hawaii. **A:** Finger-like basaltic lava flows erupt from fissures on the flanks of the shield volcano. The sheet flows inflate and thicken from beneath underneath a cooling carapace. The flows advance as lava breaks through the carapace; **B:** The inflating lavas build into a lava field and breakouts are more limited to the toes of the lava flows due to the thickening carapace. Lava feeding the toe of the advancing lava field concentrates into sub-terrainian lava feeder tubes and pipes that are thermally-insulated, high heat flux lava pathways. These facilitate the movement of lava over great distances (10s km).

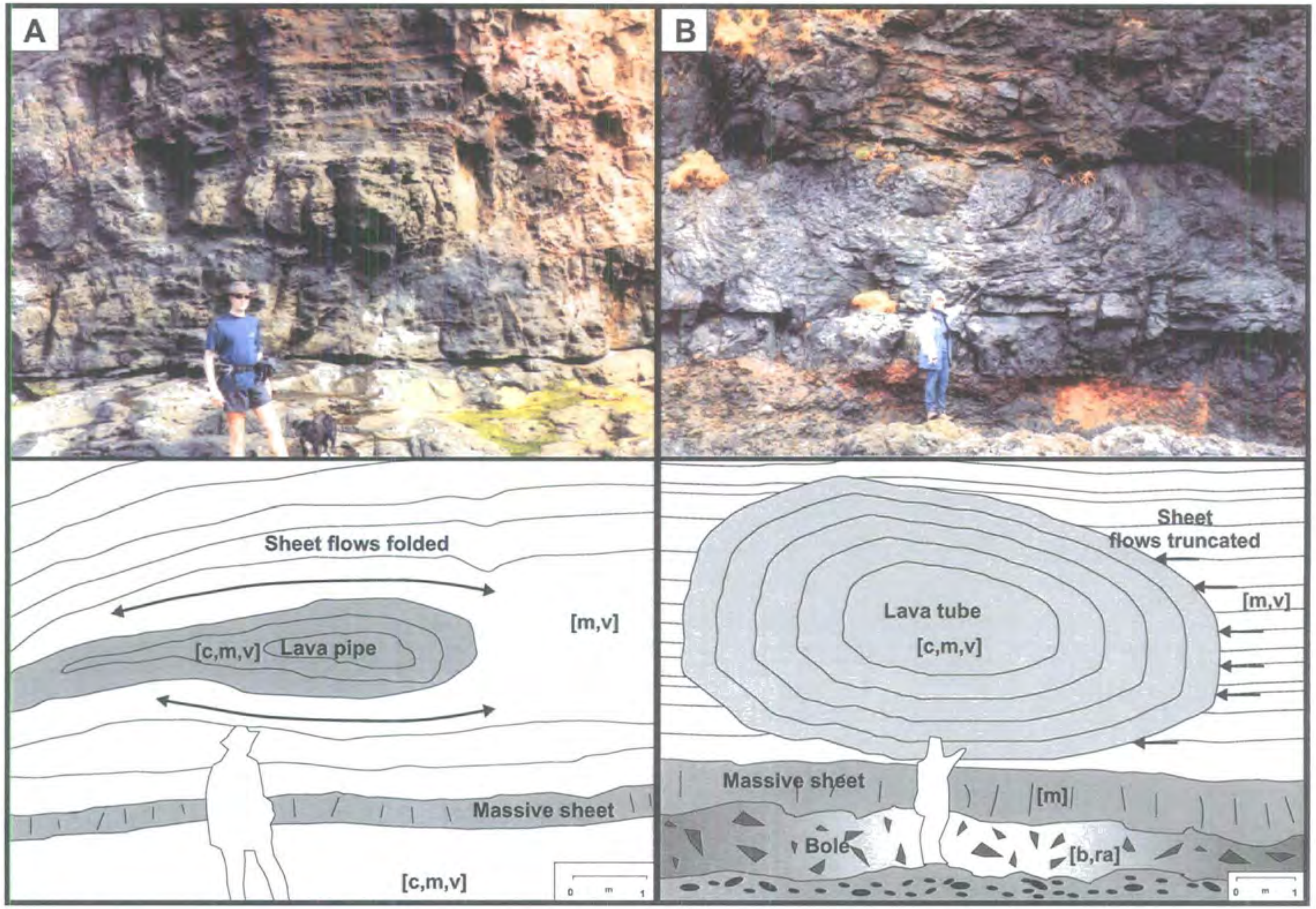


Figure 3-11 Contrasting types of olivine-basalt lava feeder tubes. **A:** Pipe-like lava tube passively intruding and gently folding the surrounding inflated pahoehoes [NG 13122 82998]; **B:** Large concentrically banded lava tube cross-cutting the surrounding rythmically banded inflated pahoehoe strata [NG 13125 82998]. (c = concentric banding; m = massive, ra = rubbly surface; v= vesiculation).

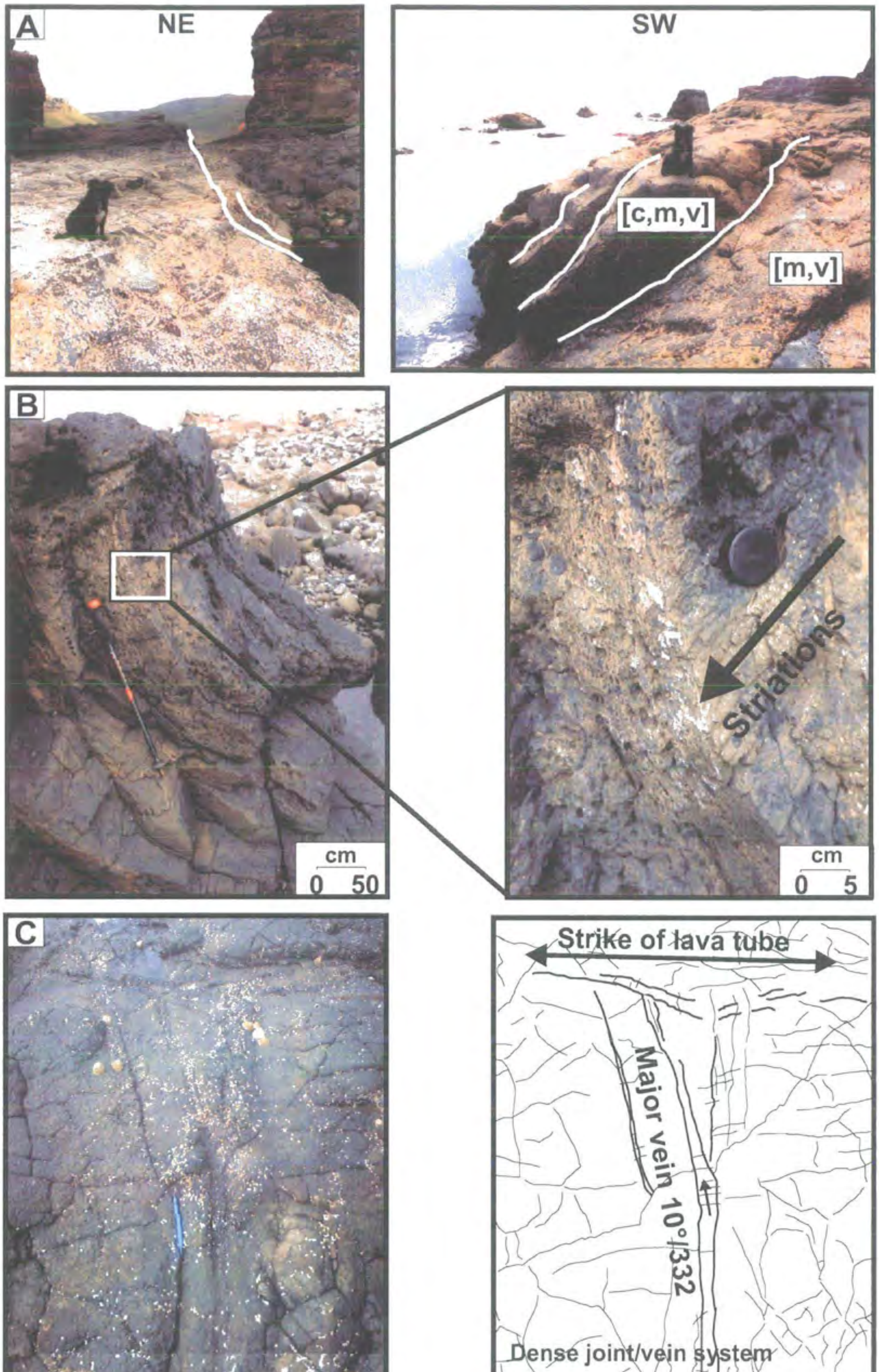


Figure 3-12 The lava feeder tube revealed on the foreshore near An Stac [NG 13119 82997]. **A:** Linear, discordant lava tube in inflated pahoehoe crosses the entire peninsula. Both photographs are taken from same location looking along the feature in two directions; **B:** Striations are revealed on the walls of the structure. The striations plunge gently towards the SW; **C:** Intense basaltic veining invades the surrounding pahoehoe flows. This is coincident with a joint system. (c = concentric banding; m = massive; v = vesiculated).

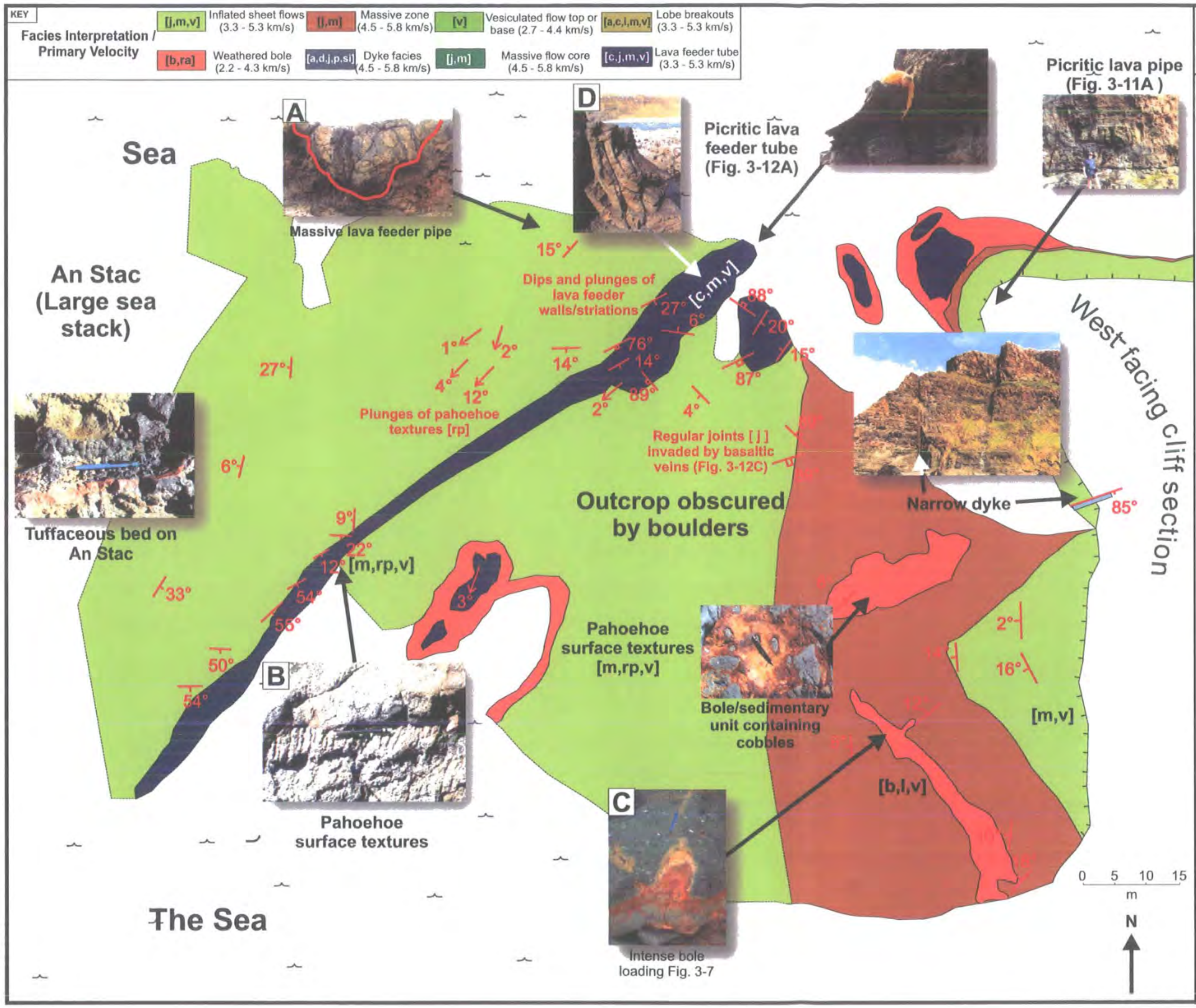
In the previous sub-sections, examples of the facies and intrafacies present in the Talisker Bay area of the Skye Lava Field have been documented. These micro-scale (cm–m) variations in lithology are potentially very important when considering the lava field in terms of its geophysical characteristics. In the following sub-sections, a series of case studies which document some of the centimetre to metre-scale variations in the lavas around Talisker are presented which incorporate the main intrafacies types introduced above. These case studies highlight the complexity of heterogeneity at the centimetre to metre-scale.

3.2 INTERPRETING FACIES AND INTRAFACIES IN TALISKER BAY: CASE STUDIES

The main geological intrafacies types have been discussed as field examples from Talisker Bay. This section studies how the intrafacies co-exist in the field outcrop sections of the bay area, and what these can tell us about the heterogeneity of the lava field on the whole. Firstly, centimetre-scale variations are studied in log sections. In turn, these are discussed in terms of the metre-scale of investigation at the same outcrop, subsequently, the concepts presented are applied to a full outcrop section.

3.2.1 Talisker Bay Wave-cut Platform sections

The area of lavas near the small sea stack section is shown and the facies summarised in Fig. 3-13. When we look closely at a these lavas, the variations in volume and distribution of vesicles, combined with the massive crystalline zones in both vertical and lateral directions gives a complex system characterisation. In vertical sections, quantification of vesicle densities produces saw-tooth patterns through the successions in each sample section (Figs. 3-14 & 3-15). The magnitude and amplitude of the limits of the vesicle density change substantially from totally massive, vesicle-free character, to up to 45% vesiculation. Where a high percentage of vesiculation exists, the mean vesicle diameter is small (c.2mm) and these are observed to be present towards the actual ropy pahoehoe tops of individual flow lobe tops where the lava is frothiest. Where the vesicle densities are lower, the vesicles are larger, but the basalt is not massive in character, we are usually observing vesicle bands that have formed due to depressurisation of the inflating flow due to lobe breakout occurrence.

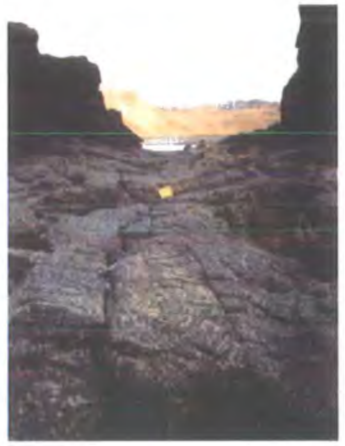


Key features of the wave cut platform

A: Massive lava feeder pipe plunging from wall of sea stack at 4°/241. Vesiculated horizons contorted beneath massive, unvesiculated core zone.

B: Pahoehoe surface texture on sheet flows indicate lava flow direction towards 2°/269.

C: Olivine-phyric basalt interacting with bole. Reaction rims of <7cm present in contact zone. Amygdales in the basalt are sub-parallel to the contact with the bole.



D: Lava feeder tube exposed East of small sea stack. The plunge of this striated, concentrically-banded structure is c.2°/237. Looking up plunge (see left), the lava feeder is observed to be heavily orthogonally jointed parallel and perpendicular to the plunge direction. Much of the jointing is exploited by basaltic veining.

Bole horizons and thick, tabular basaltic lava flows are continuous in cliff sections up to 280m high South of Talisker Bay.

Figure 3-13 Map of geological intrafacies in the area of the An Stac (small sea stack) and the surrounding wave-cut platform. Key features in the area are annotated. The wave-cut platform provides a section through a shallowly dipping succession of basalts and reveals the relationships between these lavas, their magma feeders and the sediments onto which they were erupted. Elastic velocity range estimates for geological intrafacies types are inferred from rock property data collated from the SIMBA rock property database and from Planke (1994) & Planke *et al.* (1999 & 2000). These inferred velocity ranges are tabulated in Table 3-2.

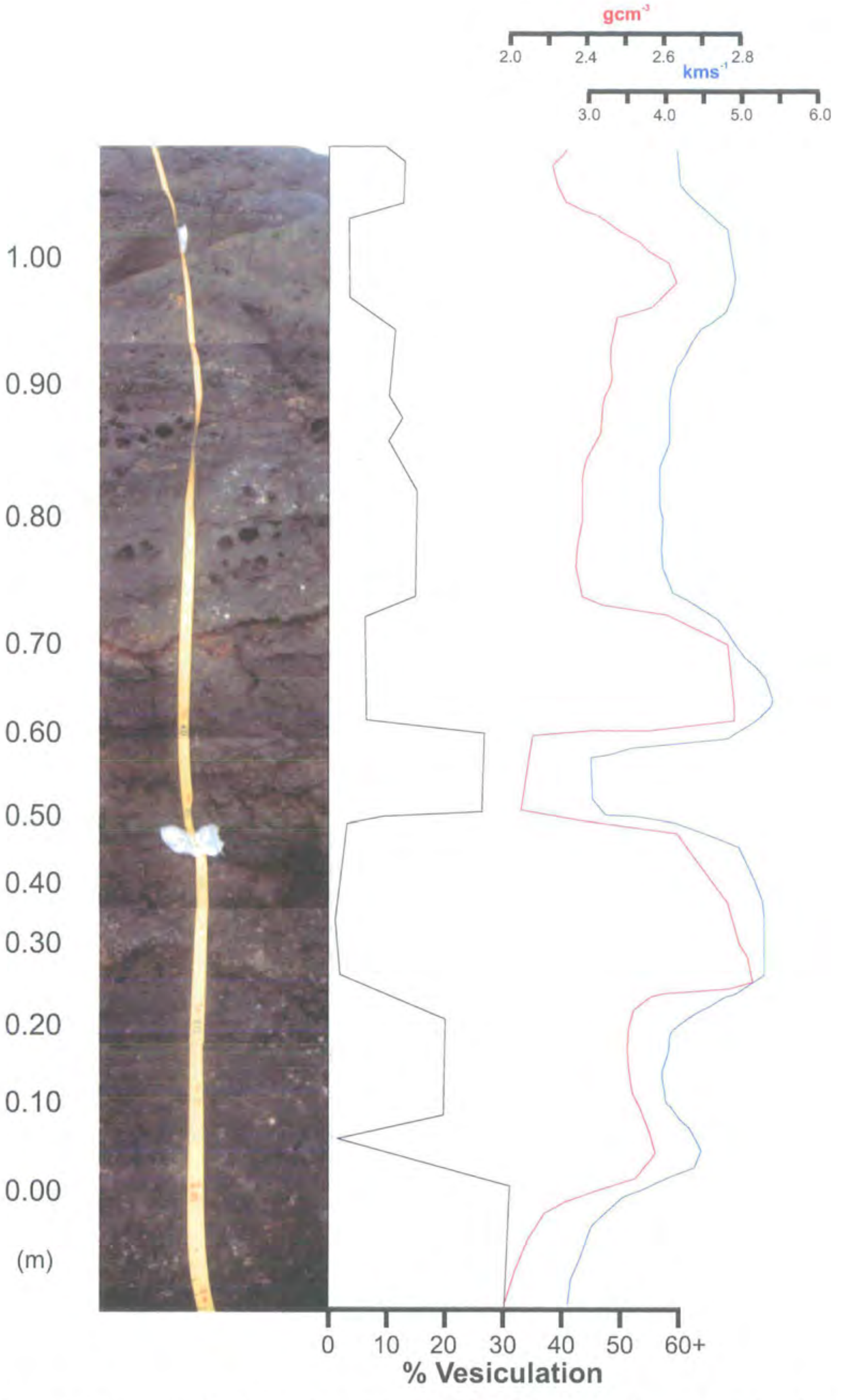


Figure 3-14 Sections through inflated pahoehoe olivine-basalts in Talisker Bay. Banded variations in the massive and vesiculated character of the basalts are indicative of a succession of inflated pahoehoe flows. Vesiculation density decreases up through the section. Note that most of the highest vesicle density zones are composed vesicles of a smaller mean diameter than zones where vesicles are present, but character is more massive. Schematic estimated geophysical heterogeneity through this section is also represented by density and elastic velocity variations. These vary strongly as the intrafacies characters in the log sections vary. Schematic geophysical wireline log responses after Planke & Flovenz (1996).

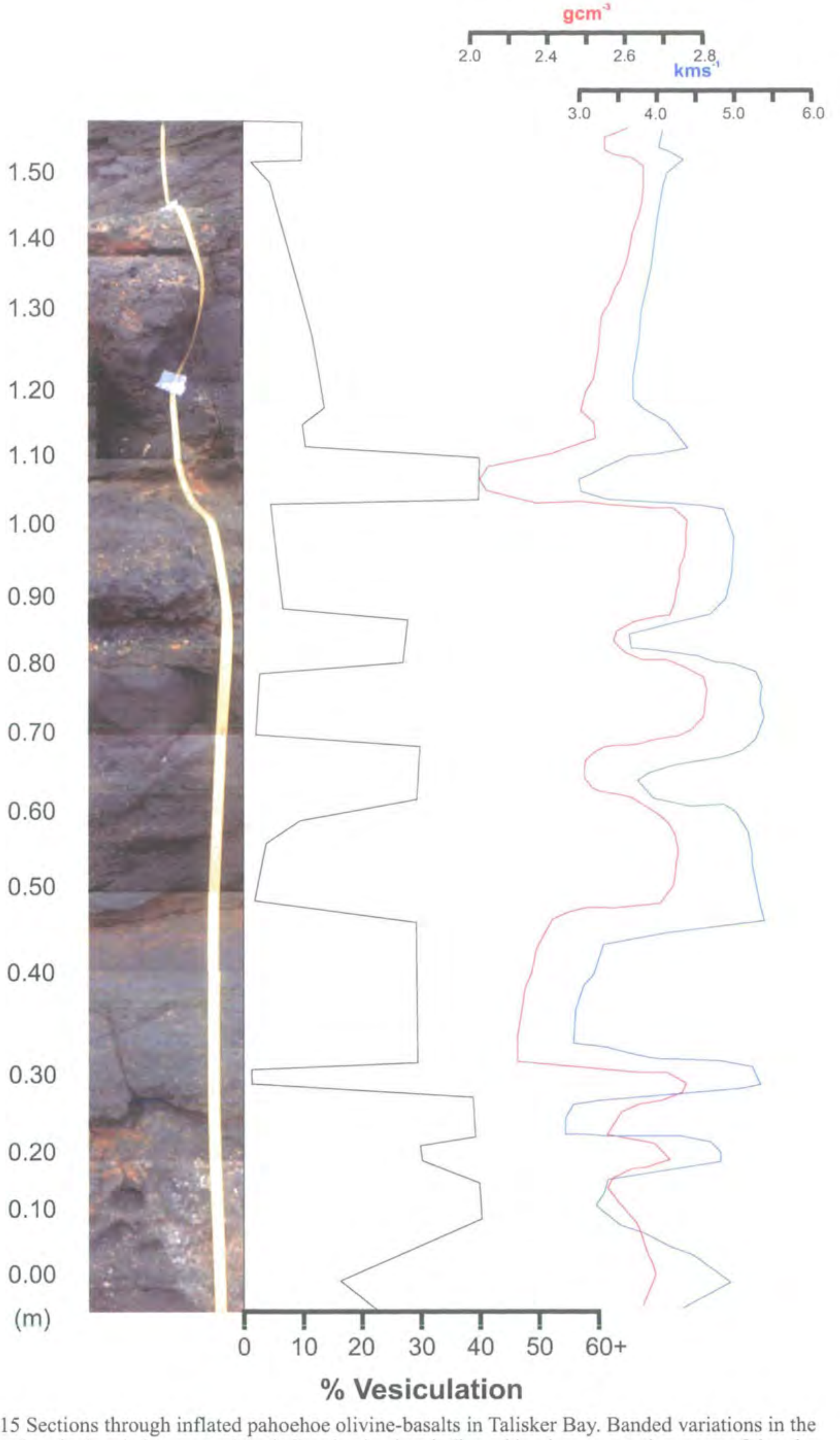


Figure 3-15 Sections through inflated pahoehoe olivine-basalts in Talisker Bay. Banded variations in the massive and vesiculated character of the inflated pahoehoe indicated by the saw-tooth pattern of the plot of vesiculation density through the lavas. Note again that % vesiculation is inversely related to primarily elastic velocity and density in terms of the geophysical characteristics of this section. Schematic geophysical wireline log responses after Planke & Flovenz (1996).

Within the confines of these small sections of study around the small sea stack of the bay area, it is possible to observe a whole host of geological variability. Even the variability on this sub-seismic scale affects geophysical data acquisition. Although the features discussed are dimensionally minor, their surface geometries are likely to be damaging to seismic data quality for example, as the complex geometries cause scattering and dispersion of seismic wave-fronts. These concepts are discussed in Chapter 6.

Having observed some of the features in the lava field on a centimetre to metre-scale, the next section builds these observations into the small outcrop scale to understand how the intrafacies discussed may co-exist in the volcanic succession.

3.2.2 Talisker Bay Small Sea Stack Section

This area essentially consists of a series of alternating bands of high (up to 45%) and low vesiculation densities (<5%) and represent a series of pahoehoe sheet flows. The section shows simple onlapping relationships between basaltic flow lobes and a massive passively emplaced lava feeder. Distinct core regions (<50cm thick) are observed amongst highly vesicular sheets. The vesiculated zones often merge around the flanks of the massive core regions. The facies distribution (Fig. 3-16) indicates there to be a balance between highly vesicular flow facies and massive flow cores across the entire section in a ratio of about 5:4.

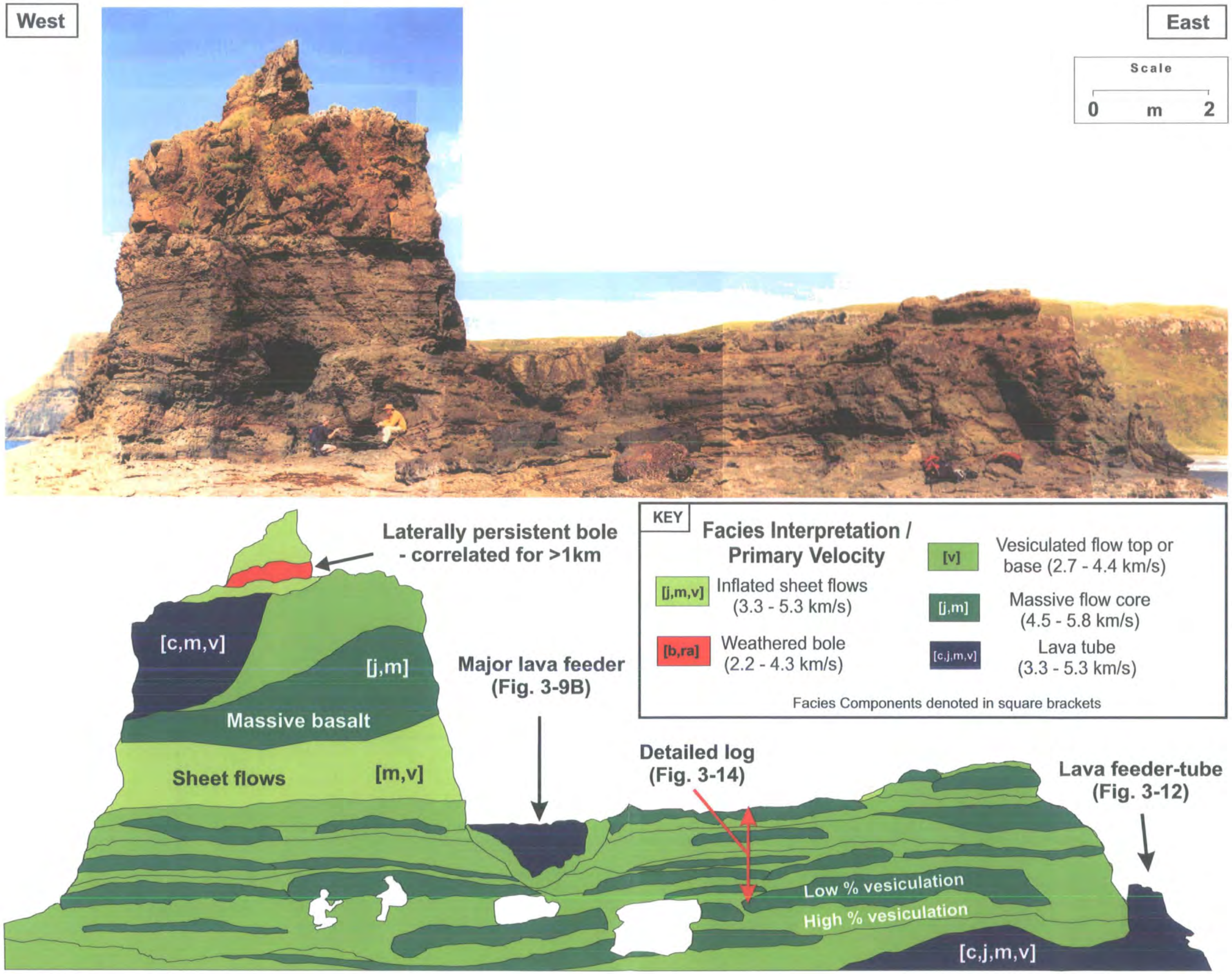


Figure 3-16 An Stac small sea stack section [NG 13117 82997] (Fig. 3-1B&C) showing lava feeders resident within the olivine-basalt succession. Lower in the outcrop it is possible to distinguish the individual massive and vesiculated zones which constitute the inflated pahoehoe. Higher up the section where the alternating zones are less obvious, they have been grouped under the inflated pahoehoe facies interpretation. Elastic velocity range estimates for geological intrafacies types are inferred from rock property data collated from the SIMBA rock property database and from Planke (1994) & Planke *et al*. (1999 & 2000). These inferred velocity ranges are tabulated in Table 3-2.

3.2.3 Talisker Bay Large Sea Stack (An Stac)

The lavas observed around the *An Stac* sea stack section provide a detailed study area of high exposure of parts of the volcanic succession which is otherwise only revealed in stream sections inland in the Minginish district. This is due to the steady westward dip of the succession in the area. Where the lavas are revealed in inland stream sections, they are discussed in terms of their stacking patterns and vertical relationships in Chapter 4.

Above the inflated pahoehoe succession of lavas are a series of thick bole beds. These are 1-2m in thickness and may be traced for over 1km in the cliffs to the south of Talisker Bay, and located in log sections inland. They are excellent marker beds for large-scale correlation exercises (Larsen *et al.* 1999; Bell & Williamson 2002). Between the boles and pahoehoe are several more massive flow units. These are degassed cores of large basalt flows. Vesiculation is extremely sparse in these zones.

3.2.4 Talisker Bay north-facing cliff section

This section explains how a cliff outcrop may be divided into zones of varying geological intrafacies, and how this geological heterogeneity relates to the geophysical properties of the flood basalt sequence. This case study outcrop section lies on the south side of Talisker Bay [NG 3122 2995] at the base of the north-facing cliffs (Fig. 3-17). It was selected for the high quality of exposure present, making it an ideal place to observe the juxtaposition of intrafacies. The sequence is geologically complex and the variety of intrafacies present in this small section has major implications for geophysical studies. Studying the intrafacies components present in parts of the geological architecture, enables prediction of the possible geophysical variability present in the outcrop section (Fig. 3-17). In order to quantify the geophysical variability in the geological architecture, we must link the intrafacies present with geophysical rock properties (Table 3-2). Below, this case study is presented using intrafacies as a system for predicting geophysical heterogeneity from the geology.

The cliff section case study is divided into zones of geological intrafacies. Each geological intrafacies is represented by a range of rock property values (Table 3-2). The geological interpretation is schematically represented in terms of a primary velocity structure in order to highlight the geophysical heterogeneity (Fig. 3-17). Quantification of the image into pixel locations and numbers allows calculation of the areas each intrafacies by thresholding the quantified pixels. The statistical variability in the geophysical rock properties can therefore be quantified for any cliff section using a combination of the image analysis and rock property data such as that presented in Table 3-2. The most localised and most profound lateral geological intrafacies changes are those of the dyke and lava feeder. Although the rock properties of the dyke are very similar to those of other massive zones (e.g. sills), dykes are considered as geophysically distinct in such sections as they are vertical structures. High velocity vertical structures affect the propagation of seismic waves differently, as only part of the wavefronts accelerate through the massive zone. The seismic waves either side of the dyke structure are relatively attenuated in the surrounding medium resulting in broken wavefronts.

The cliff section is dominated by inflated, compound-braided type olivine-phyric basalts containing highly vesicular basal and flow top zones and massive core zones up to 1.5m thick. Seismically, vesiculated zones exhibit low compressional wave velocities of 3.0-5.4kms^{-1} (Planke & Cambray 1998) and low bulk densities of 2.56-2.72gcm^{-3}. In contrast, the cores have <5% vesiculation and are high velocity zones of 5.0-5.8kms^{-1} (Planke *et al.* 1999) with high densities of 2.79-3.02gcm^{-3}. When the distribution of vesiculated and massive zones from all the olivine-phyric basalts studied is compiled into a frequency distribution plot, these lavas tend to be dominated by the more massive flow components (Fig. 3-18). Both the vesiculated zones and the massive lobe cores are laterally discontinuous, resulting in complex geological and geophysical heterogeneity (Fig. 3-19A&C).

The internal complexities of these earlier flows are distributed both vertically and laterally: however the younger, thicker flows seen higher in the lava field succession only show significant changes in vertical profile (Fig. 3-19B). These thicker flows will be discussed in more detail in Chapters 4 and 5.

The development of thin boles on lava flow tops suggests that there were many minor extrusion hiatuses during the eruption of the flows in this sequence. Although thin (<20cm), their top surface geometries are particularly rugose, which implies that they represent an effective waveform scattering surface. In addition, they contribute to minor density changes which reduce the bulk density of the lower architectural sequence.

The igneous succession in the Talisker area encapsulates much of the internal facies variability which is used in the following chapters for making interpretations of lava flow internal structure and rock property composition. The observations on this micro-scale study are incorporated into the larger scale studies as the building blocks of the lava sequences.

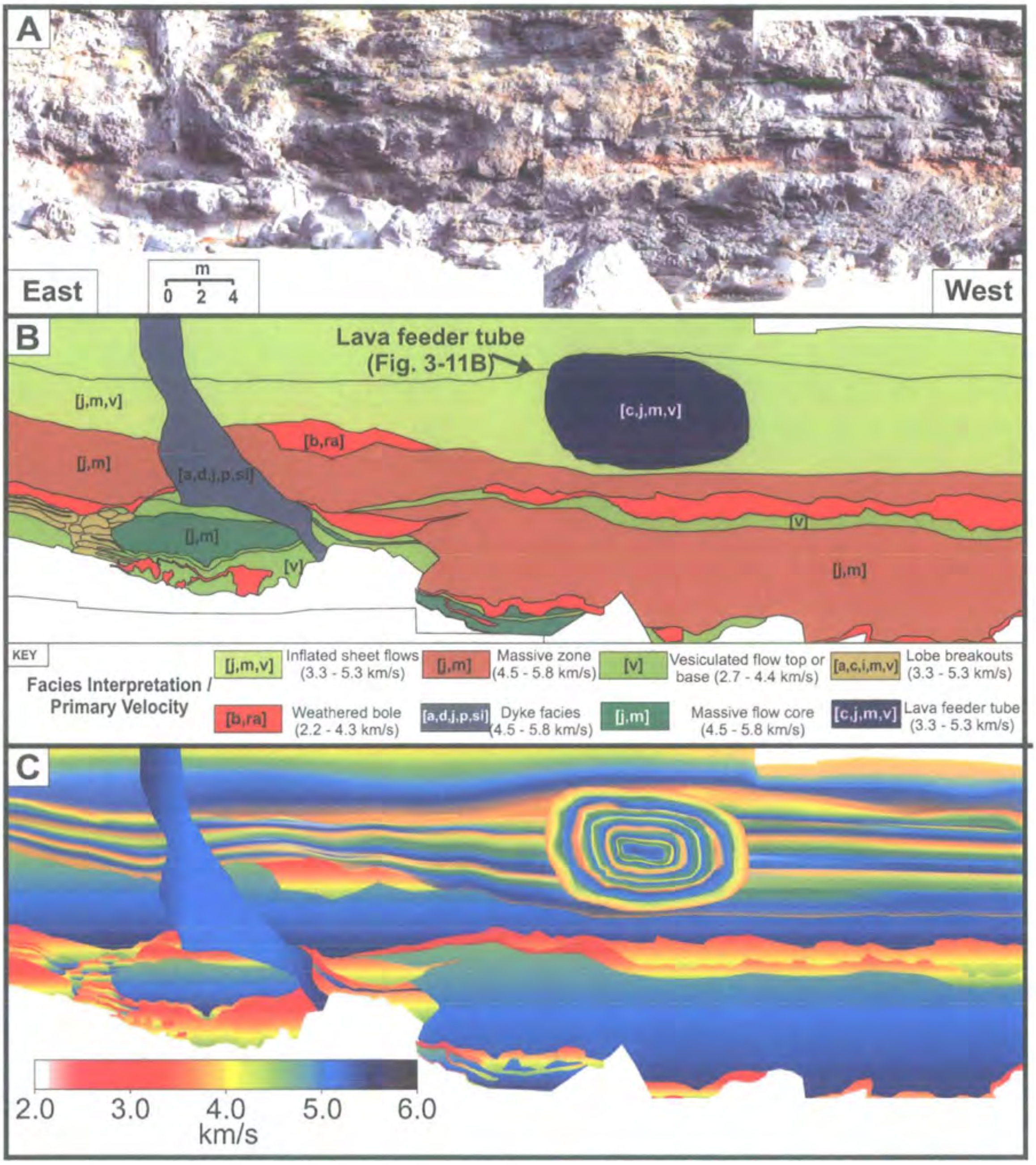


Figure 3-17 The south side of Talisker Bay north-facing cliff section [NG 13125 82998]. **A:** The cliff outcrop photographic montage; **B:** Geological interpretation showing the spatial distribution of the main intrafacies present and their constituent intrafacies components; **C:** The outcrop section schematically represented in terms of ranges of compressional wave velocity (km/s) stipulated for each intrafacies (cf. Table 3-2). Elastic velocity range estimates for geological intrafacies types are inferred from rock property data collated from the SIMBA rock property database and from Planke (1994) & Planke *et al.* (1999 & 2000).

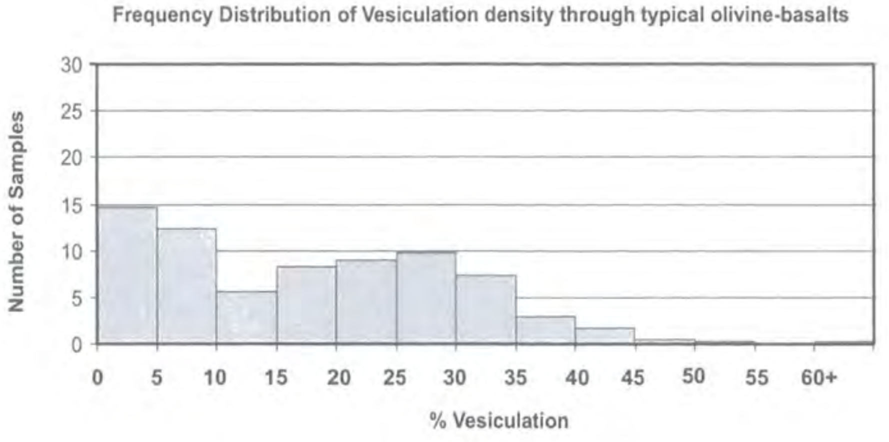


Figure 3-18 Vesicle density as percentage of bulk rock volume through sections of olivine-basalts in the Skye Lava Field.

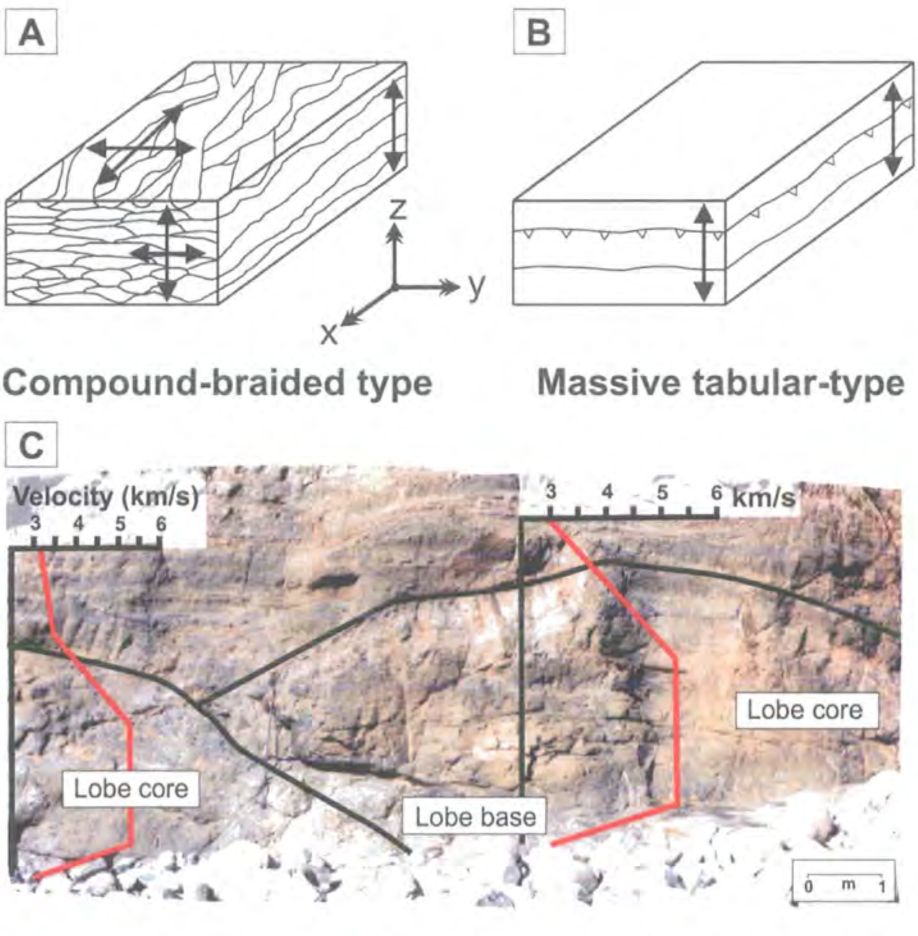


Figure 3-19 The directional properties of geophysical facies heterogeneity in two different types of lava flow architecture. **A:** Compound-braided lavas typical of low viscosity pahoehoe eruptions have complex internal and external anisotropy. Facies and rock properties vary considerably in the Y and Z-directions and to a lesser extent in the X-direction (anisotropy indicated by arrows); **B:** Massive, tabular-type flows exhibit their strongest anisotropy in the Z-direction. Geophysically, the XY plane will exhibit rugosity in both architectural styles; however, the wavelength of the rugosity is shorter in compound lavas; **C:** Outcrop schematically illustrating the variability in compressional wave velocity (Vp) through a more detailed section of the lower architectural sequence lavas. Note the simplified variability in velocity profiles both vertically and laterally across the outcrop.

3.3 IMPLICATIONS FOR THE VOLCANOLOGICAL SETTING OF TALISKER BAY

The lavas and the internal organisation of the succession in Talisker Bay suggest that the lava field developed as a slow, passively effusive series of basalts. This conclusion is reached from the indications of flow breakouts and inflation within the basalts, the well-preserved pahoehoe textures, limited soil development and the presence of a well-developed lava feeder system. The high level of preservation of these features within the study area suggests that the volumes and rates of effusion were relatively low in this part of the Skye Lava Field when compared to those predicted for some flows in flood basalt provinces such as the Columbia River flood basalts where the Roza member is considered to have effused at a rate of c.4000m^3s^{-1} (Self *et al.* 1997). The lava feeder tubes are developed on a much smaller scale than those seen in flood basalts such as the Deccan, which is consistent with the low volume, low effusion rate of volcanism interpreted to be present in the Talisker area. The Skye Lava Field in the Minginish district contains many of the architectural facies that are seen in the modern day systems of Hawaii and Iceland. Pahoehoe textures suggest that the lavas were erupted on a shallow slope, possibly on the flanks of a shield volcano (Walker 1993). Breakouts at the toe of the lava flows are indicative of an inflating flow system, with a proximal magma source. The lava feeder system and dimensions of the tubes present supports this concept. A schematic model for the lavas observed in this micro-scale study is presented (Fig. 3-20).

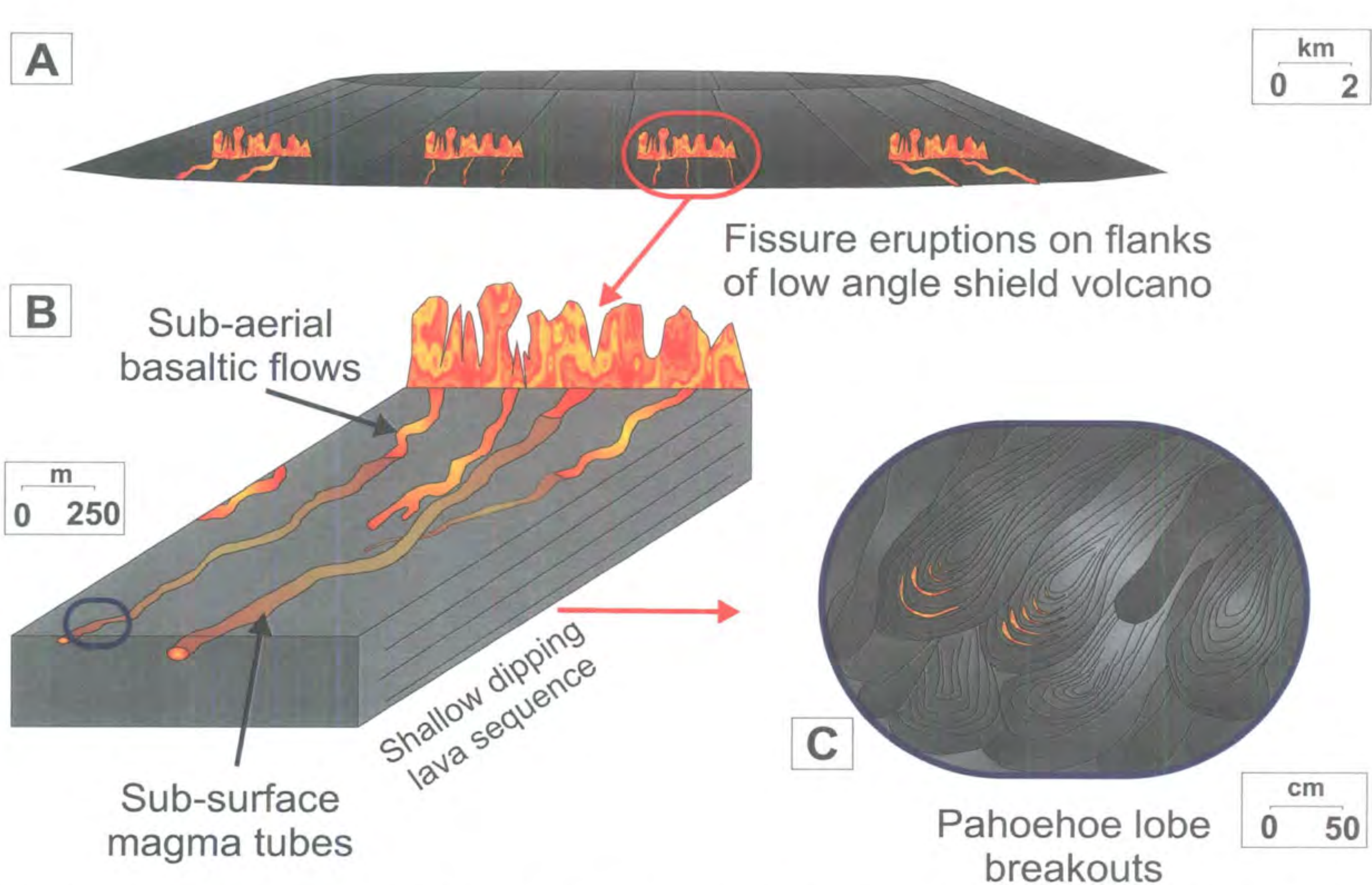


Figure 3-20 Model of lava tubes feeding the lavas of Talisker Bay showing several scales of observation. **A**: The kilometre-scale shield volcanic system exhibiting low angle slopes and passive effusive volcanism; **B**: On the flanks of the shield volcano, fissure eruptions feed the lava field via surface flows and sub-surface lava tubes housed under insulating frozen lava carapaces; **C**: Outcrop observations of lava breakouts at the toe of the growing lava field.

3.4 SUMMARY

The micro-scale observations and interpretations reveal the heterogeneities present within the lava field scale and basin-scale studies of Chapters 4 and 5. When we consider interpretations at larger scales of observation, it is essential to understand these building blocks of lava fields and the effects on the geophysical character of the lava successions. The geology of the intrafacies building blocks has been discussed in this chapter, along with some geophysical concepts (Fig. 3-21). Geophysical implications of these heterogeneities will be developed further in the next two chapters, but specifically discussed in Chapter 6. In the next part of the thesis, Chapter 4, the geometric geological modelling on a lava field scale is discussed and what implications shape and structure can have on our understanding of lava field development and problems with sub-volcanic investigation.

