LANDSYSTEM ANALYSIS OF THREE OUTLET GLACIERS, SOUTHEAST ICELAND

LANDSYSTEM ANALYSIS OF THREE OUTLET GLACIERS IN SOUTHEAST ICELAND

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Abstract

Landsystem analysis is a commonly applied methodology which focuses on process-form relationships when applied in glacial environments. It can be used to understand and recreate the geomorphological evolution of glacial deposits from modern and ancient sediments. The purpose of this study is to examine the forefields of three closely located outlet glaciers of the Vatnajökull Ice Cap in southeast Iceland to determine the factors affecting the landsystems of these glaciers. A combination of digital based methods and field work focusing on geomorphology and sedimentology were used to define the landsystems. A classification code and associated symbology was used in this study to create consistency of landsystem analysis and can be used in future similar studies of glacial environments. The three glaciers, Morsárjökull, Skaftafellsjökull and Svínafellsjökull were chosen due to their shared source and close proximity, lying within adjacent valleys. The historical changes of the three glaciers have been well documented with aerial photographs, historical maps and glacier margin measurements. LiDAR were used to interpolate 2 m digital elevation models (DEM) of the three glacier forefields. These glaciers have varying topography, bedrock type and ice distribution (hypsometry, equilibrium line altitude (ELA)) which impacts the deposition at the glacier margin. The forefields of Morsárjökull and Skaftafellsjökull exhibit many similarities in the distribution and scale of landforms similar to the characteristics of the established active temperate landsystem commonly found in Iceland. However, the forefield of Svínafellsjökull has many differences compared to Skaftafellsjökull and Morsárjökull in the scale, type and distribution of landforms and sediments. Bedrock

type, hypsometry and glacial debris content are major factors that influence differences in these landsystems. These three forefields may be used as analogues to enhance understanding of paleoenvironmental conditions that existed along the southern margin of Pleistocene glaciers that covered much of northern North America and Europe in the past.

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Chapter One

1.1 Introduction

Glaciers are dynamic in nature, from the continuous movement of the ice margin to the fluctuations in meltwater and proglacial lake levels. This dynamic environment creates a complex glacial terrain composed of sediment deposits and landforms resulting from multiple depositional processes occurring at varying spatial and time scales. In formerly glaciated terrains, including southern Ontario, buried glacial deposits commonly act as important aquifers (Slomka and Eyles, 2015). Understanding their processes of deposition and the spatial relationships between different landforms and sediments in glacial environments can be used to improve models of the subsurface and enhance paleoenvironmental reconstructions (Evans and Twigg, 2002; Slomka and Eyles, 2015).

The purpose of this study is to explore the proglacial landsystems of closely located glaciers in Iceland to determine the factors that influence the similarities or differences between them. The applicability of modern systems as analogues for paleoglacial deposits and to aid in understanding the subsurface distribution of sediments is reliant on a thorough understanding of current processes and a repository of information from a variety of glacial settings.

1.2 Study area

The study area is comprised of the proglacial fields of three outlet glaciers, Morsárjökull, Skaftafellsjökull and Svínafellsjökull, of the Vatnajökull Ice Cap in southeast Iceland (Fig. 1.1). The distal extent of the proglacial fields is determined by the location of the terminal moraines at each of the glaciers. The lateral extent of the proglacial field at Morsárjökull is constrained by its bounding valley walls (Fig. 1.1). The western border of the field at Skaftafellsjökull is bounded by the mountain Skaftafellsheiði and the eastern border is determined by the location of a medial moraine and the mountain Hafrafell (Fig. 1.1). The lateral extents of the proglacial field of Svínafellsjökull are defined by Hafrafell and the medial moraine on the northwest and Svínafellsheiði on the southeast (Fig. 1.1).