Summary of the Micro-Scale Facies Architecture of Flood Volcanic Successions

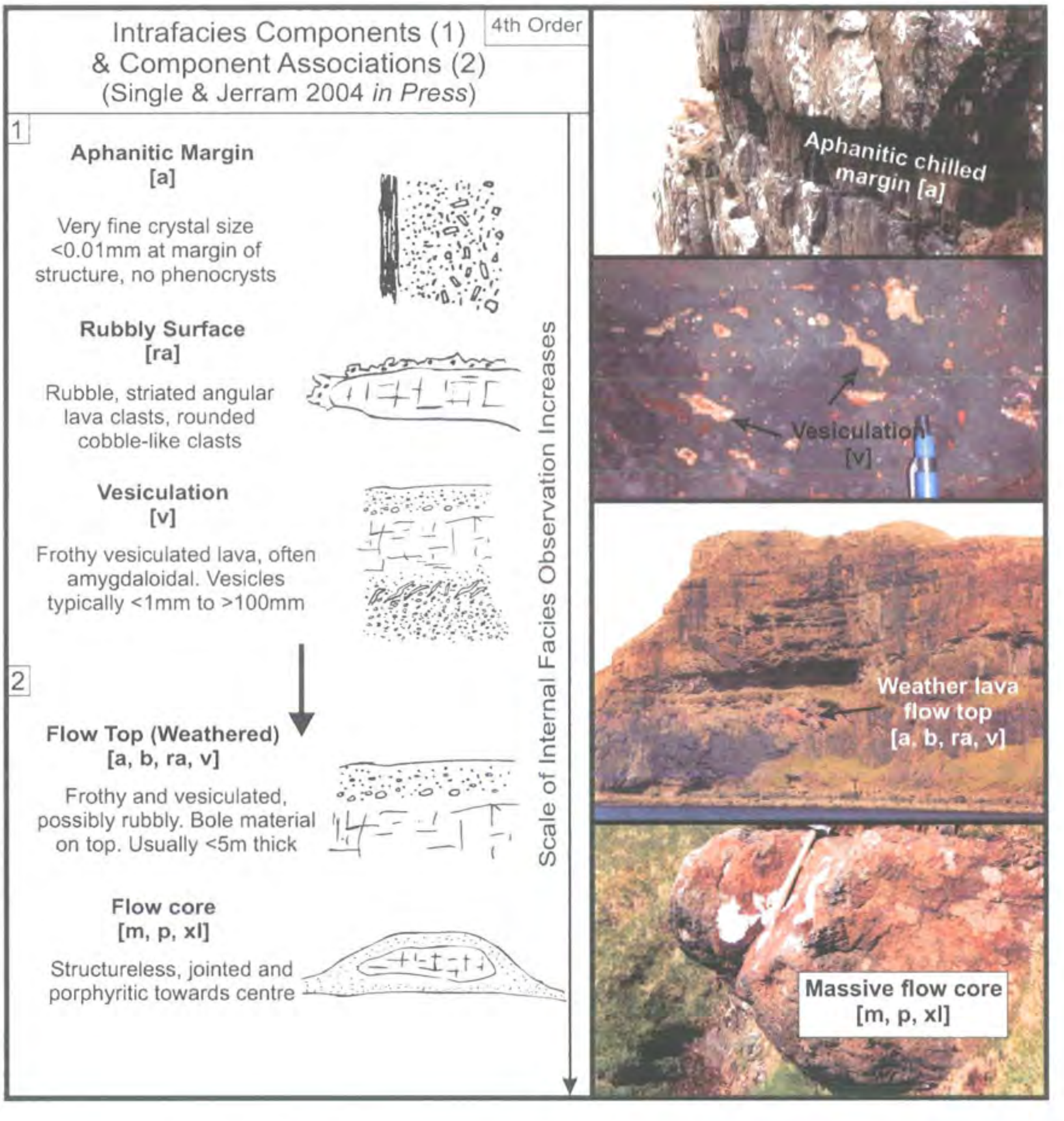


Figure 3-21 Summary of the micro-scale observations and facies interpretations in a CFB igneous succession. All observations are made at the 4th order of heterogeneity which can be studied in the field. This scale contains the geological intrafacies and their constituent components (Single & Jerram 2004 *in press*).

Chapter 4

4. MESO-SCALE ARCHITECTURE – STUDIES OF LAVA FIELD HETEROGENEITY

In this chapter, the scale of observation is increased by an order of magnitude to that discussed in Chapter 3 and the lava field scale structure and architecture of flood volcanics is introduced as the meso-scale architecture. Here, the vertical lava flow stacking patterns, and geometrical heterogeneity found in flood basalts is presented using parts of the North Atlantic Igneous Province (NAIP) and the Etendeka flood basalts of Namibia (Fig. 4-1). Finally, the area of Talisker in the Minginish district of the Skye Lava Field is used as a detailed case study model [NG 132 830].

In the following section, the flow facies architecture of flood basalts are introduced: what they are, how they are recognised and their associations in the architecture of flood basalt succession. The flow facies classification scheme of Jerram (2002) is also introduced and this scheme is applied to examples from lava field sections in the study areas selected.

In section 4.2 the architecture of the Talisker lavas of Skye is presented as a specific case study, and the flow facies architectures and stacking patterns present are developed into a kilometre-scale 3D lava field model in section 4.3.

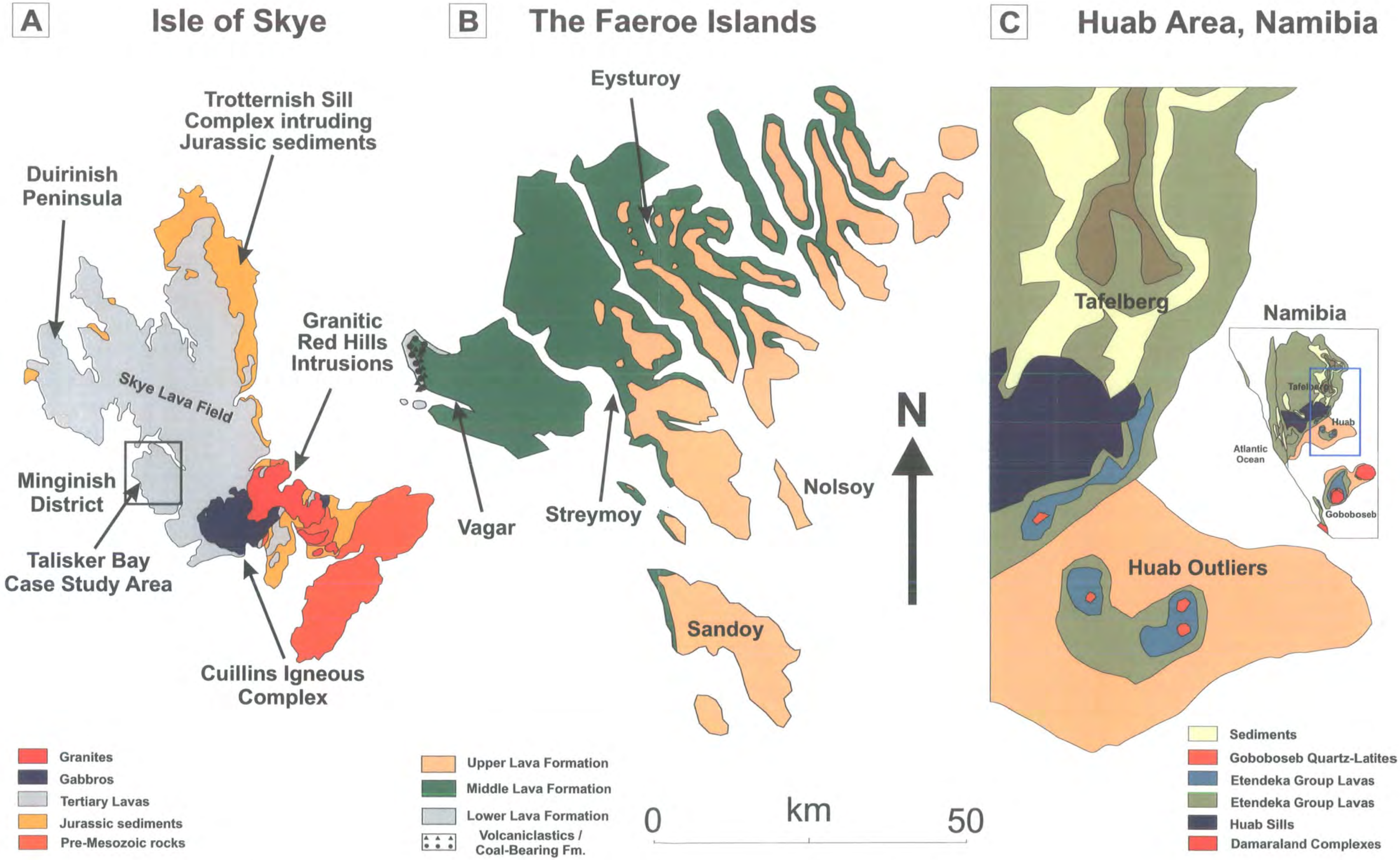


Figure 4-1 Location maps for data sources in the meso-scale architectural study. **A:** The Isle of Skye showing the Minginish district case study area, Scotland (after Emeleus & Gyopari 1992); **B:** The islands of Eysturoy, Streymoy and Vágar in the Faeroe Islands (after Ellis *et al.* 2002); **C:** The Huab Outliers area of the Namib Desert, Namibia (after Milner *et al.* 1995) (inset of location in Namibia). Approximate locations of field studies and geologically important areas are indicated. Each map is drawn to the same scale so that lava field scale comparisons may be made.

4.1 CLASSIFICATION OF THE FACIES ARCHITECTURE AND PHYSICAL VOLCANOLOGY OF THE FLOOD BASALT SUCCESSION

Classifying the physical volcanology of flood basalts on a lava field scale requires an understanding of the internal facies architectural building blocks studied in Chapter 3, and a recognition of how these are pieced together to form the lava field system. Observations and interpretations made on the lava field scale help us to understand the larger, basin-scale architecture discussed in datasets such as the offshore seismic and gravity data of Chapter 5 and to answer questions like:

- What types of lavas exist in certain characteristic reflector sequences?
- Why do some parts of the seismic contain persistent, near-parallel reflectors, yet other parts are dispersed?
- Why is the observed gravity lower than calculated in parts of the lava field?
- What are good marker horizons and how persistent are they likely to be?
- What are the characteristic stacking patterns of a developing lava field?

A classification of the facies architecture of flood basalts has been developed from field studies on a lava flow scale, and in turn, by studying the succession on a kilometre scale in order to understand how the igneous unit fit together in a basin setting (e.g. Jerram *et al.* 1999a; Jerram & Robbe 2001). The classification developed by Jerram (2002), builds on the concepts of studies on the stacking of facies in volcanic units which is used to build an understanding of the volcanology (Cas & Wright 1996; Self *et al.* 1997). The classification is broken down into two tables of characteristic facies types (Table 4-1), and their characteristic associations in the larger scale lava field stratigraphy (Table 4-2) (Jerram 2002).

In the next two sections, field examples of several of the facies types of Table 4-1, and facies associations (Table 4-2) are drawn together from field locations from the three different CFB provinces described above. Illustrating both the work of Jerram (2002) and further architectural facies types studied in this work. Subsequently, the facies architecture of the lava field in the Talisker area of Skye is studied both in 1D logs, 2D correlations and 3D models in order to understand the 3D architecture developed in the volcanological system. Facies associations are interpreted; however their scale determines that these are generally more applicable to the basin-scale architectural studies introduced in Chapter 5 where the vertical and lateral juxtapositions of facies types are observed with examples from the Faeroes Lava Group successions.

Table 4-1 Facies types found in continental flood basalts (after Jerram 2002).

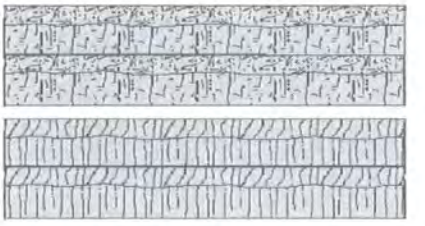
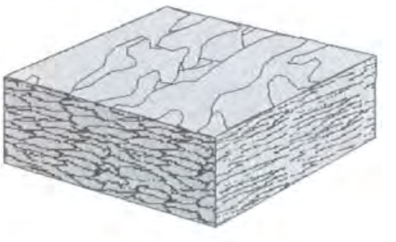
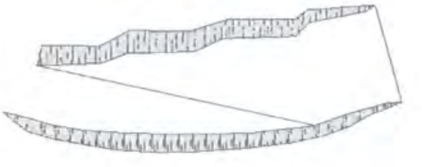
Facies type	Schematic appearance
Tabular-Classic Flow Facies	*Tabular-Classic Facies*
• Tabular laterally extensive thick flows (c.50m) several kms to 10s of km in lateral extent with some examples traveling 100s of kms. The flows, where erupted in wet environments, have classic well developed columnar jointing patterns (Lyle 2000). In arid environments e.g. Etendeka, columnar joints are poorly developed. • Examples – Columbia River Basalts, where flows were erupted into arid environments the columnar joints are not very well developed or absent. Examples – Karoo, Paraná-Etendeka.	
Compound-Braided Flow Facies	*Compound-Braided Facies*
• Thin anastamosing pahoehoe flow sheets and lobes up to several m's in thickness. Often associated with early low volume, low viscosity eruptions early in the formation of CFBs. • Examples – British Tertiary (NAIP), Etendeka, Greenland (NAIP), Columbia River Basalts.	
Dipping Hyaloclastites	*Hyaloclastites*
• Dipping prograding foresets, several ms to 10s of ms thick, of volcaniclastic hyaloclastites. These signify eruption into lakes and sea water. • Examples - commonly found in Greenland (NAIP) (e.g. Pedersen et al. 1998) and some in the BTIP.	
Ponded Flows	*Ponded Flows*
• Ponded units are quite common in CFBs where eruptions fill pre-existing topography. Units can be >100m thick, and may internally differentiate during cooling and crystalization. • Examples include; Etendeka, British Tertiary (e.g. Preshal More, Skye (Williamson et al. 1994)).	
Sill Facies	Sill Facies
• Large sills and sill complexes tend to intrude around the base of CFB where the lava pile is in contact with the sediments it erupted onto. Sills often have a classic step like geometry (Francis 1982) on a large scale making them 'bowl' like in 3D. • Examples are found in the Paraná-Etendeka, Karoo-Ferrar, Greenland(NAIP) -British Tertiary (NAIP).	
Sheeted Dykes	*Sheeted Dyke*
• Often associated with igneous centers in CFBs. Concentrations of thin dykes cutting up through pre-existing lava stratigraphy. • Examples – Karoo, Paraná-Etendeka, British Tertiary (NAIP), Greenland (NAIP).	
Others? Early volcaniclastic/flood lahars from the basal Karoo (Skilling 2001)	

Table 4-2 Facies associations found in continental flood basalts (after Jerram 2002).

Facies association	Schematic appearance
Low angle downlap/toplap • Packages of lavas from different eruption sites, possibly along fissure. Each stacking pattern building up from a different direction. These may highlight significant eruption events • Examples – Ethiopian traps, Deccan Traps, NAIP.	
Volcanic Disconformity • Onlapping relationships between batches of Tabular-classic flow facies resulting in disconformable relationships. These represent flows from different eruptive centers onlapping previous flows that have been eroded. Often very difficult to map out, as the scale of the disconformities can be >50 km, and the two flow type facies are identical. • Example – Etendeka (Jerram et al. 1999b). In many cases on a broader scale these disconformities must exist based on the distribution of different geochemical magma types e.g. Paraná-Etendeka (Peate 1997), Yemen (Menzies *et al*. 1997), Karoo (Marsh et al. 1997).	*Volcanic Disconformity* 
Onlap/Burial–Disconformity • Onlapping relationships between batches of Tabular-classic flow facies and compound-braided flow facies, representing shield volcanoes, resulting in disconformable relationships. • Examples - Etendeka, Greenland (NAIP).	*Onlap/burial -Disconformity* 
Shield Volcanoes • Usually associated with compound-braided flow facies, representing shield volcanoes preserved in the CFB. These tend to be restricted towards the base and the tops of the CFB as the flood volcanism starts up and shuts down. • Examples – Etendeka, Greenland (NAIP), Ethiopian Traps.	*Shield Volcano* 
Sediment Interlayers • Sediments interbedded with volcanics. These are found mainly towards the base of the CFB system where there is some overlap between the active volcanic and active sedimentary systems. • Examples – Etendeka, Greenland (NAIP), Ethiopian Traps Deccan Traps.	*Sediment Interlayer* 
Others? Syn-volcanic rifting folded/faulted disconformities – Etendeka, Ethiopia	

4.1.1 Architectural Facies Types

In this section, examples of some of the facies types present on the meso-scale are introduced: e.g. tabular-type lava flows; compound-braided type lavas; sills and dykes; ponded lava flows and additional field examples of vent facies and a central volcanic complex.

4.1.1.1 Tabular-Type Lava Flows

Tabular-type sub-aerial lava flow systems form from more siliceous and consequently more viscous flood basalt lava types such as basaltic-andesites (Fig. 4-2). The higher viscosity results in a high degree of order in the internal and external organisation of the lava flows produced. Tabular lava flow facies have simple internal geometries, and individual flows may be traced laterally over several kilometres. Thick sedimentary units or weathered and reddened bole beds are common on the top surfaces of individual tabular lava flows suggesting that their frequency of eruption may be low, with long periods of extrusive hiatus after each large-volume eruptive event. Tabular-type lavas may develop well-established joint systems, particularly if they form in wet environments (Lyle 2000). This may often be seen to be divided into two main zones: A colonnade and an entablature (Figs. 4-3 & 4-4A). The colonnade is recognised through its well developed columnar joint sets. Slow cooling from the base of the flow allows their development, whilst the entablature contains more disorganised jointing due to the rapid cooling effect of water circulation in fractures in the top of the flow (Lyle 2000). The classic multi-tired flows of the Isle of Staffa (Fig. 4-4A) in the Scottish Hebrides are in contrast to thick tabular flows of similar chemistry seen in the Etendeka CFBs where the lava flows are simpler and host less organised joint sets, due to the dry environment into which the lavas were erupted (Fig. 4-4B).

4.1.1.2 Compound-Braided Lava Flow Systems

The main building blocks of compound-braided lava types are the inflating pahoehoe (3.1.4.3) and small scale lava lobes (3.1.4.5) intrafacies types. In a compound-braided system (Fig. 4-2), low viscosity basalts effuse and fill localised accommodation spaces in the lava field (Self *et al.* 1998; Jerram 2002). It is this activity which produces the braided internal and external structure of such a lava succession. The internal organisation of compound-braided lavas is complex, producing a lava succession which contains a multitude of seismic scattering directions, and internal density and velocity contrasts. In ancient volcanic systems, correlation of individual flows is difficult over more than tens of metres due to the complexity of the systems combined with exposure issues. Sedimentary units and boles are sparse in compound-braided lavas due to their postulated constant and steady effusion (Self *et al.* 1997). Regular jointing is uncommon in compound lavas; a heavily-fractured habit is most often more prevalent which reduces their resistance to weathering and erosion leading to low angle slopes and their common cover of vegetation.

Studies in 3.1.4 also indicated that lava feeder tubes and pipes only seem to be present in these low-silica, lower viscosity lavas studied. No evidence of lava field toe-feeding pipes has been found in any of the more siliceous lavas studied in this work, or documented in the literature. Their absence suggests that low viscosity, high heat flux systems may be required for such tubes to penetrate and feed the lava field in its distal parts. However, in examples where high volumes of magma are erupted continuously, the inflation mechanism is thought to be a mechanism by which large tabular-type sheet flows may be produced (Self *et al.* 1997). These must be fed internally, implying that internal magma feeders should exist in the geological record.

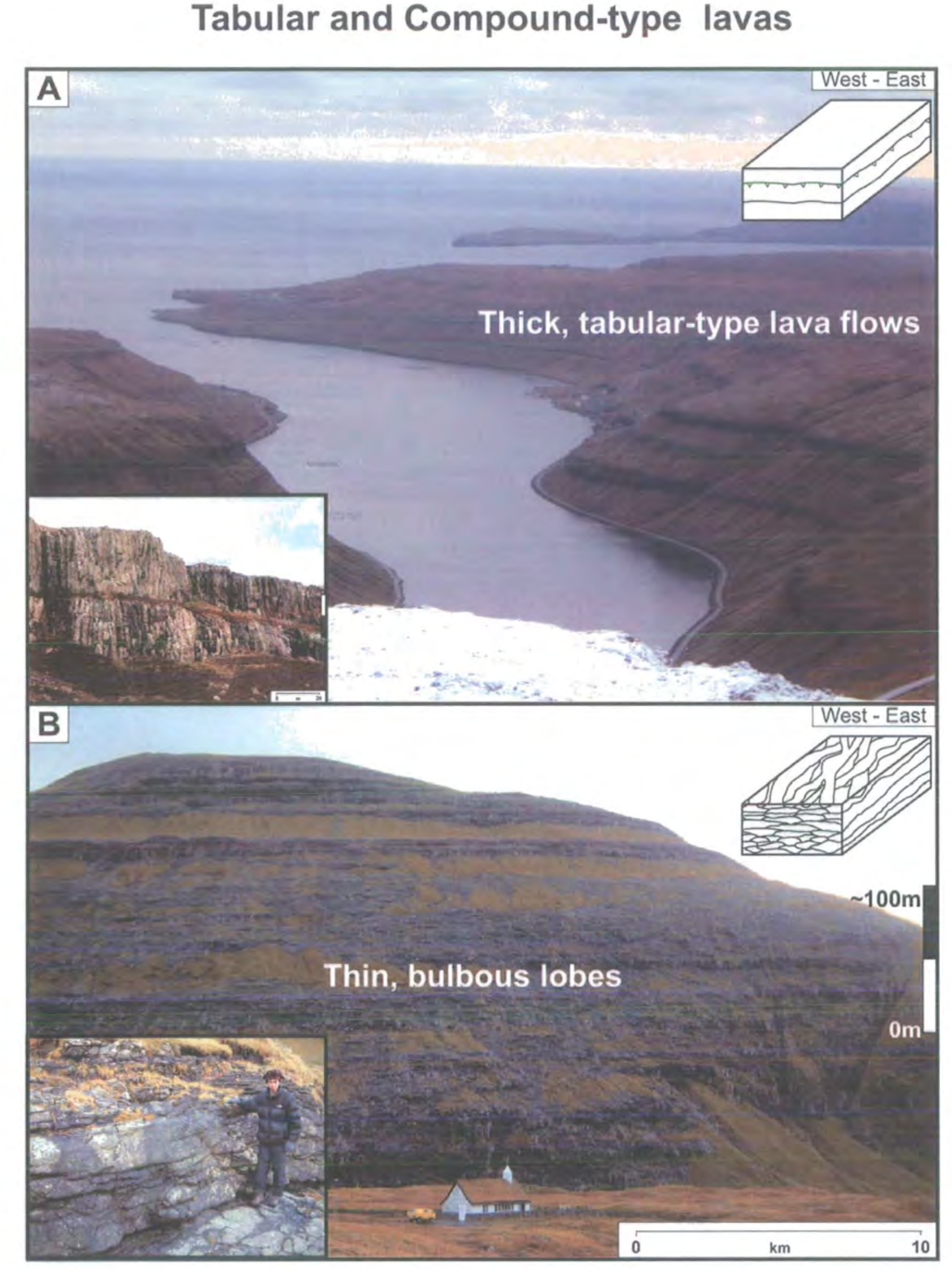


Figure 4-2 Meso-scale lava facies in cliff exposures. **A:** Massive, thick, tabular-type lavas shown dipping Eastwards on Streymoy (Faeroes). Note the lateral extent of these tabular-type lavas. Inset shows flows in the Arnaval Member (Gleann Oraid Fm.) on Arnaval in Skye. Note the flow lobes are thicker than the individual lobes in the compound system (**B**). The relationships between lobes in the tabular-type lavas may only be observed over large distances, typically over 1km; **B:** Compound lavas developed where lower viscosity lavas form lobes in an anastomosing, braided type of architecture. Cliff section shown from the MLF volcanics of Eysturoy in the Faeores. The relationships between individual lava lobes may be understood over metres to tens of metres within this flow facies type. Inset shows a small outcrop of flow break-outs in compound lavas on Vágar.

Muti-tiered tabular-type lava flows

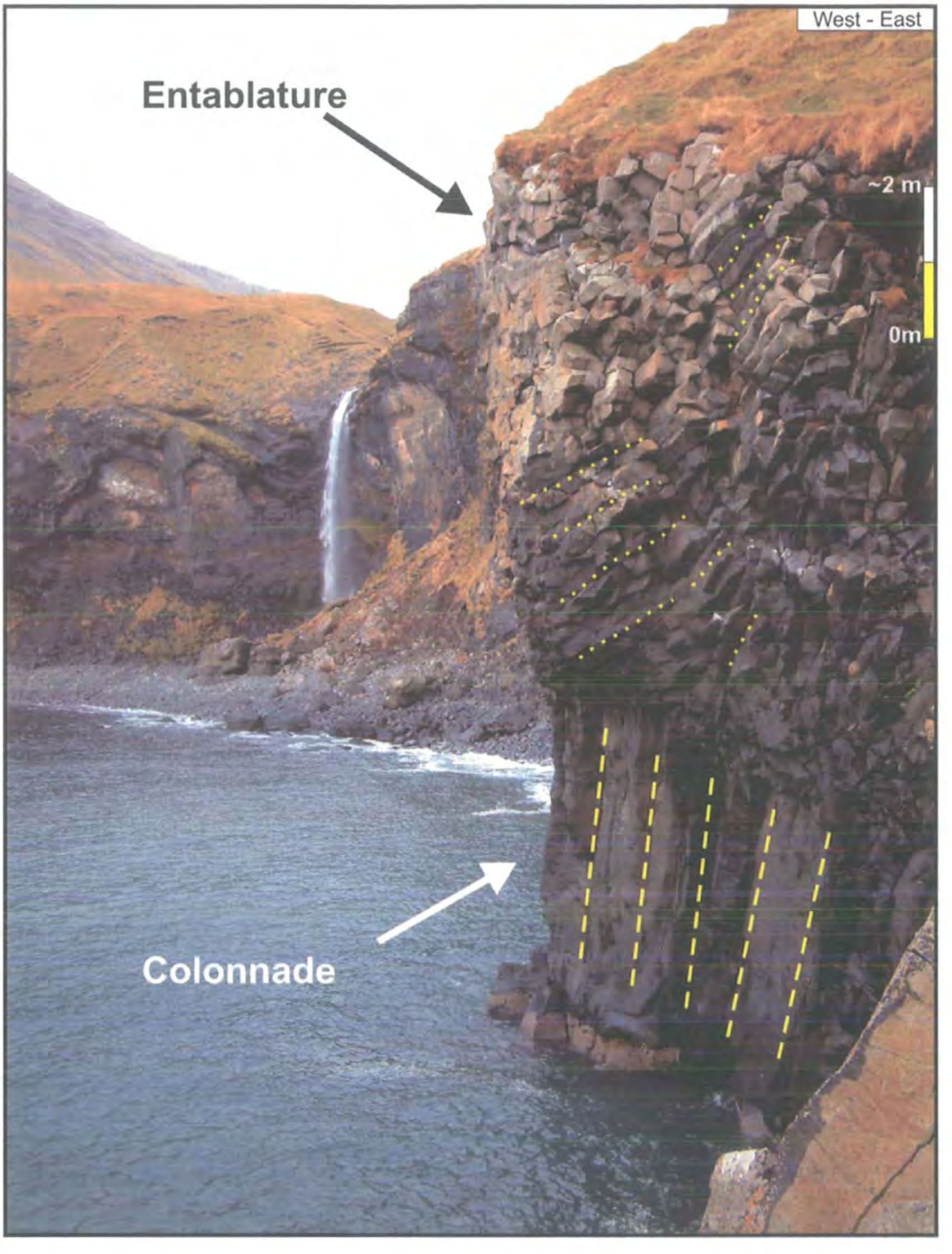


Figure 4-3 Meso-scale lava facies in cliff exposures. A multi-tiered tabular-type lava flow at the top of the Lower Lava Formation (LLF) of the Faeroes Lava Group. The base of the colonnade is obscurred by sea-level, but the section visible is c.8m thick which means that the total flow thickness is in excess of 15m. This photograph looks at cliffs near Akranessker, on the north shore of Sørvágsfjødur, west Vágar (Faeroes). Yellow dashes indicate the stark variation in joint orientations between the colonnade and entablature sections.

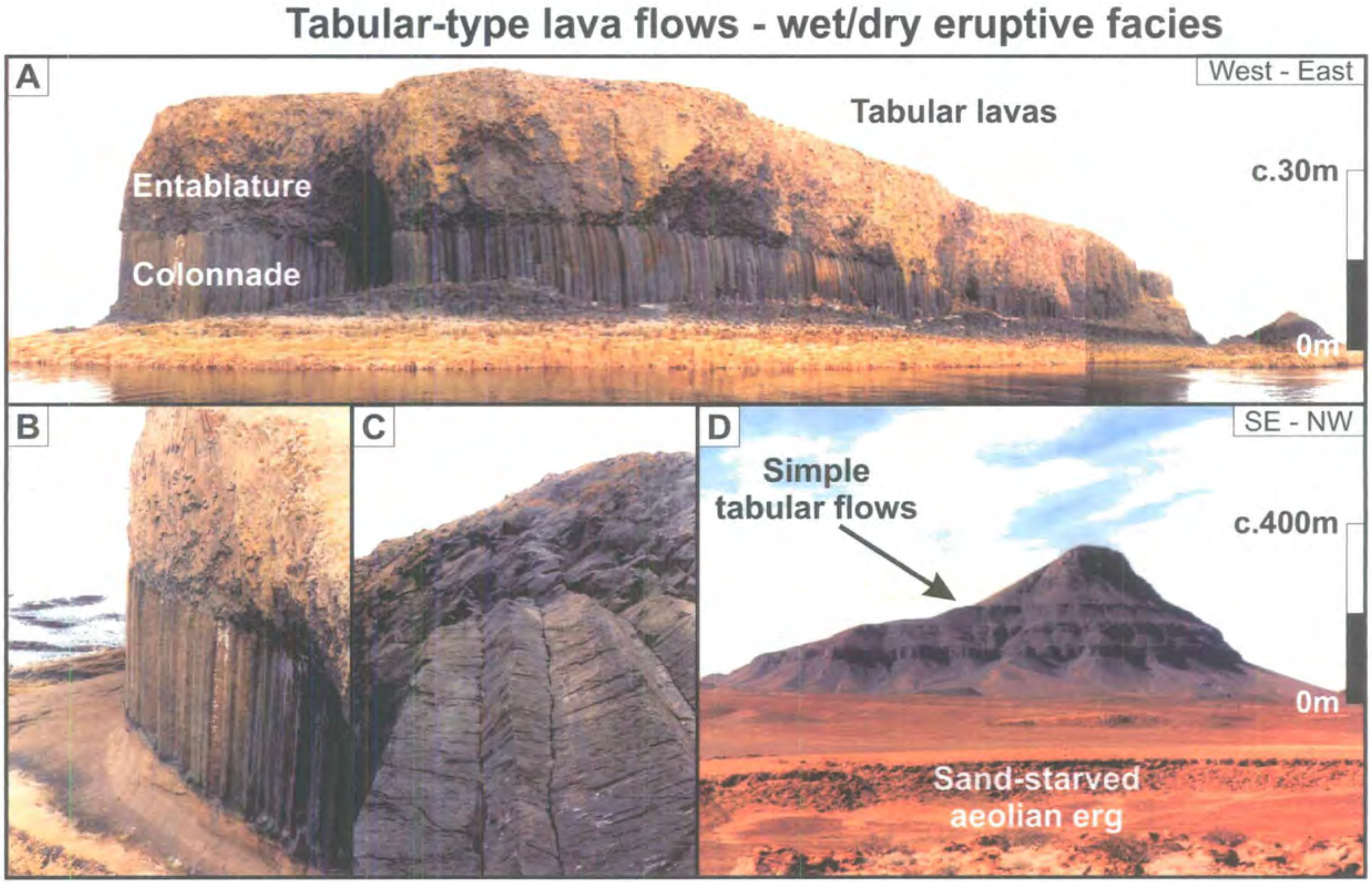


Figure 4-4 Tabular-type lava flows from different eruptive envirnoments. **A:** The Isle of Staffa in the Scottish Hebrides (NAIP) exhibits a classic wet-environment colonnade and entablature multi-tiered lava flow structure; **B&C:** Close-ups of the multi-tiered flow from above and below. The colonnade is c.12m thick and the entablature c.10m; **D:** Contrasting tabular-type lavas of the Etendeka province of Namibia where tabular-type lavas contain little internal structural zonation due to the warm and dry climate into which they were erupted (desert aeolian sandstonesin the foreground - a sand erg choked by the onset of flood volcanism: cf. Jerram *et al.* 1999b).

4.1.1.3 Sills and Dykes

Sills form substantial bodies with dish-shaped geometries, usually towards the base of flood basalt provinces. Examples of flood basalt province sills are seen in the Trotternish sill complex of NE Skye (Gibson 1990; Thomson 2003) and in the Huab sills of the Namib desert, Namibia Duncan *et al.* 1989) (Fig. 4-5). In the sub-surface, mapping of sills has been performed in 2D seismic (Chapter 5) and in 3D seismic by workers such as Smallwood & Maresh (2002) and Trude *et al.* 2003. Sills that sit towards the bases of flood basalt provinces are often tens of metres thick, several kilometres in length, and often exhibit well-developed columnar joint systems (Fig. 4-6).

Dykes are considered to be feeder conduit systems for feeding lavas being extruded at the top of the lava field, and also for feeding magma within the volcanic succession. In Carsaig Bay, south Isle of Mull, a dyke may be observed to intrude up through the Jurassic sands underlying the lava field, form a thin sill c.100m up the cliff section, then proceed up the cliffs through the lava succession present (Fig. 4-6). If a dyke has acted as a feeder for an extended period of time, this may be recognised by an increased width of metamorphic aureole on each side of the dyke highlighting the increased and prolonged heat flux. The volume significance of dykes is only a localised issue closer to dyke axes where dyke swarms may be present.

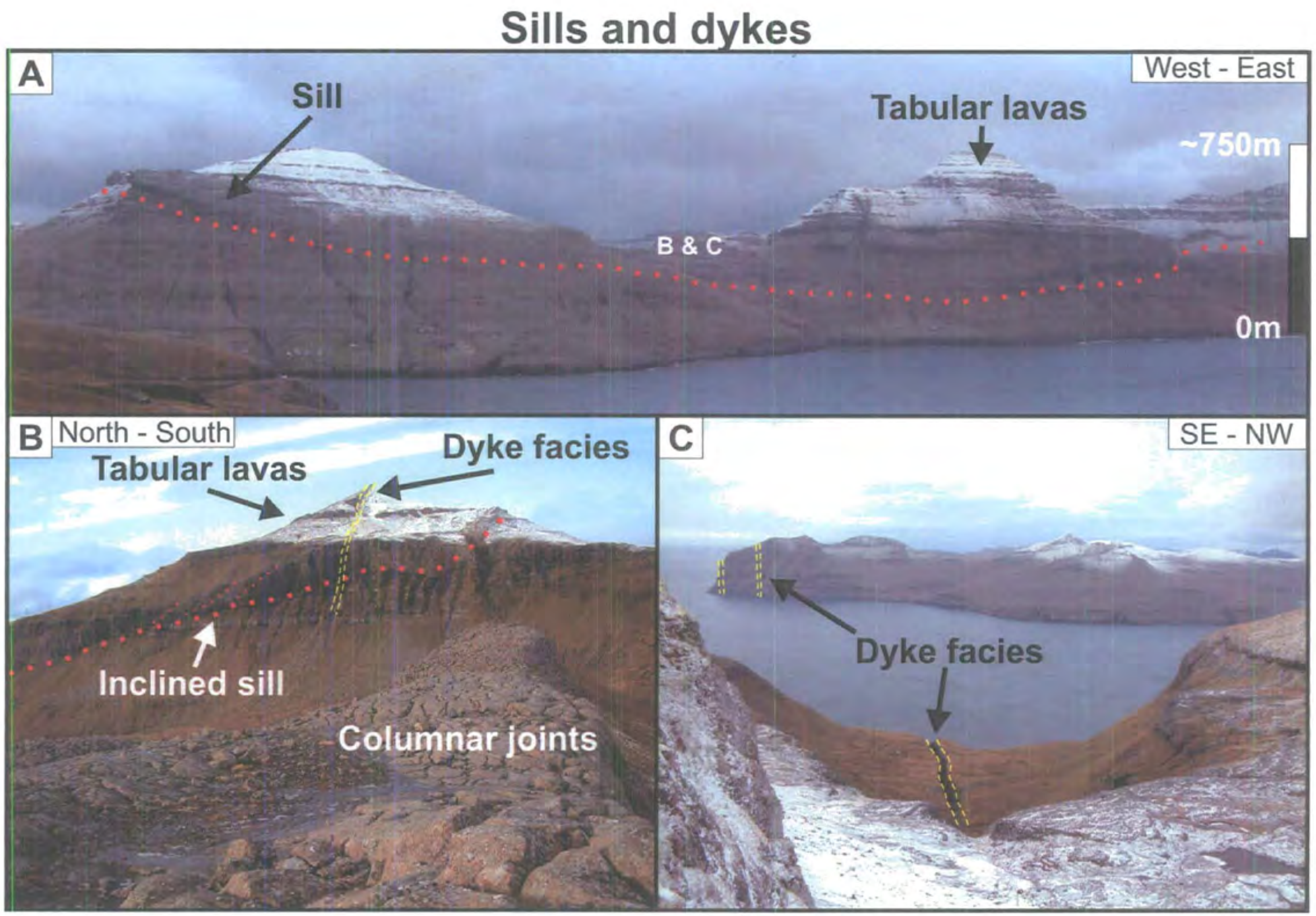


Figure 4-5 Sills and dykes flow facies architectures in the flood basalt volcanic succession of the Faeroes Islands. **A:** Looking SE from near Kvívík at a large, bowl-shaped sill south of Skaelingur on the SW coast of Streymoy. The location of photographs B and C are marked; **B:** Standing on the top surface of the inclined sill looking north where the segmented (piggy-back style intrusion) sill is seen to intrude the tabular Upper Lava Formation (ULF) and get intruded by a dyke; **C:** Looking SW from the sill to Vágar at dykes trending SW-NE.

Thick sill complexes and feeder dykes

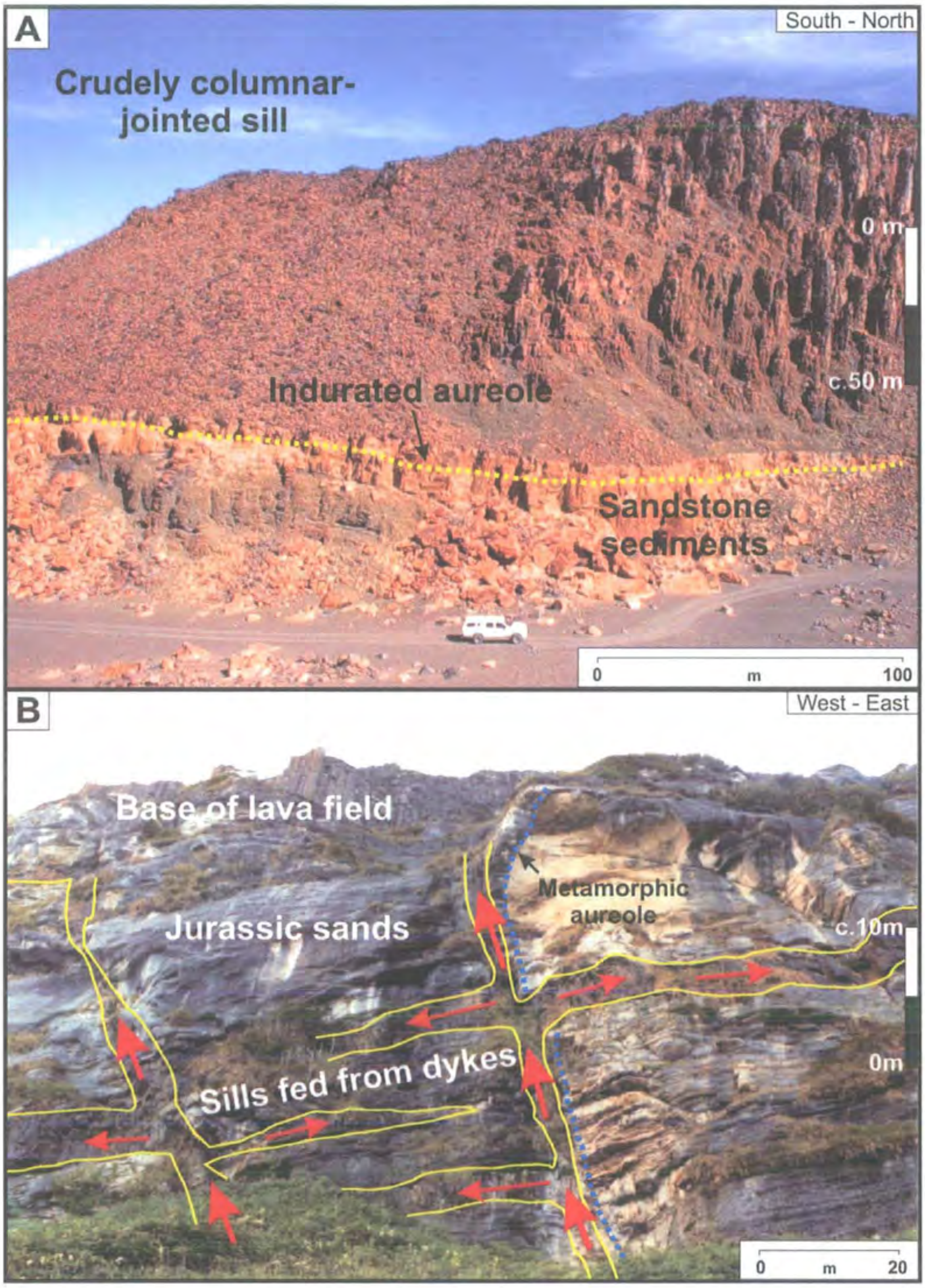


Figure 4-6 Sills and feeder dykes. **A:** A thick sill in the Etendeka flood basalts, Namibia. These picritic sills lie at the base of the Etendeka CFB stratigraphy and severely bake the aeolian and fluvial sandstones beneath; **B:** Feeder dykes in the cliffs of Carsaig Bay, Isle of Mull in the British Tertiary Igneous Province (BTIP). Metamorphic aereoles are evident where the Jurassic sands have been baked by the regular use of the conduits. Also note that the intruding sheets also intrude concordantly into the Jurassic sands as thin (<5m thick) sills.

4.1.1.4 Lava Flow Ponding

Ponding of lava flows may be facilitated by topographic lows, where lava flows fill a pre-existing valley system (Fig. 4-7A), where lava lakes form in volcanic caldera settings (e.g. present day Kileuea crater, Hawaii), or where a physical barrier prevents extruded lavas from spreading out as a normal, unconfined series of lava lobes (Jerram *et al.* 1999a). Ponded flows filling pre-existing eroded topographic lows may sit directly on eroded sedimentary or volcaniclastic material as in the cases of Preshal More and Preshal Beg, Isle of Skye (Williamson 1979; Williamson & Bell 1994).

4.1.1.5 Central Volcanic Complexes

Central volcanic complexes form substantial, coarsely crystalline bodies in the crust, and often cut though flood volcanic sequences. They may be commonly recognised by their anomalously high bouguer gravity signatures. On the Isle of Skye, the Cuillins are formed by large intrusive bodies of the Black Cuillins gabbroic centre, and the Red Cuillins granitic complexes. The gabbroic centre is considered to have fed the Preshal More type lavas of west-central Skye (Williamson & Bell 1994), prior to its intrusion through the entire sedimentary and volcanic succession (Hamilton *et al.* 1998). Fig. 4-7B shows the relationship of the huge Black Cuillins central volcanic complex in relation to the lavas around the Talisker Bay area of Skye.

4.1.1.6 Vents

A vent facies is observed in the Faeroe Islands where good cliff exposure is present at the base of the Middle Lava Formation (MLF) volcanics. Dykes and reddened brecciated material may be seen above the Lower Lava Formation (LLF) lavas on the south coast of Vágár. The example vent is a zone of highly contorted, reddened, jointed and veined intrusions through pre-existing lavas, and the Coal Bearing Formation which lies above the LLF (Fig. 4-7C). Close study of this facies has not been possible due to access restrictions.

4.1.2 Architectural Facies Associations

4.1.2.1 Lava flow Pinch-outs, Onlap and Disconformities

Thickening and thinning of individual lava flows may be observed on the tens of metres scale through to kilometres scale. Subtle onlap and pinch-out relationships are often only revealed by detailed field mapping interpretation, however, if exposure -is exceptional over long distances, it may be possible to trace the pinching out of a flow at its toe (Fig. 4-8). Pinch-outs are best observed as subtle onlapping relationships between the flows of a tabular-type lava system, where the distal ends of individual lava lobes come to a termination. Subtle onlapping and wedging out of lava flows may also reveal tectonic changes that may have occurred in the lava hosting area and also larger scale disconformities between volcanic systems (Fig. 4-8). Disconformities within the volcanic succession may be revealed in areas of high quality exposure (e.g. Fig. 4-8A) where subtle stratigraphic dip variations are noted, or as major disconformities between lavas of the same or different geochemical types (e.g. Jerram *et al.* 1999a). The timing of the development of several lava fields within one CFB province also leads to the assumption that volcanic disconformities are common in the geological record, for example in the BTIP, the timing of the Skye and Mull lavas suggests that these are likely to have subtly disconformable relationships (see Fig. 1-3 for geochronology and Jerram & Widdowson 2004 *in Press*).

Lava ponding, central volcanic complexes and vents

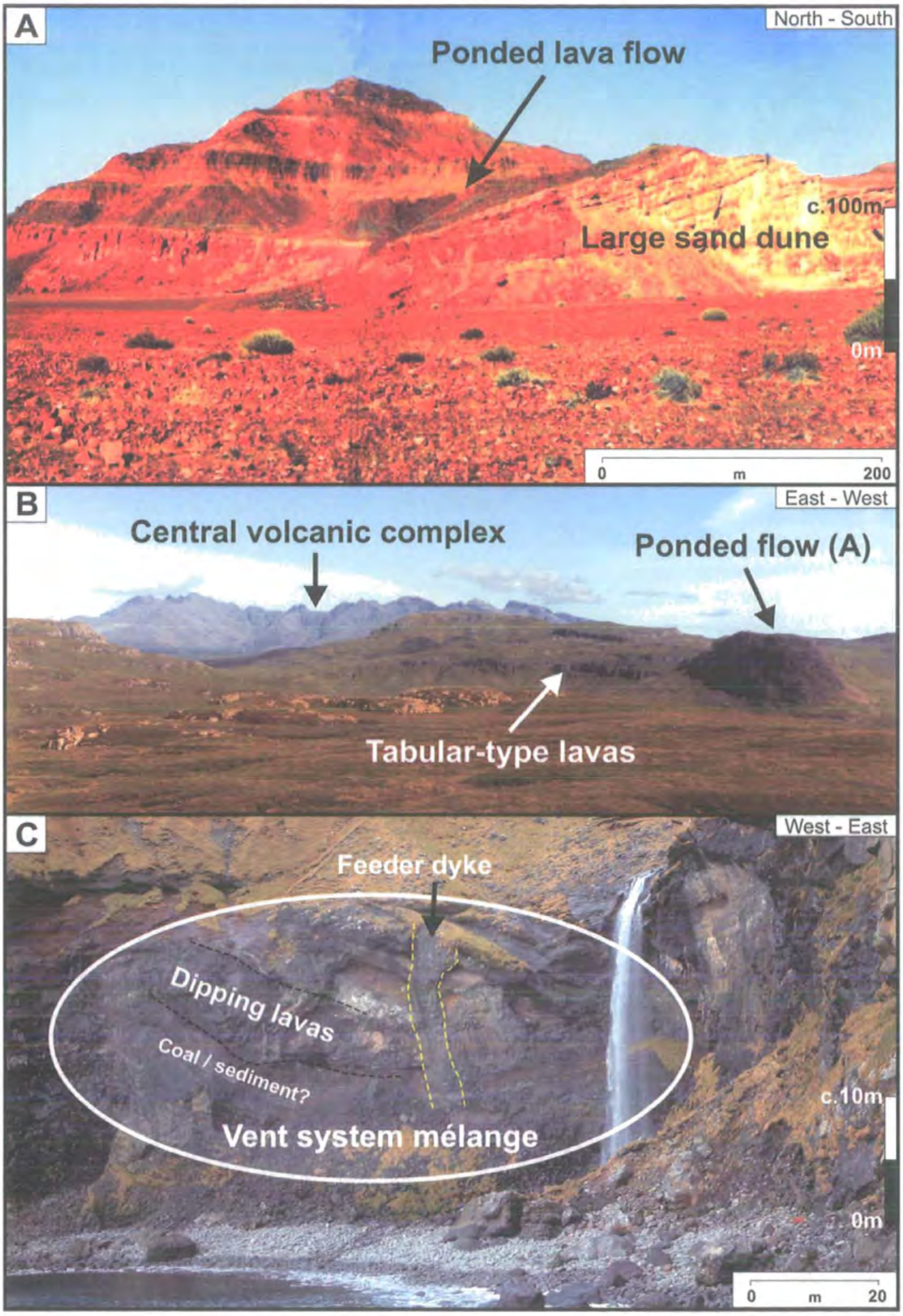


Figure 4-7 Meso-scale lava facies in cliff exposures. **A:** Thick basaltic-andesite flow ponded behind a sand dune in the Huab area of the Etendeka, Namibia; **B:** The Cuillin Igneous Complex lies SE of the foreground Skye Lava Field volcanics viewed from Beinn nan Dubh-lochan. The ponded Preshal More flow is considered to have effused from the Cuillins source; **C:** A mélange of dykes, complex joint sets, unorthodox complex dips, oxidized zones and breccias are interpreted to form vent facies in a cliff section at Akranessker, on the north shore of Sørvágsfjødur, west Vágar (Faeroe Islands).

Lava flow pinch-out, disconformity and overlap

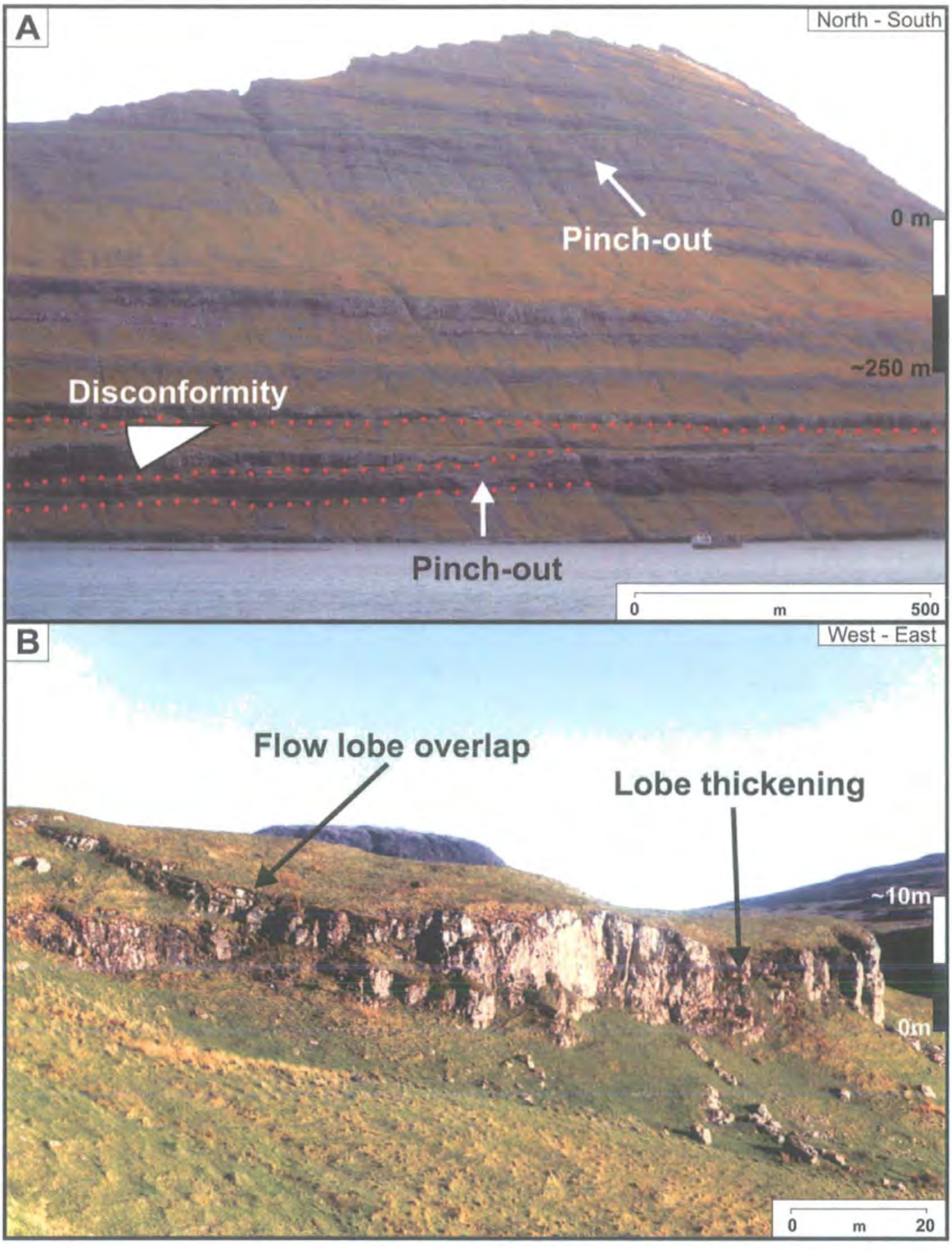


Figure 4-8 Meso-scale lava facies in cliff exposures. **A:** Large-scale lava flow pinch-outs in the Middle Lava Formation (MLF) volcanics looking east from Ljóságjogy on the 622 road round the south shore of the Funningsfjørdur (N. Eysturoy) in the Faeroe Islands. A subtle angular disconformity is illustrated where the lavas lying above the clear pinch-out close to sea-level are assuming a more horizontal attitude relative to the underlying succession; **B:** A flow overlap occurs where a later flow fills accommodation space created by the topography of previous extrusive events. At the base of the rugged part of Preshal More, a basaltic-andesite is observed to overlap an earlier flow as it propagates towards the west.

4.1.3 Facies Architectural Classification Summary

The classifying of architectural facies in the volcanostratigraphy, provides us with a simple tool for the description and interpretation of the lava flow scale (meso-scale) features of the physical volcanology. The understanding of how these facies architectural types may juxtapose forming facies associations on the lava field scale is important in developing models of the lava system on the whole. In the following section, the vertical stacking patterns of the architectural facies (Table 4-1) in the Talisker area of the Isle of Skye are discussed and their lateral variability developed in correlations through the lava field. These, in turn are brought together in the form of the 3D geometrical model of the lava field which is discussed in section 4.3.

4.2 THE FACIES ARCHITECTURE OF THE TALISKER BAY CASE STUDY AREA

Thus far, this chapter has introduced the facies architecture of flood basalts highlighting heterogeneities on the metre-scale up to the kilometre scale. This section illustrates how 1D field logging data has been analysed and incorporated into the architectural study to provide a kilometre-scale heterogeneity study of the facies architecture present in the Talisker area of Skye. On this longer wavelength scale, it is important to remember and consider the building blocks of the lava field: from the flow facies described above, down the level of the intrafacies and rock property distributions studied in Chapter 3.

Log section data covers much of the north of the Minginish district (Fig. 4-9). Twenty log sections (marked in black) have been recorded up the hillsides around Talisker, plus numerous lateral log contact traverses. The log sections have been tied into correlation panels in order to constrain the structure of the lava field on the whole. The correlation panels illustrate the direct correlations of basal contacts and prominent bole or sedimentary units throughout the lava sequence, and therefore provide a basis for breaking down the lava sequence into flow facies on the hundreds of metres to kilometres-scale. Cliff sections exhibit extensive bole beds particularly clearly; however inland, these tend to be obscured by scree and vegetation. A key to successful inland lava sequence correlation lies in developing an understanding of the thickest, more extensive tabular-type lava flows and their stacking patterns, and the presence of thick ferrallitised bole beds. Whereas boles and other extensive marker beds (e.g. tuffs) may be unseen on the Skye landscape, prominent stacked tabular-type lava flows of basaltic-andesitic compositions may be traced for hundreds of metres to kilometres in the CFB lava field succession.

The lava stratigraphy in the Talisker area of the Minginish district of Skye, has been developed by the extensive work of Williamson and Bell (Williamson 1979; Williamson & Bell 1994; Bell & Williamson 2002) (Table 4-3).

Table 4-3 The lava formations and members of the Skye Lava Field in west-central Skye (after Williamson & Bell 1994).

Formation	Member
Talisker (8)	Preshal Beg Conglomerate
Gleann Oraid (7)	Cnoc Scarall
	Sleadale
	Arnaval
Loch Dubh (6)	Eynort Mudstone
Fiskavaig (5)	Rubha nan Clach
	McFarlane's Rock
Glen Caladale (4)	Skridan
	Sgurr Buidhe
	Stac a'Mheadais
	Tusdale
Cruachan (3)	Glen Brittle
	An Crocan
Bualintur (2)	
Rubh'an Dunain (1)	Creag Mhor
	Meacnaish
	An Leac

Their sub-division of the lava field is based on the field-mapping and logging of boles and sedimentary units within the lava field and to some extent on chemostratigraphy.

In the following section, log sections are introduced (Fig. 4-9), and correlated through the lava field stratigraphy into a series of 2D correlation panels in conjunction with field examples of flow facies architecture. A generalised facies architecture-based stratigraphy of the area is then proposed as a summary of the architectural stacking arrangement of the lava succession. This is important as this scale of heterogeneity will govern the interpretation of offshore datasets through flood lava sequences.

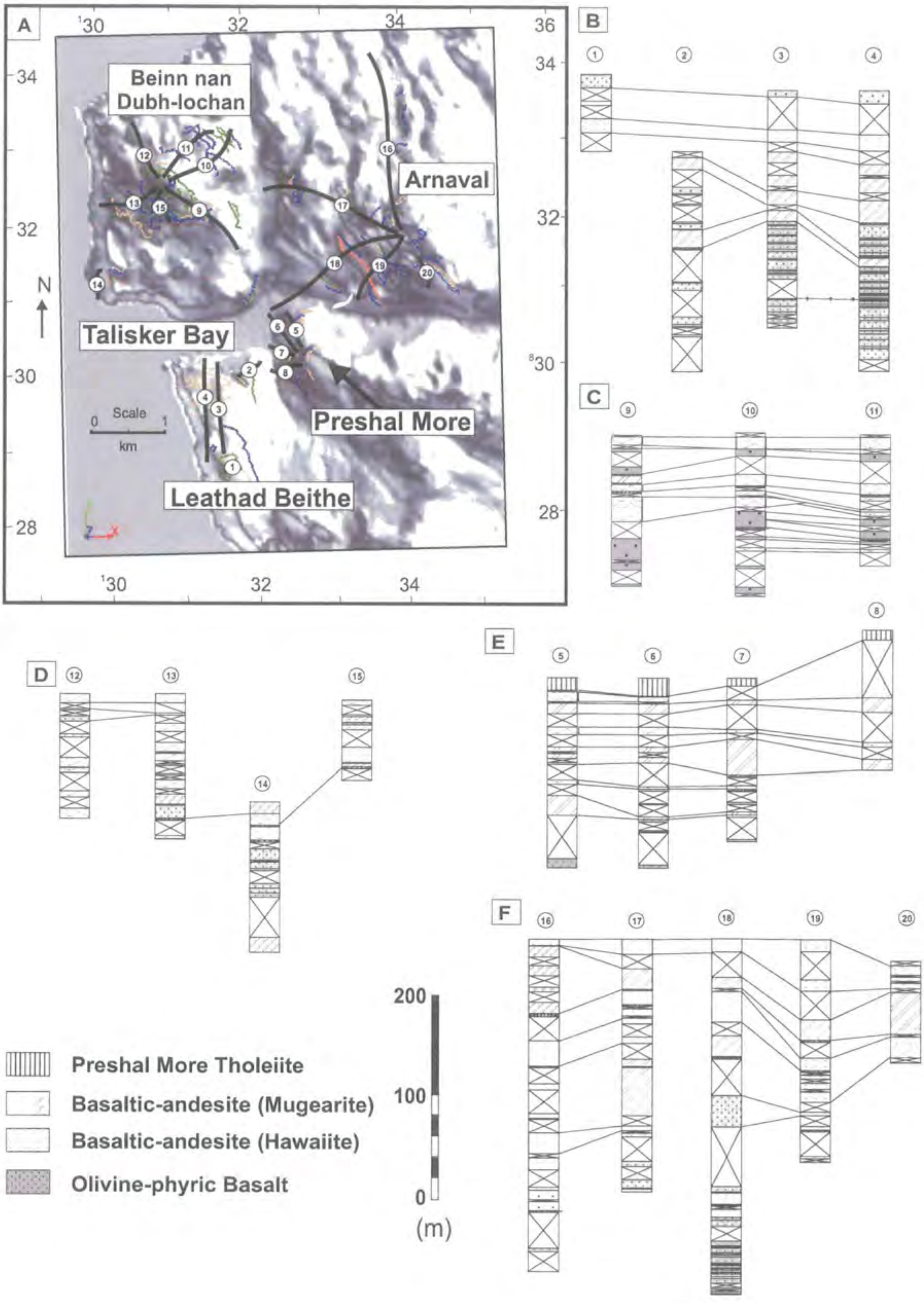


Figure 4-9 Log section data across the north of the Minginish district. **A:** Log section locations (black lines) on a map of the area; **B:** Sections on Leithad Beithe (Fig. 4-10A); **C:** Sections on Beinn nan Dubh-lochan, east side (Fig. 4-12A); **D:** Beinn nan Dubh-lochan, west sections (Fig. 4-12B); **E:** Sections on Preshal More, Northwest side (Fig. 4-10B); **F:** Arnaval mountain sections (Fig. 4-13).

4.2.1 Log section insights into Flow Facies Architecture

In this section, the lithological log data collected in the hills around Talisker are studied. The vertical log data provides an understanding of how the volcanic succession and flow facies architecture developed over the course of time, and the correlations and lateral logs allow the geometry of the lava field on the whole to be constrained. Each correlation panel of log sections is studied individually starting with the log sections which are located closest the Talisker Bay case study area of Chapter 3. By working away from the micro-scale case study area, it is easier to understand how the intrafacies building blocks discussed in Chapter 3 combine to form the flow facies architectural types discussed in 4.1.

4.2.1.1 The Leathad Beithe area (Sections 1-4)

The great thickness of volcanics logged up the hillside of Leathad Beithe to the south of Talisker Bay show a large variety of different lithologies and this variety reflects variations in the volcanological styles of the succession on the whole (Fig. 4-10A). Towards the base of the logs, the volcanics are dominated by olivine-basalts that are highly fractured and rubbly. These olivine-basalts are only visible in stream sections however these lavas may be correlated with the lava flows used in the micro-scale intrafacies studies (3.1.4) at the south side of Talisker Bay.

The correlations of thin tuff beds are possible in the two most westerly sections 3 & 4. The upper of these tuffaceous beds is considered to be correlateable with the upper tuff seen in the south of Talisker Bay in the micro-scale intrafacies study. In this high cliff section (Fig. 3-13), the tuff appears to be laterally persistent for >1km in the cliff section to the south of Talisker Bay.

Higher up the Leathad Beithe section, the thickness of massive lava core zones increases until a definite change is noted in the volcanology of the system. The thin olivine-basalts containing highly fractured and vesiculated units in compound-braided style lava succession are superseded by thicker, more resistant and laterally extensive tabular-type lavas. These are fine-grained and in many cases, plagioclase-phyric. Individual flows are >8m thick and form craggy scarps over the landscape for hundreds of metres. Many exhibit crude columnar-jointing patterns consistent with eruption into a wet environment where cooling is assisted by the action of water flow through fracture systems in the upper parts of the lava flows (Lyle 2000). A photographic montaged section of volcanics of Leathe Beithe is shown in Fig. 4-11A.

4.2.1.2 The Preshal More area (Sections 5-8)

The volcanics of the Preshal More area (Fig. 4-10B) form a similar succession to that of Leathad Beithe, however, thickening and pinch-out relationships are more obvious in this part of the lava field; particularly in the mid-section thick basaltic-andesite flows. The top of the Preshal More logs is capped by the huge tholeiitic, ponded lava flow of the Talisker Formation (Table 4-3). This sits on an eroded basaltic-andesite lava flow surface (Williamson 1979) and forms a striking columnar-jointed outlier (Fig. 4-11B).

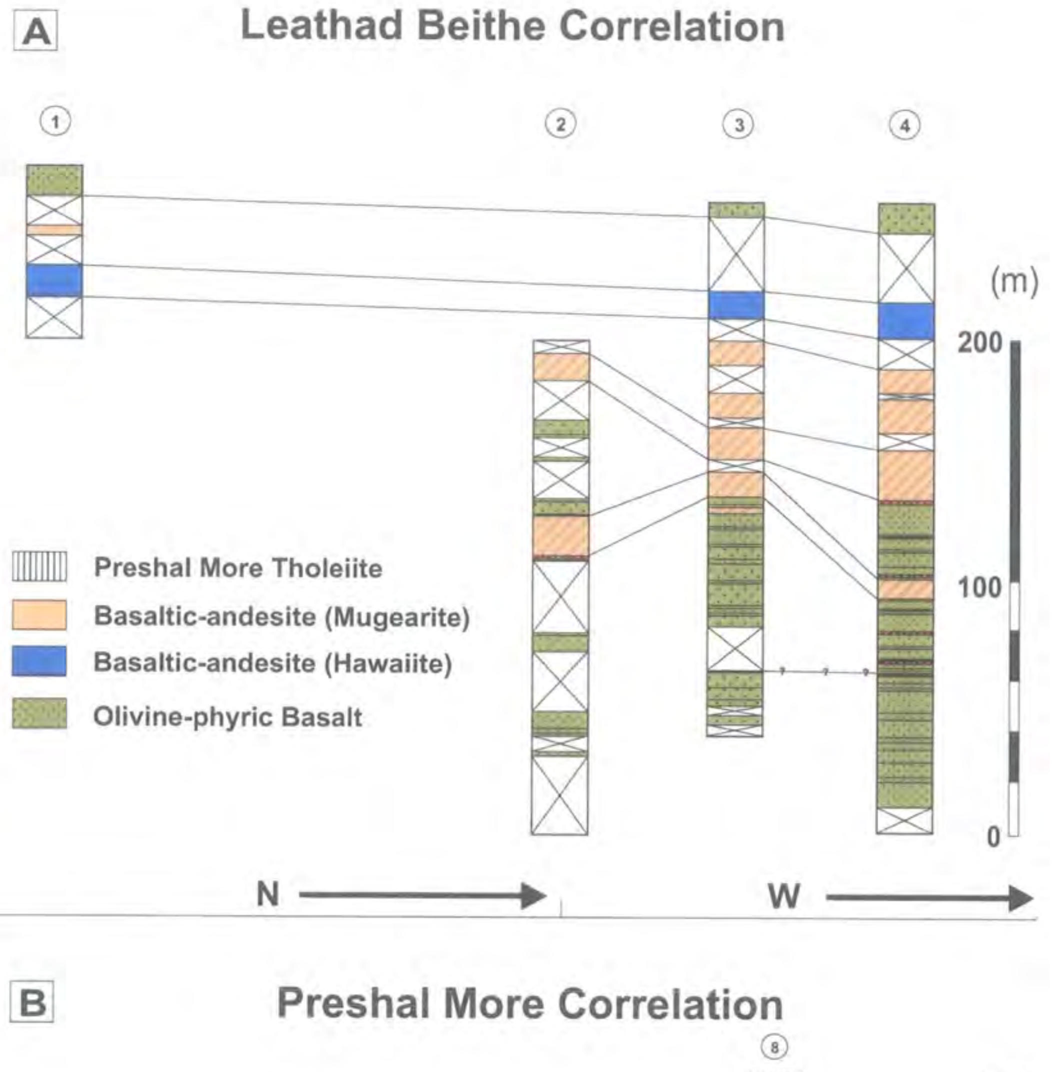


Figure 4-10 **A:** The correlation made through the Leathad Beithe / Beinn nan Cuithean section through the hills south of Talisker Bay; **B:** Correlation round the base of Preshal More through volcanics of mixed facies architecture and origin.

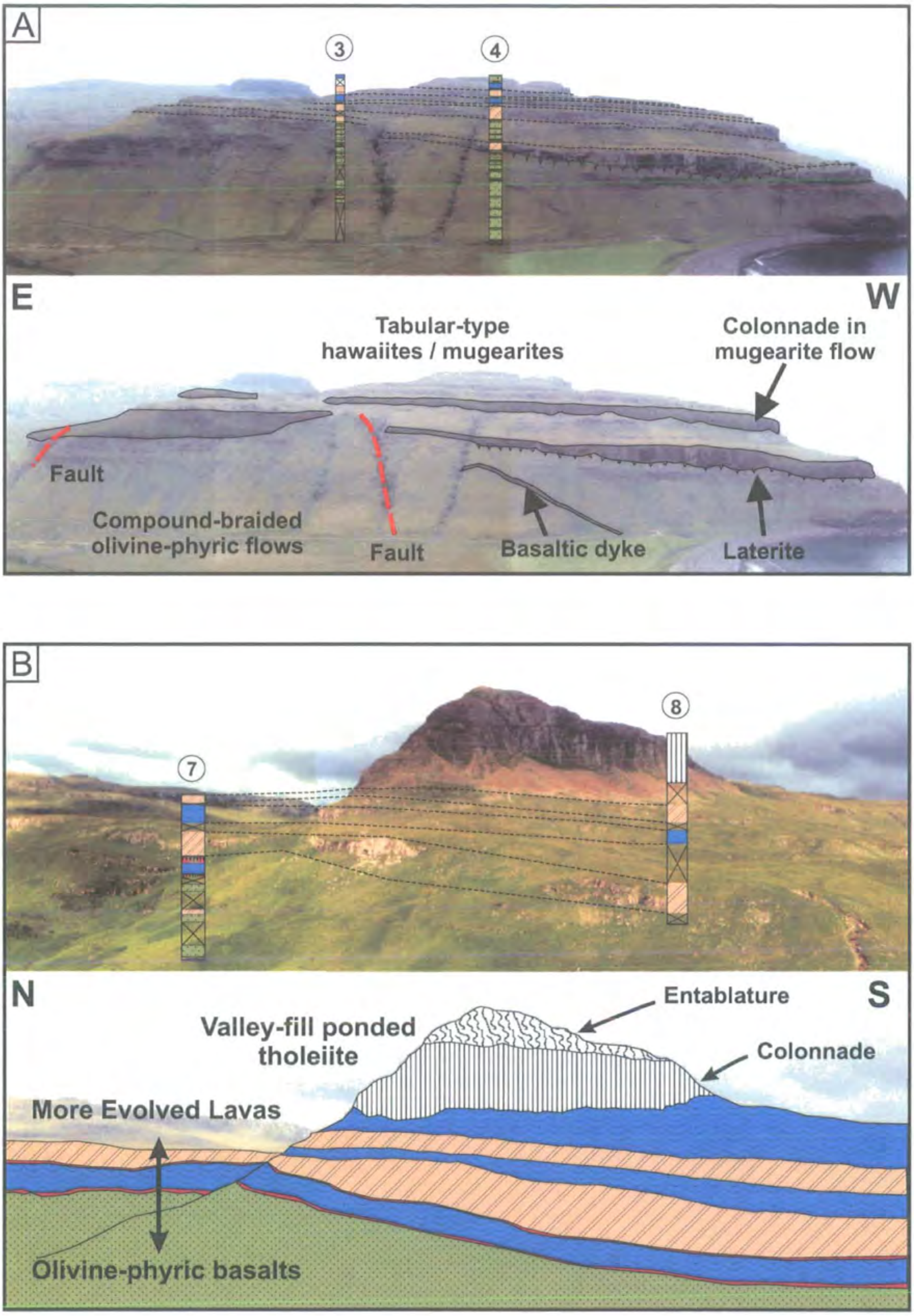


Figure 4-11 **A:** The hillside of Leathad Beithe, south of Talisker Bay. The lava sequence shows highly vegetated olivine-phyric lavas of the lower architectural sequence towards the base, and more massive, tabular-type lava flows of the upper architectural sequence higher up the succession; **B:** Preshal More sections 7 & 8 imposed on the field stratigraphy with interpretation of facies architecture beneath.

4.2.1.3 The Beinn nan Dub-lochan area (Sections 9-15)

In the log sections of Beinn nan Dubh-lochan, north of Talisker Bay, a succession of basaltic-andesites dominate the upper parts of the exposed lava field succession (Fig. 4-12). These belong to the Loch Dubh Lava Formation (Table 4-3) that overlie and interleave with the Arnaval Member of the Gleann Oraid Formation to the north of Talisker Bay. The flows are characteristically tabular and <8m thick.

4.2.1.4 The Arnaval area (Sections 16-20)

Arnaval itself offers one of the best exposures through much of the lava succession in this part of Skye (Fig. 4-13). As in the previously described logs and correlation panels, the Arnaval mountain succession displays characteristic olivine-basalts in it lower reaches. These are considered to be part of the Rubha nan Clach Member of the Fiskavaig Lava Formation on the northern side of Talisker Bay (Table 4-3) (Williamson & Bell 1994). To the south of Talisker Bay, similar olivine-basalts are seen to be present as the Skridan Formation of the Glen Caladale Lava Formation suggesting that these olivine-basalts being erupted at a similar time, but possibly from different volcanic sources.

Few tabular-type lava flows exist in the lower reaches of the Arnaval log sections, however in the upper parts, flows exist in excess of 10m thick. These are particularly prevalent in the Na Huranan cliff section which faces south over the minor road leading from Talisker to Eynort. This section exhibits a multitude of flow facies architectural styles within the basaltic-andesites present (Fig. 4-14).

At the base of the crags is a plagioclase-phyric basaltic-andesite flow about 8m thick. The top surface reveals no signs of brecciation, however it is immediately capped by a 30cm zone of holocrystalline, finely columnar jointed basalt which marks the chilled base of the next, columnar jointed flow. This flow is observed to pond in the topography of the lower lava (Fig. 4-14) and also pinch-out toward the west. The top is marked by a thin vesiculated zone no more than 1m thick. Another thick tabular flow lies above this; however this is crudely columnar and much thicker than either of the underlying flows described (c.20m). In all exposed parts, the basal contact sits on a highly weathered top surface of the flow beneath in the west of the outcrop. The field relationships shown in Fig. 4-14 however, also reveals that the ponded lava flow was effectively dammed by the topography on the lower flow surface, causing the overlying flow to onlap and wedge-out whilst the ponding prevented the development of a weathered top surface in the east. The irregular joint patterns observed in the top flow are attributed to water circulation in fractures in the upper portions of the flow. The flow correlates across the Talisker Graben, however its thickness across the graben in the west is much thinner which may indicate a magma source from the east (c.10m).

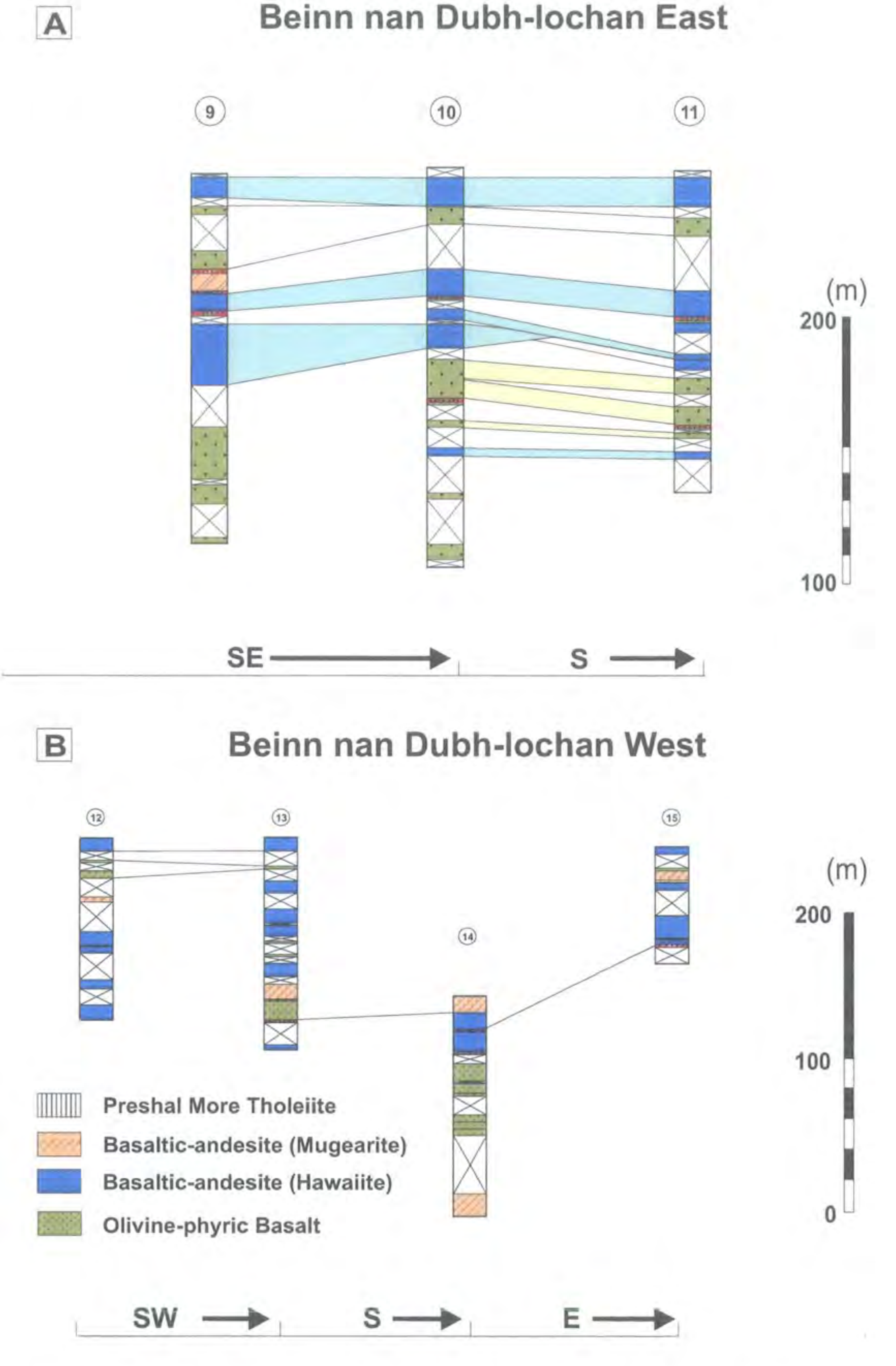


Figure 4-12 **A:** The correlation section made through the east flanks of Beinn nan Dub-lochan through the hills north of Talisker Bay; **B:** Correlation through volcanics of the west section of Beinn nan Dubh-lochan.

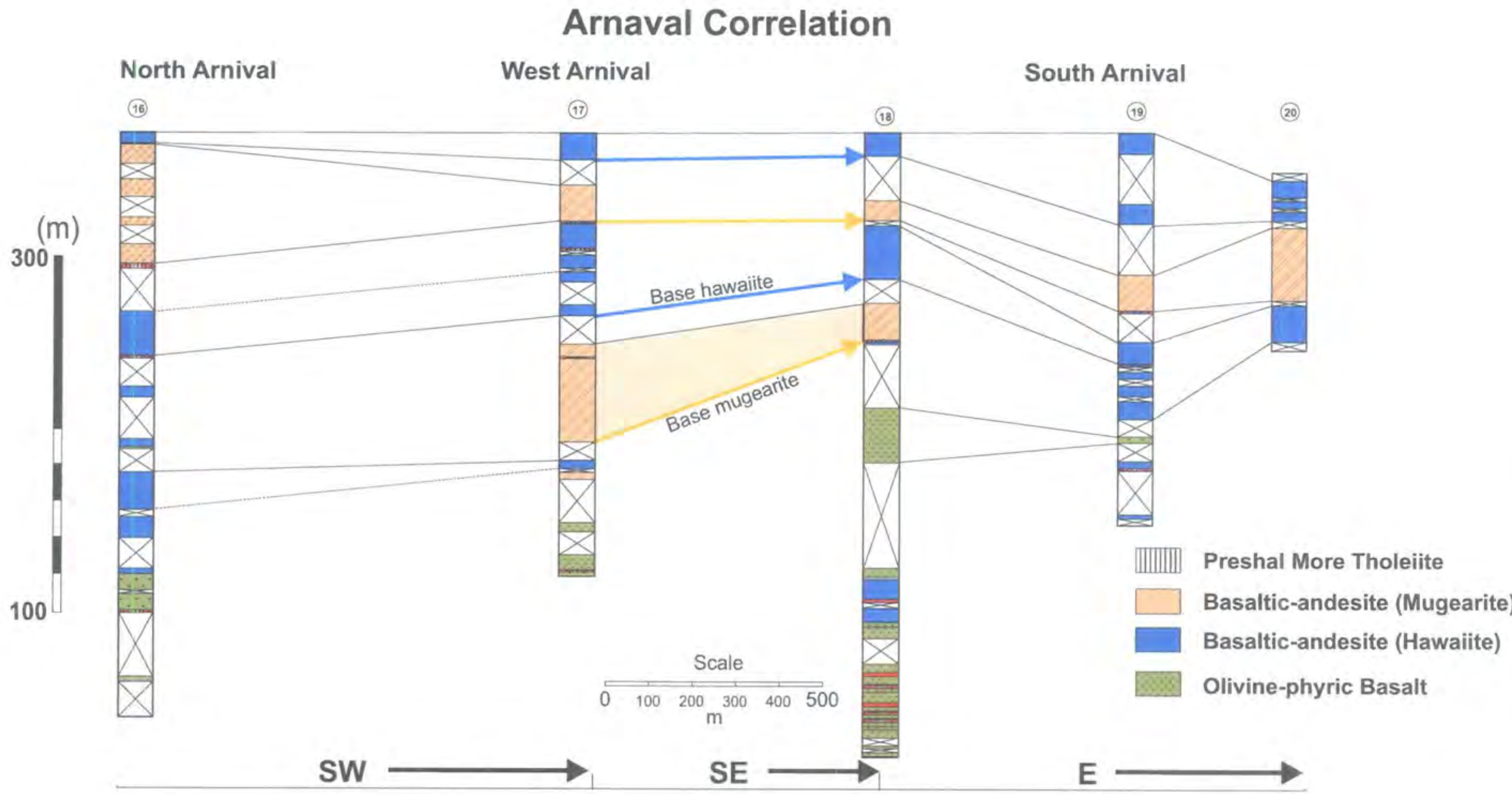


Figure 4-13 Correlation of the log sections through the volcanics of the mountain *Arnaval* in the NE quadrant of the Minginish district study area of west-central Skye. Note the thinning out of the thick mugearite in the centre of the correlation panel. The log sections reveal a transition from olivine-basalts at the base, towards more evolved, thicker flows in the higher parts of the section.

Na Huranan Cliff Section - Arnaval South

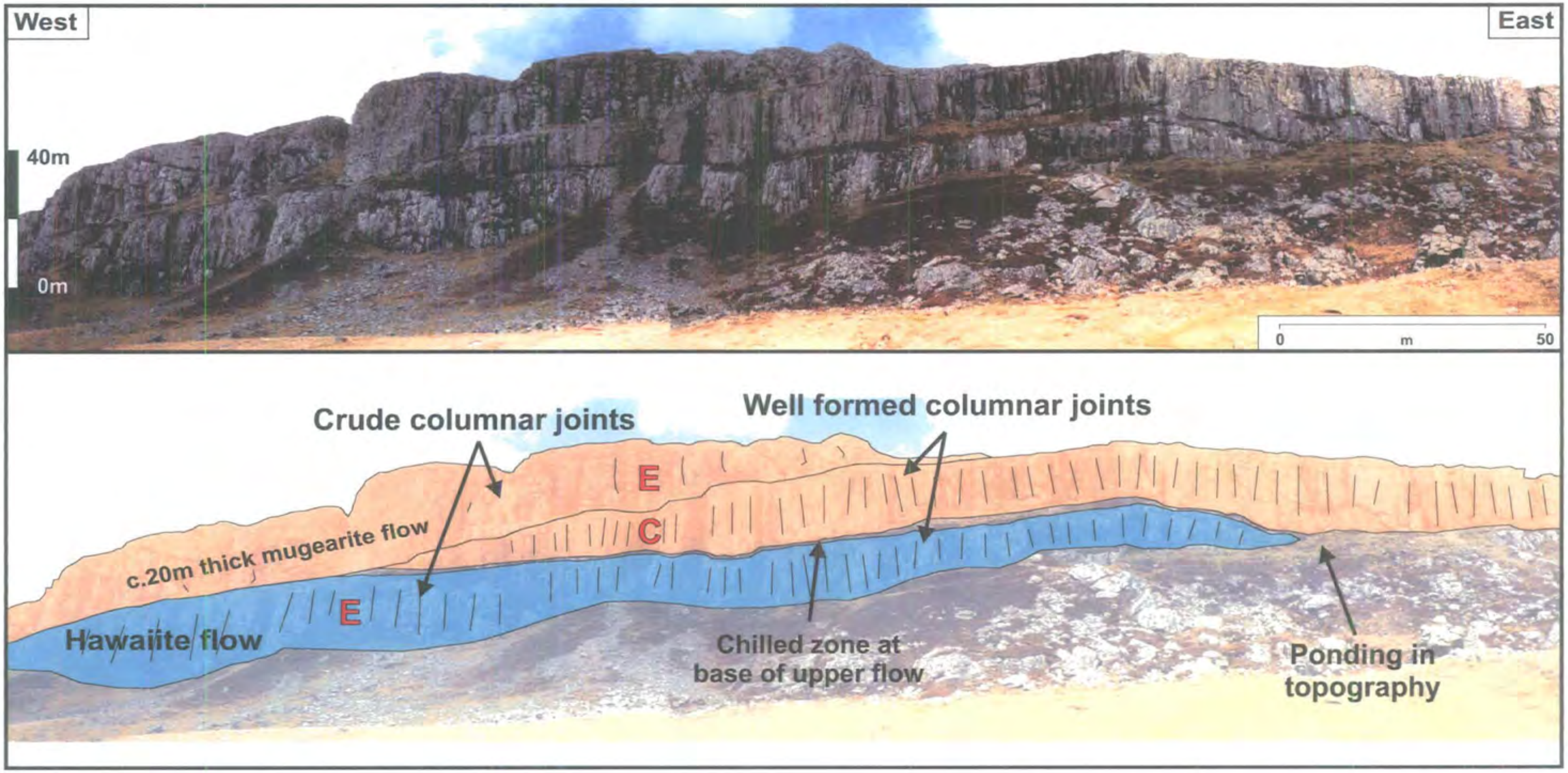


Figure 4-14 Interpretation of the south-Arnaval cliff section of *Na Huranan*. The section reveals two major flows. The lower flow is the upper portion of a fine grained basaltic-andesite flow (hawaiite). This contains crude and well formed columnar joint sets. The upper basaltic-andesite flow (mugearite) is heavily flow foliated above an a holocrystalline base of c.30cm thickness where the flow is chilled against the lower unit. Above this zone is a well developed entablature (**E**) and colonnade (**C**) sub-division of the flow structure.

4.2.2 Summary of Log Section Observations

The 1D log sections detail the vertical stacking patterns observed in the lava field in the Talisker area whilst their lateral counterparts and correlations provide information about the geometries present in the lava field and the spatial variability of the flood basalt facies architecture.

Some of the main points are summarised as follows:

- The lavas towards the base of the lava field are olivine-rich thin (<3m) and correlation is difficult over distances >10m
- The lavas high in the lava field stratigraphy are more siliceous, thick >c.8m and they are laterally extensive
- The bole beds are extensive markers for correlation and are particularly well-developed in the stratigraphically higher lavas
- Lava ponding is fairly common in a developing lava field resulting in an overall reduction in topographic variation up-succession
- There is no evidence for lava feeder tubes in the more evolved lavas

From the observations of the stacking patterns and facies architecture made in the log sections, it is possible to divide the lava field into a facies-based architectural lava succession independently of the lava formations sub-division of Williamson (1979) (Table 4-3). The next section describes this architectural succession.

4.2.3 Architectural sub-division of the Talisker Bay area lavas

The lava field of west-central Skye may be divided into three main architectural sequences based on observations made in this study: (1) lower compound-braided lavas, (2) transitional lavas and (3) upper tabular-type lavas.

Fig. 4-15 summarises the characteristic architectural sequence detailed below. The stacking patterns throughout the lava sequence across the northern part of the Minginish district are essentially characterised by an up-sequence increase in flow thickness, areal extent and individual flow volume.

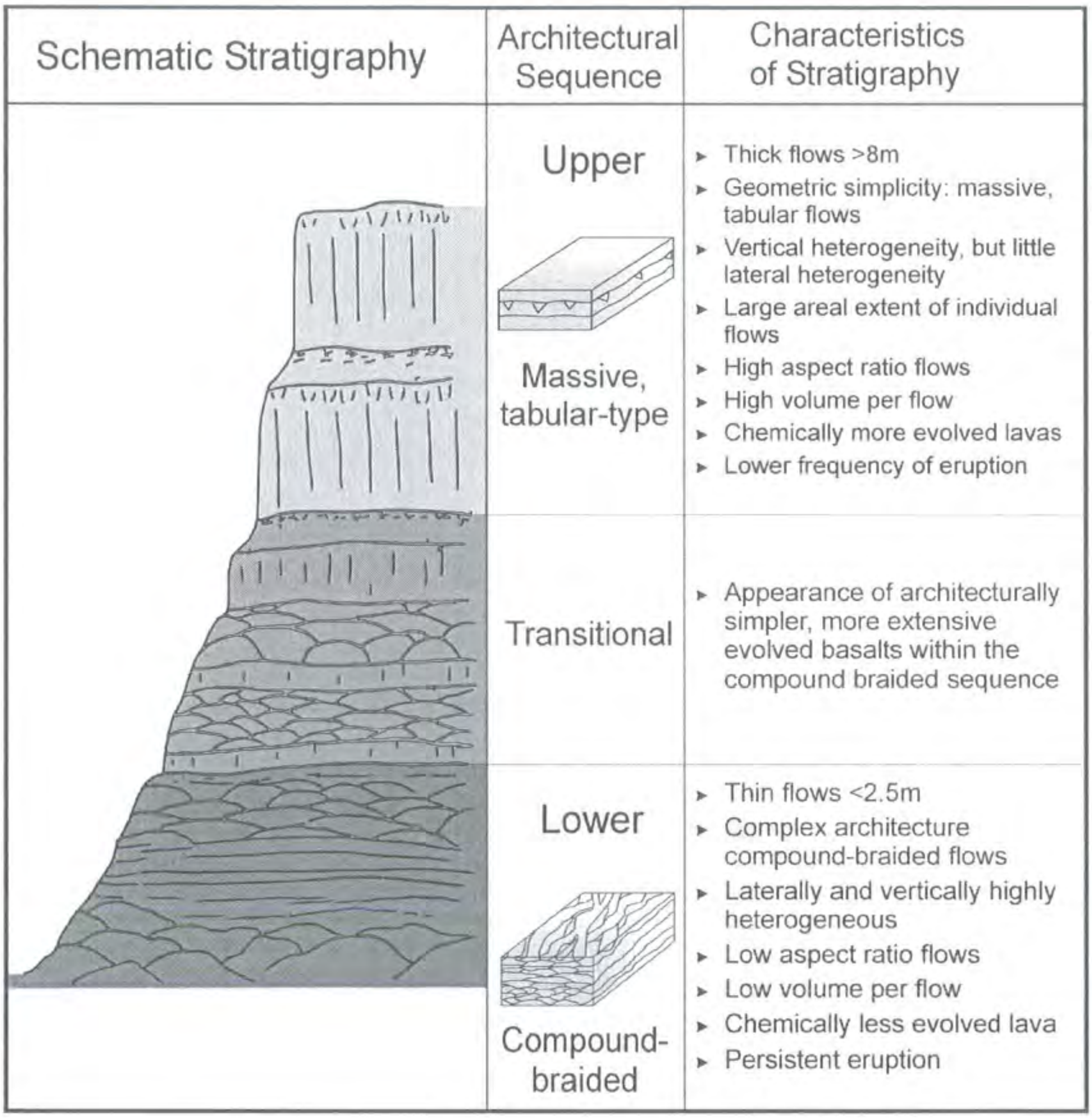


Figure 4-15 Schematic section through the three main architectural sequences of the Skye Lava Field in the Talisker Bay area of Skye. The simplified three-fold breakdown is based purely on the field observations of the architecture within the succession and is compiled. The lower compound-braided architectural sequence is represented by mainly the Skridan Member (Glen Caladale Fm.) and the McFarlane's Rock Member (Fiskavaig Fm.) in the south of the area, and by the Rubha nan Clach Member (Fiskavaig Fm.) towards the north (Table 4-3). The transitional lavas include the of the upper parts of the Rubha nan Clach and the McFarlane's Rock Members (Fiskavaig Fm.) The upper tabular-type lavas are primarily represented the Arnaval Member (Gleann Oraid Fm.), the Loch Dubh Fm. and the Talisker Fm seen on Preshal More and Preshal Beg.

4.2.3.1 Lower compound-braided lava sequence

The lower lavas are characterised by thin, highly fractured and vesicular olivine-phyric basalts. In most of the landscape, these form areas of relatively featureless topography as they are easily eroded. In stream sections, lava flow bases <0.4m thick may be distinguished by presence of pipe vesicles, in conjunction with a vesicle density of <40%, and possibly thin, glassy basal margins. Above these basal zones, massive flow cores with low vesicle densities form <2.5m thick zones displaying regular jointing. Massive core zones grade upwards into more profuse vesiculation (<25%). As the flow top is approached the vesicle density increases and the size of the vesicles reduces. At the flow top, a zone of vesicles generally <0.1m thick is noted where the vesicle density may be as high as 80%.

In the lower lavas, lateral correlation is generally impossible over scales of >30m. Architecturally, the sequence appears to form part of a compound-braided lava system (e.g. Jerram 2002). Individual flows are usually <3m thick, have low aspect ratios, and evidence in cliff sections indicates that younger lava flows fill accommodation space developed between older lobes. The lavas are commonly picritic suggesting a high temperature and low viscosity of extrusion. The volumes and style of volcanism suggest that the lower sequence may have formed on the flanks of a low-angle shield volcano: a similar setting to present day Hawaii (Kent 1998).

4.2.3.2 Transitional mixed sequence

This sequence marks a transitional eruptive phase between the low-viscosity compound-braided olivine-phyric basalts and architecturally more simple, tabular-type basalts observed in the upper sequence described below. The transitional mixed sequence contains olivine-phyric lavas with occasional thin, more evolved flows of basaltic-andesites <6-7m thick.

4.2.3.3 Upper tabular-type lava sequence

The upper lavas of the west-central lava field are dominated by the Arnaval Member of the Gleann Oraid Formation (Williamson & Bell 1994; BGS Scotland Sheet 70). The lavas are characterised by thicker flows (>8m thick). Six main flows form much of this sequence in the Preshal More-Arnaval area. The summits of both Arnaval and Stockval are capped by mugearite flows >12m thick in each instance. Flow bases are often recognised by zones of brecciation <0.5m thick lying above the vesiculated tops of earlier flows. Above the breccia zones, the flows grade into massive core zones that are commonly flow-foliated due to the alignment of phenocrystal plagioclase. Many flow core zones in the upper lavas display superb columnar jointing colonnades, indicating that many of the flows were erupted into wet environments (Lyle 2000). The crystal size reduces through the upper parts of the core zones and vesiculation again increases. Many flow tops terminate in highly vesicular (>50%), 'frothy' zones that may be up to 3m thick. Many of these flow tops are reddened, suggesting that the frequency of eruption in these upper lavas was reduced, allowing time for the development of thick boles or palaeosols during hiatuses in the eruptive cycle.

Lavas in the top of the upper sequence stratigraphy are commonly laterally extensive over the kilometre-scale; however, several substantial flows lower in the upper sequence and in the transitional zone are not correlatable over such distances, probably due to ponding of the flows in the pre-existing topography: the distribution of these flows is controlled by the filling of accommodation space in small, possibly fault bounded basins developed in the underlying strata.

The lavas of this upper sequence are of tabular-type facies architecture (Jerram 2002), having high aspect ratios and simple forms with little lateral variability in their compositional, textural or structural characteristics. Individual flows cover larger areas than those of the lower and transitional sequences and are substantially thicker. This is attributed to the more evolved composition of the lavas, the pre-existing topography being filled, and their simple architecture. Although these flows are the largest seen in the Skye Lava Field, they are not comparable in thickness or extent to some flows seen in other provinces: for example the Rosa Member Basalt in the Colombia River Basalts has an estimated volume of 1300km^3 (Self *et al.* 1997) in a province where flows commonly exceed 100km from source to toe.

Now that the 1D log sections/traverses and 2D sections have been used to develop an understanding of the vertical stacking patterns and lateral facies variations in the lava field, in the next section, this data is integrated into a 3D, field-constrained model of the Talisker lava field.

4.3 THE TALISKER AREA 3D GEOMETRICAL MODEL

Now the 3D geometrical model of the lava field in the Talisker area is introduced and described in detail: how the model was built; the geometries and stacking patterns present within the 3D model and analysis of the volumes of lavas erupted in the architectural sequences described above.

4.3.1 Building the 3D model

The precisely located 1D vertical log sections and traverses define the basal contacts of prominent weathered beds, tuffaceous horizons and massive lava flows through the volcanostratigraphy. The accurately located field data points were imported into the GoCad™ 3D modelling environment and georeferenced to the Talisker area Digital Terrain Model (DTM). If variations in altitude existed in the log section data relative to the DTM, the data points were mapped onto the DTM surface. The basic procedure for incorporating data and building models in GoCad™ can be referred to in Chapter 2.6 and is again summarised in Fig. 4-16.

Log-section locations that have known correlations across the lava field were linked by use of correlation curves (Fig. 4-16A-C), and surfaces interpolated through the lava field using the log-section data locations as property control points (Fig. 4-16C&D). This procedure results in a meso-scale 3D model constructed of a series of lava base and top surfaces that are known correlations through the lava field succession, and develops the lava field model on the kilometre-scale from metre-scale logging and facies analysis. Interpolation of these surfaces by GoCad™ provides indications of the likely locations of the main faults in the area, of the general structural dip, and of the stratigraphy that is missing the valleys due to erosion (Figs. 4-16E&F & 4-17).