The three glaciers, Morsárjökull, Skaftafellsjökull and Svínafellsjökull, which are all located on the southwestern side of the Vatnajökull Ice Cap (Fig. 1.1), were chosen for study based on multiple criteria. The glaciers are closely spaced in adjacent valleys of the Öræfajökull Mountain limiting the impact of climatic factors and ice source on the development of their sediments and landforms. The three chosen glaciers have abundant data available on the forefields including complete historical margin positions from 1930 until present, aerial photographs from multiple years, historical maps, bedrock composition and LiDAR data. The glaciers themselves also have available information such as the hypsometry, equilibrium line altitude (ELA), area, slope and length. These data are critical for understanding the movement of the glacier margin, the timing of deposition of landforms and connecting the landforms to the depositional processes of the glacier. Morsárjökull, Skaftafellsjökull and Svínafellsjökull are easily accessible by car and hiking, reducing potential logistical problems associated with more remote locations in Iceland. Finally, the sedimentology and landform characteristics of the glacial forefields of these three glaciers have not been studied extensively, providing an opportunity to add to the existing literature on Icelandic glaciers and landsystem analysis.

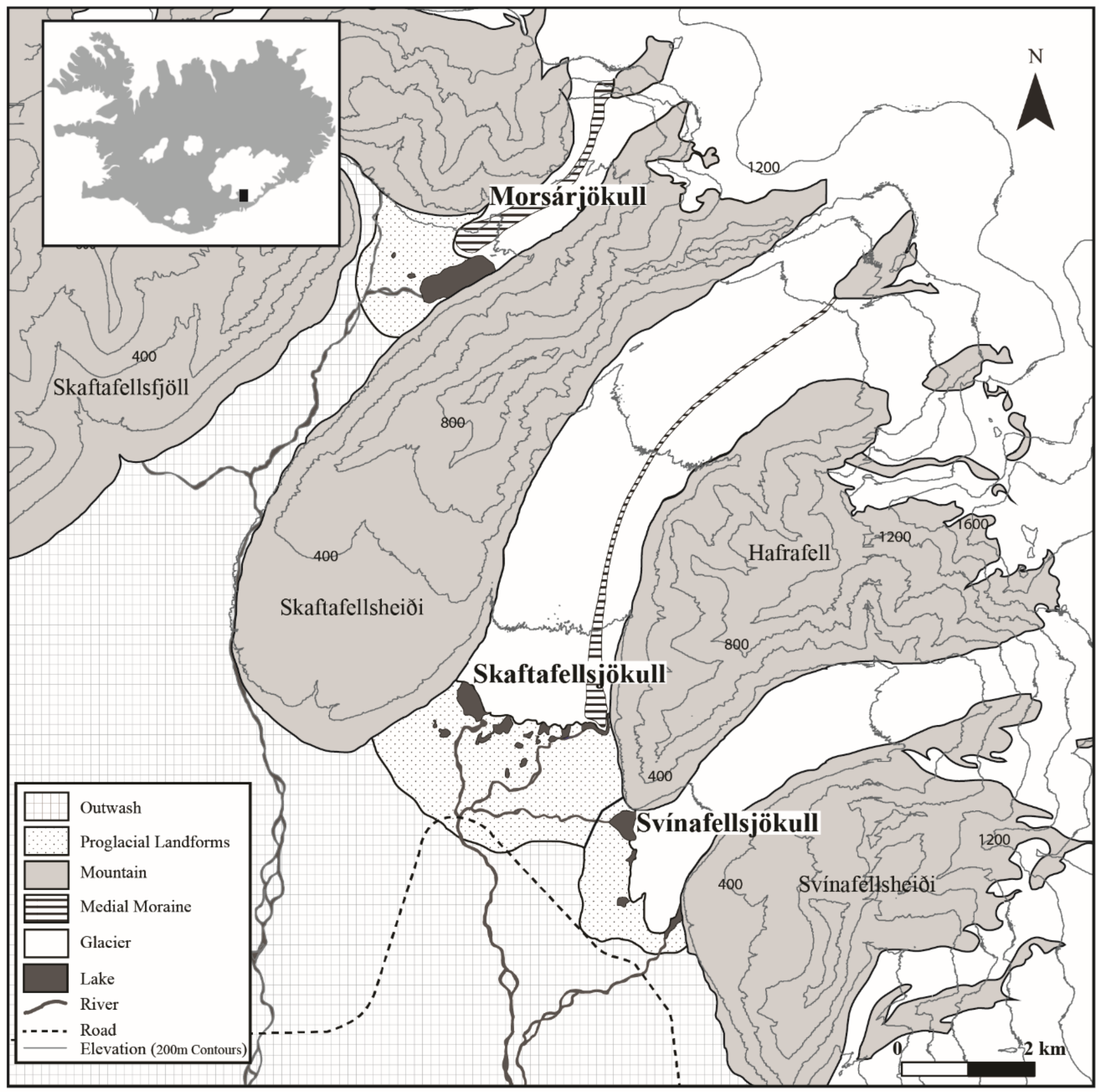

Figure 1.1: Study area located in southeast Iceland (inset map) showing the extent of the proglacial fields of Morsárjökull, Skaftafellsjökull and Svínafellsjökull.

1.3 Landsystem Analysis

Landsystem analysis is a methodology of evaluating and classifying terrain based on the identification and documentation of landforms and sediments and an understanding of the depositional processes that created them. Landsystem analysis has developed over the past 40 years to become a commonly applied methodology in glacial landscapes to understand process-form relationships and the distribution of sediments (Evans and Twigg 2002). The value of this method lies not only in its ability to classify and simplify complex terrain (Christian 1958; Evans 2003), but also in its application to the understanding and mapping of subsurface deposits (Cooke and Doornkamp, 1990; Eyles, 1983a). A common application of landsystems analysis in glacial geology is in modern systems, such as those of Iceland and Svalbard, where there is current deposition of glacial materials and surface expression of the landforms. The documentation of recent fluctuations of glacial margins has allowed for temporal and spatial analysis of the processes occurring at the margins of glaciers with differing dynamics and the landforms they generate (Bennett et al., 2010). Understanding the current state of landsystem analysis and its potential weaknesses is critical to its application in future studies.