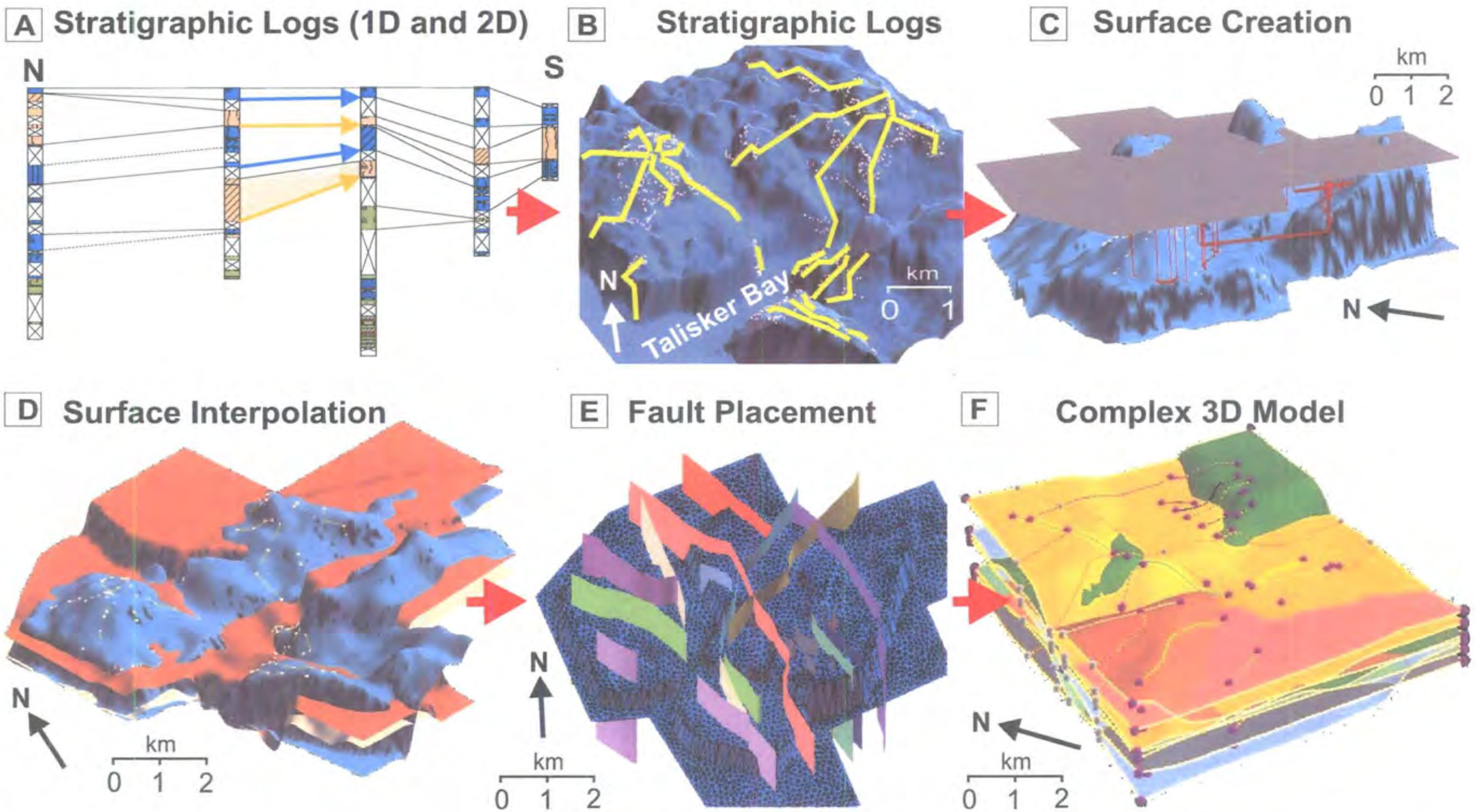


Figure 4-16 Building a 3D model of a volcanic sequence. **A:** 1D log section data are collected through the lava field and correlated in 2D panels; **B:** Log section data (1D) located on a 2D DTM of the field case study area; **C:** Precise locations of correlatable data points marked as *Property Control Points*; **D:** Correlatable points interpolated as a 2D surface - interpolation reveals eroded lava sequence material; **E:** Faults added to the 2D surface model; **F:** Complex 3D model of lava field developed incorporating multiple flows, correlations and faulting.

These models are extremely valuable to the geologist, as volumes may be calculated between the 3D model surfaces; converting the model to a true 3D volume. They are also excellent for geophysical studies into lava field surface rugosity as they highlight geometries present within the lava field; with and without the complications of actual fault-planes (fault plane interpolations are inherent to a well-constrained model).

The interpolated models may be further enhanced by the incorporation of fault surfaces in order to make complex structural models; these require cutting of surfaces by fault planes, fixing of sets of property control points and re-interpolation for accurate results. Creating closed volumes for volume calculations in such models is fraught with problems, as GoCad™ is designed for petroleum reservoir modelling, where a high level of true 3D control exists within the dataset being modelled (3D seismic data). In the complex model built in Talisker, the post-volcanic normal faulting is assumed to be vertical, so that the computing errors are reduced to a minimum, yet the lava field may still be compartmentalised. This assumption is made on examination of the known faulting in the area, which reveals most of the faults to be near-vertical structures.

The following section looks at the distribution of lavas, the geometries present in the lava field succession and considers some of the volume estimates calculated from the three architectural sequences described in 4.2.3.

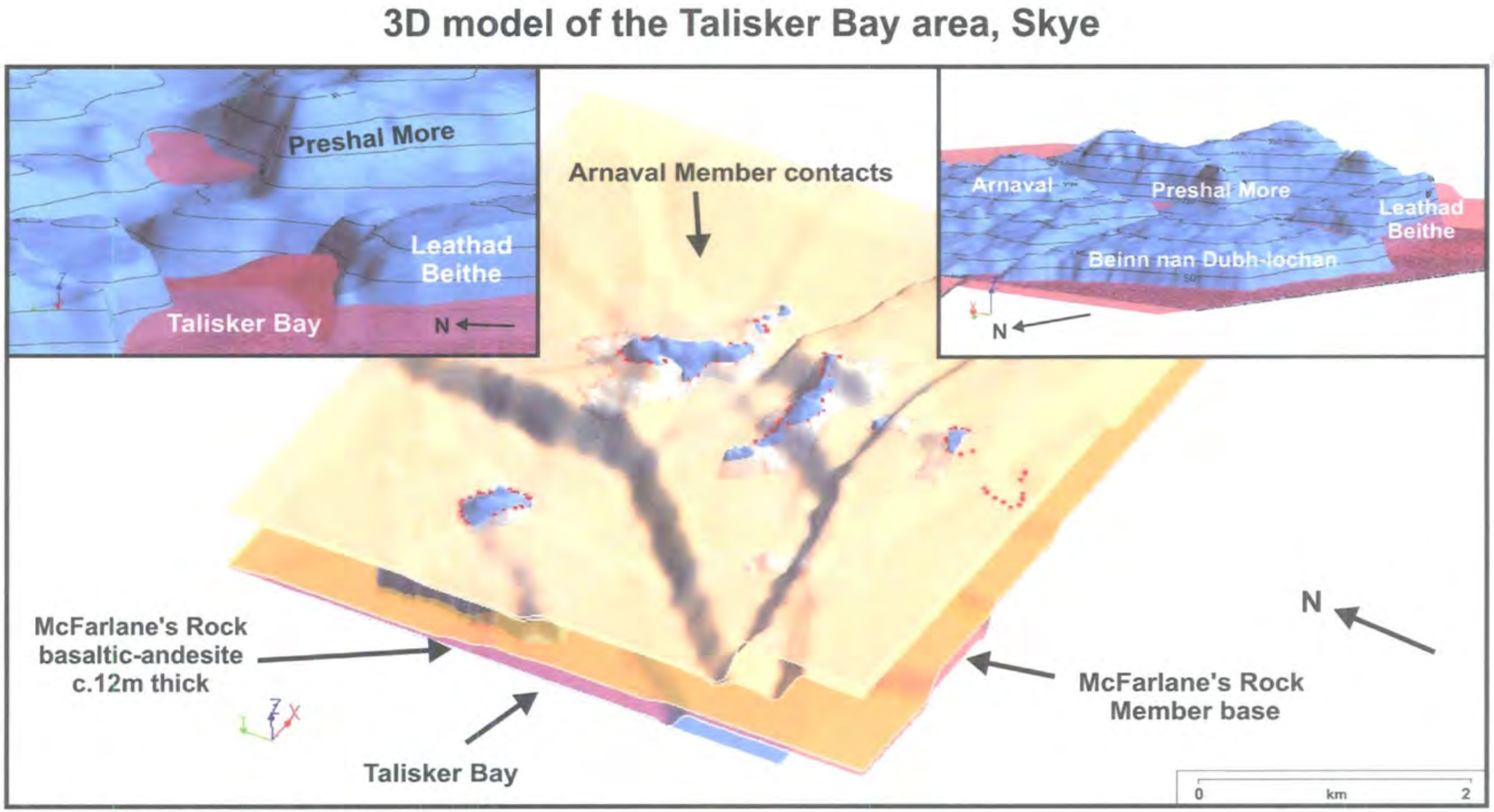


Figure 4-17 The 3D model of the Talisker area of Skye. Blue represents the present-day topography which is displayed through prominent contacts in the lava field. These contacts are displayed as 2D surfaces with slight transparency so that structure may be observed deeper in the Skye Lava Field. The lowest contact observed in the north of the model is that of the base of the Fiskavaig Formation's McFarlane's Rock Member (Table 4-3). This represents the base of a major mugearite flow which is seen higher up the succession on the Leathad Beithe log section. The pale brown coloured surfaces higher up the succession in the model are the basal contacts of Arnaval Member flows that may be correlated across the west-central lava field. Insets show views of the Minginish district with the base McFarlane's Rock Member contact cutting through the topography (transparent red).

4.3.1.1 Lava Distributions and Geometries

3D models built over the meso-scale provide a wealth of geometric information for geological and geophysical studies, with a focus on shape heterogeneities: i.e. geometrical information, structure and contact topography or rugosity. The distributions of the lavas may also be determined and modelled both within the present day topography, and in eroded parts of the stratigraphy. Thus reconstructing the lava field succession prior to erosion.

The lava field in the Talisker area gently dips towards the west (Fig. 4-18). In combination with this gentle tilting, are a series of post-volcanic normal faults that cross-cut the entire exposed succession (Fig. 4-19). The throws of the faulting in the area are relatively small and of the order of just a few metres. The maximum throw interpreted is in the Talisker Graben where the Talikser Fm. observed on Preshal More is downthrown by the order of c.100m. the combination of structural dip and the normal faulting means that the greatest thickness of volcanics lies in the Arnaval and Stockval areas in the east of the Minginish district.

The most accurately constrained part of the 3D model lies in the Arnaval Member, where the thick tabular-type lava flows of the upper architectural sequence (4.2.3.3) sit on thick sedimentary beds and boles across the lava field. These are correlated and the stacking patterns confirmed. The transitional lava sequence is taken to lie between the base of the McFarlane's Rock Member and the base of the Arnaval Member (Table 4-3). The McFarlane's Rock Member is mainly represented by a thick basaltic-andesite flow which is exposed on the north shore of Talisker Bay, the hills of Leathad Beithe, and also to the east of Arnaval and Stockval (Williamson & Bell 1994). The thick tabular-type basaltic-andesite flow thickens towards Talisker Bay to a maximum exposed thickness of c.12m (Fig. 4-17).

Volcanological and Structural dip

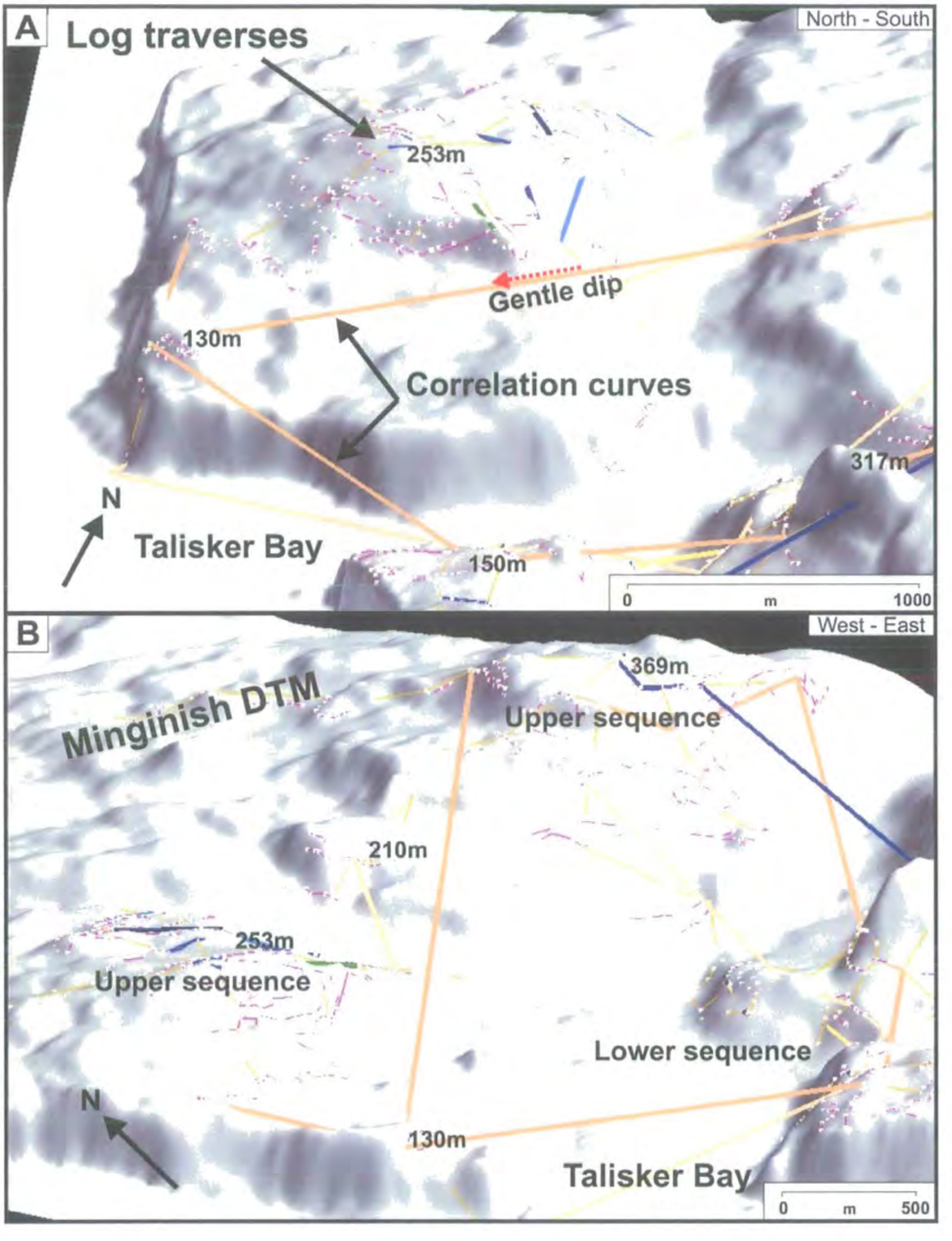


Figure 4-18 The general dip of the lava field in the Talisker area, Skye. **A:** Looking north across the Minginish district at the Digital Terrain Model (DTM) showing the log sections, traverses and correlation curves through the model; **B:** Looking into Talisker Bay from the SW at correlations through the architectural sequences of the lava succession. The gentle dip towards the west may be attributed to several factors: post-glacial neotectonic tilting; subsidence; tilting induced by the intrusion of the Cuillins igneous complex; primary volcanological dip (e.g. dip on the flanks of a shield volcano).

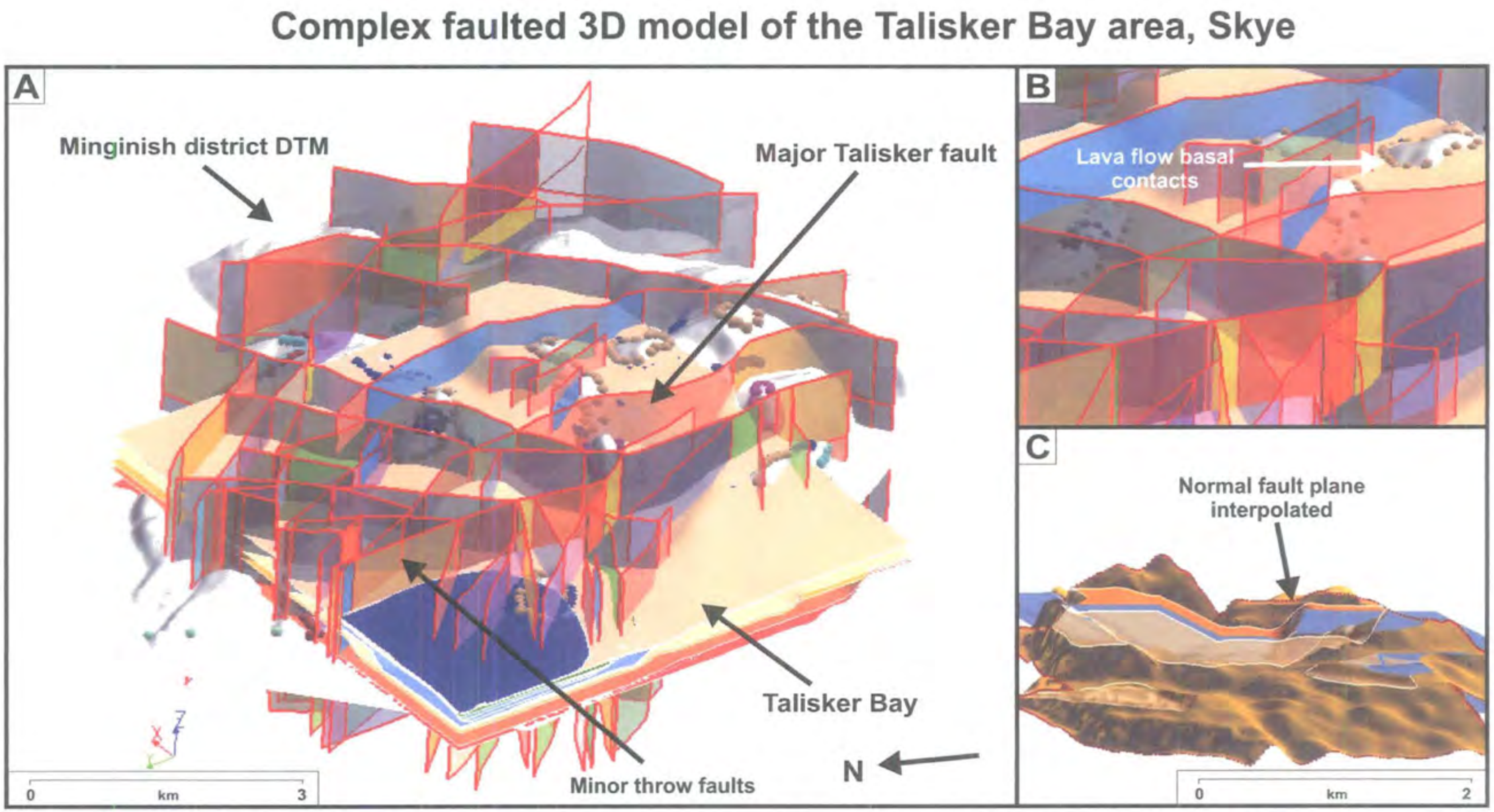


Figure 4-19 The complex 3D model of the Minginish district. **A:** The grey-shaded digital terrain model (DTM) for the Minginish district lies at the base of the 3D model. Several correlated horizons and the normal fault sets cut the area. The major Talisker fault is indicated as a major fault plane. Smaller normal faults with small offset branch in NW-SE and NE-SW sets from the main fault zone and compartmentalise the lava field; **B:** A zoom into the heart of the faulted lava field showing 1D log traverse points sitting on the DTM surface; **C:** Fault planes interpolations in the simple model from underneath the DTM.

The distribution of lavas in the Talisker area is modelled geospatially in 3D. This provides us with another means for determining their potential source regions. Flow indicators such as flow foliations in the Arnaval basaltic-andesites and vesicles within the olivine-phyric lavas of the lower and transition sequences suggest that several magma sources were active contemporaneously in the Talisker area through time. This may represent different vent sources and/or along-fissure variations during the build up of the lava sequence. By modelling the volcanic succession in 3D, the relationships between some of the formations may be determined and their volcanological relationships interpreted. Fig. 4-20 shows the relationships developed between the Loch Dubh Fm. and the Arnaval lavas. In 3D, the Loch Dubh lavas build out onto the surface of the extruded Arnaval lavas from the north in the area of Beinn nan Dubh-lochan. As the eruption reached a climax, the volumes being erupted and the rate at which they were being erupted were considerable enough to smother the contemporaneously erupting Arnaval basaltic-andesites before the source waned and the Arnaval Fm. over-stepped the Loch Dubh Formation.

The geometries revealed within and at the bases of the successions in Talisker also prove to be heterogeneous. The simple stacking arrangements that are assumed to be present within a steady erupting lava field are proven to be infrequent in most parts of the lava field: the simplest stacking patterns being hosted by the more evolved, simpler flow types higher in the succession.

From the field and model evidence, it has been shown that the chemically more evolved lavas higher in the succession are thicker and geometrically more simple. In the next section, the volumes of each of the lava types is analysed in a 3D layer model (true 3D).

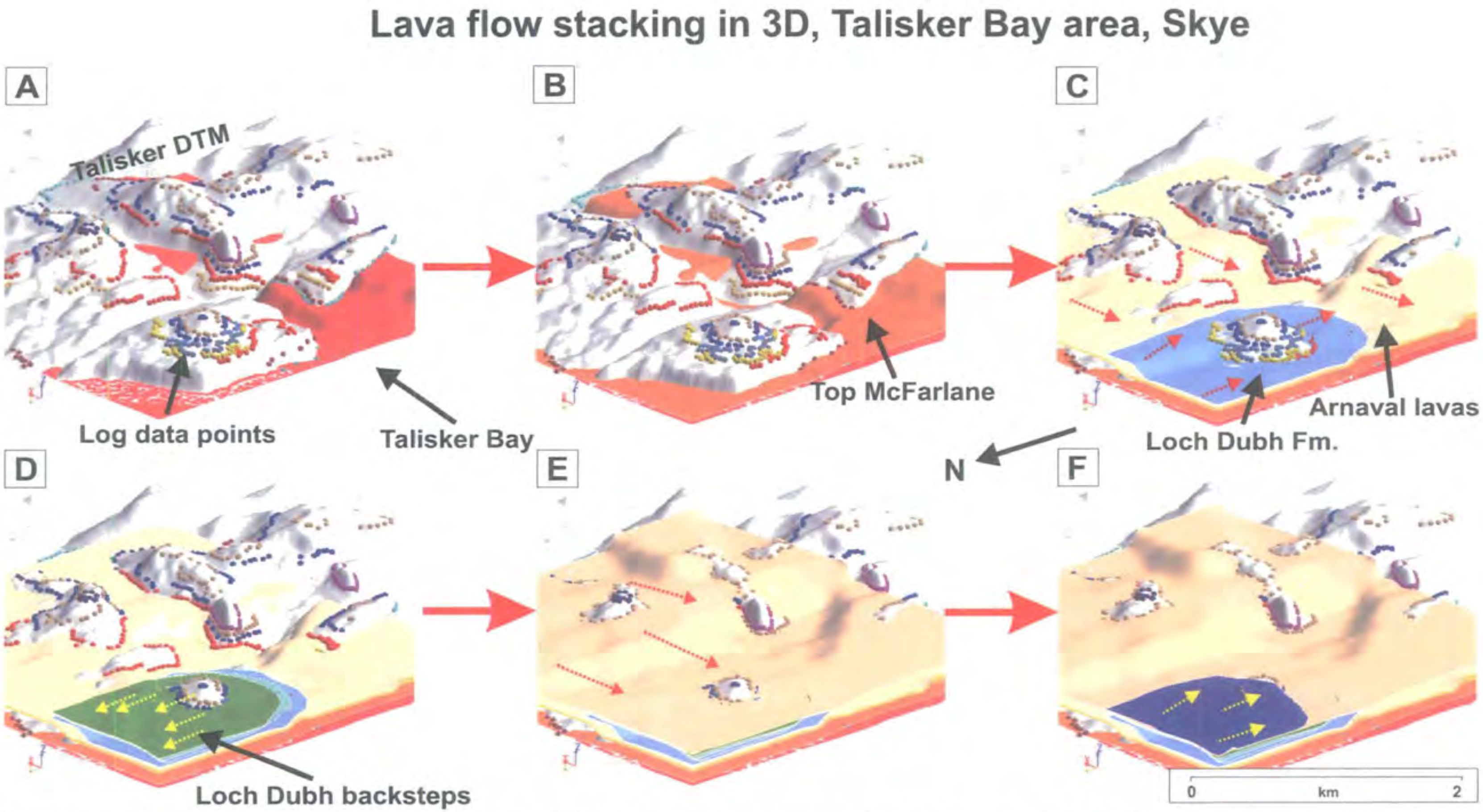


Figure 4-20 The 3D stacking patterns in Talisker. **A:** The DTM of Minginish showing the base McFarlane's Rock Member; **B:** Top of the McFarlane's Rock Member correlated through the model area; **C:** Thick, tabular-type Arnaval flows blanket the transitional architectural sequence from the east and the Loch Dubh lavas contemporaneously effuse from the north in the NW of the area; **D:** The Loch Dubh lavas back-step as their source wanes; **E:** A thick Arnaval basasaltic-andesite onlaps and oversteps the Loch Dubh lavas; **F:** The Loch Dubh Fm. continues to erupt into the Talisker area during a hiatus in the eruption of the Arnaval succession.

4.3.1.2 Lava Volumes

The lavas which dominate the stratigraphy in the Talisker area are those of the lower architectural sequence: i.e. the compound-braided type olivine-phyric lavas. The upper architectural sequence dominates hill and cliff outcrop sections, but much has been lost to erosion.

In order to be able to compare the volumes present in the different architectural sequences in the Talisker area, the 3D lava field model needs to be moved into true 3D: i.e. a series of layers reconstructing the lava sequence in areas of erosion. The lower, transitional and upper sequences have been built into layers through the volcanic succession, and their volumes calculated in order to gain an improved understanding of the physical volcanology in the area. Instead of making field estimates from an eroded succession, it is possible now to ask: for the given 3D model volume, which eruptive sequence is of the highest volume and why?

The simple 3D lava field structure model covers an area of c.85km^2 (Fig. 4-21). This is broken down into representative regions and layers between the bounding contacts of the architectural sequences. The McFarlane's Rock Member represents the top of the lower sequence volcanics; the base of the Arnaval Fm marks the base of the upper sequence volcanics.

In the model area, the volume estimates for each of the architectural sequences are as follows:

- Upper sequence volcanics c.17.0km^3 of tabular-type lavas
- Transitional sequence lavas c.7.4.km^3.
- Lower sequence lavas comprise c.12.7 km^3 of compound-braided lavas.

True 3D volume model of the Talisker Bay succession

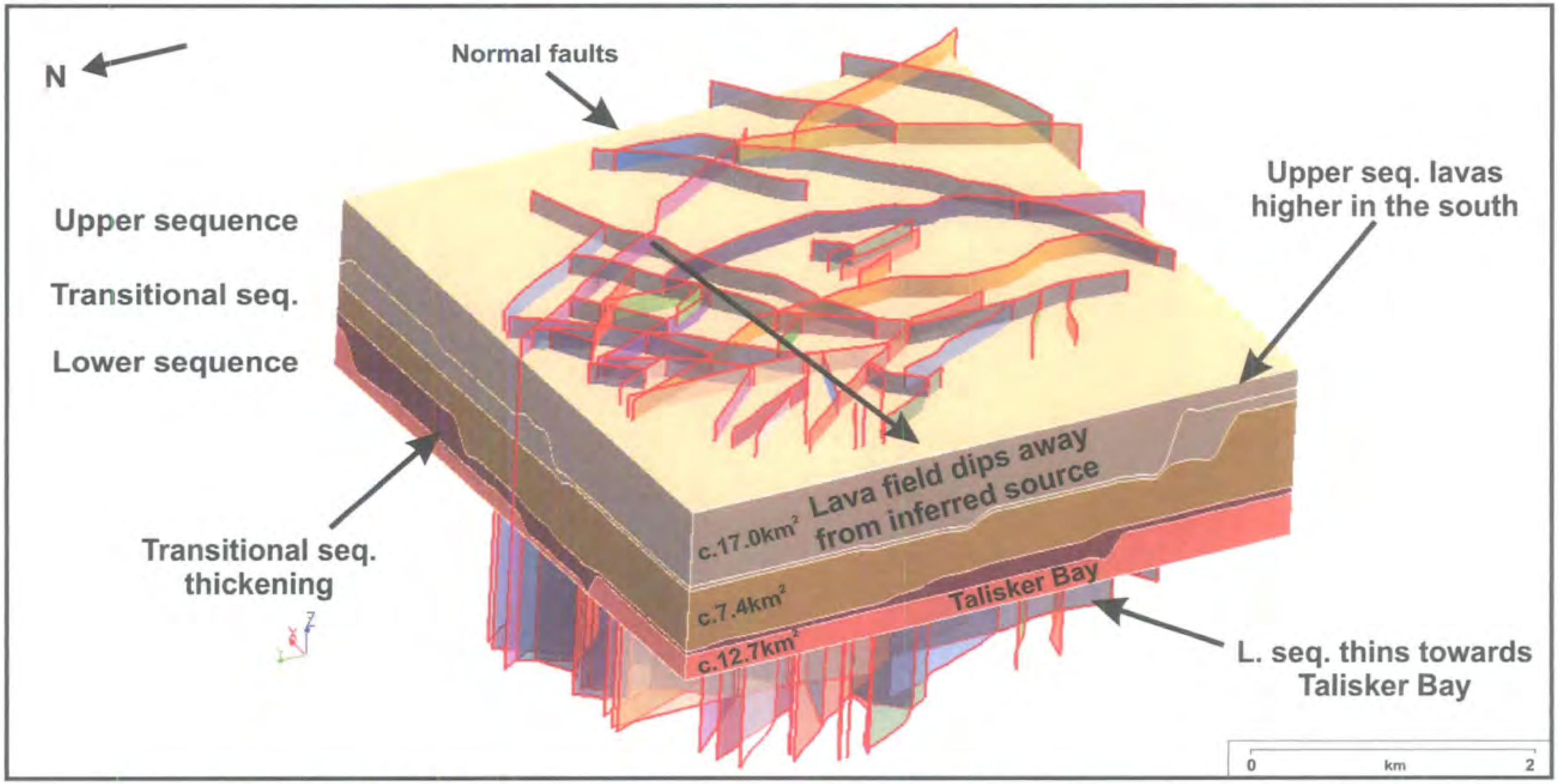


Figure 4-21 The true 3D volume model of the Talisker area. Block volume model shows the Skye Lava Field succession dipping steady towards Talisker Bay. The dip is steepest in the lower architectural sequence and may be related to the lower sequences' interpreted volcanological settingon the shallowly dipping flanks of a shield volcano. The transitional and upper lavas fill the residual accommodation space in the top of the exposed lava field.

From studies in the field, the lower architectural sequence appears to dominate the lava field succession, however, when the missing stratigraphy of the lavas is taken into account, the upper architectural sequence is the higher volume sequence for the given volume, assuming that the top of the upper succession lava marks the top of the 3D model. These results are discussed in the next section.

4.3.2 The Volcanology of the Talisker Area

The metre to kilometre-scale structure of the Skye Lava Field in west-central Skye provides information about the lateral continuity, geometry and stacking patterns present in the architecture of the volcanics. In this study, lava field scale observations suggest that we can divide the lavas into three main facies types, each with characteristic architectural sequences. The variations in the facies sequences have been established from vertical section logging through the lava field. The styles of volcanism have directly affected the architectures present throughout the sequence. The vertical change in architecture can be related to the evolution of the lava field: more primitive, olivine-rich flows assume complex architectures of the compound-braided system, effused passively, but constantly, with only minor hiatuses. Increasingly evolved lava flows are more vertically and laterally homogeneous, yet these flows are more laterally extensive and thicker. This observation is important as it suggests both an effusion rate and compositional link to the style of volcanic facies present.

Volcanologically, it is realistic to assume that the missing stratigraphy in the lava field of Talisker, is indeed of tabular-type basaltic-andesite flows, as studies from CFB lava successions in several provinces observe the gradual system shift from passive olivine-rich basaltic lavas through to more evolved basatic-andesites of tabular-type architectures as the magma sources evolve with time (Milner *et al.* 1995; Peate *et al.* 1997; Jerram *et al.* 1999; Jolley & Bell 2002a; Single & Jerram 2004 *in press*).

In the lower architectural sequence of the lava field, the simple 3D lava structure volume has a calculated approximate volume of 12.7km^3 of compound braided lavas. Within the cliff sections and in the log section data, these are interpreted to form a compounded stack of over 12 lobe units based on the number of massive core zones deemed to be present in the sections seen above sea-level. The thicknesses of the pahoehoe lobes seen in the Talisker area are consistent with the observations of Self *et al.* (1997) in the Hawaiian inflated pahoehoe sequences, and form a substantial part of the Talisker succession.

In the upper architectural sequence which is dominated by the Arnaval Member, the volume estimate calculated from the simple 3D model for the area including eroded stratigraphy is for a sequence of about 17.0km^3 of lavas. This sequence consists of over 8 major massive, tabular-type flows in the eroded stratigraphy, all over 8m thick. These form a stack of lavas containing prominent core zones and weathered tops resembling a series of lavas akin to those observed by Planke (1994) in the Upper Series lavas of the Vøring volcanic margin. The individual flows form very similar thicknesses to those in that area of the North Atlantic Igneous Province, but are thinner than those of the high level stratigraphy in the Paraná-Etendeka Flood Basalts (Milner *et al.* 1995; Jerram *et al.* 1999b).

If the lava volumes present in the model area of the upper architectural sequence are considered to be just present in the model area part of the Minginish district, then c.17km^3 may be considered to be a reasonable estimate of the low-side lava volumes for this sequence with a mean individual flow volume of 2.1km^3 over the model area. On the Duirinish Peninsula, about 15km NW of the Talisker area modelled, thick tabular-type lavas may be seen to constitute a thick section of the stratigraphy forming the large summits of the Macleod's Tables. If these flows are correlatable with those of the upper architectural sequence modelled in Minginish, this could add c.27km^3 of erupted lavas to the upper sequence with individual flows hosting volumes of c.3.5km^3 (Fig. 4-22). However, even if this volume is added to the volume of the upper lava sequence flows in Talisker, the scale of volcanism represented in the Skye Lava Field per flow is an order of magnitude smaller than the volumes seen in the Columbia River Flood basalts (Hooper 1997).

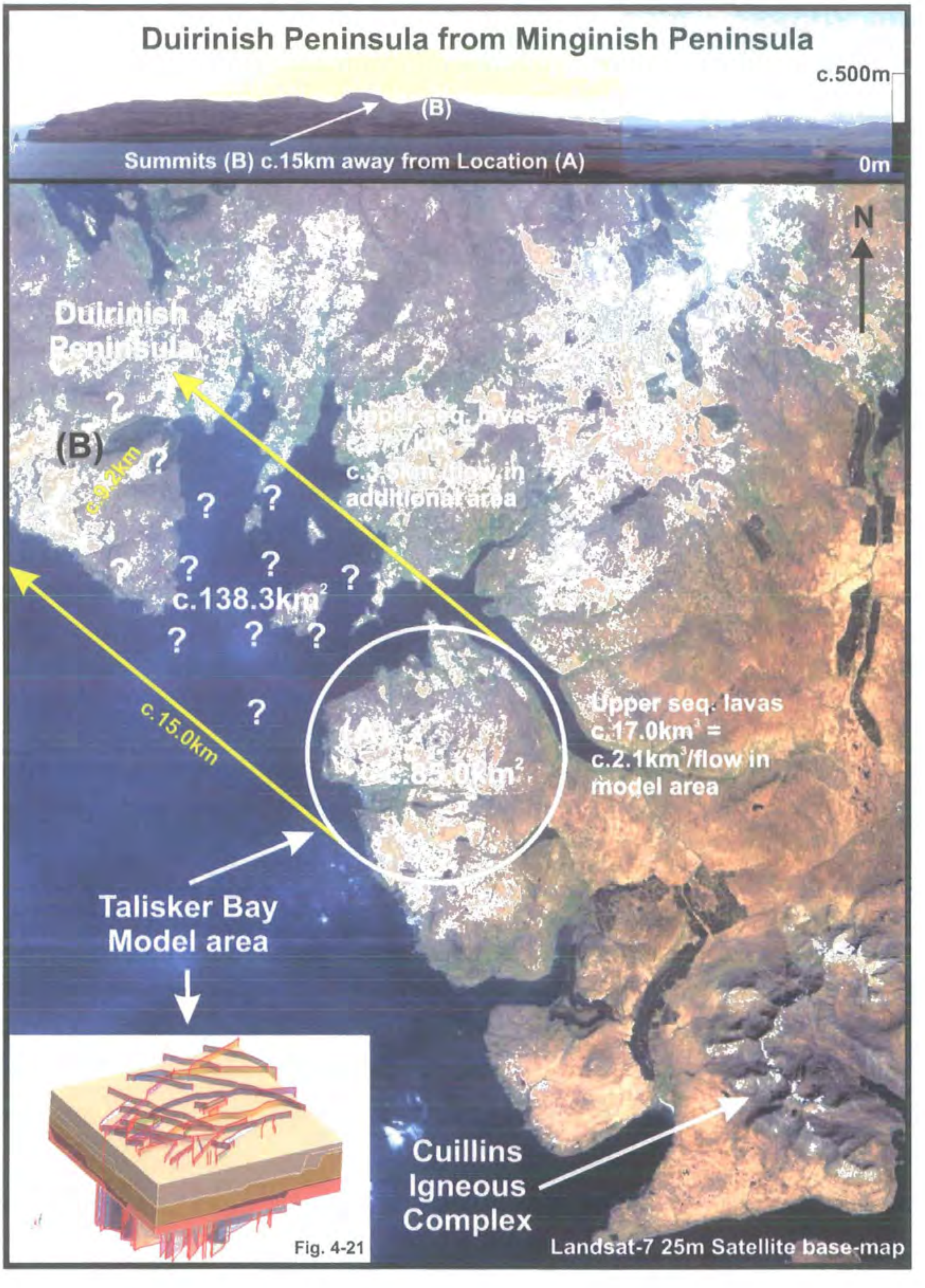


Figure 4-22 The peninsulas of Minginish and Durinish on the west coast of Skye showing the Skye Lava Field and estimates of potential lava volumes.

4.4 SUMMARY

Field investigations have revealed a variety of flow facies architectures hosted within the volcano-stratigraphy of flood basalt provinces (Fig. 4-23). The use of true digital 3D as a modelling tool, allows the quantitative analysis of field data and the ability to visualise volcanic successions by methods not possible by analogue means.

The field studies presented provide valuable analogue material for seismic scale studies over tens of kilometres and their implications will be considered in Chapter 5 when the observations and interpretations are upscaled into basin-scale geological models of flood basalt successions (the macro-scale).

Summary of the Meso-scale Facies Architecture of Flood Volcanic Successions

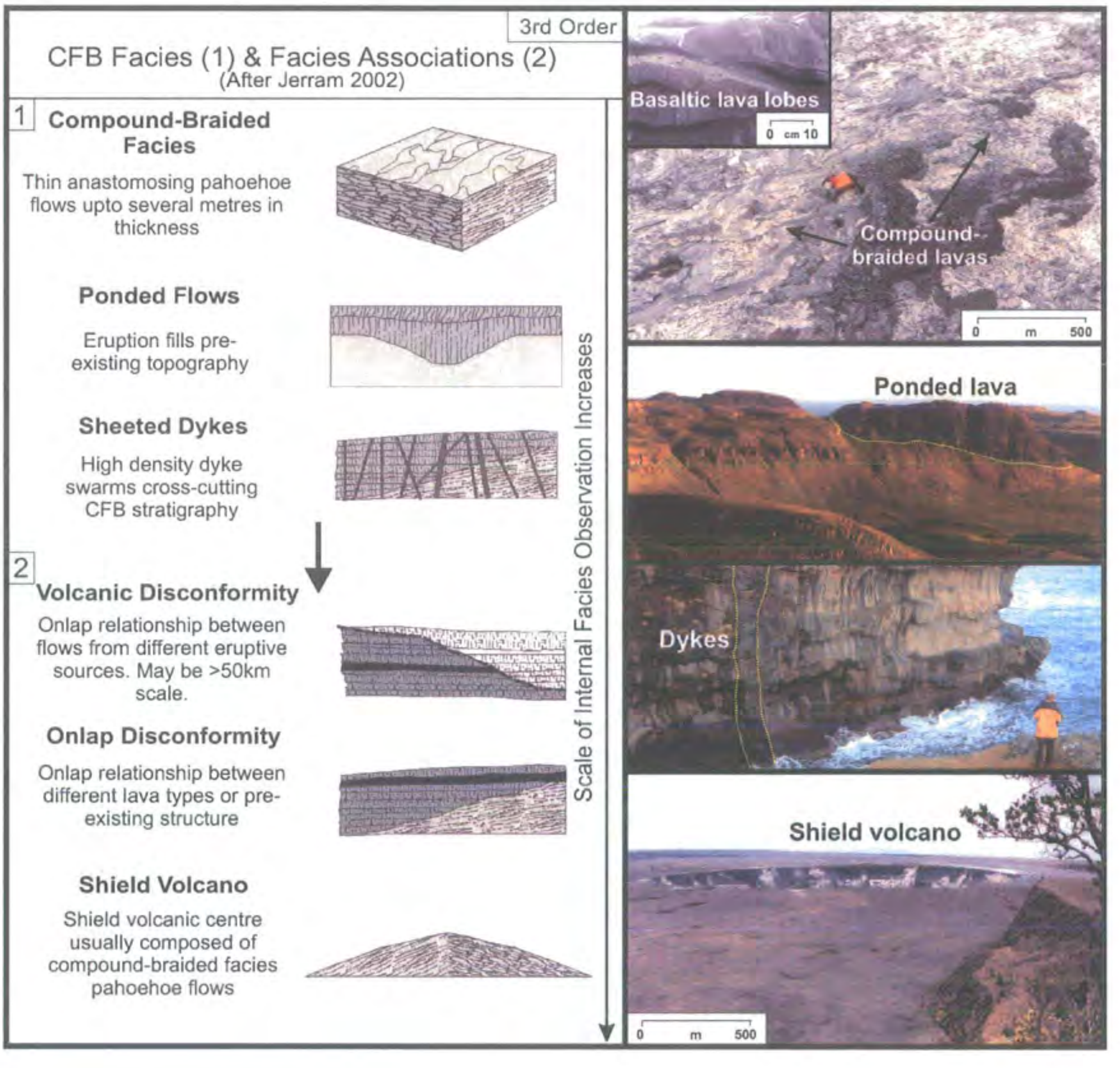


Figure 4-23 Summary of igneous architecture in flood volcanics at the lava field scale (meso-scale). Meso-scale CFB architectural studies are considered over metres to kilometre-scale and are considered to be 3rd order heterogeneities. Chapter 4 has studied the lava field structure and architecture by looking at various data types, including fieldwork and 3D modelling and also using the ideas developed in Chapter 3 of the intrafacies of this next order of heterogeneity. The meso-scale facies architecture (i.e. building blocks of lava fields) leads into the next order of heterogeneity analysed in this thesis: the basin-scale (macro-scale) architecture of flood volcanics. Top and bottom photographs are from Kilauea on Hawaii and are courtesy of D.A. Jerram.

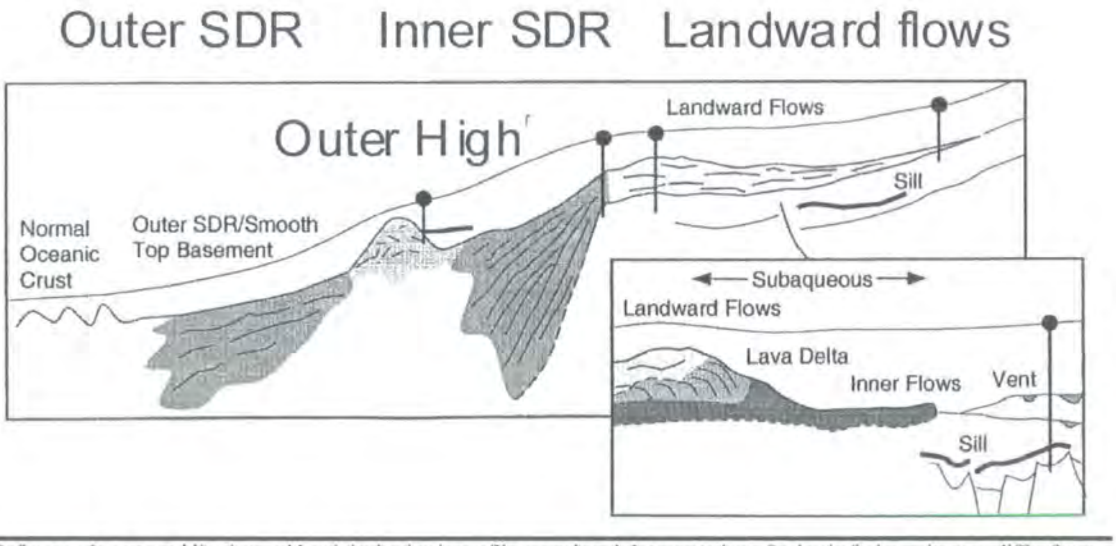
Chapter 5

5. MACRO-SCALE ARCHITECTURE: A CASE STUDY FROM THE FAEROES LAVA GROUP

The case studies presented in Chapters 3 and 4 have developed an understanding of the internal geometric variability and facies characterisation within lava fields typical of flood volcanic successions. Chapter 4 has concentrated on the geometries, stacking patterns and facies present at a meso or lava field-scale, whilst Chapter 3 has studied the internal variability within these facies at a micro or lava flow-scale. In the following chapter, the macro or basin-scale architecture and facies are studied in offshore seismic data, utilising the understanding of flood volcanism established in the previous onshore case studies. Table 5-1 provides an overview of the characterisation of seismic-scale volcanic facies which has been developed by the work of Planke *et al.* (2000). The next section introduces the characteristics of the Faeores Lava Group succession from its' onshore exposure on the Faeroes Islands. Subsequently, interpretations of geophysical data are presented, and developed into 3D geometric and conceptual facies models.

Table 5-1 Dominant Characteristics of the Main Volcanic Extrusive Seismic Facies Units on Rifted Volcanic Margins (after Planke *et al.* 2000 and references therein).

Seismic Facies Unit	Reflection Characteristics			Selected References*
	Shape	Boundaries	Internal	
Outer SDR	Wedge	Top: high-amplitude, smooth or with pseudoescarpments. Overlying: onlap or concordant. Base: seldom defined	Divergent-arcute or – planar. Disrupted, non-systematic truncations.	Skogseid & Eldholm 1987; White *et al.* 1987
Outer High	Mound	Top: high-amplitude, disrupted or planated. Overlying: distinct onlap. No base.	Chaotic	Roberts *et al.* 1984
Inner SDR	Wedge	Top: high-amplitude, smooth or with pseudoescarpments. Overlying: onlap or concordant. Base: seldom defined	Divergent-arcute. Disrupted, nonsystematic truncations.	Hinz 1981; Mutter *et al.* 1982; Talwani *et al.* 1984; Larsen & Jokobsdottir 1988; Keen & Potter 1995; Barton & White 1997; Lizarralde & Holbrook 1997; Talwani *et al.* 1983; Boldreel & Andersen 1993
Landward Flows	Sheet	Top: high-amplitude, smooth. Overlying: conform or overlap. Base: low-amplitude, disrupted.	Parallel to subparallel. High-amplitude, disrupted.	Talwani *et al.* 1983; Boldreel & Andersen 1993
Lava Delta	Bank	Top: high-amplitude or reflection truncation. Base: reflection truncation.	Prograding clinoform. Disrupted.	Wood *et al.* 1988; Boldreel & Andersen 1993
Inner Flows	Sheet	Top: high amplitude, disrupted. Overlying: conform or overlap. Base: negative polarity, but often obscured.	Chaotic or disrupted, subparallel.	Talwani *et al.* 1983; Wood et al. 1988; Skogseid *et al.* 1992; Boldreel & Andersen 1993



References* are to publications with original seismic profile reproduced. Interpretation of seismic facies units may differ from those in the publications. Outer and Inner SDR indicate zones of Seaward Dipping Reflectors.

5.1 THE GEOLOGY OF THE FAEROES LAVA GROUP

The interpretation and modelling of the facies of the Faeroes Lava Group has been concentrated across the area of the GFA-99 seismic data which lies approximately 60km SE of the Faeroe Islands in the Faeroe-Shetland Basin (Fig. 5-1). Much interest has been shown in this basin by petroleum companies who consider the sub-volcanic plays to be mature and worthy of exploration (Waagstein 1988; Laier *et al.* 1997). The GFA-99 data was acquired by Schlumberger Geco-Prakla for petroleum companies wishing to explore and prospect in these deep waters. The interest shown in the basin and sub-volcanic plays has been stimulated by many industry-sponsored conferences (e.g. "The Hydrocarbon Habitat of Volcanic Rifted Passive Margins", Stavanger Hedberg 2002) that have focussed on volcanic passive margins, with particular onus on the Faeroes, Rockall and Vøring areas. Regular meetings of the Geological Society (London) Petroleum Group have hosted presentations of the latest collaborative research between academia and industry into the structure, distribution and characterisation of sub-surface volcanic successions (e.g. Hobbs & Martini 2002; MacGregor 2002; Fliedner and White 2003; White *et al.* 2003).

Geological interpretation of the GFA-99 2-D seismic dataset has covered several iterations of interpretation in Two-Way-Time (TWT) with accompanying gravity data being modelled in ARK Geophysics prior to the final seismic interpretation. The seismic interpretation concentrated on the geometry and stratigraphy of the igneous succession and also on the internal structure of the Faeroe-Shetland sequence. An overview of basin structure prior to the eruption of the Palaeogene is presented in Fig. 5-1. In the next section, the onshore exposure of the

Faeroes Lava Group is introduced, after which the offshore data interpretation is studied in detail.

5.2 THE ONSHORE SUCCESSION

The igneous succession in the Faeroes was erupted during the Palaeogene prior to the opening of the NE Atlantic. The lavas are all geochemicaly tholeiitic which suggests that their eruption was coincident with a high degree of partial melting of the mantle (Waagstein 1988). The group consists of three main formations that overlie a sequence of more than 1000m thickness of basaltic volcaniclastics:

- Upper Lava Formation (ULF)
- Middle Lava Formation (MLF)
- Lower Lava Formation (LLF)

The complete thickness is thought to be 6500m-7000m in total of which 3000m are observed above sea-level (Ellis *et al.* 2002). Their onshore distribution is shown in Fig. 5-2. The Faeroes Lava Group is considered to have erupted between c.60.56-57.5Ma (Ellis *et al.* 2002) however the dating is poorly constrained above the LLF. The top of the LLF is marked by coal-bearing sediments; the Coal-Bearing Formation which is constrained to 57.5Ma (Ellis *et al.* 2002). However, volcanism continued after this hiatus in the MLF and ULFs early in Chron 24r (>55Ma).

In this study, the offshore succession was interpreted using the characters and geometries of the seismic reflectors, combined with the understanding of facies architectures of flood volcanics developed from the British Tertiary Igneous Province (BTIP) and the Etendeka province of Namibia. The opportunity to observe the actual Faeroes Lava Group in onshore exposures on the Faeroe Islands succession arose close to the end of the research project. Photographs of typical field examples of the Faeroes Lava Group are shown in Figs. 5-3 & 5-4.