1.3.1 Development of the Landsystem Concept

Landsystems analysis was first popularized through its use by the Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) as a method of evaluating the land use potential of large areas of undeveloped land (Christian, 1958; Cooke and Doornkamp, 1990; Evans, 2003). The survey intended to describe, classify, and map large areas of land which lacked scientific information to determine potential agricultural usage (Christian, 1958). Landsystem analysis is a hierarchical method (Fig. 1.2) which classifies a region into areas that contain a recurring pattern of topography, soils and vegetation known as a landsystem, which represents a natural unit (Evans, 2003). To be considered a landsystem it must have internal consistency while being distinct and recognizable from the surrounding systems (Christian, 1958; Eyles, 1983a). A landsystem is further divided into land units (or tracts) which are components of the land surface that have similar physical attributes and were created by similar depositional processes (Christian, 1958; Cooke and Doornkamp, 1990). Land units are further classified into elements which represent a single uniform component of the landscape (Christian, 1958; Eyles, 1983a).

Topography and geomorphology are the most critical attributes to determine during the initial phase of mapping as they are the most readily available data, easily recognized, and influence other important characteristics (Cooke and Doornkamp, 1990; Evans, 2003). Topography and geomorphology are commonly documented using aerial imagery to map the area while field work is used to check the map and interpretations made from aerial imagery, and to provide information on soil and sediment characteristics (Cooke and Doornkamp, 1990). Despite the wide application of the landsystems concept as a methodology for analyzing land use and land development prospects there are weaknesses in this method. The identification of landsystems is often based solely on qualitative observations which can lead to subjectivity (Cooke and Doornkamp, 1990), though these observations can be parameterized to reduce bias (Speight, 1973). The method has been applied internationally due to its ease of use, its applicability to multiple disciplines, and its ability to include multiple factors in simplifying complex landscapes (Cooke and Doornkamp, 1990). Since its implementation in land development planning the use of landsystems has spread to other disciplines including glacial systems (Evans et al., 2015b; Schomacker et al., 2014; Spedding and Evans, 2002; Eyles, 1983b), ecosystems (Asner et al., 2016) and anthropogenic effects (Verburg et al., 2015).

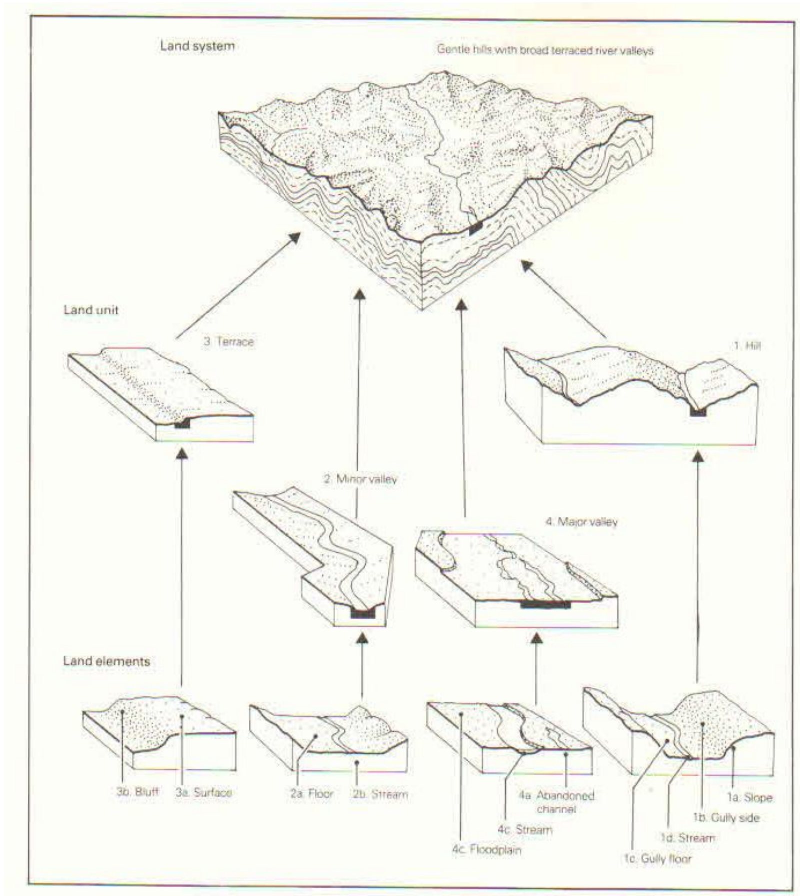

Figure 1.2: Figure from Cooke and Doornkamp (1990) which shows the hierarchy of the landsystems methodology providing examples of each level of division. The largest division is the landsystem composed of land units (or facets or tracts) which are in turn composed of smaller land elements.

The application of the landsystems methodology to enhance understanding of glacial deposits changed the focus from regional development and land use classification to landscape characterization of glaciated terrains (Evans, 2003). Unlike traditional applications wherein landsystem analysis was used to understand the characteristics of the first few meters of subsurface sediments and soils, its use in glacial deposits aims to understand spatial distribution of sediments to the underlying bedrock (Eyles, 1983a). Speight (1963) was one of the first to use landsystems to analyze a glaciated terrain where landform associations were characterized as "subdivision of a landscape in which the landforms have such an ordered arrangement, consistency of slopes, uniformity of erosional development, and degree of obliteration of detail as would indicate that they originated together as a land surface" (Fig. 1.3). The focus of glacial landsystems then moved towards the characterization of process-form relations to understand the sediment distribution associated with the landforms and related environmental conditions (Evans, 2003).