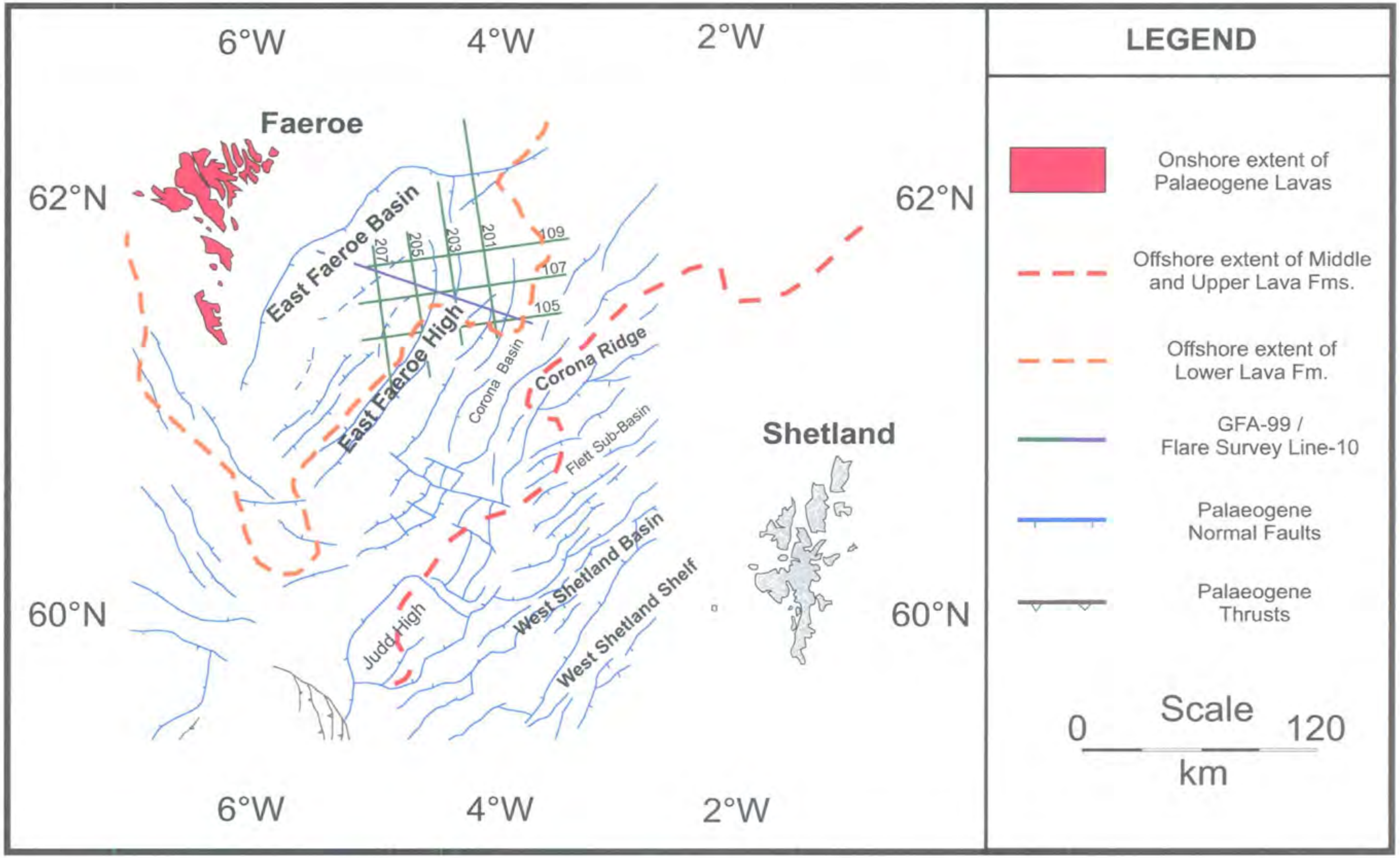


Figure 5-1 The pre-Palaeogene structural framework of the area of the GFA-99 seismic dataset. The postulated extent of the Faeroe Lava Group in the Faeroe-Shetland Basin are also shown. (Modified after Ellis *et al.* 2002). Location of the Amerada Hess Flare-10 line is also displayed across the GFA-99 area.

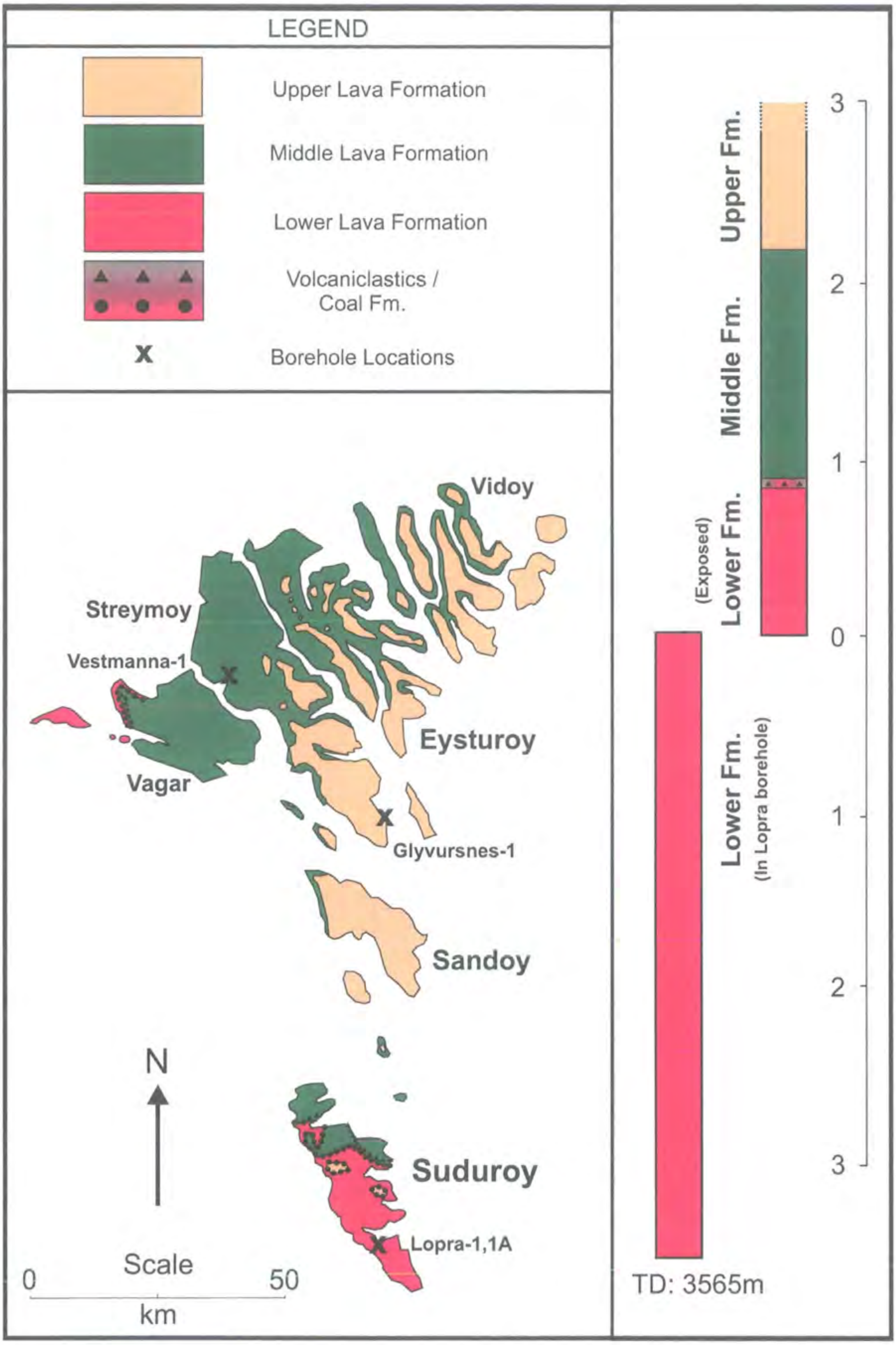


Figure 5-2 The distribution of the Faeroes Lava Group on the Faeroes Islands and the stratigraphy compiled from onshore data and the Lopra-1,1A (1981) well drilled on the island of Suduroy. The wells of Vesmanna-1 (1980) and Glyvursnes-1 (2003) are also located (after Ellis *et al.* 2002).

The Lower Lava Formation (LLF) is the oldest formation of lavas in the Faeroe-Rockall Plateau and has a thickness of over 900m onshore the Faeroe Islands of Mykines, Suduroy and Vágar where the lavas are easily accessed at their contact with the Middle Lava Formation c.4km west of Bøur on the SW coast (Fig 5-3A). On Suduroy the Lopra-1/1A borehole failed to reach the base of the succession at a drilling depth of 3565m (Hald & Waagstein 1984).

On the Faeroes, and in the Lopra-1 borehole, a thick weathered zone caps the LLF: the Coal-bearing Formation. This hiatus in the eruptive activity is represented by the deposition of laccustrine sediments and the development of a thick coal sequence which has been mined. This zone is approximately 10m in thickness, but has been noted to be locally up to 20m thick. The formation has been geochronologically constrained by the use of combined palynological and isotopic dating to the age range c.60.56 to 57.5Ma by Jolley *et al.* (2002) and some of the deepest lavas drilled in Lopra-1/1A have been constrained by Waagstein *et al.* (2002) at c.58.8+/-0.5Ma(1σ) by Ar/Ar whole rock dating.

The Middle Lava Formation (MLF) volcanics are considered to have a thickness of c.1400m estimated from onshore outcrop on the Faeroe Islands (Ellis *et al.* 2002). The complete succession may be seen from its base on the island of Vágar in the west, to Eysturoy and other islands in the east and is dominated by olivine-phyric compound-lavas (Figs. 5-3B & 5-4A).

The Upper Lava Formation (ULF) Faeroe lavas form a substantial thickness of volcanics both on the Faeroe Islands and offshore in the western parts of the Faeroe-Shetland Basin. Over 900m of ULF volcanics exist on the Faeroes, mainly consisting of simple, tabular-type lavas (Ellis *et al.* 2002) (Fig. 5-4). The ULF is considered to have erupted during magnetic chron C24R (Waagstein 1988), which places this activity into a cycle of eruptive activity which occurred prior to the opening of the NE Atlantic Ocean.

A schematic summary of the Faeroes Lava Group is shown in Fig. 5-5 from the water-borne volcaniclastics observed deep in the Lopra-1/1A borehole to the ULF observed onshore on Streymoy and Eysturoy; the two largest islands of the Faeroes chain.

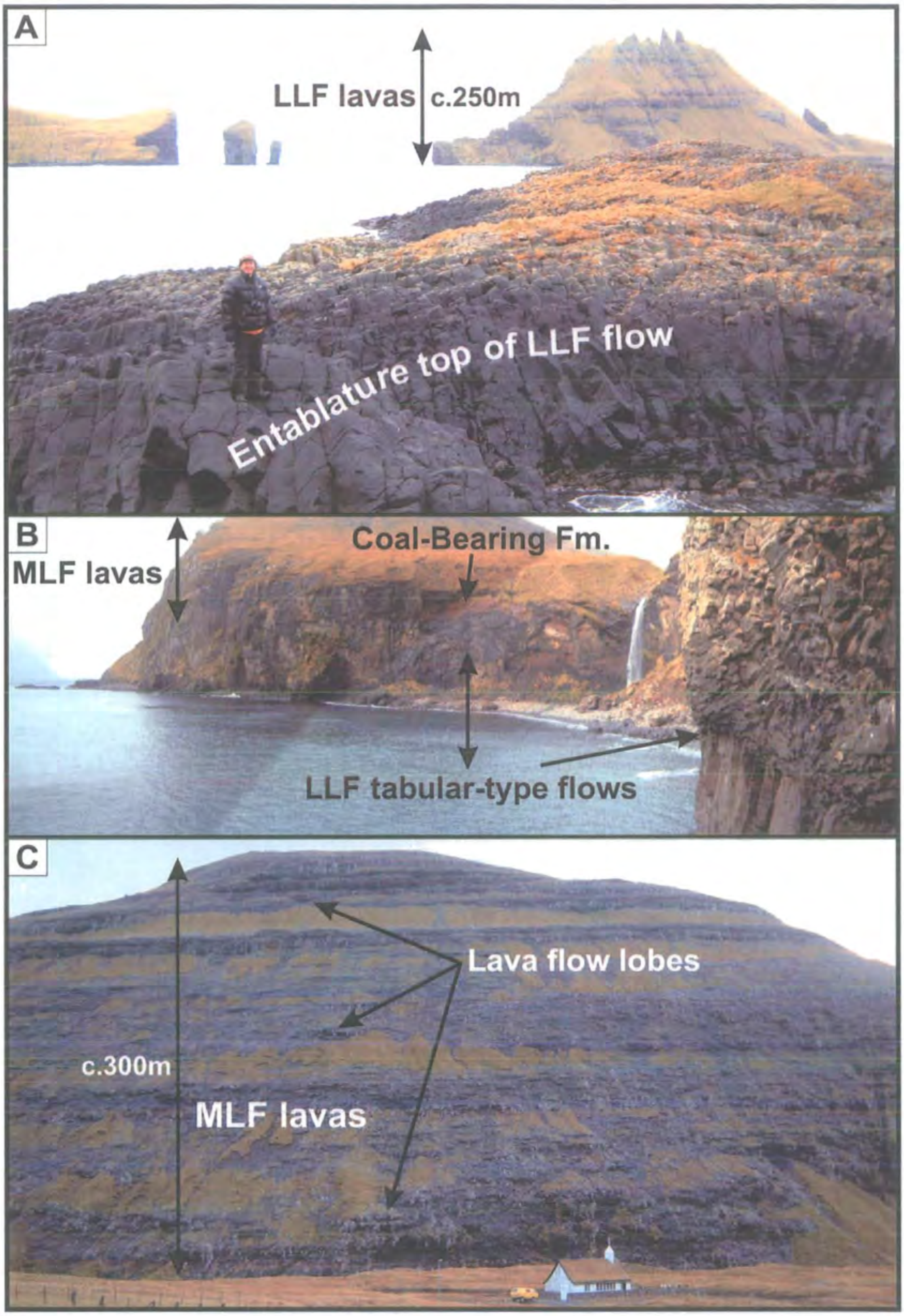


Figure 5-3 Field examples of the Faeroes Lava Group. **A:** The entablature-jointed top surface of a LLF tabular-type flow near Akranessker, on the north shore of Sørvágsfjødur, west Vágar; **B:** Cliffs near Akranessker where a thick LLF flow dominates the foreground. The coal-bearing formation is visible underlying the MLF in the background cliff section; **C:** Looking south from Saksun towards the rubbly outcrops of olivine-phyric MLF lavas forming the mountain of Nónið in the NW of Streymoy. Note the dark, fractured appearance of these typical MLF lavas and the inability to correlate lava lobes over more than a few metres laterally.

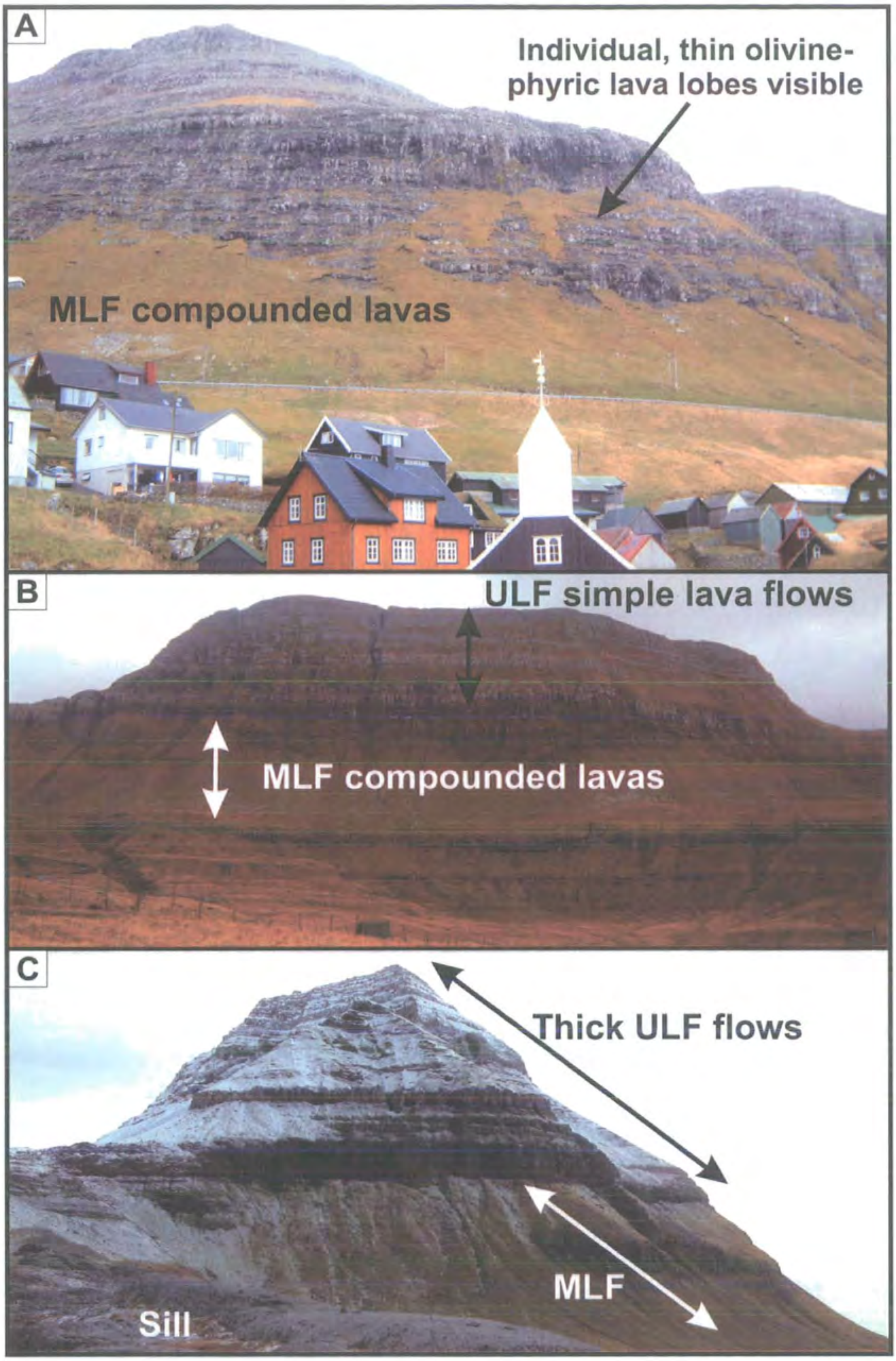


Figure 5-4 Field examples of the Faeroes Lava Group. **A:** Individual olivine-phyric basaltic lava lobes are seen protruding from the highly vegetated a rubbly scarp in the MLF seen looking NE from Bøur on the south coast of Vágar; **B:** The contrasting volcanostratigraphic field characteristics of the MLF & ULF seen from Sðyradalur, west of Torshaven on the SW coast of Streymoy; **C:** Looking south towards Stallur summit on Streymoy (6°57'W 62°05'N) at a succession of thick tabular lavas of the ULF sitting on vegetated MLF lavas that form the more gentle slope and the lower parts of the hill.

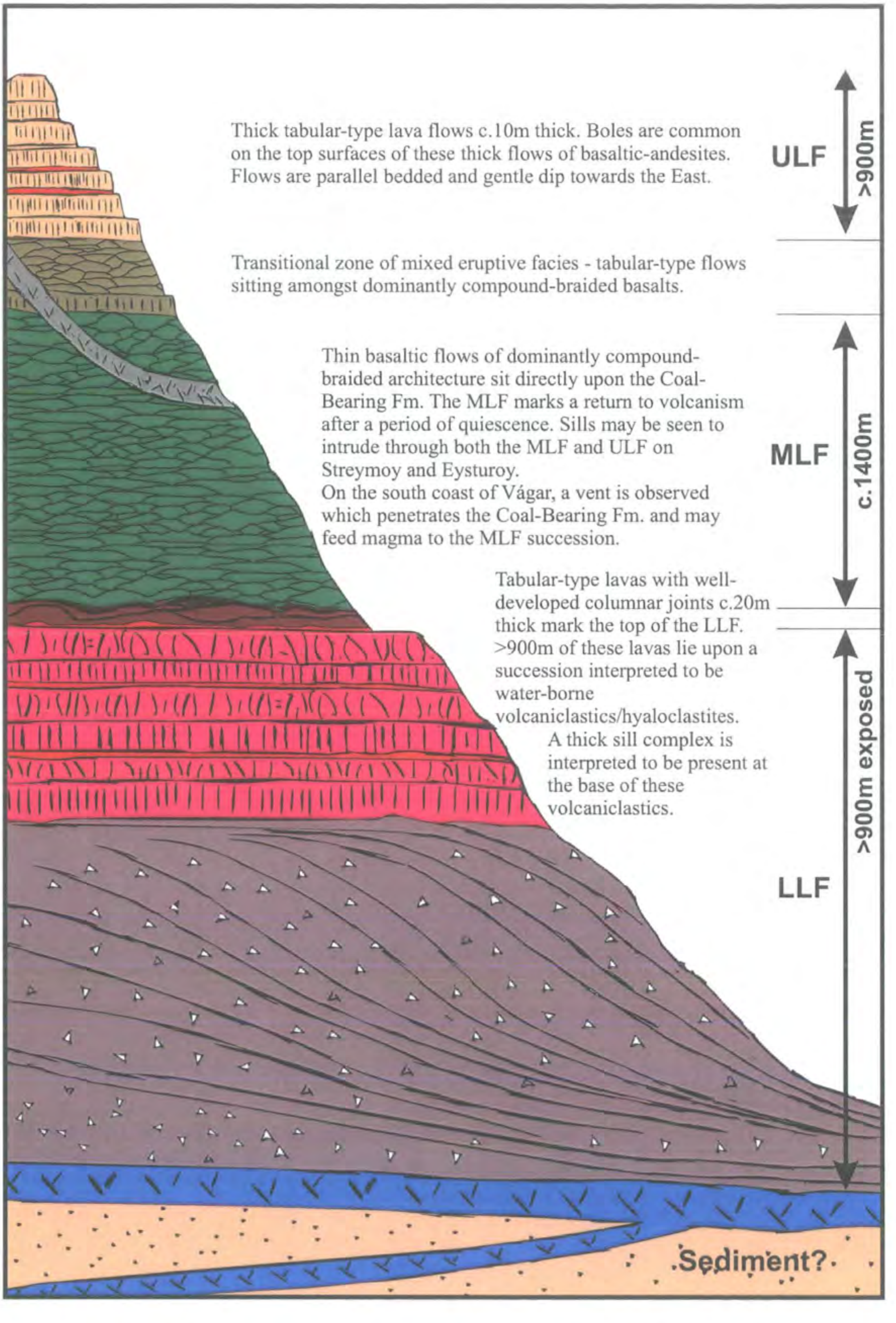


Figure 5-5 Schematic diagram of the onshore Faeroes succession constructed using field exposures of the Faeroes Lava Group, and information/interpretation from the Lopra-1/1A borehole. **A:** The Upper Lava Fm (ULF) is represented by >900m thickness of dominantly thick tabular-type lavas; **B:** The Middle Lava Fm. (MLF) is c.1400m of thinner, compounded lavas lying below a transitional zone of mixed facies; **C:** The Lower Lava Fm. (LLF) is considered to be thick succession of tabular-type flows overlying water-born volcaniclastics. >900m is exposed onshore, and Lopra-1/1A continued to drill volcaniclastic material at a total depth of 3565m below sea-level.

5.3 THE GEOLOGICAL INTERPRETATION OF THE GFA-99 2-D SEISMIC DATASET

The sections that follow describe the offshore succession seen in the GFA-99 seismic data. The interpretations made in this 2D seismic data survey have been constructed based on the understanding of the building blocks of flood volcanic successions that have been developed from the field work and modelling studies of Chapters 3 &4. The intrafacies concepts developed on an intraflow-scale, and the organisation of vertical and lateral stacking patterns on a lavafield-scale, are the backbone behind the ideas the GFA-99 offshore seismic interpretations. These new offshore succession interpretations presented in this thesis have been constructed and interpolated in GoCad™ as a component of SIMBA Work Package 1. A workflow describing the application of these interpretations as part of SIMBA is described and discussed in Martini *et al.* (2005 in press). The succession is discussed in reverse time order, from the high-resolution near-surface data to a gravity interpretation of the deep structure. The sedimentary succession is briefly introduced, followed by a discussion of the lava sequences, the postulated underlying basin structure and sub-volcanic section. The geological history developed from the interpretation is then discussed with facies architectural models.

The most complete published geological interpretation across the Faeroe-Shetland Basin incorporates seismic and industrial borehole data across the basin. Borehole data was unavailable to this project however the proposed interpretation of Ellis *et al.* 2002 is shown in Fig. 5-6. The interpretation of the volcanic succession in this study started with line 105, as this line is considered to contain the highest seismic resolution data. After the interpretation of line 105, the subsequent six lines were interpreted and tied into line 105 in order to achieve a best interpretation fit.

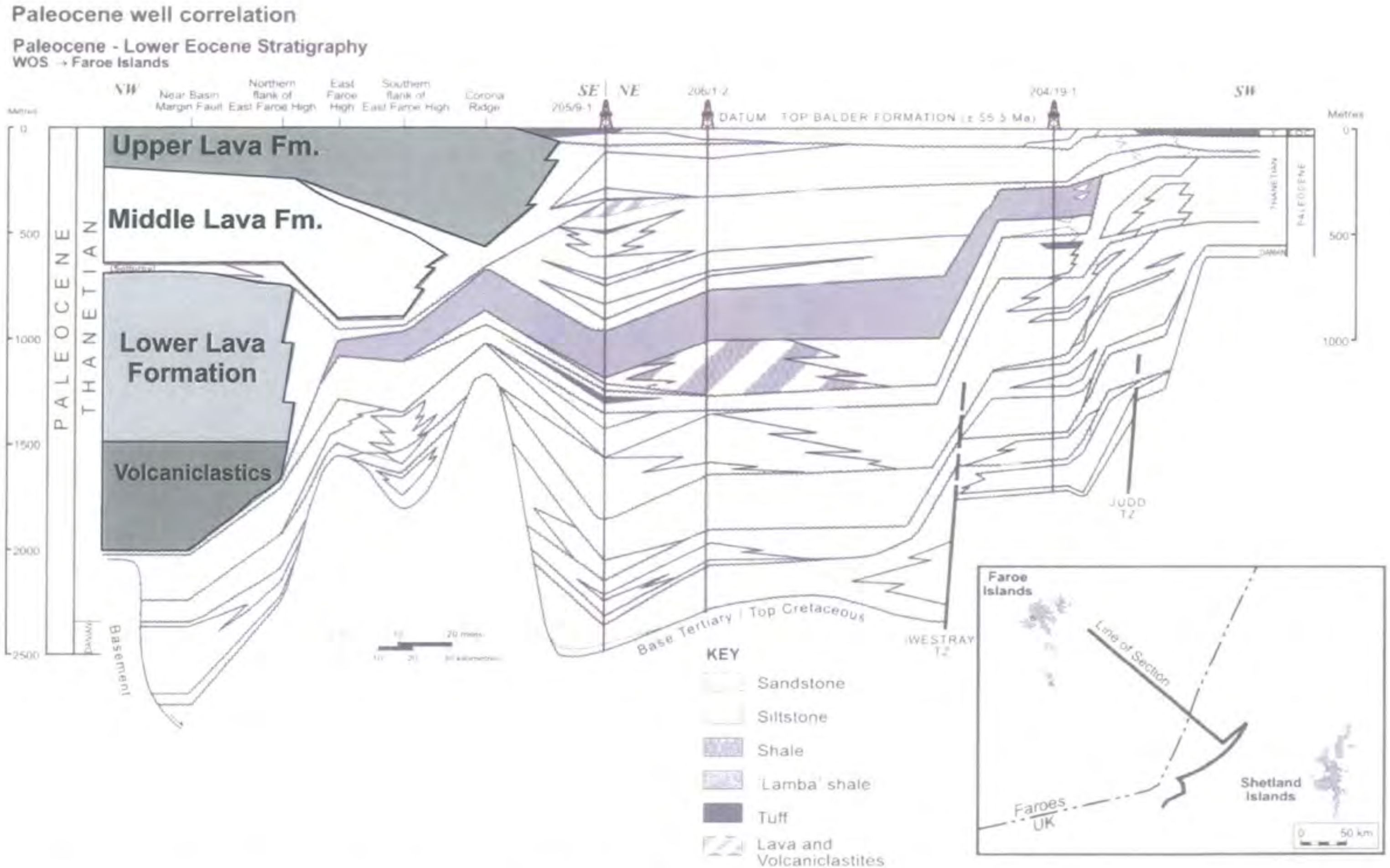


Figure 5-6 Proposed correlation across the Faeroe-Shetland Basin (after Ellis *et al*. 2002). The correlation made NW of Well 205/9-1 covers the GFA-99 2-D seismic survey area, running roughly parallel to the Flare-10 line. The Faeroes Lava Group is highlighted on the left of the section.

5.4 SEDIMENTARY SUCCESSION

The sedimentary succession is broadly divided into two main sequences; the Upper and Lower sediments. Only a brief account of the post-volcanic sedimentary succession is described, as these sediments are relatively homogeneous compared to the volcanic sequences and have not been identified as one of the prime causes for poor sub-basalt imaging. Though the sea-bed is identified as a major cause for multiple reverberations on the seismic data, when combined with the scattering characteristics of the basalt, this poses a non-trivial processing problem.

5.4.1 Horizon Interpretations and Distribution

The top of the upper sediments depositional system is marked by the strong sea bed reflector. The upper sediments (post-Oligocene) cover most of the data area, but thin dramatically in the north of where volcanics are interpreted to be close to the sea bed (Fig. 5-7A). The top of the lower sediments (Eocene and Oligocene) is represented by a strong, laterally persistent reflector that sits proportional and parallel to the stronger top volcanics pick beneath. Downlapping interpretations are common in the top 500ms (TWT) of the upper sediments (Figs. 5-7C & 5-8), whilst erosional truncations and onlapping relationships dominate below this upper veneer. The top surface of the lower sediments is populated by small-throw normal faults. This creates a heavily broken top lower sediments horizon pick which lies above a sequence of sediments that have little internal structure and broadly parallel reflectors.

5.4.2 Thickness

The upper sediments form a sequence with a maximum thickness of c.950ms (c.800m). The lower sediments form a sequence up to c.1650m thick in the eastern part of the data towards the Corona Basin area. The lower sediments thicken to a maximum where the underlying lava field forms a steep scarp (possibly due to normal faulting) in the east of the data area.

5.4.3 Facies Interpretations

The upper sediments are considered to be an erosional turbiditic sequence of muds and sands that have several unconformable contacts with the underlying lower sediments. Though much of the sequence is apparently conformable, anticlinal structures that developed in the lower sediments during the Miocene inversion episode (Boldreel & Andersen 1993) have been eroded in lines 105, 203, 205 and 207 (Fig. 5-8). Towards the base of the upper sediments, incised valley fills may be interpreted (Fig. 5-7C). These incised valleys are considered to have developed during the Miocene inversion as the sediments were uplifted and exposed to sub-aerial erosion.

The sub-parallel reflector sequence that is represented through the lower sediments suggests that these are likely to a series of suspension-fed muddy deposits laid in relatively deep, quiescent water far from any source of eroded detritus. The top horizon-pick is heavily affected by minor normal faults. The intensity of the faulting suggests that these may be part of a mud-based polygonal system (Stuevold *et al.* 2003). The subsequent Miocene inversion uplifted parts of the basin providing sediment for the deposition and resedimentation which led to the formation of the more turbiditic upper sedimentary succession.

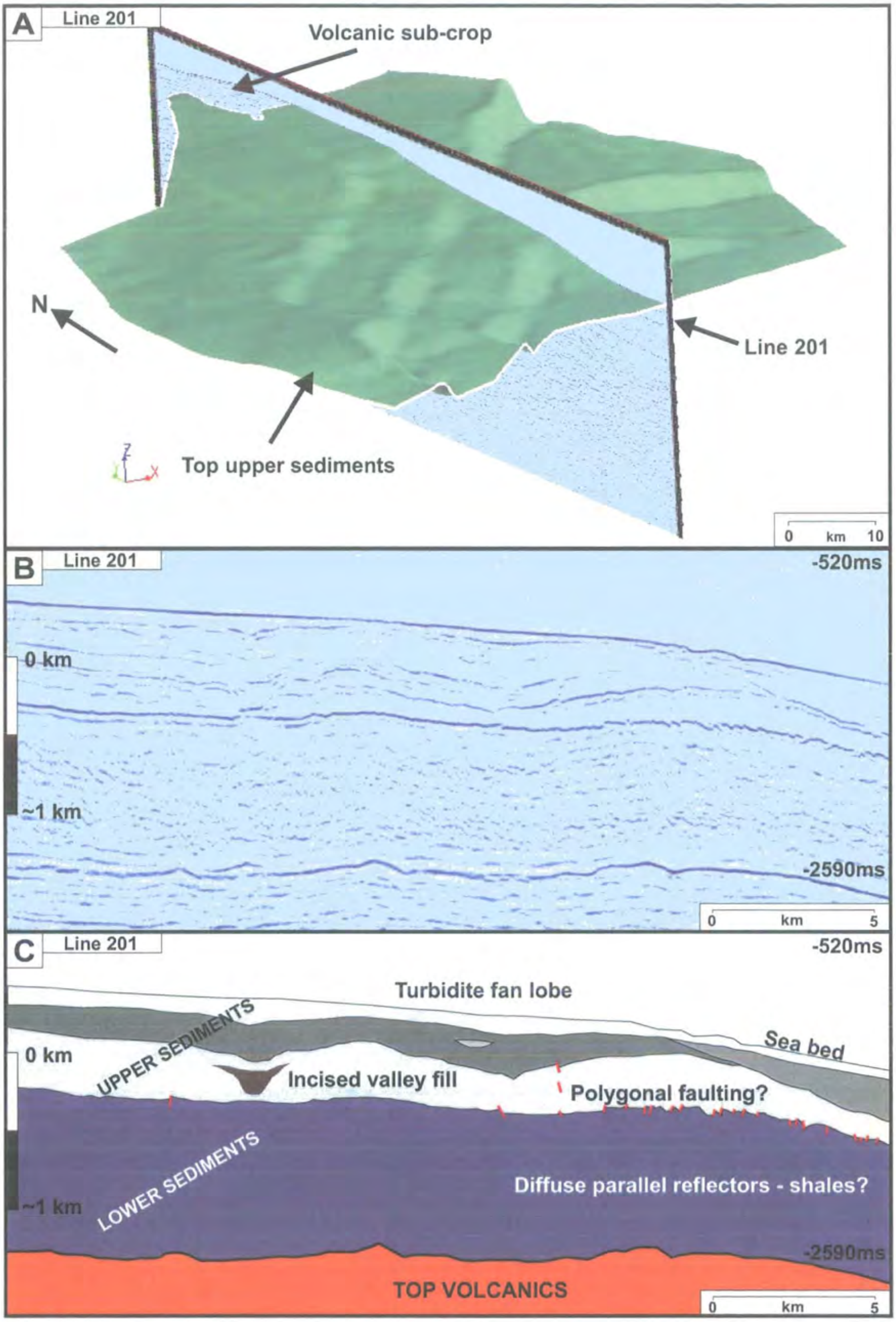


Figure 5-7 Post-volcanic sedimentary succession in the GFA-99 seismic dataset; **A:** The areal extent of the upper Sediments interpolated through the 2D data (green). Note the sub-crop is not sediments in the north of the image. Depth of Line 201 TWT section is 8 seconds; **B:** Close-up section of line 201; **C:** Interpretation of the upper and lower sediments in the same portion of line 201. Faults in the sedimentary sequence are marked in red. Vertical scale is in ms of TWT. Approximate scale in km is also stipulated.

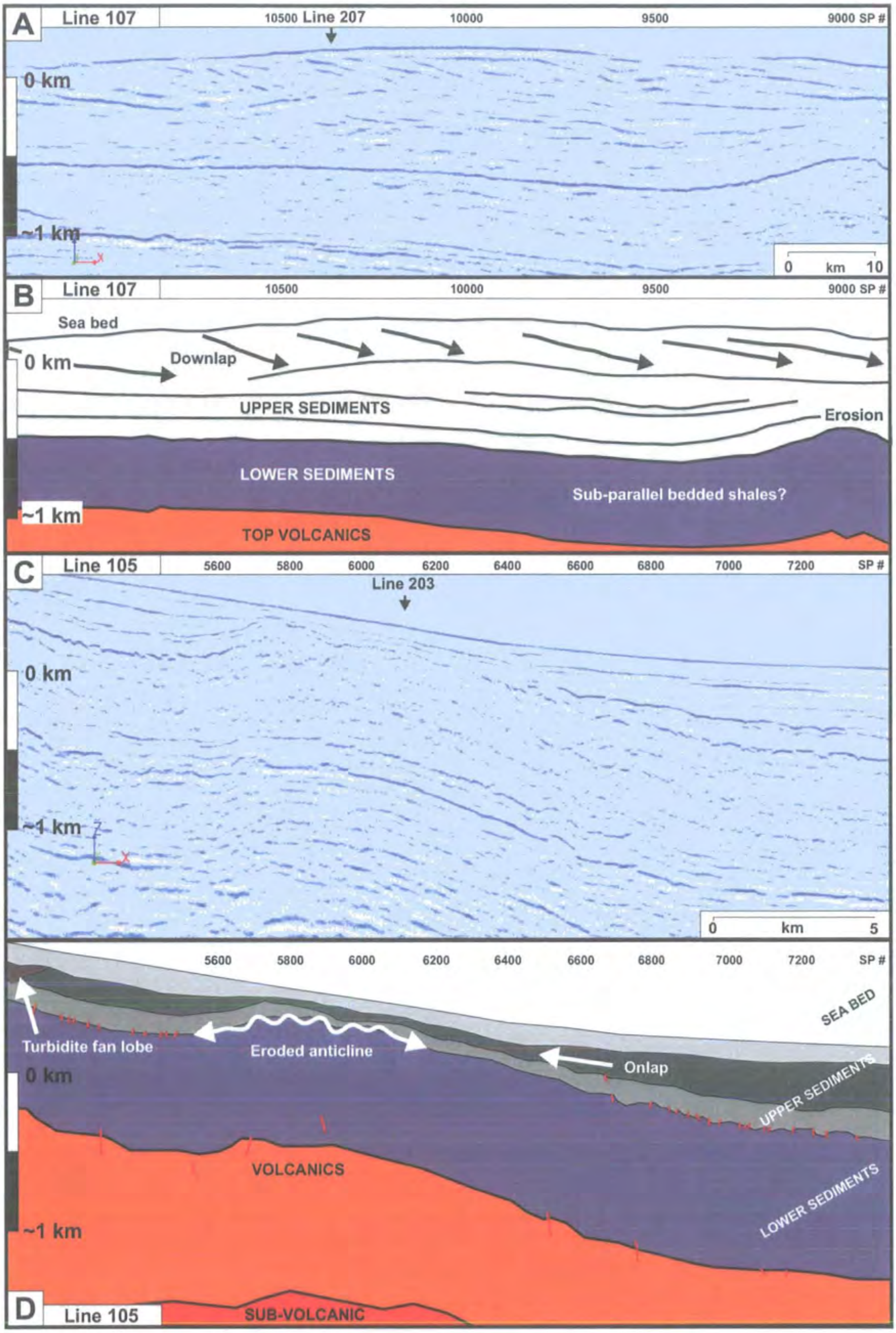


Figure 5-8 Post-volcanic sedimentary succession facies in the GFA-99 seismic dataset. **A:** Section of line 107 showing dipping reflectors in upper sediments and sub-parallel bedding in the lower sediments; **B:** Interpretation of the same section of line 107; **C:** Section of line 105 showing the relationships between the upper and lower sediments; **D:** Interpretation of the upper and lower sediment contacts and facies in the same portion of line 105. Faults are marked in red. Vertical scale in ms TWT specified with approximate vertical scale in km.

5.5 UPPER LAVA FORMATION VOLCANICS

The following section studies the offshore interpretation of the Upper Lava Formation (ULF) volcanics through the GFA-99 dataset: How the sequence is recognised in the seismic, the facies interpretations and the estimated thicknesses present within this part of the NAIP flood basalts.

5.5.1 Horizon Interpretation and Distribution

The ULF is recognised by a laterally extensive reflector. This reflector starts at about 1580ms in the west of line 105 and at a similar depth in each of the other W-E seismic lines of 107 and 109. The reflector is characterised by being the strongest amplitude reflector below that of the sea bed, and by the rugose nature of its top surface. The top ULF pick is heavily affected by the Eocene to Miocene compressional phases associated with changes in the spreading dynamics of the NE Atlantic (Andersen & Boldreel 1995). The top pick is faulted in much of the GFA-99 area, but a characteristic feature of the top ULF is the presence of thrusts that pierce the pick, and the presence of associated thrust-tip folds (Fig. 5-10). The new interpretation and models of the Faeroe-Shetland Basin built in this research have been made possible by the use of the GoCad™ 3D environment. Thrust faults have been interpreted on individual 2D seismic lines, and their planes interpolated between lines, resulting in this new structural interpretation of the GFA-99 area.

The gently dipping ULF volcanics cover over $9.4 \times 10^3 km^2$ of the dataset area and follow the general structural dip towards the SE into the Corona Basin where they pinch out (Fig. 5-9C). The Faeroes Lava Group is at its shallowest in the north of the GFA-99 area where the ULF is interpreted to be close to the sea floor.

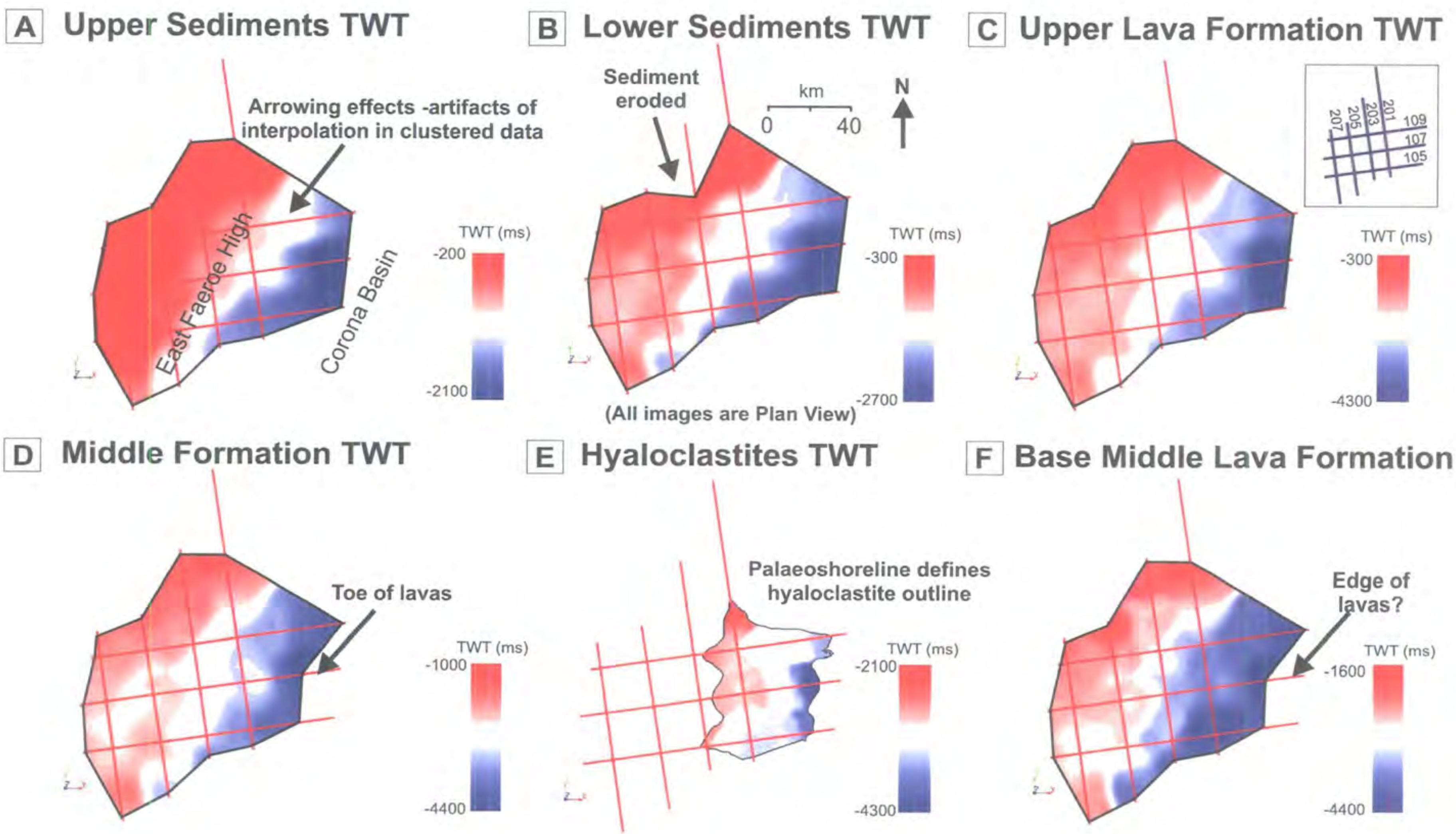


Figure 5-9 Depth maps to important horizon picks interpolated and represented as 2D surfaces in Two-Way-Time (TWT). GFA-99 grid is shown for location purposes. Note that the depth to the top of all of the interpolated reflectors increases towards the SE as the succession dips into the Corona Basin, east of the East Faeroes High. Artifacts of interpolation are apparent in the diamonding effects observed between the 20km-spaced 2D seismic lines.

5.5.2 Thickness

The ULF succession maintains a reasonably constant thickness of about 500ms TWT across most of the study area, apart from where the formation feathers out towards the south and east. The maximum thickness of c.950ms TWT is represented in the NW parts of the dataset towards their source on the Faeroes. The thickness is mainly comprised of parallel, laterally persistent reflectors, except for in the SW, where a divergent reflector sequence is observed to dip down into the region of the Corona Basin. In the north and west of the lines, the parallel, persistent reflectors form the entire thickness present. Towards the SE, many of these reflectors pinch out and appear to shallowly downlap as the lavas thin above dipping, divergent sequences. This thinning provides an indication of the maximum extent of the ULF distal to the Faeroe Islands. The character of the sequence suggests that the lavas pinch out close to the east end of GFA-99. This notion is supported by the observations of Ellis *et al.* (2002).

An approximation of the thicknesses of volcanics in the Faeroe Lava Group has been made using the following relationship:

$$\Delta Z = Vi_1 * ((1/2000) * T_1 - T_0)$$

Where: ΔZ = Thickness (m)

Vi_1 = Interval velocity of seismic unit (ms^{-1})

T_1 = TWT to base of seismic unit (ms)

T_2 = TWT to top of seismic unit (ms)

This may be written as the following property script in GoCad™:

```
{thickness = Vi * ((1/2000) * TWT_thickness) ; }
```

Where: thickness = The property of the client Surface (m)

1/2000 = Conversion for TWT to One-Way-Time (m)

TWT_thickness = The host Surface property of TWT thickness (ms) Vi = A specific Interval Velocity (ms^{-1}): This must be substituted with a numerical value in the property script

From the geological interpretation of the seismic, this GoCad™ property script is able to provide an estimate of the thicknesses of the various volcanics using an assumed interval velocity and the TWT thickness maps calculated in Figs. 5-11 & 5-12. The calculated thickness of the ULF shows considerable thickness variations across GFA-99 (Fig. 5-16). The formation is at its thickest in the north and the west which is more proximal to the source region for the volcanic sequences where c.1400m are calculated to be present where the interpretation of the GFA-99 data is reliable and multiples are at a minimum. As stated, the preserved onshore thickness is c.900m, with the top of the formation missing due to erosion. Therefore up to c.500m of lavas may be missing from the onshore exposures of the ULF on the Faeroes.

Late Palaeocene to Miocene compressional structures in the Faeroes Lava Group

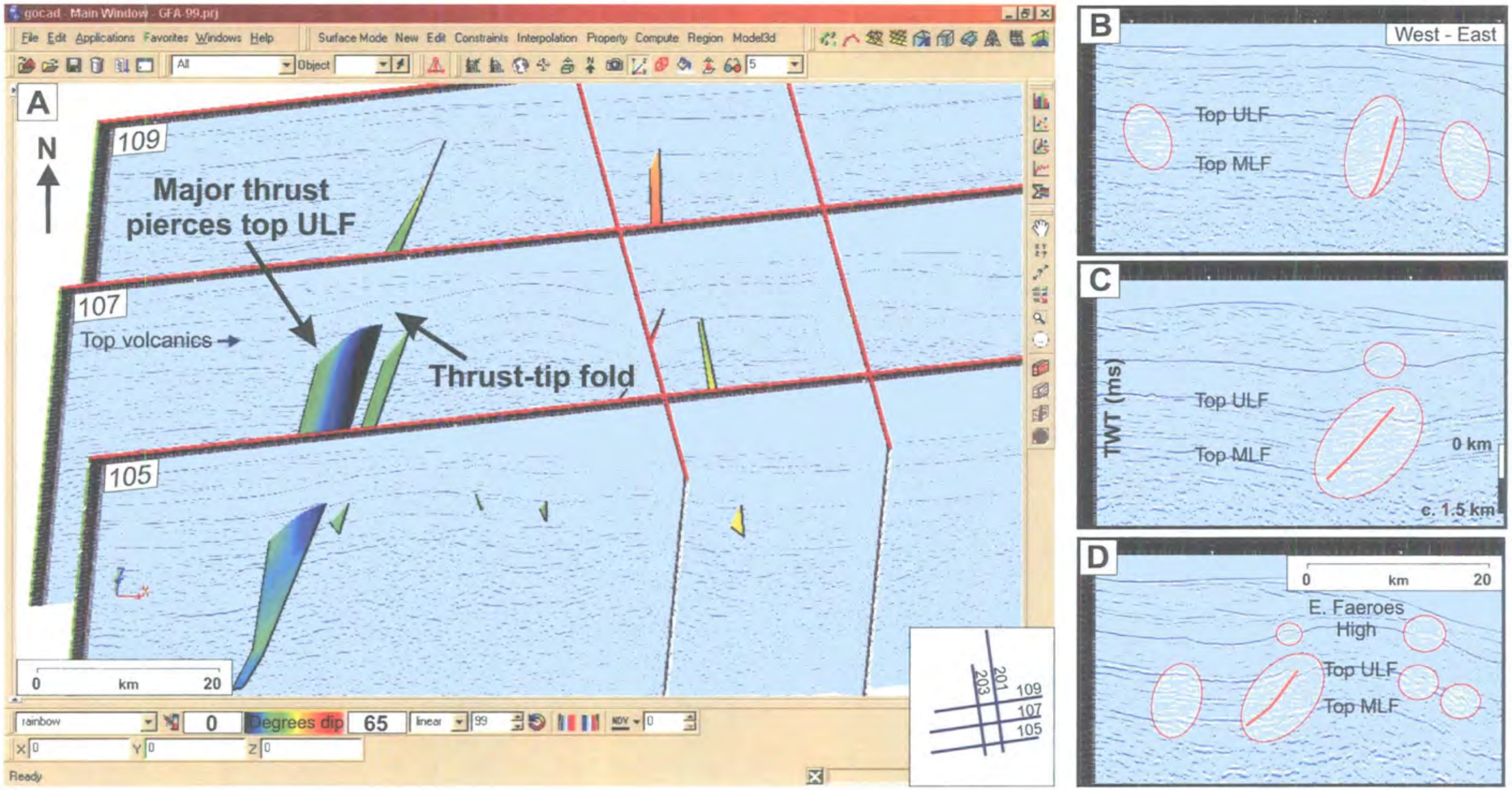


Figure 5-10 Late Palaeocene to Miocene compression has created a series of inversion structures in the Faeroes Lava Group; some also having an expression in the overlying Eocene-Oligocene sediments within the lower sedimentary succession described in the body text. **A:** A 3D view of the main faults cutting through the GFA-99 seismic data. Note the high dip angles of some parts of the reverse faults and compressional features. These are attributed to transpressional inversion; **B** to **D:** Detail of compressional structures and zones of compressional deformation in GFA-99 lines 109, 107 and 105.

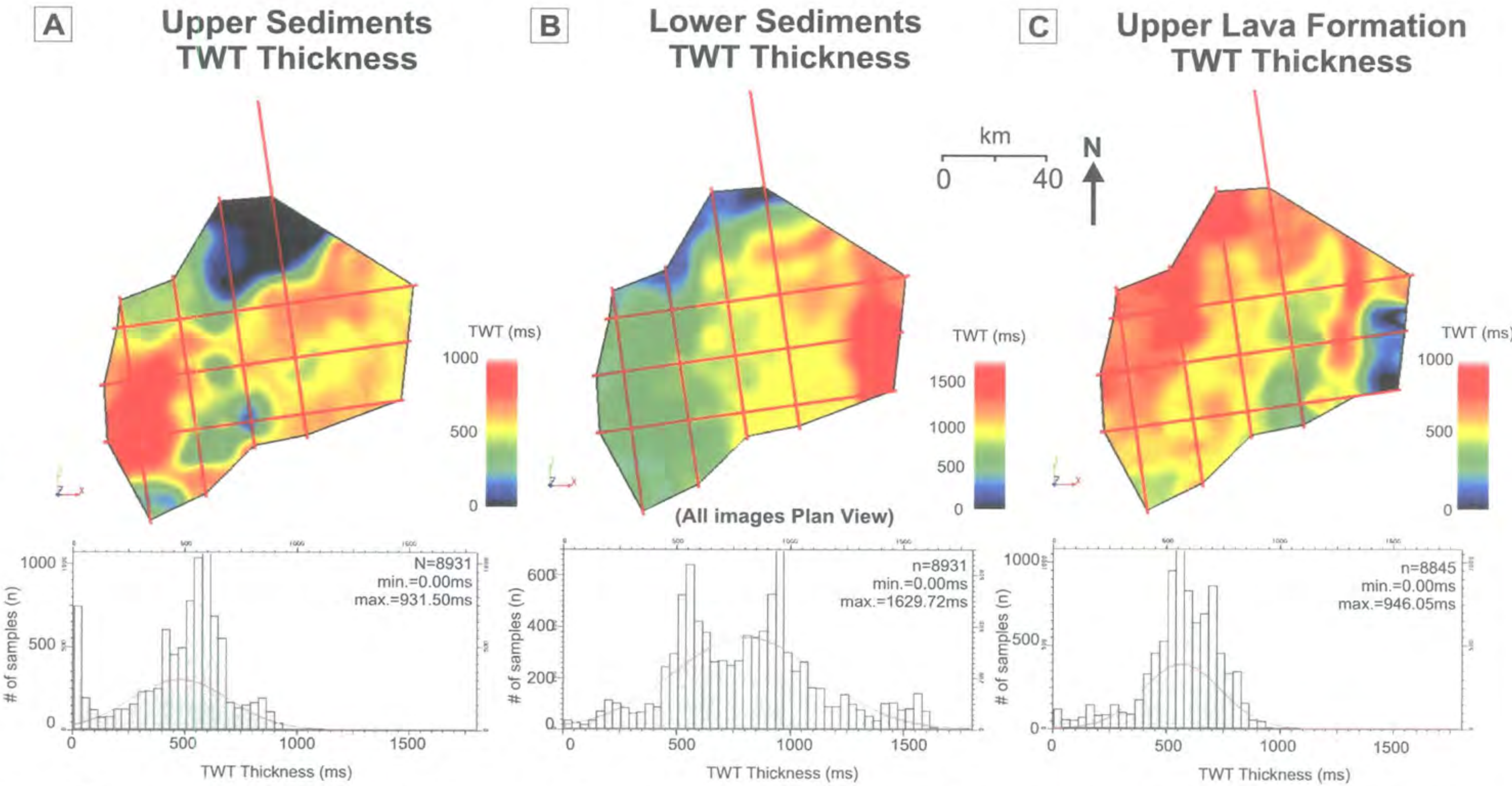


Figure 5-11 Two-way-time (TWT) thicknesses of major parts of the Faeroes succession in the GFA-99 data. **A:** The upper sediments are absent in the north of the area, and thicken towards the SW into the Faeroe Basin; **B:** The lower sediments thicken towards the east where the underlying lavas thin and are normally faulted towards their most eastern extent; **C:** The Upper Lava Formation (ULF) has most substantial thickness on the NW of the data area, toward the Faeroe Islands where over 900m of the ULF are revealed onshore. Histograms show the TWT thickness distributions through each of the interpolated 2D interpretations.

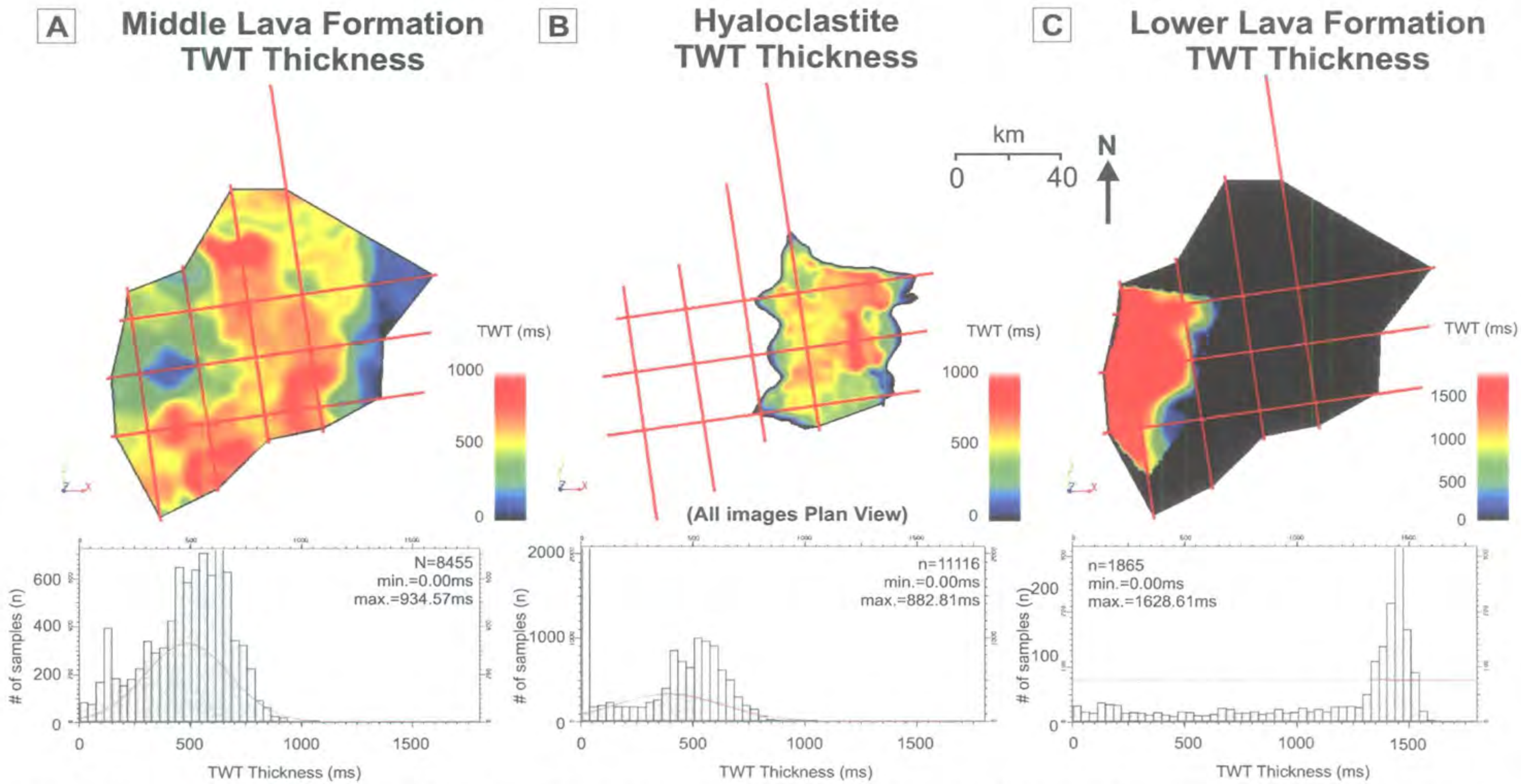


Figure 5-12 Two-way-time (TWT) thicknesses of major parts of the Faeroes succession in the GFA-99 data. **A:** The Middle Lava Formation (MLF) volcanics are absent in the north of the area, and thicken towards the East Faeroe High. To the East of the East Faeroe High, the MLF thins and the ULF forms a hyaloclastite volcaniclastic delta sequence on top of the MLF; **B:** The best defined hyaloclastite volume lies in the east of the study area in the Upper and Middle Formations where volcaniclastics have prograded into the area of the Corona Basin; **C:** The Lower Lava Formation (LLF) thickness in this figure, are estimated from the seismic data alone.

5.5.3 Facies Interpretation

5.5.3.1 Tabular Lavas

The seismic reflectors in the NW and upper parts of the ULF interpretation have strong amplitudes and are laterally persistent. Individual high amplitude reflectors may be picked over tens of kilometres. This simple character and the lateral extent of the reflectors suggest that the volcanics in these parts of the ULF may be of tabular-type facies (Jerram 2002). From onshore studies, the ULF volcanics have been shown to be composed of simple type flows of about 10m mean thickness (Ellis *et al.* 2002). Between many of the flows, sedimentary horizons are developed similar in character and thickness to those seen in the Skye Lava Field successions on the Isle of Skye. The Upper Fm. lavas are dominated by plagioclase-phyric flows in the central Faeroes (Ellis *et al.* 2002), studies on Skye have shown that more evolved lava types such as the hawaiites and mugearites (basaltic-andesites) tend to develop more simplistic internal and external morphologies due to their increased erupted viscosities and inflated modal silica contents. Much of the ULF may therefore be considered to be akin to the lavas seen in the Arnaval Member of more evolved flow types in west-central Skye. The field analogues for the ULF are taken from the basaltic-andesites of the Arnaval Member of the Talisker Bay area of the Skye Lava Field, from the Etendeka flood basalts of Namibia and the Faeroe Islands (Figs. 5-17 to 5-19).

5.5.3.2 Lava Delta Fans

In the south and east of the GFA-99 area, beyond N-S line 201, the tabular-type lavas of the western parts of the formation are noted to spill into a series of basinward dipping reflectors (Fig. 5-14). These are interpreted to form a hyaloclastite fan or apron in the Corona Basin region and dip down towards the ESE. The reflector sequences in this part of the ULF are of the highest resolution in the lines 105 and 107. Although the divergent nature of the reflectors is clear, the boundaries of any particular sequence are less clearly defined. The hyaloclastites show complex internal morphology in comparison to the more simple lava types interpreted in the bulk of the ULF. The complexity of the internal morphologies of the lavas means that the distinction between the ULF and the underlying MLF is difficult to interpret, especially through the hyaloclastite zones. The interpretation of the presence of an ULF hyaloclastite apron has been made by detailed picking of the volcanic internal reflectors, paying particular attention to onlap, downlaps and pinch-out relationships within the formations apparent. The presence of a hyaloclastite apron in the ULF indicates that the Faeroes Lava Group was filling a water-filled basin in the east of the GFA-99 area; lavas moving into this accommodation space from their source near the Faeroes. A more distinct boundary between the ULF and the MLF is observed in the north and west of the data area, where the interpreted hyaloclastites are not deemed to be present. Fig. 5-13 displays a basic interpretation of the GFA-99 line 105, showing some of the more prominent tabular-type picks in the data, and also some of the downlapping features present in the hyaloclastite deltaic succession. More detailed interpretations of the volcanic sequence are illustrated in Figs. 5-14 and 5-15. Hyaloclastites are also found in the MLF and their formation and significance will be discussed in detail in the following description of the MLF.

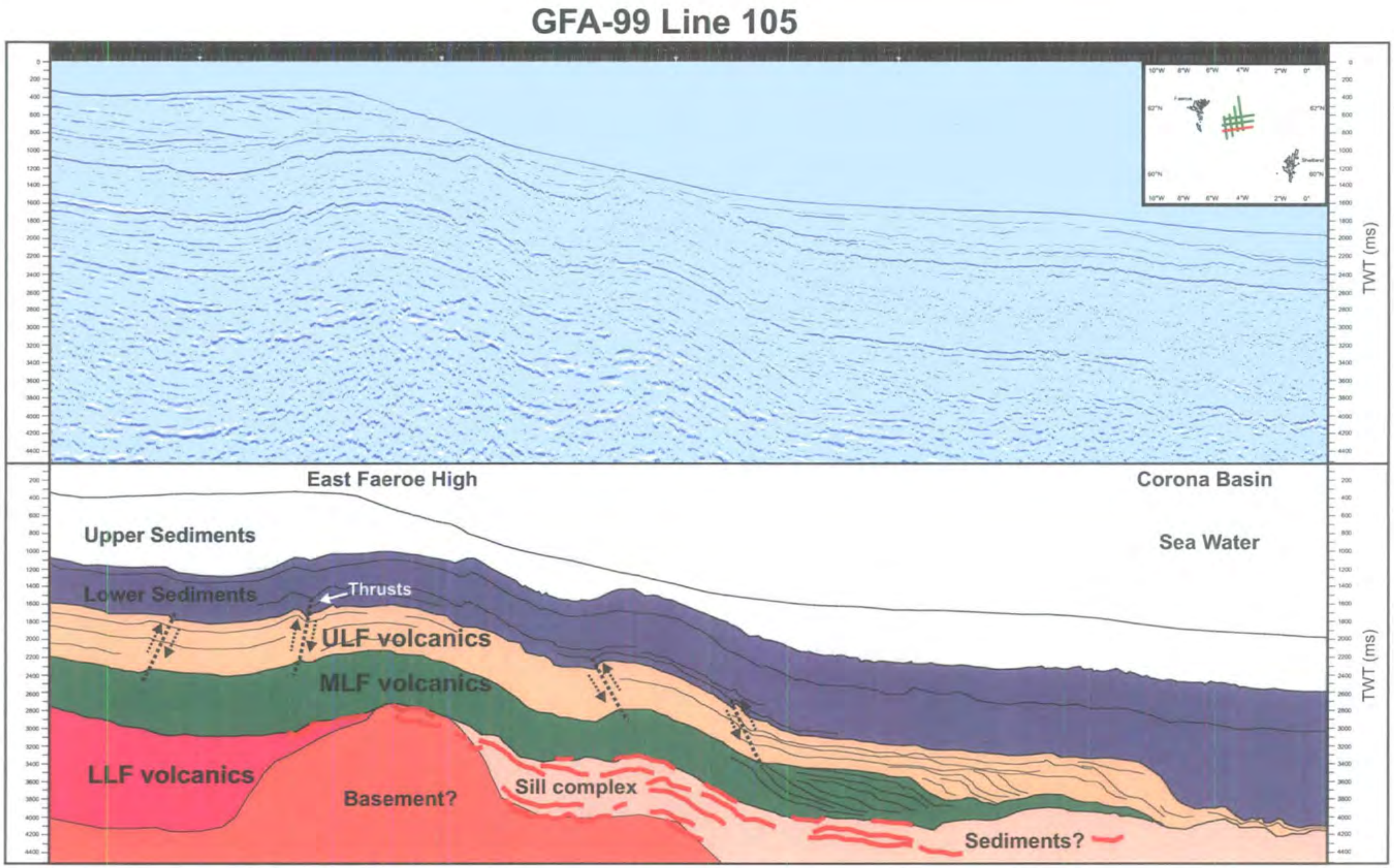


Figure 5-13 Geological interpretation of the GFA-99 line 105 (red on inset location map). The strong reflectors at the base of the succession are interpreted to be thick sill complexes. In the west of the section, LLF volcanics form a thick hyaloclastite delta which reaches as far as the East Faeroe High. The MLF is interpreted to consist of compound braided pahoehoe type lavas that fed off the Faeroes area to form a hyaloclastite apron in a substantial water-body. Sub-aerial tabular type lavas form the bulk of the ULF, except in the most distal part of the basin, where hyaloclastites extend the MLF apron system.

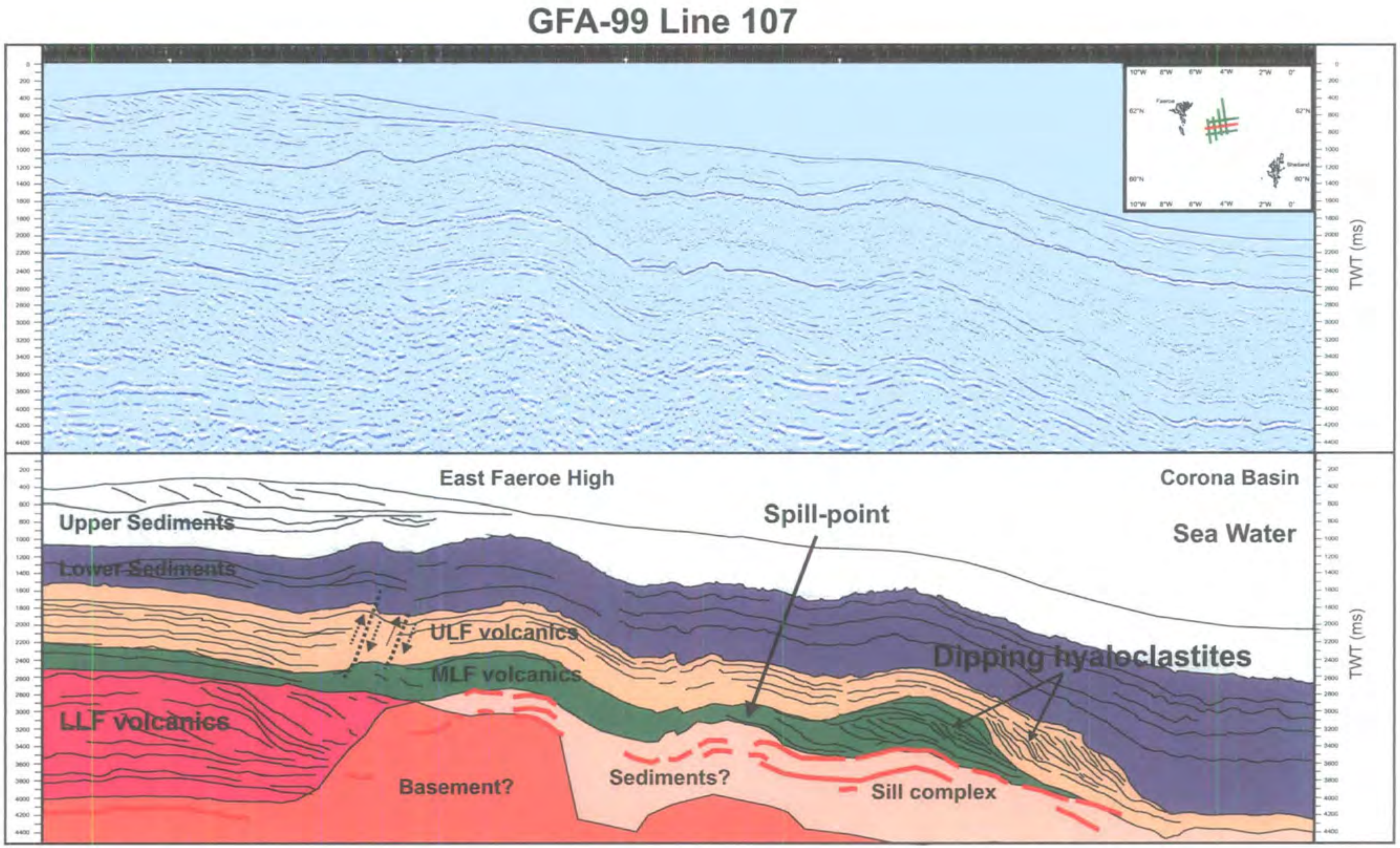


Figure 5-14 Geological interpretation of the GFA-99 line 107 (red on inset location map). Succession base marked by a series of sill-type reflectors. In the west, dipping reflectors of the LLF are interpreted to form a wedge of hyaloclastites beneath compound lava types of the overlying MLF. The ULF contains laterally persistent strong reflector characteristics interpreted to be representative of a tabular lava type succession. In the east of the Middle and Upper Lava Formations are the NE continuation of the hyaloclastite apron sequence.

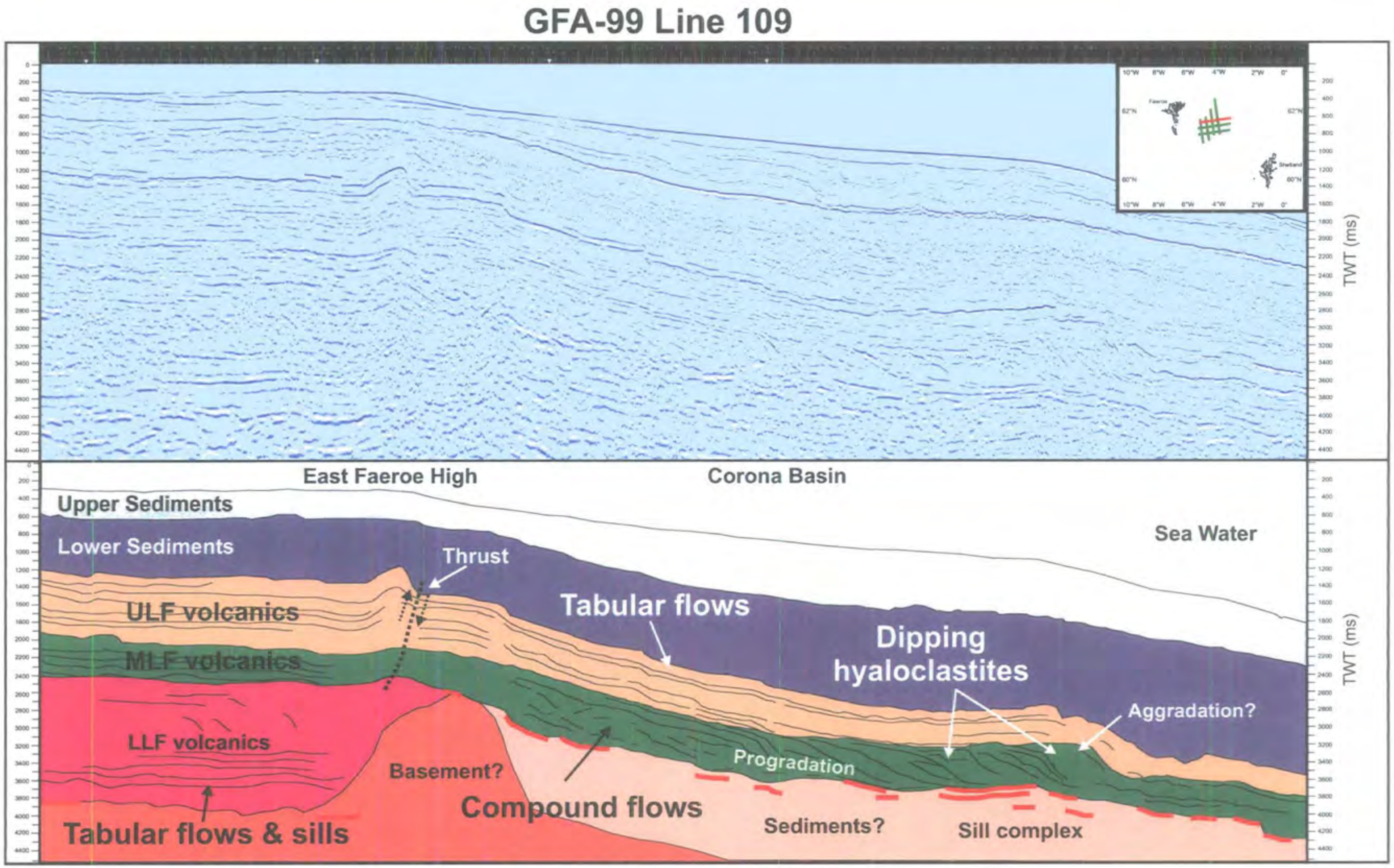


Figure 5-15 Geological interpretation of the GFA-99 line 109 (red on inset location map). The complete volcanic succession thins towards the east. A geological interpretation of the possible extent of the LLF volcanics is suggested in the west of the section. This is considered to be represented by sub-horizontal tabular-type flows overlain by a sequence of dipping hyaloclastites of a massive thickness of c.1400ms. The LLF volcanics apparently terminate near the axis of the East Faeroe High.

5.6 MIDDLE LAVA FORMATION VOLCANICS

The MLF volcanics are now discussed in detail. The interpretation in this part of the Faeroes Lava Group is more difficult than the ULF due to a loss in seismic resolution. This is caused by the greater depth of the MLF, the dispersive and high acoustic impedance properties of the overlying ULF volcanics, and also the different internal facies architecture of the MLF noted from the onshore exposures on the Faeroe Islands.

5.6.1 Horizon Interpretation and Distribution

Whereas the top of the ULF is a distinct, high amplitude reflector beneath the lower sediments (due to the high acoustic impedance contrast over the sediment/lava interface), the intra-volcanic contrasts are minor, unless seismically significant facies changes occur within the succession. In much of the ULF/MLF interface offshore, there is no obvious seismic boundary and arbitrary boundaries are interpreted. The two formations are usually referred to together in most of the literature due to the arbitrary nature of the boundary interpreted in seismic. In this interpretation, the top of the MLF is taken as the highest amplitude pick which sits approximately 600-1000ms beneath the top ULF pick.

On the basis of the geometries of the reflector sequences present, and the amplitude of key reflectors within the volcanics, the MLF is divided into three main sequences (Figs. 5-17 to 5-22):

- Compound-braided sequence
  - Broken, indistinct seismic reflectors
  - c.1300m thickness of olivine-rich pahoehoe type lavas
- Hyaloclastite Deltaic sequence
  - Down/top-lapping foresets of divergent & convergent reflectors
  - c.400m thickness of foresets
- Mixed Transitional sequences
  - Mixed broken & persistent reflectors

In the SE of the GFA-99 area, the base of the MLF is interpreted to be the series of high amplitude broken reflectors deep in the volcanic succession. These are interpreted to be sill complexes at the base of the volcanic succession (5.8) and form zones of over 1000ms TWT of strong, lozenge-like reflectors. The convergence of downlapping reflectors is also taken as a base-succession marker in this part of the data. The MLF is present across the entire GFA-99 area, but thins to a minimum in the eastern extremity of the dataset, as in the case of the ULF. This is due to the large distance from the eruptive source near the Faeroe Islands (>100km).

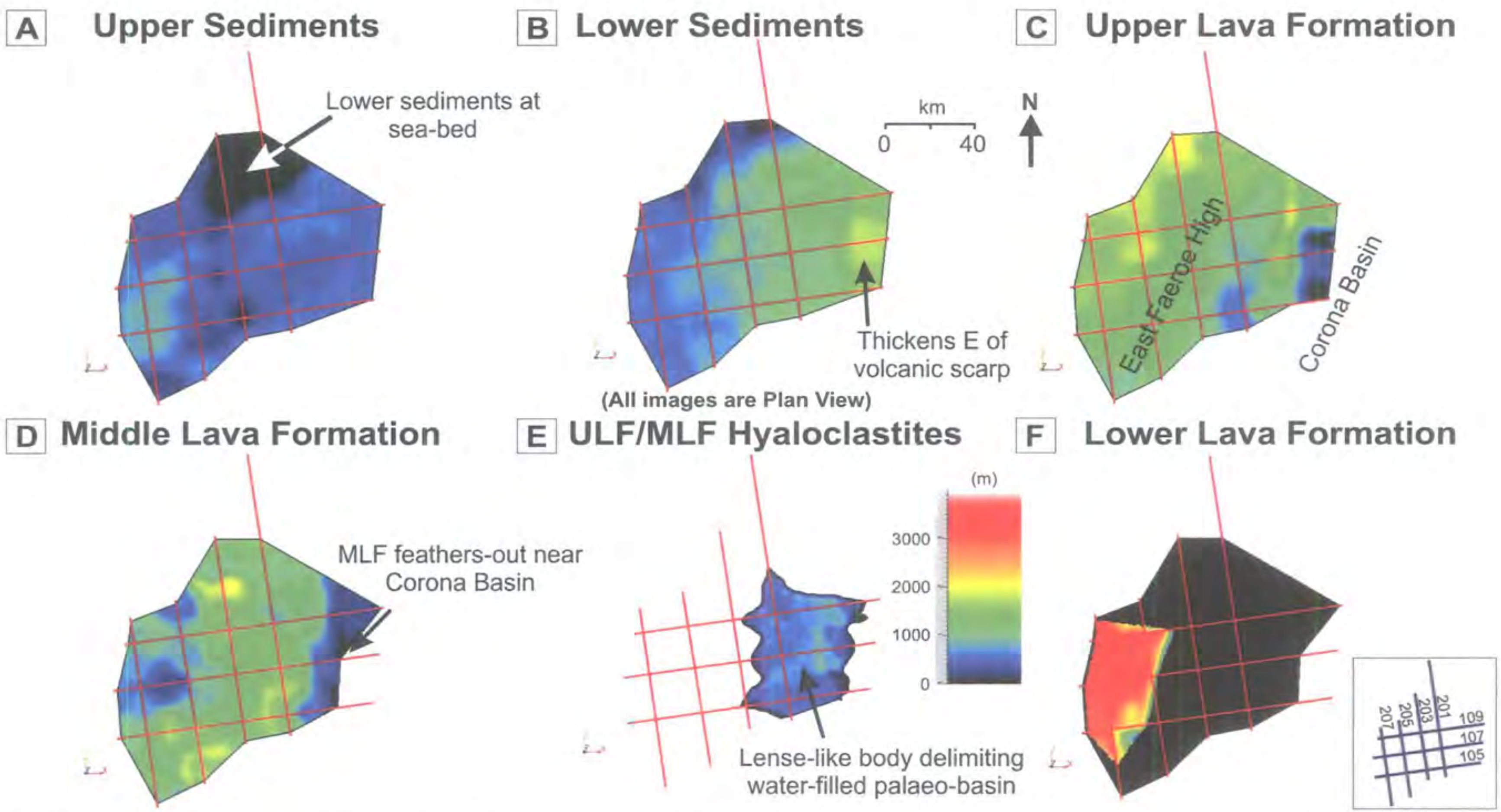


Figure 5-16 Isopach maps of the calculated thicknesses of the major parts of the Faeroes succession in the GFA-99 data in metres. **A:** Upper sediments have zero thickness in the north where the lower sediments are interpreted to reach the sea-bed; **B:** Lower sediments blanket the study area with a constant thickness except beyond the eastern limit of the volcanic where the succession fills the extra accommodation space developed at the foot of the volcanic scarp; **C:** ULF volcanics form a succession similar in thickness to the MLF from the offshore interpretation suggesting that c.500m of ULF has been eroded onshore; **D:** MLF thicknesses are similar to ULF, however a palaeo-high in the interpreted LLF causes localised thinning in the west of line 107; **E:** ULF/MLF hyaloclastites form a lozenge-like body which represents the shoreline of a palaeo-water-filled basin (c.600m deep) with areal dimensions over 40x60km (i.e. equivalent to the area within the M25 motorway, London, UK); **F:** LLF wedge-like body of volcaniclastics onlaps a palaeo-high and is not easily interpreted beyond the palaeo-high in the rest of the data area.

Tabular lavas - Onshore analogue

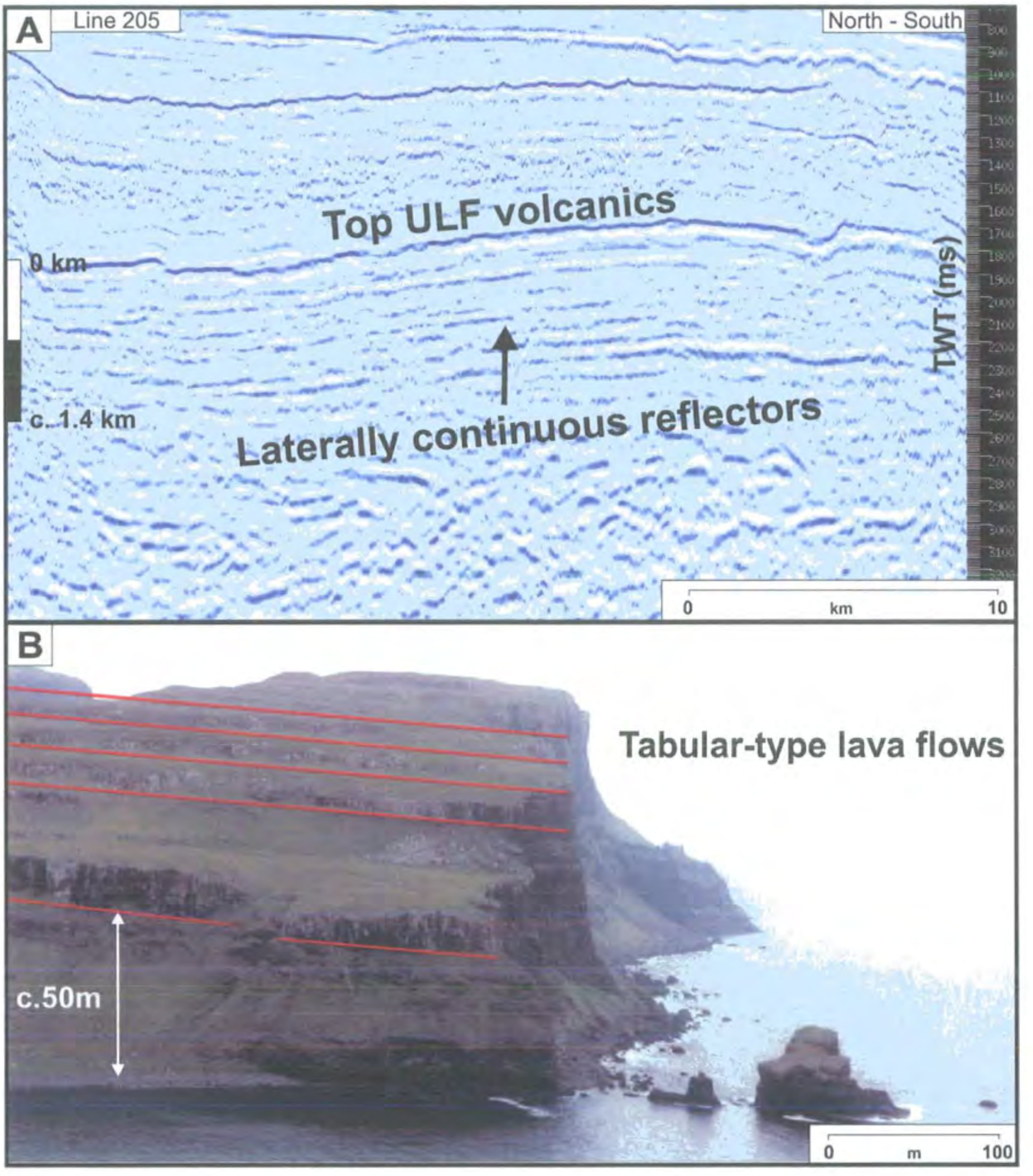


Figure 5-17 An onshore analogue for the lavas seen in the ULF and in mixed zones of the MLF which are interpreted to be tabular-type lavas. The tabular lavas form laterally extensive thick flows (c.10m thick) that may be correlated over kilometres in the seismic signature, and also in the field. Onlapping and off-lapping relationships are not immediately obvious in the field and need to be discovered by large-scale field mapping. **A:** A section of GFA-99 line 205 showing the characteristics of this architectural facies type; **B:** Looking south over Talisker Bay at the mountain *Beinn nan Cuithean* in the Skye Lava Field on the Isle of Skye. Note the thick character of these flow and their structure which often contains a colonnade and entablature organisation.

5.6.2 Thickness

Thickness of the MLF varies considerably through the 2D seismic. The maximum thickness of the formation is c.930ms (c.1870m) and the lavas pinch-out entirely in the SE. Errors associated with these values may be mainly attributed to the difficulties of interpretation of the MLF base, and to a lesser extent the MLF top, as discussed above. The thickest part of the volcanics lies through the centre of the dataset where a N-S swathe of volcanics have a mean thickness of c.1300m. This agrees well with the preserved onshore thickness of c.1400m (5.2).

Fig. 5-16 shows a thickness map for the interpreted hyaloclastite volcanics that are considered to be present in both the MLF and the ULF. This body has a maximum thickness of c.700ms TWT or c.700m (using Vi=2000ms^{-1}), with most data points in the body clustering around the 400-600m thick range (Fig. 5-16). This represents a massive thickness of fragmental volcaniclastics that are interpreted to have been erupting into a substantial water body. The calculations of Ellis *et al.* (2002) suggest the hyaloclastites form foresets between 150-500m in thickness. The present study confirms a similar calculated-scale of hyaloclastite foresets.

5.6.3 Facies Interpretation

The facies present within the MLF fall into three main caterogies:

- Compound-braided lavas
- Hyaloclastite apron
- Mixed transitional lavas

5.6.3.1 Compound-braided Lavas

Much of the western part of the dataset contains broken, dispersed reflectors that are not correlateable over the large distances (kilometres) possible in the tabular-type lavas interpreted to be present in the ULF. This is attributed to the lavas being formed of mainly olivine-rich compounded lavas sequences such as those seen towards the base of the succession studied in the Talisker Bay case study area. The stacking patterns are complex in the vertical section, but also laterally as the eruptive style of these more olivine-rich lavas tend to form compound-braided systems (Fig. 5-20).

5.6.3.2 Hyaloclastite Apron

Hyaloclastites are interpreted to form a large thickness of the MLF. The dipping reflectors are observed to dip steeply towards the ESE and form a body which runs NNE-SSW through the study area. The spacing of the seismic lines is too great (20km) to understand whether the hyaloclastites form individual deltas, but their widespread occurrence in the MLF in lines 105, 107, 109 and 201 suggest the body to be more like an apron than individual deltas. The thickness of the hyaloclastites in the MLF indicate the presence of a deep water body proximal to the sites of eruption near the Faeroe Islands; the hyaloclastites prograding basinward towards the Corona area and appear to be on a similar scale to hyaloclastite dipping successions in west Greenland (Figs. 5-21 & 5-22). The possibility of there being a thick sequence of hyaloclastites in the MLF/ULF successions has important implications for the observed bouguer gravity of the area. Hyaloclastites are low density volcanics, and also have low elastic velocities when compared to plagioclase-phyric tabular lavas for example. Therefore, they are an important consideration to both seismic and gravity geophysical modelling. Figure 5-23 shows the seismic velocity spectrum for the interpreted hyaloclastite zone. In the interpreted hyaloclastites, the estimated primary velocity is considerably lower (2300-3900ms^{-1}) than for 'typical basalt' surrounding the hyaloclastite volume (5000-5900ms^{-1}). The implications for the gravity modelling of lavas are highlighted in Figs. 5-24 & 5-25. In the first of these figures, a simple gravity model is constructed assuming that the basalts host homogeneous internal densities. The calculated gravity response based on such an assumption is proved to be invalid as a reduction of density is required in the central portion of the line 107 modelled. By altering the density of the zones demarked as potentially hyaloclastite bodies in the ULF/MLF & LLF to reduced values, brings the calculated density closer to the observed bouguer gravity (see 5.7.3).

Tabular lavas - Onshore analogue

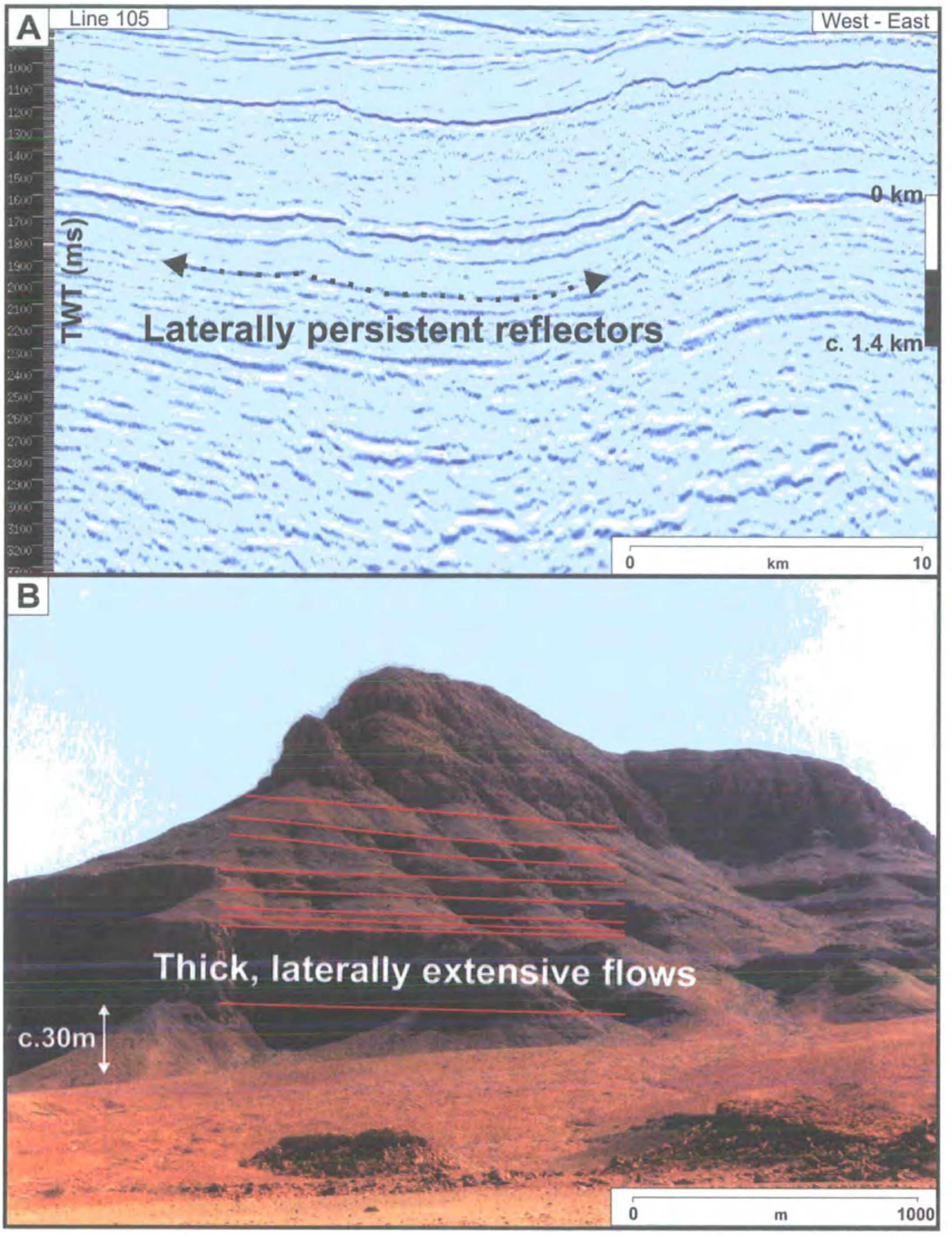


Figure 5-18 An onshore analogue for the seismic zones which are interpreted to be tabular-type lavas. The tabular lavas form laterally extensive thick flows (c.10m thick average) that may be correlated over hundreds of metres to several kilometres. **A:** A section of GFA-99 line 105 showing the characteristics of this architectural facies type; **B:** The mountain *Awahab* in the Etendeka flood basalts of Namibia showing such volcanic facies in the field. Note the sub-parallel nature of the contacts between these flows and their persistence through the entire mountain section. The flows schematically marked by red bases are correlable for tens of kilometres throughout the Huab area of Namibia. The top flow (the Goboboseb Quartz-Latite) may be traced into the Paraná sector of the Paraná-Etendeka flood basalt province.

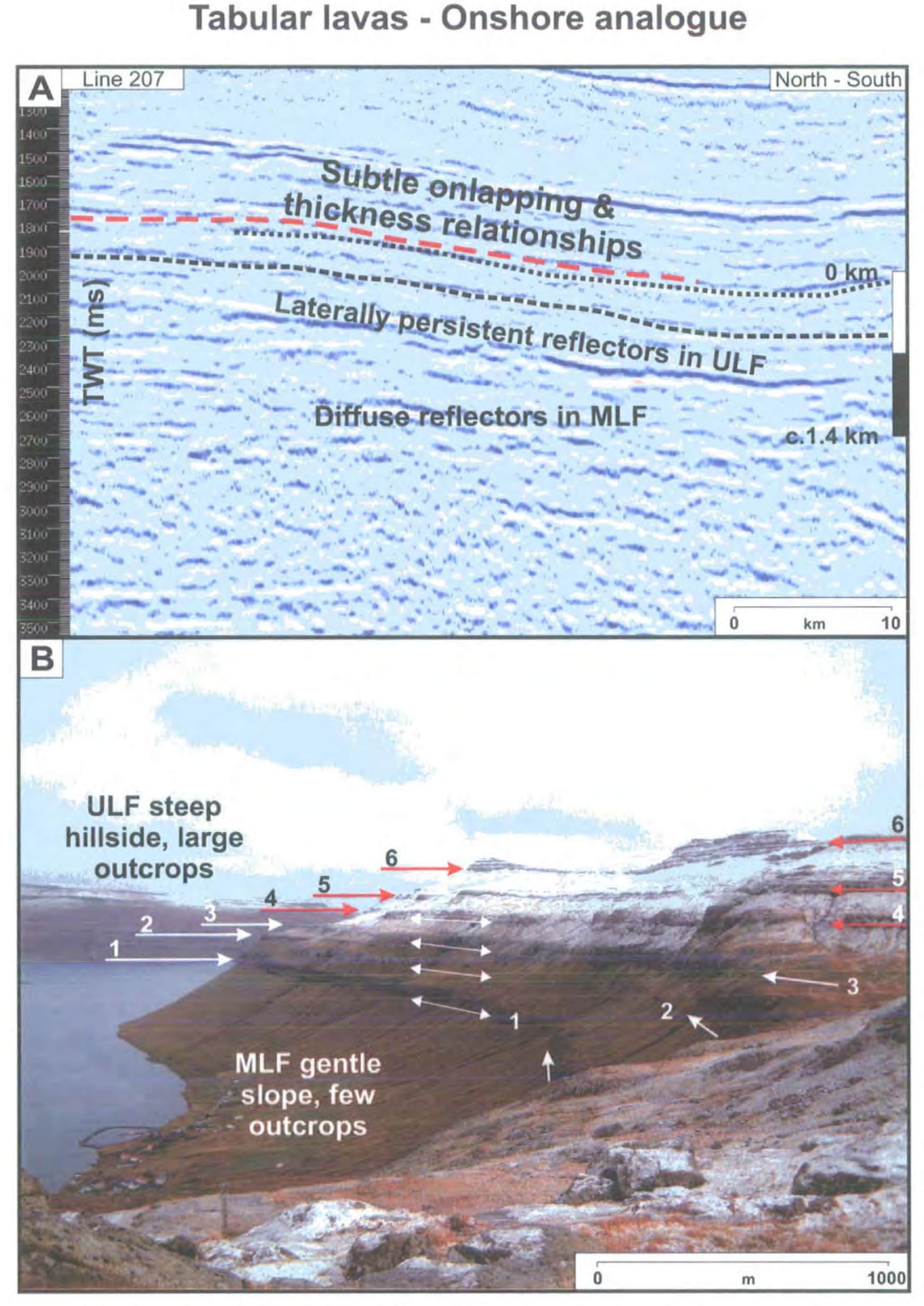


Figure 5-19 An onshore analogue from the Faeroe Islands onshore succession for the seismic zones which are interpreted to be tabular-type lavas. The tabular lavas form laterally extensive thick flows (c.10m thick average) that may be correlated over hundreds of metres to several kilometres. **A:** A section of GFA-99 line 207 showing the characteristics of this architectural facies type; **B:** Cliff section looking NE down the Kollafjørður on the east coast of Streymoy at c.300m thickness of ULF tabular-type lava flows. Six obvious ULF lava flow basal contacts have been indicated on this particular mountain side section. Note the poor exposure of the MLF in comparison with the ULF.