The landsystems methodology rapidly developed as a tool to provide engineers with understanding of the subsurface and its characteristics in areas of previously glaciated terrain (Evans, 2003; Eyles, 1983b). Eyles (1983a) proposed three major glacial landsystems: subglacial landsystem, supraglacial landsystem, and glaciated valley system. Each of these focused on the process-form relationship of a certain type of glacial system, i.e. subglacial deposits which include all components of a subglacial system including till and associated landforms such as streamlined forms and eskers, compared with earlier works which focused predominantly on the method of deposition (Evans, 2003). The landsystem concept has continued to expand within glacial systems to include variability based on climate (i.e. subpolar; Alexanderson et al., 2002), ice dynamics (i.e. surging; Kjaer et al., 2008), and location of the glacier (i.e. plateau icefield; Evans et al., 2015a).

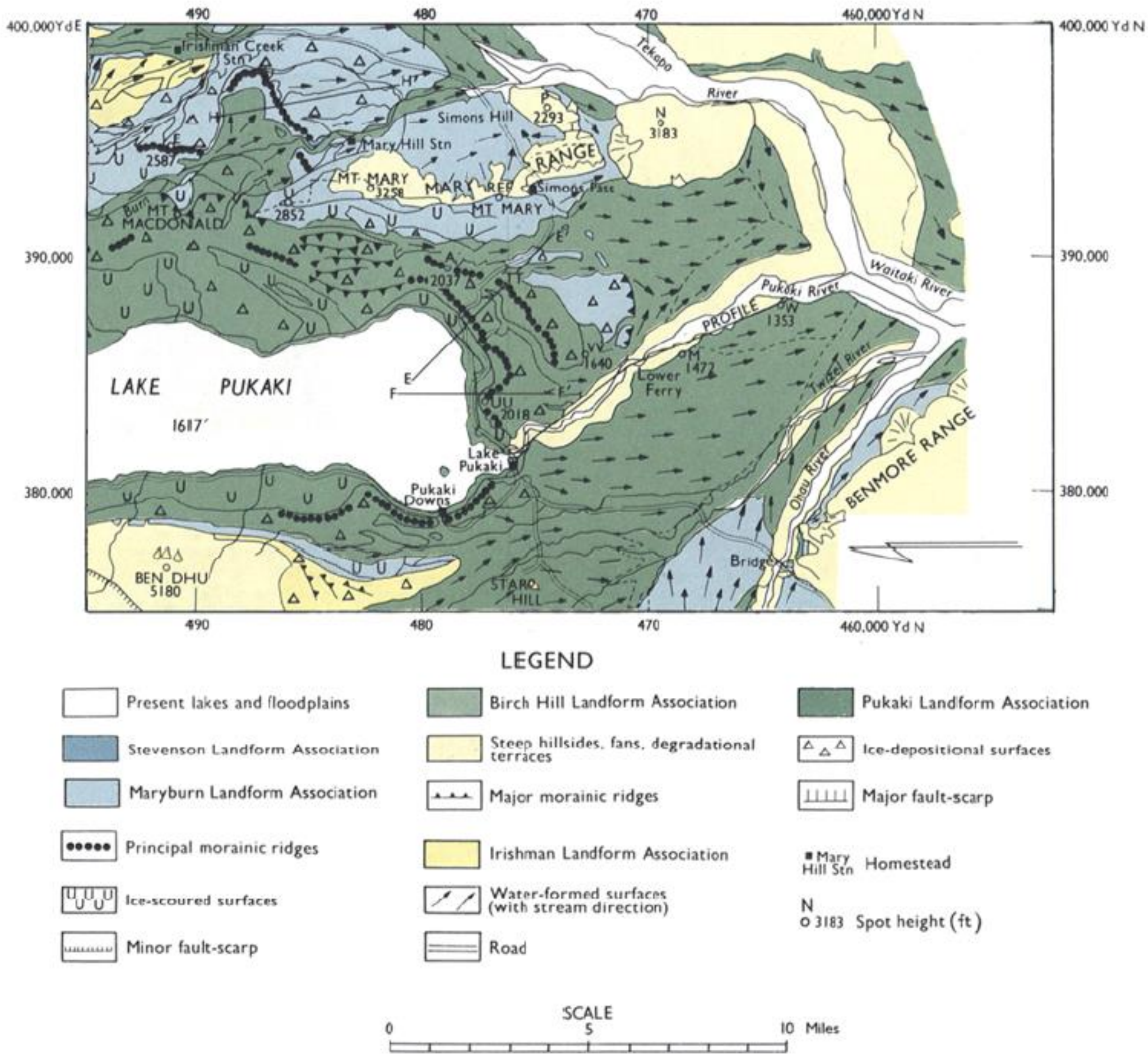

Figure 1.3: An adaptation from an early application of landsystem analysis in a glacial environment completed by Speight (1963) in New Zealand. Speight used the term landform association, which is comparable in meaning to landsystem.

The holistic approach of landsystem analysis permits the complex terrain in glacial systems to be simplified and classified based on geomorphological and sedimentological characteristics (Eyles, 1983a; Evans and Twigg, 2002). The integration of multiple data sources provides robustness to the examination and permits the use of quantitative and qualitative analysis.

1.3.2 Utility of Landsystem Analysis

Landsystem analysis has been successfully employed as a methodology for understanding the process-form relationships occurring in glaciated basins and to determine the genetic origins of sediment (Evans and Twigg, 2002). It is important to understand the temporal and the spatial evolution of glacial landscapes in order to predict the potential distribution of sediments in buried glacial deposits (Eyles, 1983a). The value of the landsystem methodology is in its potential use in areas of Quaternary glaciation, such as southern Ontario, where it can serve as a tool for mapping and modelling of the subsurface. It is most easily applied to surficial deposits and to the interpretation of deposits created by the most recent glacier advance, although it can be applied to more deeply buried deposits through the use of subsurface investigative techniques and outcrops (Eyles, 1983a). Successful interpretation of ancient glacial deposits is reliant on an appropriate understanding of the characteristics of modern glaciated terrains (Evans and Twigg, 2002; Eyles, 1983a).