Compound Braided lavas - Onshore analogue

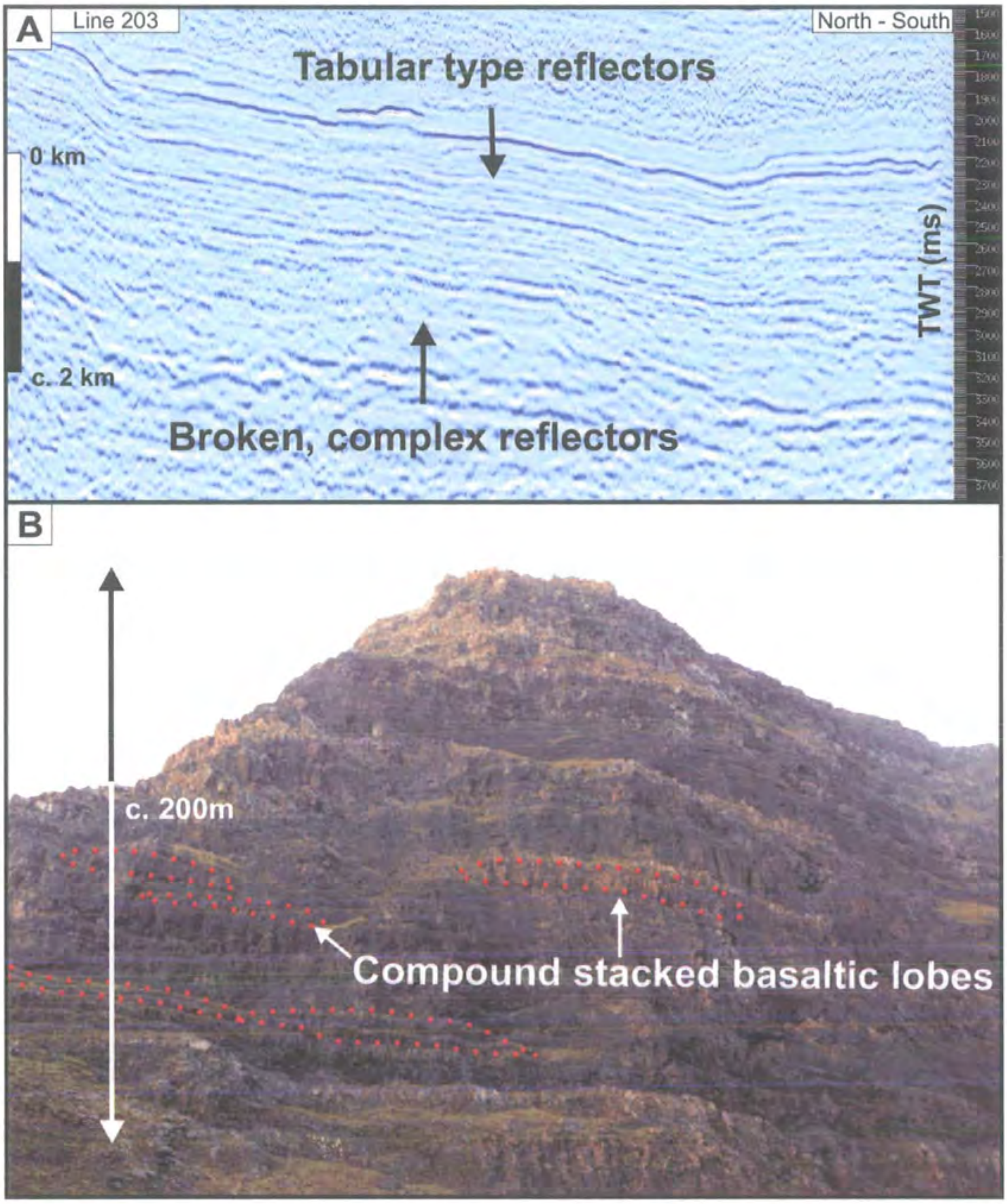


Figure 5-20 An onshore analogue for the lavas seen in the western parts of the MLF. **A:** A section of line GFA-99 line 203 showing both tabular-type lavas, and the contrasting seismic signatures between these and the compound-braided lava types of the underlying MLF; **B:** The cliff section of Waterstein Head on the Duirinish Peninsula of NW Skye. This cliff section is 296m in total height. Over 200m of this height is comprised of compound-braided basalts that are internally complex, and are stacked into a complex stacking arrangement both vertically and laterally. The outlines of several basaltic lobes are marked with red stipple.

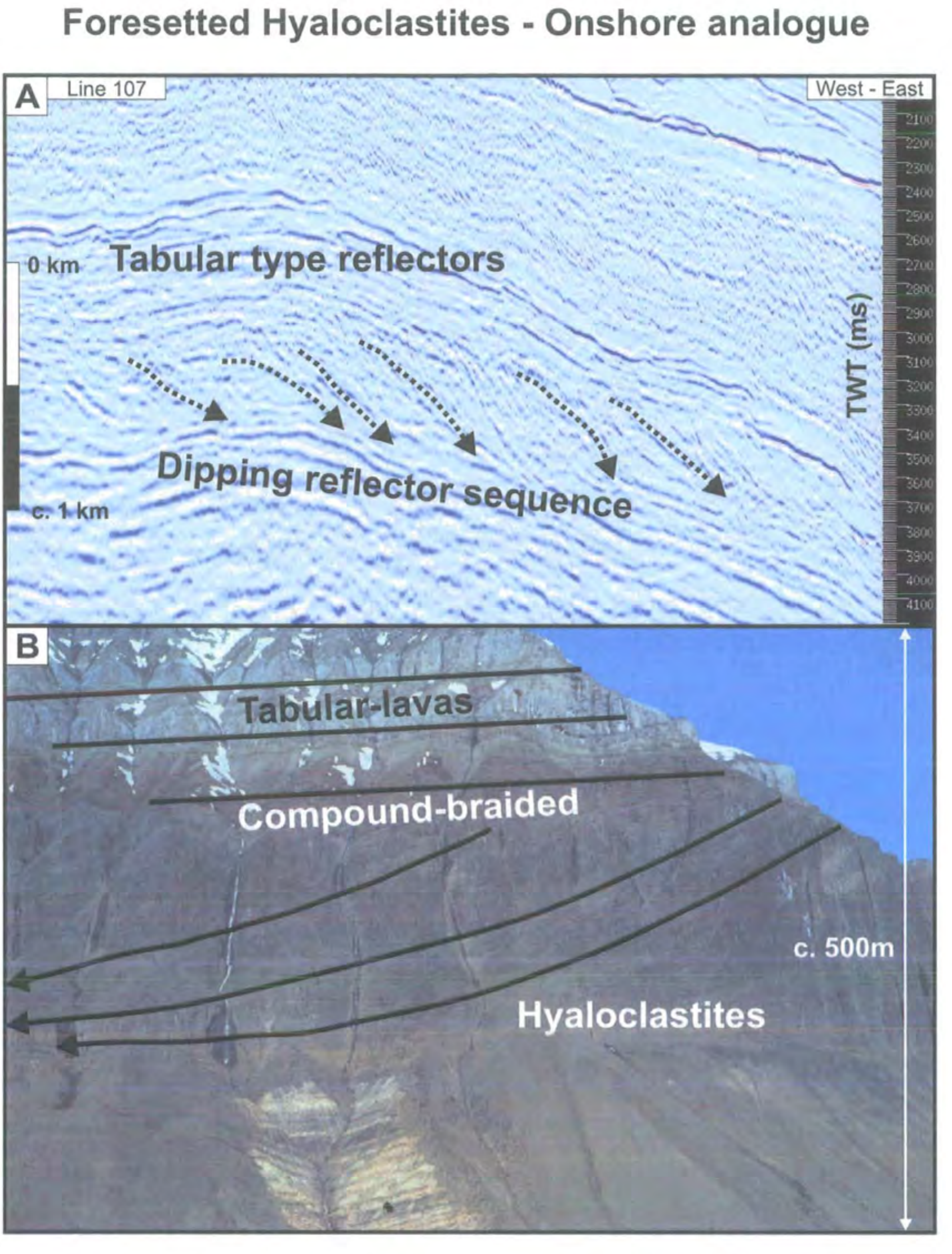


Figure 5-21 Dipping hyaloclastites facies type. **A:** Portion of GFA-99 line 107 showing prominent dipping reflector sequences in the MLF. These are interpreted to represent a succession of lava delta volcanics similar to those seen in the Nausuaq area of west Greenland; **B:** Cliff section in the Nausuaq area shows hyaloclastites dipping and prograding east onto Jurassic sediments. Above the thick pile of hyaloclastites are compound-braided, then subsequently tabular-type lavas stacked sub-horizontally. The compound and tabular-type lavas are sub-aerial lavas so the section shows a water-filled basin-fill, and subsequent overlying landward flows (Planke 2002). Image courtesy of D.G. Pearson.

Foresetted Hyaloclastites - Onshore analogue

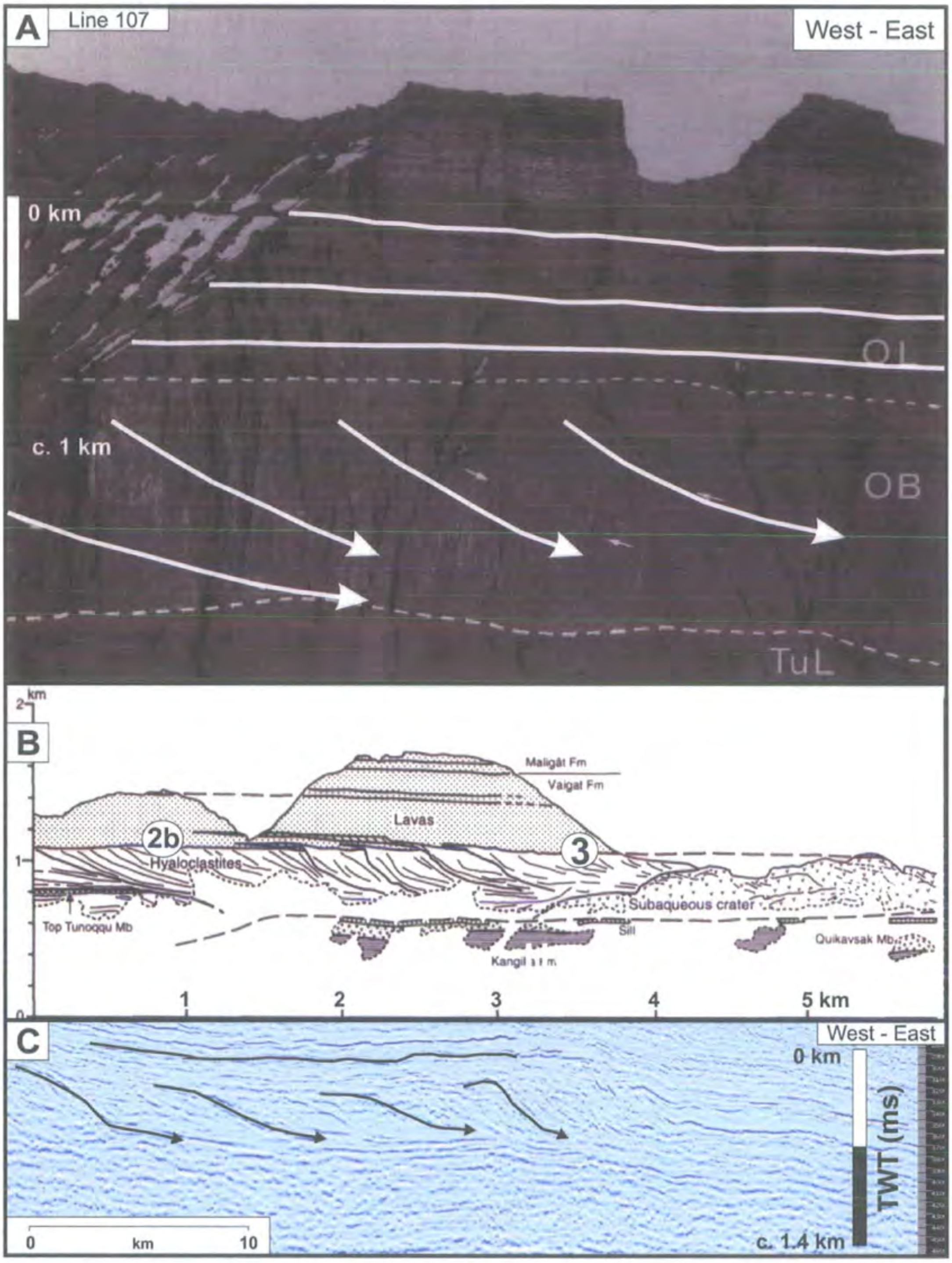


Figure 5-22 Dipping hyaloclastites facies from west Greenland. **A:** Hyaloclastite breccia (OB) deposited in the Naajat lake. The foresets are 200m high. Arrows indicate single foresets. The breccias overlie lava flows of the Tunoqqu Member (TuL); **B:** Hyaloclastite infill of the Naajat lake (after Pedersen *et al.* 1993). Water depths of up to 450m may be estimated from the heights of the foresets. Note that the subaerial lavas were flooded by the rise of the lake level (2b) to (3). The breccias downlap onto the subaqueous crater; **C:** The east section of GFA-99 line 109 where thick hyaloclastites are developed in both the ULF & MLFs on a similar scale to those of Naajat lake.

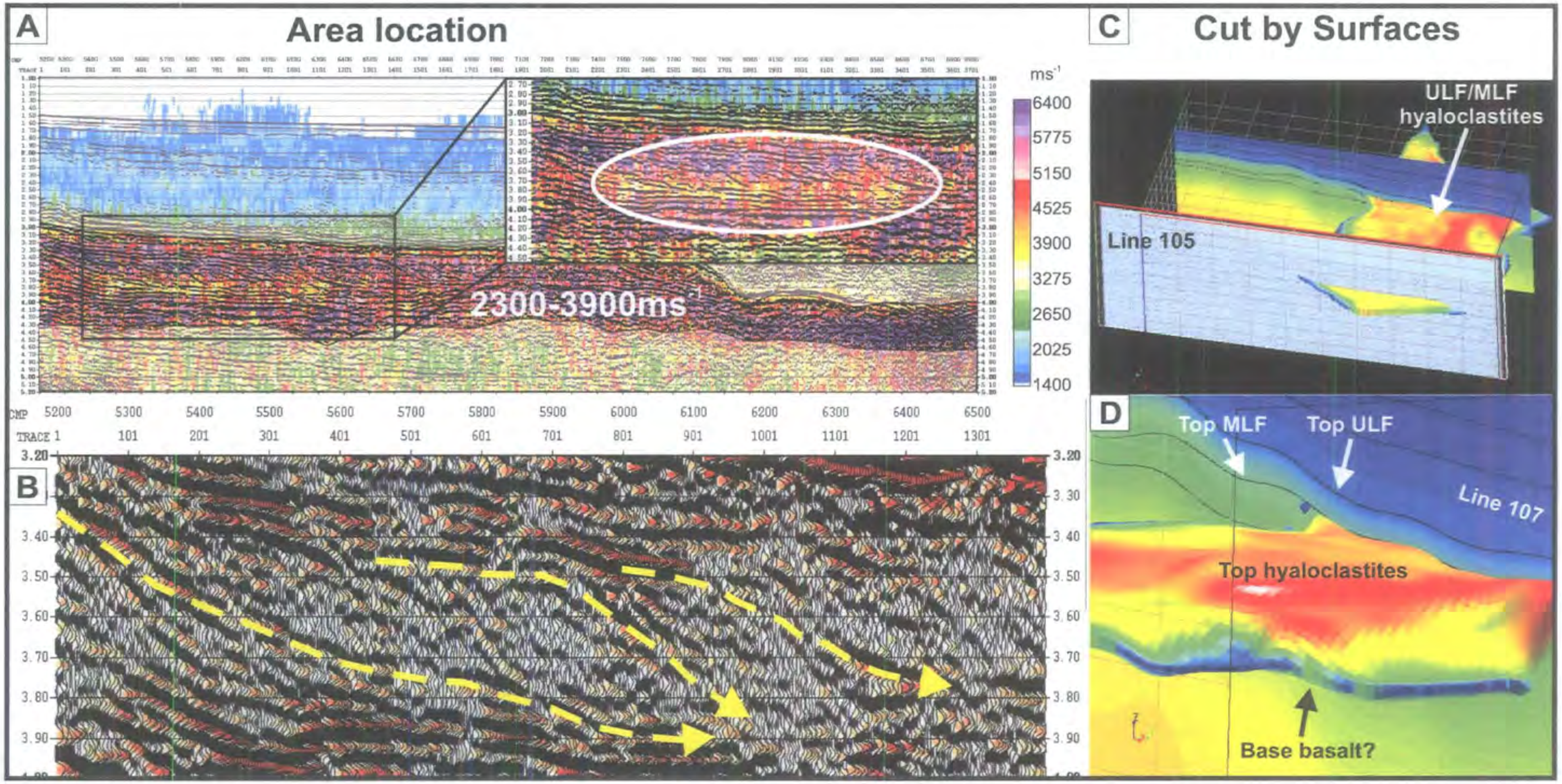


Figure 5-23 Analysis of the hyaloclastite pile interpreted to be present in the ULF/MLFs. **A:** PMO velocity estimation of the GFA-99 line 105. The PMO velocity analysis of the whole thickness of the line divides it into 8 seismically distinct units. These units are distinct by way of their PMO analysed velocities. Analysis of the basalt units shows internal velocity contrasts consistent with varying internal geometries (see inset); **B:** PMO stack spectrum analysis at full offset (180 to 11600m) showing divergent geometries within the basalt unit; **C:** The hyaloclastite volume modelled within the ULF/MLF; **D:** Closer view of the hyaloclastite volume showing its relationship to the ULF/MLF picks in the central part of line 107 in the 3D environment.

5.6.3.3 Mixed Transitional Lavas

Mixed transitional lavas are interpreted to be present in all of the GFA-99 lines where more prominent, laterally extensive reflector zones are seen amongst broken reflector zones. Although it is possible that sedimentary horizons may also cause the large acoustic impedance contrasts, this is not considered a plausible explanation due to the lack of any thicknesses of sedimentary rocks in compound-braided type lava sequences. Mixed facies of compound-braided and tabular units exist at the MLF/ULF transition on the Faeroe Islands (*pers. comm.* Passay 2003, University of Glasgow). Evidence for similar mixed zones exist in the Skye Lava Field of Talisker Bay (5.2) where the style of volcanism is seen to evolve with time, up through the succession as the lavas are effused from progressively more evolved sources.

5.7 LOWER LAVA FORMATION VOLCANICS

The depth at which the top LLF volcanics exists in the data makes it extremely difficult to interpret. Its presence and structure is therefore ratified by the use of gravity data. An interpretation is now presented based on a combination of the seismic reflector characteristics and gravity models. Gravity models were built in ARK Geophysics prior to both the collection of Faeroes field data and before the seismic interpretations were finalised.

5.7.1 Horizon Interpretation and Distribution

It is not possible to accurately interpret the boundaries of the succession, or if the LLF exists at all in more than just the three W-E lines of 105, 107 and 109. The LLF must be also present in N-S line 207, but its interpretation is difficult to justify to the east of this particular line. The easterly extent of the formation is interpreted to be coincident with the East Faeroe High. Base LLF picks are represented in Figs. 5-13 to 5-15 by a pick based on the interpretation of sills at the base of the succession as strong, bright seismic reflectors, and the downlap of dipping reflectors.

5.7.2 Thickness

The Lopra-1 well indicates the succession to be extremely thick beneath the Faeroe Islands. The seismic data alone predicts a thickness of up to 1630ms TWT maximum (Fig. 5-12C), but this holds only with an absence of data reliability over the major part of the data area. The most reasonable estimate of LLF thickness is made by combining gravity data into a gravity model along the profile of line 107. It is not possible to accurately interpret the thickness of the LLF from the seismic, however the modelling of the seismic in combination with the bouguer gravity data stipulate a base-case model thickness in excess of 2700m (Fig. 5-26). This is consistent with the observation from seismic alone, of a maximum thickness of c.3530m. This highlights the need for a multi-disciplinary approach to help solve basalt cover and sub-basalt imaging problems.

5.7.3 Facies Interpretation

The facies interpretation is based on observations of the geometries present within the possible LLF succession, and by creating gravity models along the seismic W-E lines. A basic interpretation of line 107 is shown in Fig. 5-24. This gravity model is based on the seismic picks alone, and studies the effect of hyaloclastite piles on unfiltered gravity profiles. The LLF is missing entirely in the model, and there is no sub-volcanic density contrast. Fig. 5-24 provides an unsatisfactory interpretation of the data; several aspects of the interpretation need strong improvements. Improvements are made to this poor-case gravity model in the subsequent sections and associated figures (Figs. 5-25 to 5-27).

5.7.3.1 Water-borne Volcaniclastics

An improved gravity model of line 107 is shown in Fig. 5-25. The reduction in density of the central portion has improved the calculated gravity response by adding sediment to the sub-volcanic part of the succession. Again, by using gravity, we can identify the possible locations of sediment underneath the volcanics. This will be discussed in the next section. In the west of the line, a seismic interpretation of the LLF is added in geometry only. The succession is considered to hold no density contrast with the overlying ULF or MLFs. The observed bouguer gravity does not support this notion. The mass of the entire west side of the line is too high. In line 107 in particular, dipping reflectors are observed in the interpreted LLF succession. This suggests that the LLF may be represented by hyaloclastites and volcaniclastics similar to those seen more distal and basinward in the MLF and ULF. By reducing the density of the interpretation of the LLF in this model of line 107 to potentially that of a hyaloclastite, a strong fit between the observed and calculated gravity is achieved (Fig. 5-26). The LLF is known to form thick tabular-type lavas in the Lopra-1/1A section; beneath these, the drilling was terminated in a thick pile of sub-aqueously deposited volcaniclastics/hyaloclastites. In the area of GFA-99, these are considered to be represented by the basinal progradational lava delta hyaloclastites suggested by gravity interpretation.

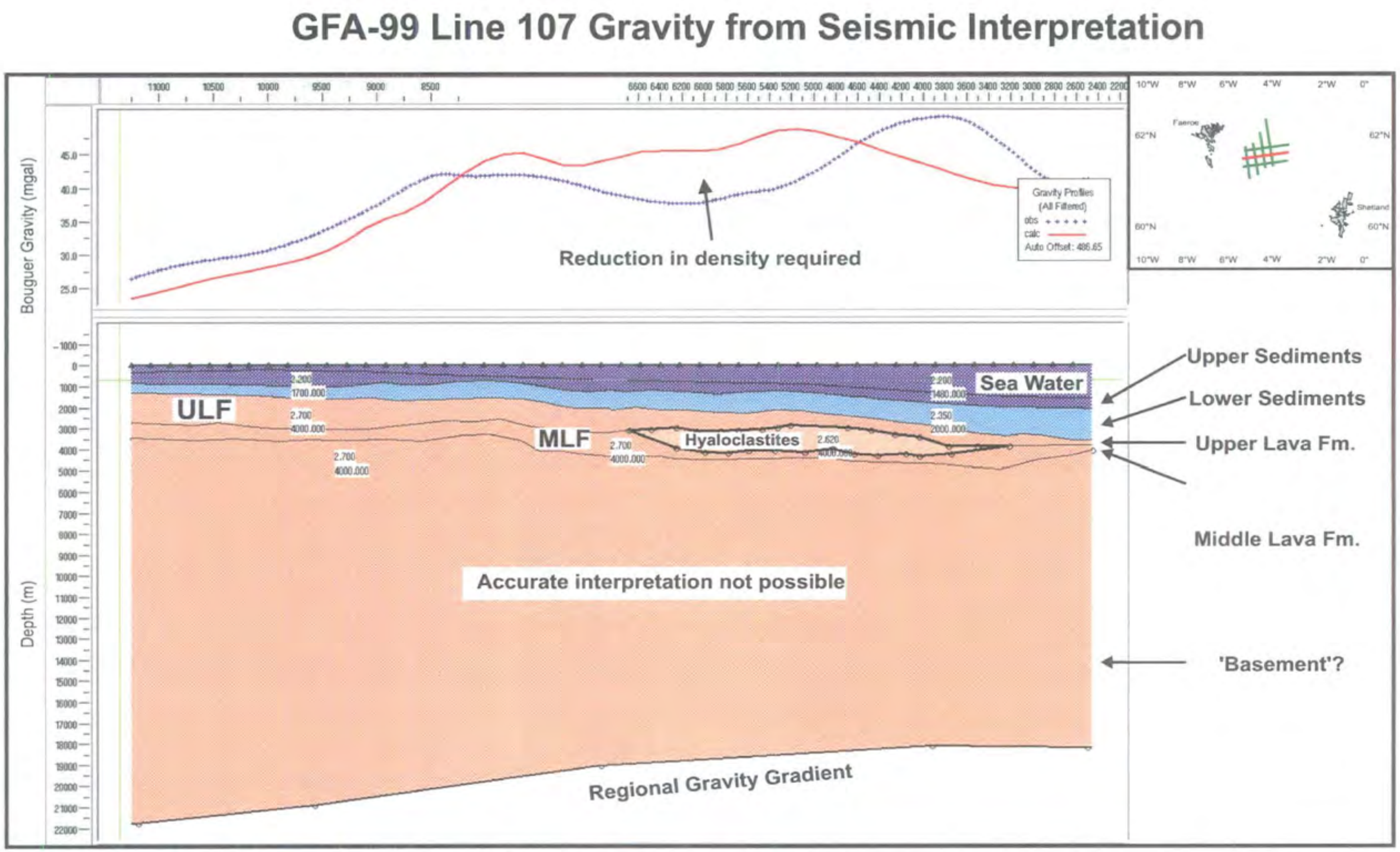


Figure 5-24 Gravity model of GFA-99 line 107 (red on inset location map) built from seismic interpretation picks only. The observed gravity anomaly along line 107 requires a significant volume of low density material to be present in the central portion of the line. The seismic data alone is unable to form an accurate interpretation without ratifying the interpretation with the observed bouguer gravity which runs along the GFA-99 lines. The above model is inaccurate in several areas, particularly in the centre of the line where mass-loss is required both within, and beneath the volcanic succession.

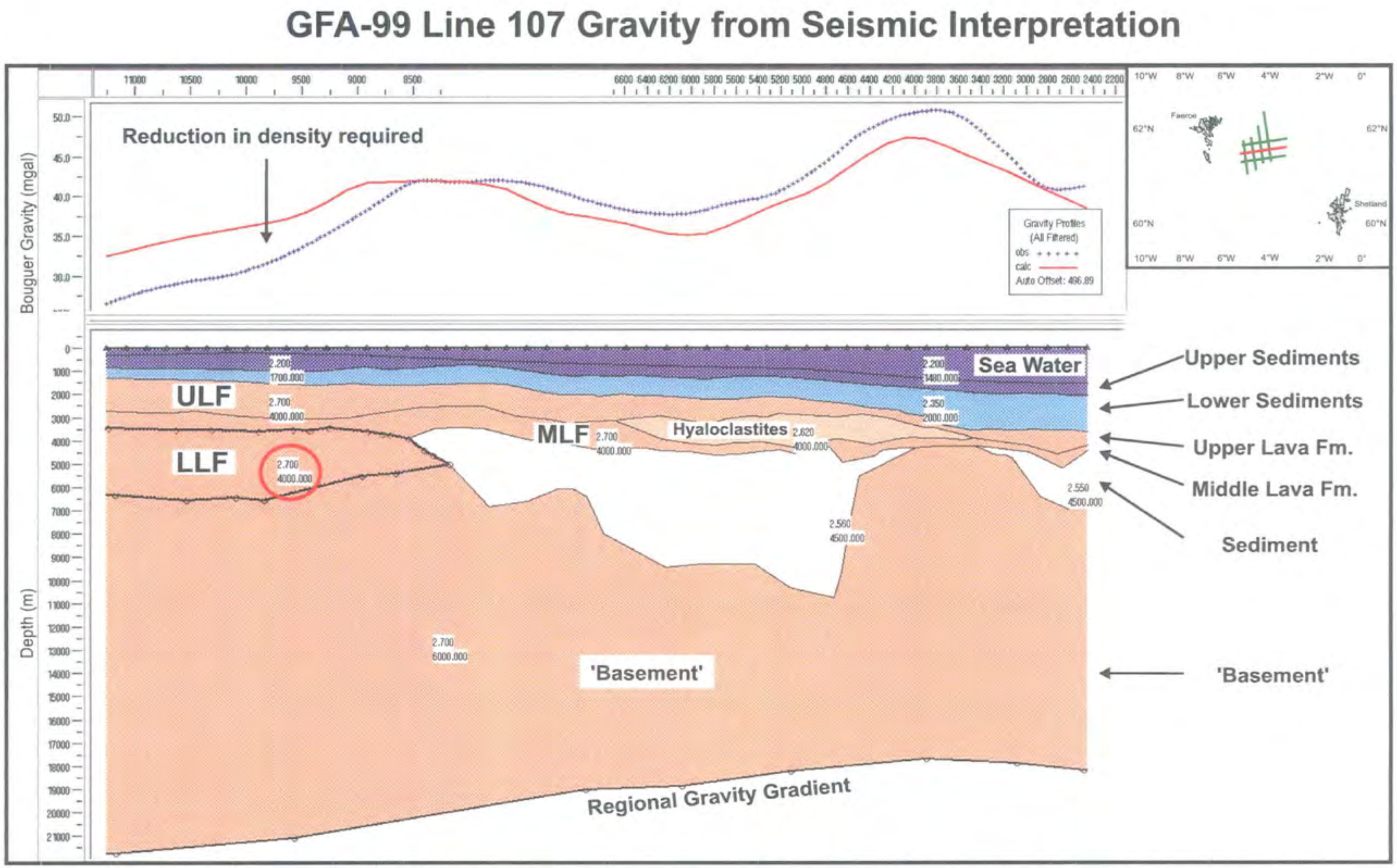


Figure 5-25 Gravity model of GFA-99 line 107 (red on inset location map) built with sub-volcanic sediment, and MLF hyaloclastites, but using the interpretation that the LLF volcanics are basaltic lavas with a stipulated density of 2.70gcm^{-3}. Note that the calculated bouguer gravity profile requires a significant reduction in density in the interpreted LLF in order to honour the observed anomaly.

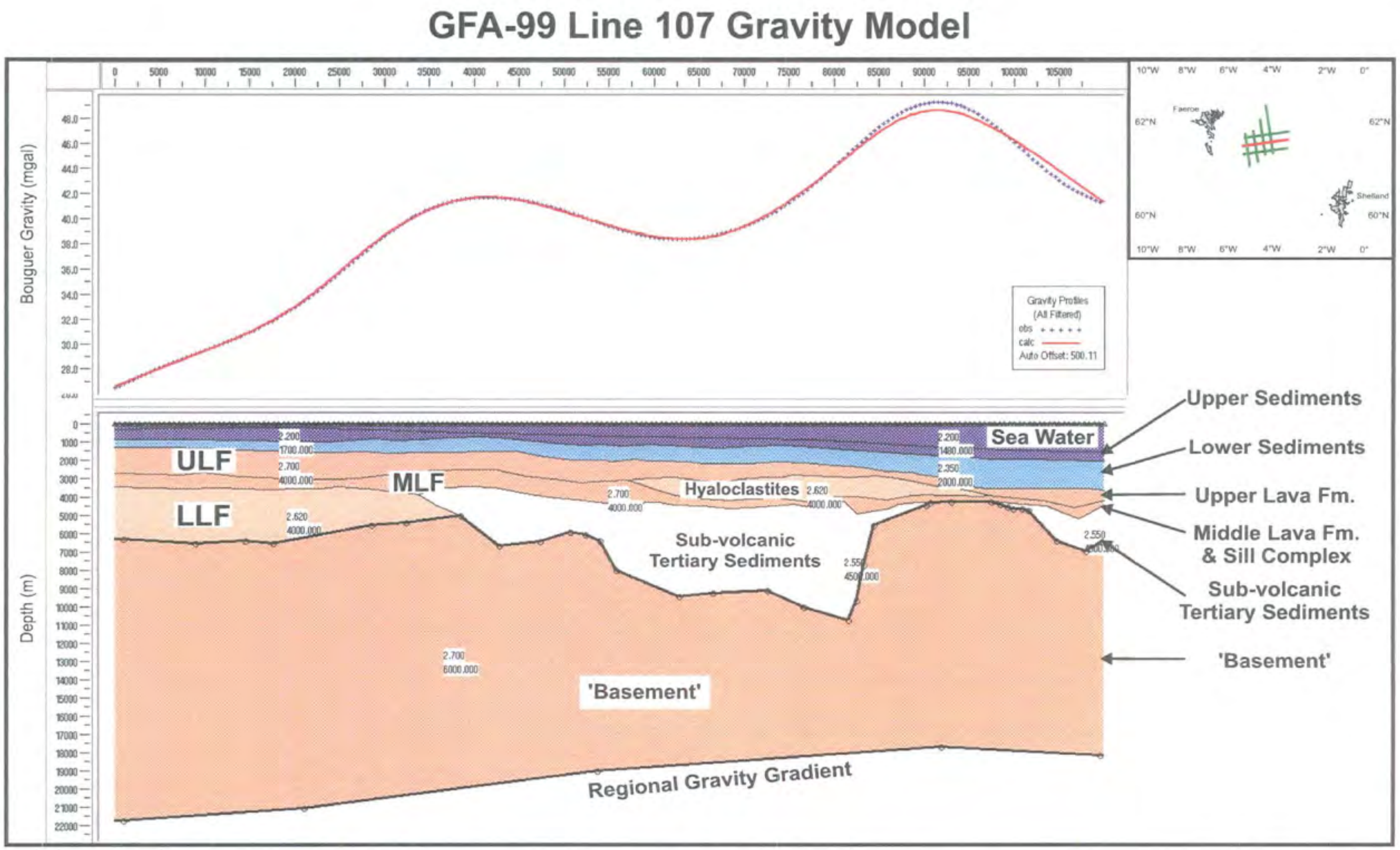


Figure 5-26 Geological interpretation and model of the GFA-99 line 107 (red on inset location map) incorporating bouguer gravity data. The observed gravity anomaly along line 107 requires a significant volume of low density material to be present in the central portion of the line at a sub-volcanic level. The observed gravity profile strengthens the argument for a significant succession of LLF hyaloclastite at the west end of the section where the density of the LLF geological interpretation needs to be reduced at that level in the stratigraphy. The gravity profile interpretation is filtered to 45km low-pass wavelength: At this wavelength, the gravity calculated from the model has a maximum deviation of 0.7mgal from the observed bouguer data.

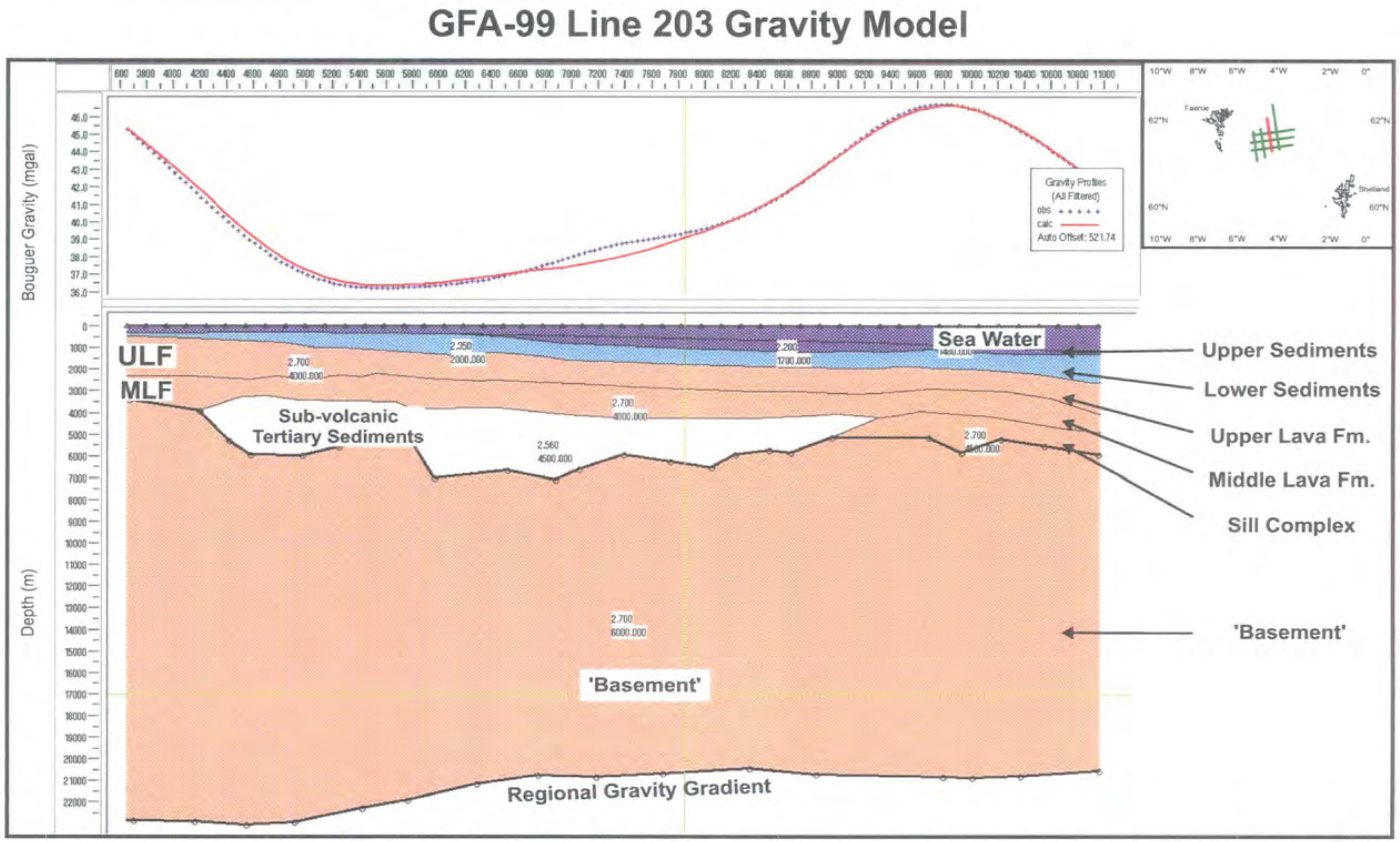


Figure 5-27 Geological interpretation and model of the GFA-99 line 203 (red on inset location map) incorporating bouguer gravity data. The observed gravity anomaly along line 203 requires the modelling of a more complex, faulted basement topography. A significant body of sediment is interpreted to lie beneath the volcanics, but the hyaloclastites of both the ULF/MLF and LLF are absent in this line. Sill complexes are likely to affect the gravity profile at the base-volcanics, top pre-volcanic sediment zones in the stratigraphy. The data is low-pass filtered to 35km. At this wavelength, the line 207 model is geologically and geophysically reasonable within 0.8mgal, and further enhancements in the model will only be made by adjusting the post-volcanic sedimentary succession interpretation.

5.8 THE SUB-VOLCANIC SECTION

The sub-volcanic zone is the part of the dataset which has interested the petroleum industry enough to acquire seismic datasets such as GFA-99. The sub-volcanic section is considered to be a mature petroleum play. The top of the sub-volcanics is marked by interpreted sill complexes.

5.8.1 Sills

Sill complexes are observed at the base of the lava sequences of Skye, in great thicknesses on the northern Trotternish Peninsula in particular where over 50m of sills sit beneath the base of the lava succession. Similarly, in the Etendeka flood basalts of Namibia, the substantial Huab Sills complex again fills a large volume of dense material at the base of the province lava sequences (Duncan *et al.* 1989). In the GFA-99 data, high amplitude reflectors fill what is considered the basal zone of the lava field. Although individual reflectors are rarely over 5km long, they are interpreted to represent a series of sills in the Faeroe-Shetland Sill Complex (Smallwood & Maresh 2002) seated at the base of the succession across most of the GFA data. The sills are at their most prominent at the interpreted base of the MLF beneath the hyaloclastite zones, and landward, beneath the interpreted compound lava types (Figs. 5-13 to 5-15).

5.8.2 Sediments and Basement

The presence of sub-volcanic sediments and the shape of the basement surface have been interpreted by the use of gravity data. Figs. 5-26 & 5-27 present 2D gravity models of the GFA lines 107 and 203. These contain the greatest amount of vertical and lateral facies variability in the entire dataset. A simple, normally faulted basement is interpreted from bouguer gravity data filtered to wavelengths longer than 350km. On top of the basement a large thickness of sediment is modelled for a gravity data fit ratified to the 45km high cut filter level: i.e. the calculated bouguer gravity interpretation hold true with the observed gravity as deep in the section as the top of the volcanics. The sediment maximum thickness on top of this basement is 6000m.

5.9 SUMMARY

The succession of volcanics in the GFA-99 data area, potentially has a maximum thickness in excess of 6830m which is calculated in this study. Down to the top of the sub-volcanic sediments, or top LLF, where present, the succession has a thickness of c.2700 across much of the area. A further 2700m or more of LLF may exist beneath this ULF-MLF total thickness as estimated from the combined gravity and seismic modelling. These thicknesses compares well with the estimates of Ellis *et al.* (2002) who suggest the complete thickness of the volcanics discussed to be c.5550m combining data from the Faeroe Islands and offshore data.

In summary, the extrusive activity began c.60.56Ma (Ellis *et al.* 2002) with the eruption of volcaniclastics into a substantial water-body which lay in the environs of the present day Faeroes. Their presence may be interpreted offshore to the SE of the islands. During the LLF, the volcanics filled this former water-filled basin and erupted into the sub-aerial environment. Thick tabular-type lavas (flows c.20m thick) formed a lava succession >900m thick in the Faeroes area and this eruptive phase waned c.56.4+/-0.5Ma (Ar/Ar) in the beginning of Chron24r (Waagstein *et al.* 2002).

A thick sedimentary sequence c.10m thick developed on top of the LLF. This eruptive hiatus terminated c.55Ma, early in Chron24r and the MLF blanketed the Faeroes platform with thin, olivine-rich flows of dominantly compound-braided facies architecture. These are similar to those seen towards the base of the Skye Lava Field studied in Chapters 3 and 4 (Fig. 5-28). Offshore, these formed water-borne prograding hyaloclastite fans that grew into a slope-apron of low density, foreset-bedded volcaniclastic material architecturally similar to the volcanics seen in west Greenland (Pedersen *et al.* 1993) (Fig. 5-29). The convergence of the foreset-beds marks the base of the volcanic succession in the offshore data.

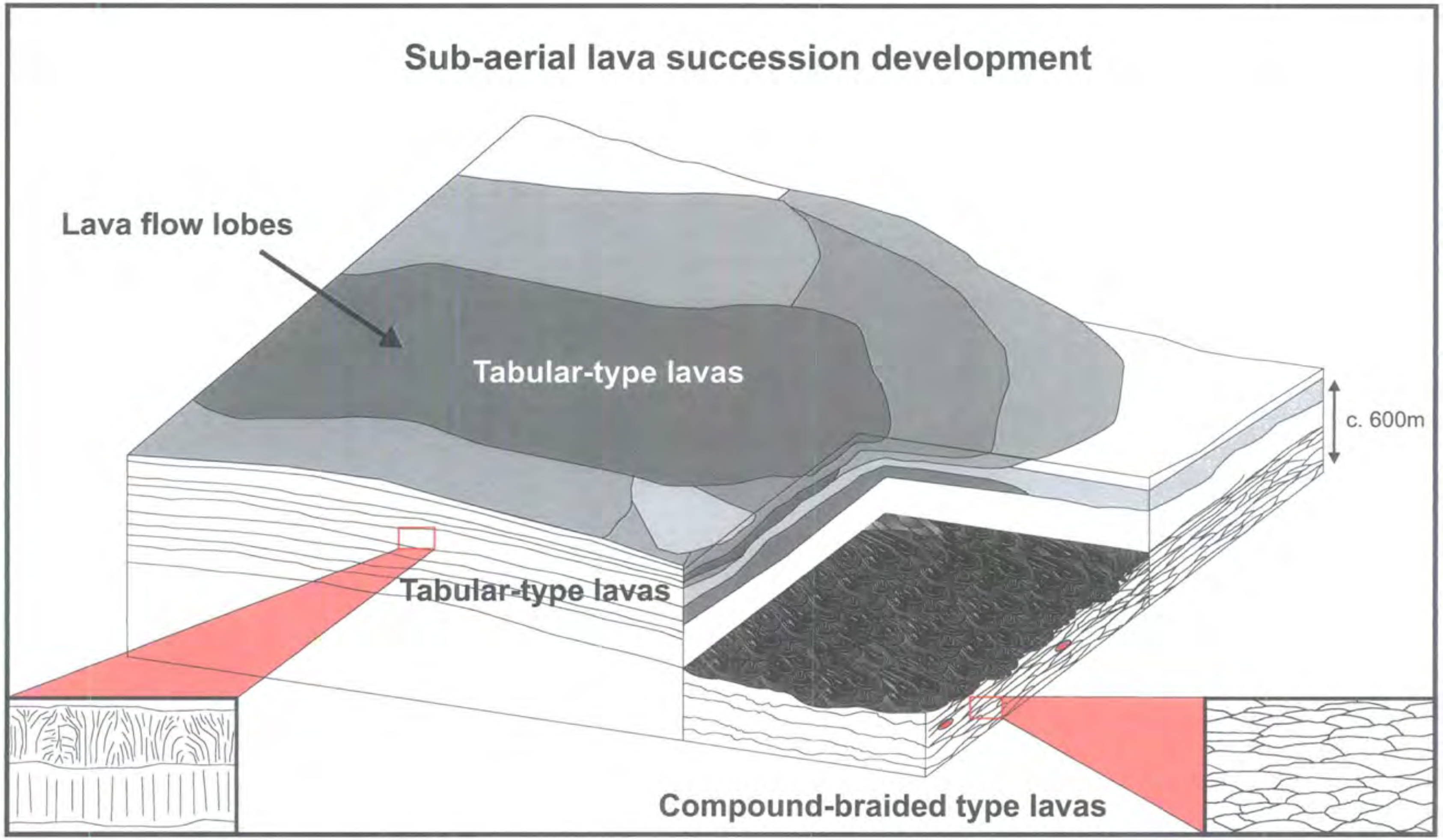


Figure 5-28 Development of the lava field in the Faeroes Lava Group ULF and MLF. The onshore volcanics primarily break down into the architectural groups of braided lava types and tabular-type basalts. The dominantly compound-braided MLF is characterised by flows of low aspect ratio with complex internal morphologies with interspersed simpler, tabular-type flows. The transition into the ULF is considered to be above where the lavas assume the tabular-type architecture of thicker flows, covering larger areas with a more evolved geochemical signature. The distinction between the ULF and MLF is distinct onshore, however in the GFA-99 seismic data, the boundary is more arbitrary, but interpreted by the change in seismic character across the two formations.

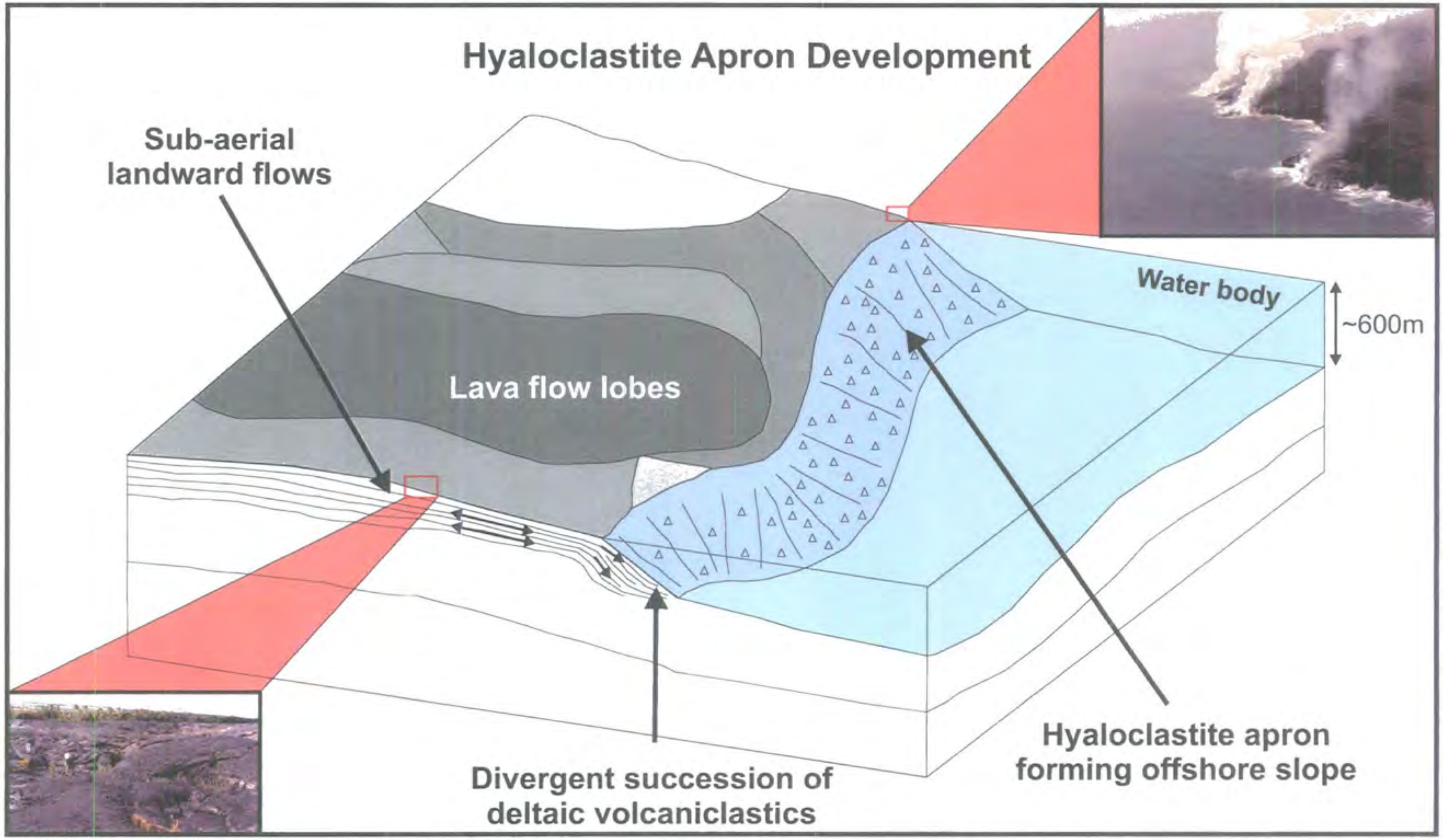


Figure 5-29 The development of a hyaloclastite apron pile as the lavas prograde into a substantial water body in the distal parts of the ULF/MLF and potentially in the LLF as interpreted from seismic, bouguer gravity modelling and from Lopra interpretations. As the lavas meet the water body, they explode and fragment and develop into a debris fan forming a steep margin to the advancing volcanics. The character of these debris fans produces divergent reflector sequences in seismic data. These are considered to be of lower density than the onshore volcanic successions due to the volcaniclastic nature of the deposits.

The boundary between the MLF and the overlying ULF is gradational onshore: a transitional phase of volcanism represented by mixed volcanic facies. Olivine-rich thin compound-braided lavas are interspersed with minor, relatively thin (c.5m) tabular-type flows. The ULF base is marked by the first thick, laterally-extensive tabular-type lava c.10m thick of basaltic-andesitic composition.

The sub-division of the volcanics into facies zones is made possible by taking into consideration a combination of data types, including the field geology facies studies of Chapters 3 & 4, geological interpretations of seismic, and its integration with regional and profiled gravity data. Combining gravity interpretations into the geological interpretation of seismic data has also provided a tool for ratifying both the geological interpretation of the horizon picks and also the facies units within the data. The facies architectural studies presented in the CFB system basin or macro-scale are summarised in Fig. 5-30.

In Chapter 6, the integrated, micro to macro-scale architectural studies of CFB sequences are discussed: the implications for the physical volcanology of flood basalts, and how these facies architectural studies may improve the geophysical characterisation of flood volcanic successions.

Summary of the Macro-scale Facies Architecture of Flood Volcanic Successions

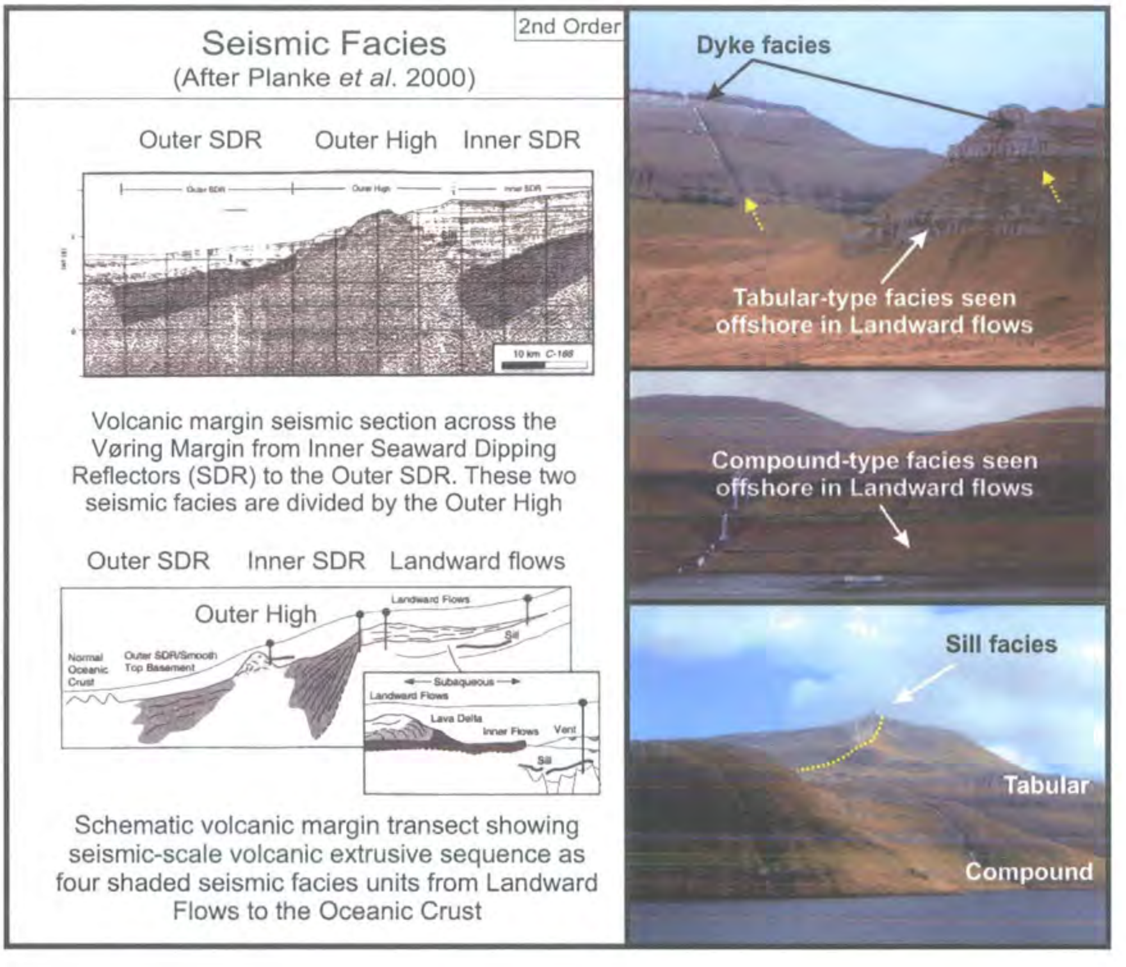


Figure 5-30 Summary of igneous architecture in flood volcanics. Seismic or basin-scale macro-facies cover architectural scales of tens of kilometres and are considered to be 2[nd] order heterogeneities. Note that 1[st] order heterogeneity is the analysis of flood basalt architecture on the Large Igneous Province (LIP)-scale (2.1), whilst 5[th] order observations are at the microscopic level. Chapter 5 has studied the sub-province CFB architecture by looking at various data types, including using the data developed in Chapter 4 of the building blocks of this basin-scale CFB architecture. In this chapter, the sub-province (macro-scale) facies architecture (e.g. juxtaposition of lava field facies) of CFBs completes the assessment of the orders of heterogeneity studied in this thesis.

Chapter 6

6. DISCUSSION AND IMPLICATIONS

In Chapter 6, it is time to look at the wider picture: how has this work improved understanding of the flood volcanic system, and what are the implications of the research? The chapter is broken down into four main sections. These synthesise the volcanological aspects of the research, and also show how understanding the geological heterogeneity in flood volcanics may help us approach solving sub-basalt imaging problems for petroleum exploration.

6.1 THE STRUCTURE AND ARCHITECTURE OF FLOOD VOLCANICS

The organisation of this thesis has been designed to systematically approach the study of the structure and facies architecture of flood basalts. By characterising their constituent building blocks on a centimetre to metre-scale (micro-scale; Chapter 3), and modelling the internal structure of CFB lava fields (meso-scale; Chapter 4), it has been possible to make geological interpretations of the structure and facies architecture of offshore geophysical data (macro-scale; Chapter 5). Facies architectural studies from each scale of heterogeneity have been summarised at the end of each chapter. If the architectural orders of scale are drawn together, it is possible to understand how each of the orders of heterogeneity piece together to form the complete flood volcanic system (Fig. 6-1). The upscaling of architectural interpretations is now discussed.

On the micro-scale, the intrafacies scheme has been introduced as a method by which we can characterise the internal facies present within individual igneous units. The characterisation of the intrafacies of the Skye Lava Field provides a geological assessment of the physical volcanology of the CFBs, and a way by which the igneous succession may be characterised in terms of geophysical properties (6.3).

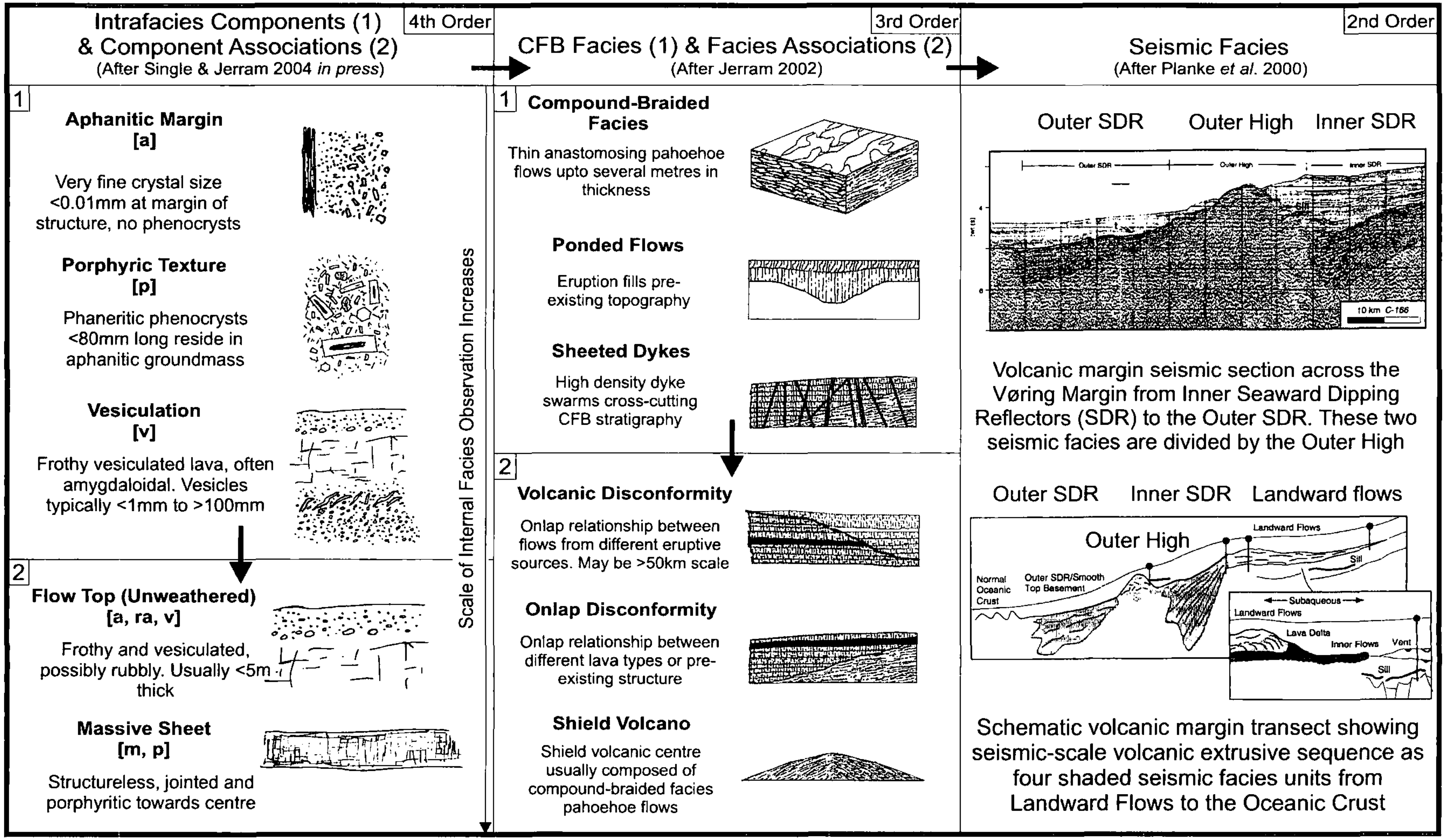


Figure 6-1 Scales of facies variation in continental flood basalts (CFBs). Left column: Contains the smallest level of heterogeneity (4th tier) which can be studied in the field. This contains the scales of intrafacies and their constituent components. Middle column: Flood basalt facies and facies associations form kilometre-scale architectural features of the igneous sequence. Right column: Seismic scale facies cover architectural scales of tens of kilometres and are considered to be 2nd tier heterogeneities. Note that 1st tier heterogeneity is the analysis of flood basalt architecture on the igneous province scale, whilst 5th tier observations are at the microscopic level.

For example, micro-scale observations have been used to interpret large-scale lava field features: e.g. vesicles orientations and pahoehoe textures have been used to identify magma sources directions and these, in combination with lava feeder tubes, interpret a gentle-slope shield volcanic setting. The micro-scale observations have also highlighted the links between the physical volcanology, facies architecture and the rock property distributions within the types of igneous facies (6.3).

Using interpretations of the intrafacies architecture made at the micro-scale, 2D and 3D models on the lava field scale of observation have been broken down into architecturally distinct facies sequences. These contain both quantitative geometrical data which describes the shape of the contacts and the igneous units in the lava field, and also define estimates of the volumes of the various lava facies types present and eroded from the modelling area. The geometries of the lava flow relationships within the lava field are characterised by their constituent architectural flow facies (e.g. tabular-type lavas) and the associations of these flow facies (e.g. onlapping relationships).

By studying an onshore CFB lava field at both the micro and meso-scales, an understanding of the internal structure has been assembled, from the individual igneous units, through to the way by which they are juxtaposed, thus forming a lava field. The value of understanding the CFB architecture from the smallest scale possible in onshore lava fields, through to interpreting seismic data is a theme fundamental to this research. The timing of the research work performed, and the various data interpretations made and assembled into this thesis underlines the value of geological fieldwork in making interpretations of geophysical data: initial interpretations of the GFA-99 dataset were performed during June 2001, when fieldwork in the Skye Lava Field was not possible due to the outbreak of foot and mouth disease. Studies of the building blocks of the Talisker area of the Skye Lava Field in Summer 2000 however, provided invaluable prior understanding of lava field structure, facies architecture and likely geophysical character of facies types for seismic interpretation and facies analysis.

In summary, the successful building of geologically realistic models of igneous successions in CFBs, on volcanic rifted margins and in Large Igneous Provinces in general, is dependent on an understanding of the constituent elements of architecture that construct the succession from the intrafacies level through to the seismic facies level (summarised in Fig. 6-1).

6.2 THE EVOLUTION OF FLOOD VOLCANIC SUCCESSIONS

The evolutions of the flood volcanic successions studied in this thesis have many characteristics in common with other CFB provinces globally. The successions also contain evidence for a series of differences in the way by which they developed. These common and disparate characteristics are now summarised in Table 6-1.

Essentially, the common parts of the evolution of each of the provincial volcanic successions sees a gradual change in style of the volcanism, reflected in a change in characteristic chemistry of the lavas being erupted. At the onset of the flood volcanism, each province characteristically erupted olivine-rich basalts which reflect high degrees of mantle partial melting, most likely related to mantle plume impingement on the base of the lithosphere during the early stages of continental break-up (Cox 1980; Courtillot *et al.* 1999; Menzies *et al.* 2002). Over the course of CFB succession development, the types of lavas being erupted is observed to become more siliceous and be dominated by tabular-type basaltic-andesites. These lava types often form some of the best preserved parts of the lava fields. Variations from this gradual change in volcanic facies architecture may reflect changes in the plumbing of the volcanic system, and palaeogeographical and palaeoenvironmental changes that may have lead to different facies developing (e.g. volcaniclastics developing on the flanks of a shield volcano due to alterations in base-level).

Table 6-1 The evolution of the Skye Lava Field, Faeroe-Shetland and Etendeka flood volcanic successions.

Event Stages	Skye	Faeroes	Etendeka
Waning Volcanism	Eastern Red Hills Centre intrusions (Granitic)	-	-
6	Western Red Hills granites	-	Continued eruption of tabular flows of basaltic-andesites and quartz-latites
5	Cuillins Igneous Complex Intrusion (Gabbro)	ULF – Tabular-type lavas c.10m thick	Thick tabular flow of Springbok quartz-latite (Bryan *et al.* 2002)
4	Preshal More lava (Ponded tholeiite)	Transitional zone of mixed facies lavas	Continued eruption of basaltic-andesites
3	Skye Lavas – Tabular basaltic-andesites (Plateau lavas?)	MLF – Thin (<4m) compound-braided olivine-basalts (Shield volcanic lavas?)	Goboboseb quartz-latite (rhyolites) marks first silicic flows (Bryan *et al.* 2002)
2	Skye Lavas – Transitional-type basaltic-andesites	Hiatus and development of c.10m thick sediments	Large flows of tabular basaltic-andesites (Jerram *et al.* 1999a)
1	Skye Lavas – Thin, compound-braided olivine-basalts (Shield volcanic lavas?)	LLF - Emergence to sub-aerial environment. Thick (c.20m) tabular-type basaltic-andesites	Continued eruption of olivine-basalts of thin (c.3m) compounded lobes
Onset	Explosive eruption of tuffs	Eruption of basaltic volcaniclastics into water-filled basin?	Passive eruption of olivine-basalts choking sand-sea (Jerram *et al.* 1999b)

In terms of flow volumes, the eruptive facies observed suggest that in the early phases of flood basaltic effusion, the volcanic succession builds slowly and passively; erupting relatively small volumes of lava at relatively low rates ($<20m^3s^{-1}$) (Walker 1993). During the evolution of the successions, the shift in facies architectural styles and lava types is paralleled by a reduction of the frequency of eruption events (thick boles commonly marking hiatuses on thick tabular lava tops) and an increase in individual flow areas and volumes.

6.3 IMPLICATIONS FOR SUB-BASALT IMAGING

The systematic study and characterisation of the evolution of flood volcanic successions and their internal and external facies architectures is crucial to the geophysical characterisation of such sequences, and provides constraint to geophysical models of the stratigraphy present in volcanic rifted margins being investigated by petroleum exploration companies.

In this section, the inter-relationships of rock properties are briefly discussed (Fig. 6-2) and a summary strategy presented which outlines the integration of geological information into geophysical models of flood basalts (Fig. 6-3).

6.3.1 Rock Property Heterogeneity

The geological facies variations present in flood volcanic successions, both geometrically and in their rock property characteristics, directly affect the quality of geophysical data acquired in areas affected by the presence of a blanket of volcanics (Fig.1-1). In order to build better-constrained, more accurate geophysical models it is important to understand how the geology relates to geophysical properties. A rock property map (Fig. 6-2) schematically develops the idea of a link between geological and geophysical characteristics of CFBs.

Central to the prediction of geological facies architecture is an understanding of the magma type. The rock property map shows that the chemistry of the magma affects much of the geological system and architecture, and hence, the rock property distributions and actual quantification of rock properties present in an igneous system. For example, olivine-basalts are silica-poor with relation to basaltic-andesitic lava compositions: the links in the rock property map and the understanding of the architecture of the different lava types gained in Chapters 3 and 4 mean that in each of these different geochemical lava types we can expect a host of architectural and rock property characteristics to be different. These include the lava viscosity (affects flow architecture and geometry), density of the stratigraphy (affects gravity modelling), elastic velocities (affects seismic processing) and resistivity of the succession (affects magnetotellurics (MT) studies). The rock property map summarises the links between geology and geophysics in a qualitative manner: the intrafacies scheme however, provides a simple qualitative way of identifying igneous facies but must be considered as a quantitative tool for the characterisation of rock properties as it provides a link between many of the facets of the rock property map.

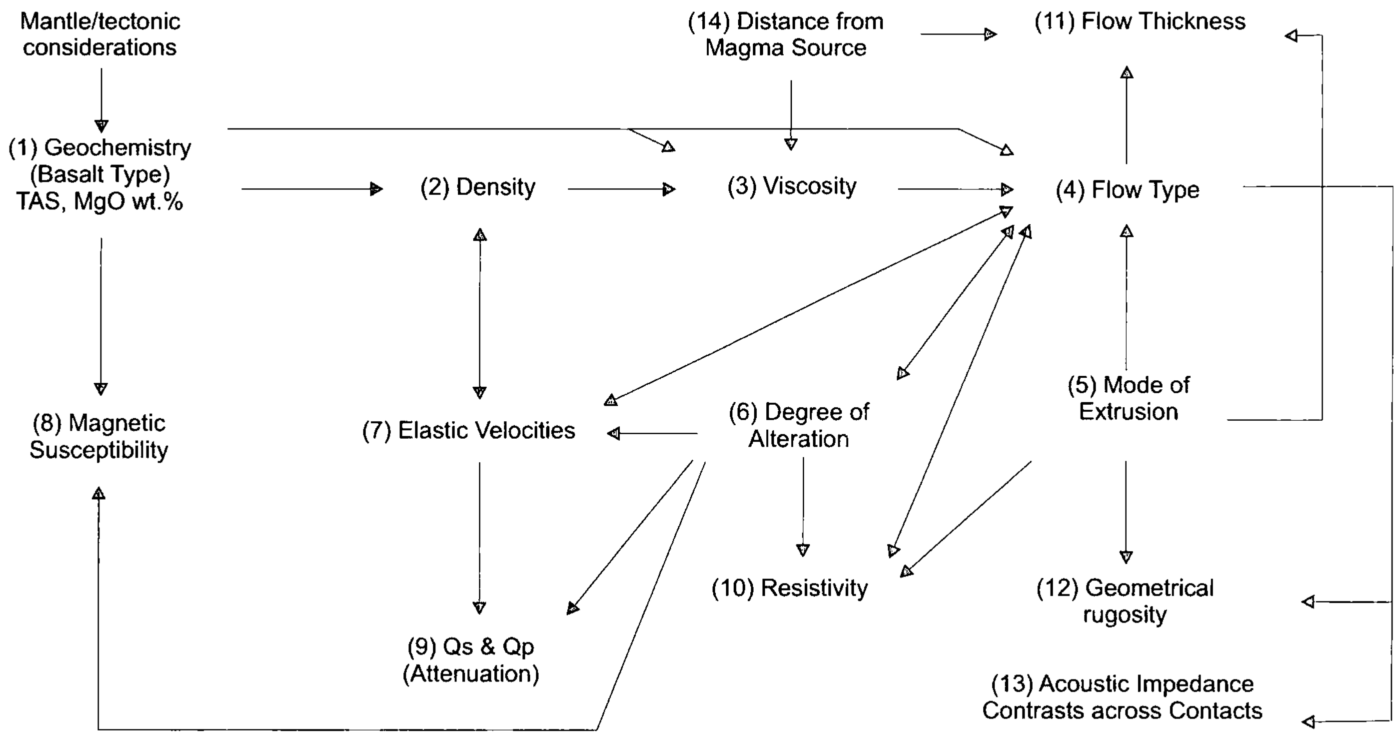


Figure 6-2 The links between lava types and rock properties. The rock property map schematically represents the dynamic system behind rock property heterogeneities in flood basalts. Essentially, much of the facies architecture discussed is, to a large extent dependent on the geochemistry of the magma. As the facies architecture is linked to the magma chemistry, the distributions of rock property heterogeneities in the igneous succession may also be considered to also be attributed to some extent by the host chemistry.

6.3.2 Geometrical Heterogeneity

The geometrical heterogeneities present in the lava successions studied consist of the shapes of contacts within the igneous system. Geometrical heterogeneities have shown to be particularly well developed both in the onshore lava field studies in the architecturally complex and faulted Skye Lava Field, and also in the offshore GFA-99 data which contains complex facies juxtapositions. Geometrical heterogeneities are important considerations for geophysical modelling of flood basalts as surface shape affects the propagation of seismic wavefronts and can cause heavy scattering problems if rugose interfaces are present even on a micro-scale in a lava field. Geophysical models for flood volcanic successions have been historically over-simplified and considered to be relatively homogeneous bodies in terms of both shape and internal rock property characteristics. An improved geophysical characterisation of flood basalts in outlined in the next section.

6.3.3 Geoscience Information Integration

Through the creation of the SIMBA research project (Appendix 4) the field studies, 3D models and seismic interpretations researched in this thesis have been incorporated into improved geophysical models of flood basalt successions. These models have been built as deliverables of the several Work Packages that form the basis of the collaborative research goals. Project SIMBA continues beyond the date of completion of this PhD research and thesis, and the complete documentation of the integrated geological and geophysical approach towards solving sub-basalt imaging problems, from all SIMBA partners will be available in 2006. The final report will be appended to this thesis on CD, when the full report has been collated.

A strategy implemented by SIMBA for improving geophysical models of flood volcanics is now summarised (Fig. 6-3). The details of this strategy are documented in Martini *et* al. (2005 in press) (cf. Appendix 5 & appended CD).

A schematic geological 2D profile through a sequence of flood basalts was created using the field study information from the BTIP, Namibia and the Faeroes successions (Fig. 6-3A). The profile incorporates realistic geological architecture, vertical stacking patterns and vertical and lateral facies changes that directly relate to the observations of field relationships and seismic interpretations in Chapter 3, 4 & 5. The dominant features to note in this schematic 2D profile are the filling of basin topography at the base of the lava sequence, and also the transition up through the lava sequence from olivine-phyric compound flows to geochemically more-evolved tabular-type flows towards the top.

Seismic data was built into a geological geometrical interpretation in the area of maximum data control using the GFA-99 dataset from the Faeroe-Shetland Basin. The maximum data control area lies at the cross-over of seismic lines 107 and 203 (cf. Chapter 5). Across this area, 500m gridded surfaces were interpolated through the TWT seismic interpretations of the volcanic succession and overlying sediments, depth converted (Fig. 6-3B) and exported to the Geophysics Group at University College, Dublin (Martini *et al.* 2005 *in press*). The geometrical horizon data was gridded and converted into a block model which statistically incorporates the lava succession heterogeneities present in the 2D geological profile (Fig. 6-3C to E). The resulting velocity model is a more realistic geophysical representation of the geology present in a flood volcanic succession.

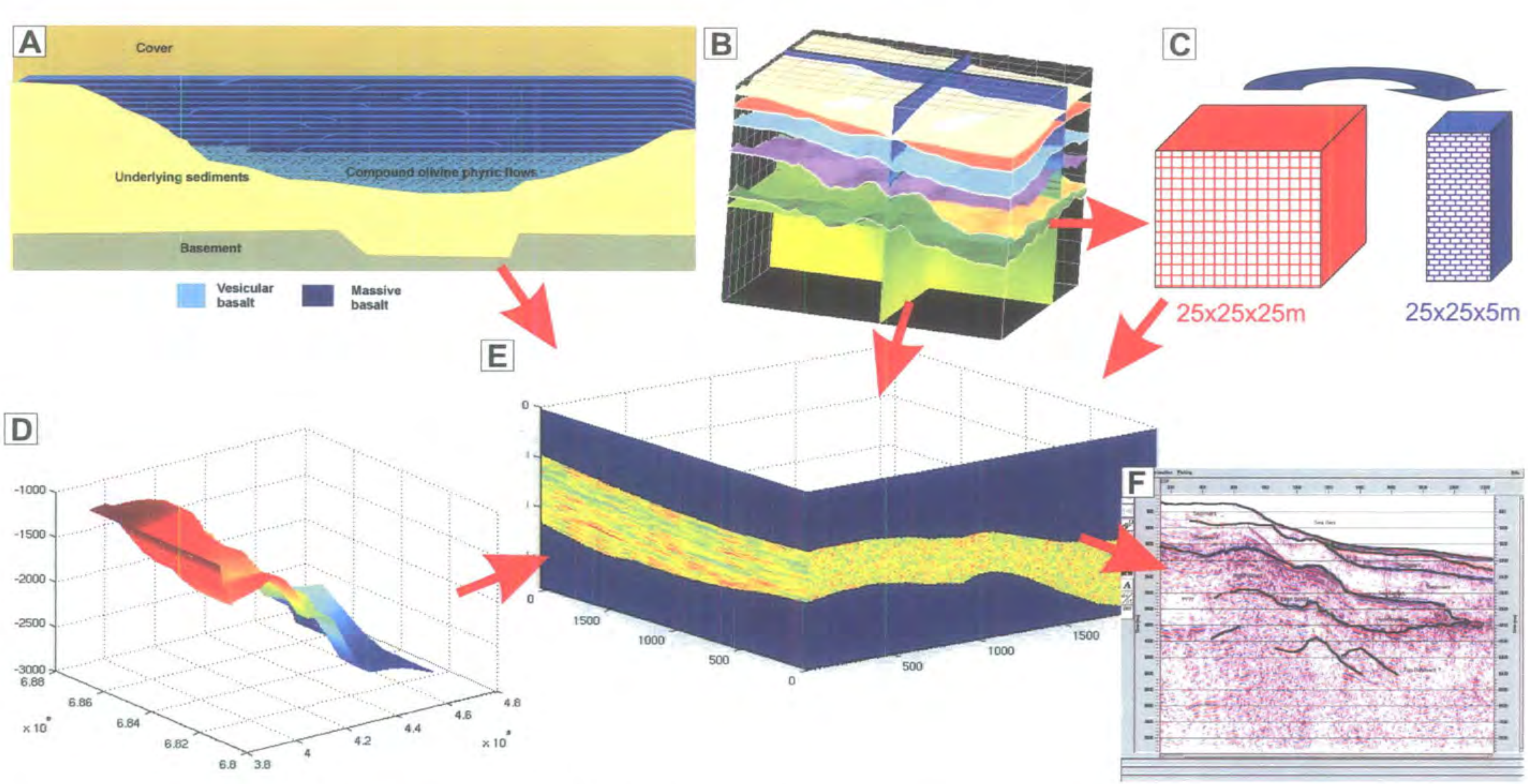


Figure 6-3 Conceptual multi-disciplinary approach to modelling CFB heterogeneity for improving sub-basalt imaging. **A:** A schematic 2D model of a flood basalt volcanic succession using typical facies information from the micro and meso-scale architectural studies; **B:** Geological interpretation of seismic dataset modelled and interpolated in GoCad™ in 3D and subsequently depth converted; **C:** Geological 3D model gridded; **D:** Surfaces imported as [X,Y,Z] into grid; **E:** Rock property heterogeity populated into the layers using rock property statistics and field 2D model from **(A)**; **F:** Improved geophysical modelling leads to improved imaging and geological interpretations. Geophysical modelling performed by Francesca Martini (University College, Dublin), and Richard Hobbs (University of Durham: ex-Cambridge SIMBA partner).

6.4 GEOSPATIAL GEOLOGICAL MODELLING

Geospatial geological modelling has been used as a tool for creating geometric models of flood volcanics in 3D during the course of the PhD research. It is very important to note that the very subject area of geospatial modelling has changed extremely rapidly during the course of the PhD project. At the beginning of the research, Geographic Information Systems (GIS) technologies were in their infancy, and as such, so were the means for producing results that we now expect so quickly from more advanced computer software run on technologically rapidly developing computers. For example, in 2001, the process of creating a digital terrain model (DTM) was extremely laborious, involving tracing contours by hand off paper maps onto transparencies, scanning the transparencies into *.jpg files before importing them as a property onto Voxets in GoCad™. Each contour required converting to a PointSet and was in turn built manually into a series of Curves. Each Curve altitude subsequently needed to be individually shifted from Z=0 to their correct elevations, prior to building the surface for the DTM models. By the end of the research however, the quality of software, availability of work utilities, digital imaging and image processing, modelling techniques and availability of data has completely changed. Data such as DTM models have become freely available for internet download, in conjunction with a whole host of satellite information, for example, and the wealth of data resources has grown at an exponential rate. This in turn means that future work is able to use a huge variety of information, and apply excellent, rapidly improving intuitive analysis modelling tools to problems with greater ease and reliability than ever before. Integration of data will only improve in the future, and the cost of implementation of new tools (e.g. 3D outcrop data acquisition laser rangers and differential GPS) is also rapidly reducing. The tremendous rate of technological development therefore means that the whole scope of future work in geospatial modelling has completely changed, come the end of the research project. Improvements and present problems with geospatial geological modelling are now briefly discussed.

6.4.1 Improvements in our Geological Understanding

Application of advanced computer modelling techniques to our geological information has many advantages over traditional evaluation techniques. A major advantage lies in the true 3D visualisation of information: working in true 3D reduces problems of mentally visualising 3D relationships that exist geospatially. Data may be interpolated in 3D space therefore providing volume information more easily than traditional manual techniques. This powerful visualisation is further enhanced by the ability to assign numerical values of properties to any data location, allowing us to work in [X,Y,Z,property] space. Calculation of volumes within 3D geospatially accurate models is fast and superior in accuracy to traditional 2D based methods, as volumes are constrained to the exact 3D Voxet cell distributions within a given data-driven 3D model.

The 3D modelling environment allows us to integrate a multitude of data types in one space. Therefore we can visualise and analyse geological data in conjunction with property information and remote sensing data of many types. Creating a property (e.g. density) at any point in 3D space, and constructing models from geological data points, combined with seismic, gravity, satellite and well data all in one 3D space, provides a complete multi-disciplinary data integration, analysis and interpretation tool combined with powerful visualisation. In this environment, both geologists and geophysicists can work together to interpret information in a non-exclusive, fully integrated manner.

6.4.2 Problems with Geospatial Modelling

Although geospatial geological modelling improves our understanding of the structure, stratigraphy and geological architecture of the subsurface and also allows us to quantify our interpretations, problems and uncertainties exist and these must be considered when undertaking any geospatial modelling project.

The largest areas of uncertainty in geospatial modelling of geological field data are the errors introduced whilst upscaling the information through several dimensions. Geological field data is inherently 1D or 2D information: i.e. geological log sections and geological cross-sections or correlations. The interpolation of surface contact information from outcrops through topography introduces error, particularly in faulted successions. In order to limit this error, it is essential that 3D models are only built from well constrained geological contacts, and it is essential that workers understand the modelling error introduced by a lack of 3D data constraint in field outcrops.

The second largest geospatial modelling problem area is the production of data artefacts. Artefacts in models predominantly develop during the modelling of geological surfaces, where the modelling software makes a mathematical interpolation of surface location in 3D space without regard for geological realism. This occurs when correlating, interpolating and upscaling through several dimensions, for example: interpolating a correlable surface through a series of contact data points. Artefacts may form features such as step-like surfaces between data points of varying Z-value or such errors as surfaces intertwining and cross-cutting in geologically unfeasible ways within a geological model. The complexity of the artefacts developed is increased if faulting is present, and surfaces may require laborious manual fine-tuning: copying, cutting and forcing surfaces into geological realistic geometries within correlable stratigraphic successions.

6.5 SUMMARY OF SYNTHESIS

This study has applied a systematic approach to the study of flood volcanic facies heterogeneities over a range of scales, incorporating a range of data types and techniques.

A brief summary of the main conclusions of this thesis are now presented; upscaling from the micro to macro-scales of observation:

I. Assessment of centimetre to metre-scale (micro-scale) geological intrafacies by use of descriptive intrafacies components is a useful qualitative way by which the internal facies architecture of igneous units may be classified.

II. Intrafacies may be used as a quantitative tool for the geophysical characterisation of rock property heterogeneity present at an intra-flow scale.

III. Particularly pertinent rock property heterogeneities are caused by the presence of sedimentary/bole beds, massive lava flow cores, vesiculated zones and dykes.

IV. On a meso-scale, understanding the volcanostratigraphy and vertical stacking patterns of igneous units is central to the characterisation of the lava field in 3-Dimensions.

V. Lava fields show architectural evolution trends that link to the geochemistry of the lavas being erupted. Thin olivine-basalts of compound-braided flow facies architectural habits are gradually replaced with thicker tabular-type basaltic-andesites, and more silic lavas as a CFB province evolves through time.

VI. Lavas erupted during the onset of volcanism fill pre-existing topography as sub-aerial valley fills, and sub-aqueous volcaniclastics. Early lavas may build gently-sloping shield volcanic features e.g. the lower lavas of the Skye Lava Field and Huab area of the Etendeka.

VII. Individual lava flow thicknesses increase up-stratigraphy. This increase is coupled with an increase in flow aspect ratio, volume, geochemical evolution (also viscosity) and lateral extent; and a decrease in architectural complexity, lateral heterogeneity and eruption frequency.

VIII. On a macro-scale, the juxtapositions of flood volcanic lava field-scale facies must be considered and an understanding of the sub-macro scale facies architectures applied to geophysical interpretations.

IX. Combining geophysical data types with geologically analogous concepts helps us to build more robust, better constrained seismic interpretations.

X. The successful building of geologically realistic models of flood volcanic successions is dependent on an understanding of the fundamental building blocks from the intrafacies level through to the seismic facies level.

XI. These building blocks must be characterised in terms of their facies, geometrical and rock property heterogeneities in order to better constrain and improve geophysical models of flood volcanic successions.

XII. Geologically more realistic geophysical models of CFBs that integrate multiple geoscience data types will help improve our chances of solving sub-basalt imaging problems for petroleum exploration.

6.6 FUTURE WORK

The research work performed for this thesis has highlighted areas which are of interest for future study in order to improve the understanding of flood volcanic successions and combine geoscience resources for improved sub-basalt imaging.

Some recommendations for future work include:

- Use of the 3D modelling environment for the further integration of geoscience data types. The first integration case study will incorporate geological, seismic, gravity, MT and well data over the north Skye SIMBA acquisition and case-study area (Appendix 5).
- Performing detailed geophysical field laboratory experiments to determine actual rock properties present in outcrop sections studied using the intrafacies scheme.
- Quantification of the links between individual rock property types and geological facies architecture in the rock property map.
- Use of 3D seismic data for the detailed modelling meso-scale lava field structure and geometrical heterogeneity.
- The use of the field-based 3D lava field models for backward-modelling pseudo-seismic experiments using the new seismic processing methods developed by SIMBA.

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Appendices

Appendix 1

Internet Links: Computer Software and Data Sources

Computer Software and Data Sources

Many pieces of software, conversion utilities and data sources were used during the research. Appendix 1 provides internet links to sources of information for these packages and for data downloads sites.

Licensed Software

Software Name	Internet Website URL
GoCad™ 3D modelling software	http://gocad.org/
ER Mapper	http://www.globalmapping.uk.com/acatalog/copy_of_ERMapper_Software.html

Shareware/Freeware Software

Software Name	Internet Website URL
4D Vista	http://www.mve.com/Home/Software/4DVista
Dxf2xyz	http://www.guthcad.com.au/freestuff.htm
NIH Image	http://rsb.info.nih.gov/nih-image/Default.html
Nimamuse	http://earth-info.nga.mil/geospatial/SW_TOOLS/NIMAMUSE/
Panorama Factory	http://www.panoramafactory.com/
QuickStitch	http://www.panoguide.com/software/reviews/quickstitch360_v10.html http://www.enrouteimaging.com/
Scion Image	http://www.scioncorp.com/
UTHSCSA Image Tool (Developed at the University of Texas Health Centre at San Antonio, Texas	http://ddsdx.uthscsa.edu/dig/itdesc.html ftp://maxrad6.uthscsa.edu (for download)

Internet Data Sources and Information

Data Site Name	Internet Website URL
3D-MATIC Links Page	http://www.faraday.gla.ac.uk/links.htm
The Data Depot	http://data.geocomm.com/
Digital Globe	http://www.digitalglobe.com/
Edina – Digimap	http://edina.ac.uk/digimap/
Geoscience Data Index (GSI)	http://www.bgs.ac.uk/geoindex/index.htm
GIS Café	http://www.giscafe.com/
Landsat	http://www.landmap.ac.uk/download/choose_selection_mthd.htm
Landsat Data Reseources	http://landsat.gsfc.nasa.gov/main/data.html
Lynx	http://www.lynxinfo.co.uk/
Macaulay Land Use Research Institute	http://www.mluri.sari.ac.uk/
NASA	http://www.nasa.gov/home/
Terrainmap.com	http://www.terrainmap.com/
UKOGL	http://www.ukogl.org.uk/
USGS Hawiian DTM Index	http://wrgis.wr.usgs.gov/dds/dds-55/pacmaps/hw_index.htm
US Department of Commerce NOAA National Geophysical Data Center	http://www.ngdc.noaa.gov/ngdc.html
Geochemistry course, Cornell University	http://www.geo.cornell.edu/geology/classes/geo455/Chapters.HTML
Interactive Periodic Table of the Elements	http://site.ifrance.com/okapi/periodic3.htm

Appendix 2

Geophysical Data Details

Geophysical Data Details

Location of GFA-99 Seismic

UTM Coordinates of the Western-Geco GFA-99 Seismic Data, Faeroe-Shetland Basin

Line #	S.P.	x	y
Line 201	3653	448427	6815506
	13454	430694	6936685
Line 203	3653	417280	6902059
	10954	430219	6811749
Line 205	12254	401220	6873980
	5853	413307	6794695
Line 207	1153	382651	6866522
	7754	393962	6784810
Line 105	1953	377318	6814258
	10454	482397	6829829
Line107	2453	484720	6850753
	11254	375909	6834787
Line109	2453	380384	6854931
	11054	486672	6870852

Sandwell Bouguer Gravity

The properties of the Sandwell Bouguer Gravity data used in the Gravity modelling work are as follows:

```
1) Data Input:

Sandwell v7.2 satellite gravity data supplied by the
National Oceanographic
Atmospheric Agency, U.S.A.
The following data is included in the v7.2:
     All ERS-1 GM data (two 176-day cycles Ocean Product)
     All GEOSAT/GM data
     Stack of 62 repeat cycles of GEOSAT/ERM
     Stack of 16 repeat cycles of ERS-1 35 day repeat.
     Data point spacing is 2 minutes.
```

2) Bouguer gravity:

Bouguer correction derived from ETOPO5 bathymetry data using a density of 2.2gm/cc.
Formula used for Bouguer correction is:

bc= 0.04188*rho mgal/m.

Bouguer gravity calculated by summing free air gravity and Bouguer correction.

3) Gridding

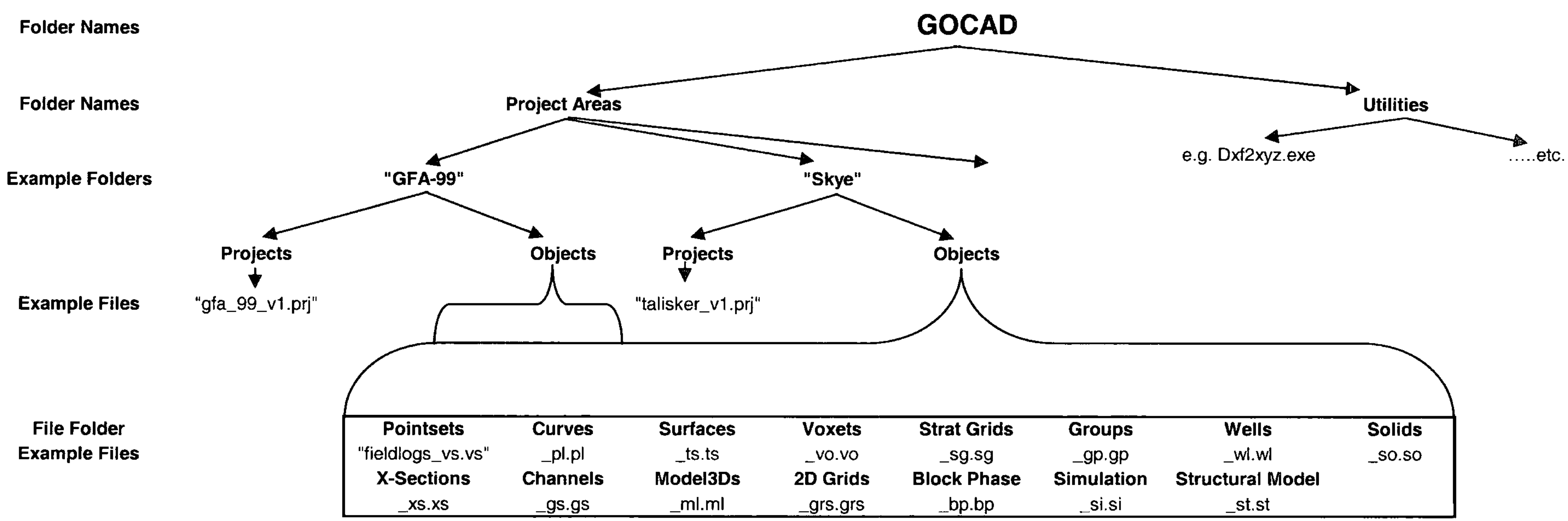
Data gridded at a pitch of 2000 metres with a proprietary gridding program, using a multi-pass method of spline fitted curves.
The grid was then sampled down to 1000 metres for smoothing purposes.

Appendix 3

File Management in GoCad™

GoCad™ projects contain many objects and these should be saved separately in combination with whole project saves. Good data management practise is essential to the efficient use of the software. The table below is a recommended hierarchical file storage system for the control of data in this package.

Recommended folder and file storage system for GoCad 3D Modelling Software



Folder hierarchy starts at the GoCad folder level. From this level, the folder tree divides into a series of simple folders for projects and the objects associated with those projects.

Folders and files that lie on the same table row lie at the same level of hierarchy in the system. **Bold** names represent folders, files are in normal type.

Appendix 4

The SIMBA Research Project

The SIMBA Research Project

The SIMBA EU 5th Framework research project comprises industrial and academic partners for an integrated approach to tackling sub-basalt imaging problems. The members of the consortium and their areas of research are tabulated below. Partners combined research into a series of Work Packages (WPs). Geological modelling comprises WP1.

SIMBA Partners

Partner	Primary Research Interest	Website URL
Total GRC	1D seismic processing	http://www.total.com
Norsk Hydro	Rock properties	http://www.hydro.com
ARK Geophysics	Potential field data acquisition and modelling (Gravity/Magnetics)	http://www.arkgeo.com
IFP	1D pseudo-seismic modelling	http://www.ifp.fr/IFP/en/aa.htm
University of Brest	Magnetotellurics (MT)	http://www.univ-brest.fr/
University of Cambridge	2D seismic processing	http://www.esc.cam.ac.uk/new/v10/index_about_people.html
University College, Dublin	Surface rugosity and seismic diffraction modelling	http://geophysics.ucd.ie/fmartini.shtml http://geophysics.ucd.ie/cbean.shtml
University of Durham	Geological fieldwork and 3D geological modelling	http://www.dur.ac.uk

As part of this PhD, a gravity survey was acquired for ARK Geophysics and a shallow seismic survey was performed with Cambridge University over north Skye on the Waternish Peninsula. The University of Brest acquired an onshore MT survey over the same area of north Skye, and an offshore survey over the GFA-99 seismic data area of the Faeroe-Shetland Basin.

Appendix 5

Papers published and submitted in support of thesis

Papers published in support of thesis

Three papers are available in conjunction with this thesis at time of writing. The titles, abstracts and keywords are contains in Appendix 5, and full manuscripts are stored in *.pdf format on the appended CD.

Papers due for publication in 2005 and 2006, contain details of some of SIMBA's integrated geological-geophysical research in improving sub-basalt imaging, details of which will be documented in the SIMBA Final Report. A copy of this final report will be appended to this thesis on CD, when it becomes available in late 2005 or early 2006.

Single, R.T. & Jerram, D.A. 2004. "The 3D facies architecture of flood basalt provinces and their internal heterogeneity: examples from the Palaeogene Skye Lava Field". *Journal of the Geological Society, London*, **161**, 911-926.

Below is a copy of the abstract and keywords; however full version of the manuscript is appended to this thesis on CD in *.pdf format.

"The 3D facies architecture of flood basalt provinces and their internal heterogeneity: examples from the Palaeogene Skye Lava Field"

Richard T. Single & Dougal A. Jerram

ABSTRACT

Quantifying the facies architecture of flood basalt provinces is important as it can be used to understand the physical volcanology and rock property variations throughout the lava sequence. The 3D facies architecture and internal heterogeneity of the Skye Lava Field, for example, provides important insights into the evolution of the British Tertiary Igneous Province, and valuable information to aid in the exploration of potential offshore reservoirs underlying significant flood lavas along the North Atlantic Margin. The volcanic stratigraphy of the Talisker Bay area of the Isle of Skye, Scotland, comprises (1) lower compound-braided lavas (flow lobes <3m thick), (2) transitional lavas (flows <8m thick), (3) upper tabular-type lavas (flows <20m thick), representing a relative increase in eruptive volume. A 3D model of the lava sequence was reconstructed using detailed digital geological mapping, revealing estimated volumes of: the lower sequence, 12.7km^3; the transitional sequence, 7.4km^3; and the upper sequence, 17.0km^3. The lower sequence lavas formed on the flanks of a shield volcano and were sourced from the NE. Volcanological features such as lava feeder tubes, pahoehoe textures and lobes indicate a scale of volcanism similar to present day Hawaii. The within-flow heterogeneity of the basalts is characterised using an 'Intrafacies Scheme', allowing comparison of variations in lithofacies with characteristic (geophysical) rock properties of compressional wave velocity and density.

Keywords: Flood basalts, 3D architecture, sub-basalt imaging, rock properties, structure, Skye Lava Field, density, velocity.

Martini, F., Hobbs, R.W., Bean., C.J. & Single, R. 2005. "A complex 3-D volume for sub-basalt imaging". *First Break*, (in press).

Below is a copy of the abstract and keywords; however full version of the manuscript is appended to this thesis on CD in *.pdf format.

"A complex 3-D volume for sub-basalt imaging"

F. Martini, R.W. Hobbs, C.J. Bean & R. Single

ABSTRACT

Thick successions of basalt and basaltic-andesite lavas flows were extruded during continental break-up and they cover pre-existing sedimentary basins often of interest for hydrocarbon exploration. With conventional seismic acquisition and processing methods, it is difficult to image both the internal architecture of the volcanic succession as well as the underlying sub-basalt structure. The use of synthetic data can help us to understand the poor sub basalt imaging quality and to develop effective acquisition and processing approaches useful for real data. Moreover, non seismic methods have been successful in improving understanding of overall geometries of sub-basalt targets. Therefore, integration of seismic and non seismic data seems to yield promising results and needs to be explored further.

From all these considerations, the necessity of a realistic 3-D basalt model that would allow simulating realistic seismic and non seismic data, on one hand to test seismic acquisition and processing techniques, and on the other to develop strategies for geophysical data integration into a common methodology to overcome the sub-basalt imaging problem.

A complex 3D model was built adapting all the information available from interpretation of seismic data, log data, gravity data and geological observation. Seismic and non-seismic synthetic data have been produced on the model.

In this paper we present the methodology to develop the 3-D model as well as the initial results from data simulations. The model and the data are available to the public, through the authors of the present paper.

Keywords: 3-D, Modelling, Imaging, sub-basalt, Integrated Geophysics, seismic, magnetics, gravity, magneto-telluric.

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Below is a copy of the abstract and keywords; however full version of the manuscript is appended to this thesis on CD in *.pdf format.

"3-D magnetotelluric inversion and model validation with gravity data for the investigation of large volcanic provinces"

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ABSTRACT

20 magnetotelluric (MT) soundings were carried out on the Isle of Skye, Scotland into the framework of a project on joint interpretation of gravity, seismic, geological and MT data to provide a high-resolution 3-D model in volcanic province context. The full 3-D inversion of the MT data jointly interpreted with gravity reveals the upper crust's structure. The Lewisian basement, 13 km depth, is controlled by the NNE trending Precambrian rift. The basement is overlaid by a 4.5 km thick sequence of Torridonian sandstones. The Mesozoic sediments above have small scale depocentres and are covered by a few hundred meters of Tertiary lava flows. The interpretation of the resistivity model shows that three-dimensional magnetotelluric inversion is an appropriate tool for the imaging of sedimentary structures beneath extrusive basalt units.

Keywords: Magnetotellurics, 3-D inversion, gravity, rifted margin.