Each of the landsystems defined in modern settings are proposed as a specific analog for a location or ice condition of paleo ice sheets. For example, due to the rapid movement of surge-type glaciers they have been linked to paleo ice streams and rapid moving ice lobes which probably had similar behaviours and characteristics (Evans et al., 2016; Kjær et al., 2008; Schomacker et al., 2014). Active temperate glaciers are commonly associated with mid latitude Pleistocene glacier margins (Evans and Twigg, 2002). The plateau icefield at Eiríksjökull examined by Evans et al. (2015a) can be used as an analogue for upland glaciation common in the cold stages of the last glaciation in the mid latitudes. The probable similarity between the ice dynamics of the modern systems and paleo-ice conditions exemplifies the need to have an understanding of glaciers with varying ice dynamics, locations, climate and topography. Continued research on differing glacier regimes and settings can allow for the improvement of models of ice movement and deposition, providing information to establish critical boundary conditions (Ingólfsson et al., 2015).

Landsystems analysis focuses on determining the process-form relationship between landform-sediment assemblages and glacier characteristics. This requires understanding of the entirety of a glacial terrain; a single landsystem tract or landform is unlikely to be diagnostic of the entire system and/or glacial conditions occurring at the glacier margin. Individual landforms are formed through multiple processes, limiting their utility as indicators of specific processes. For example, crevasse squeeze ridges are considered diagnostic of surge-type glaciers; however, this landform is also found at active temperate glaciers (Evans et al., 2016b). Similar processes form crevasse squeeze ridges at the two glacier types and their presence alone is not diagnostic of a specific glacier type.

Many glacial landforms, such as eskers, have low preservation potential over long time periods (Evans et al., 2016b). The potential for erosion by subsequent glacial advances and post-glacial processes impedes analysis of paleoglacial landforms. The concertina esker, which is found at surge type glaciers, is easily eroded and can be destroyed by successive surging events (Schomacker et al., 2014). This landform is unlikely to be preserved in older glacial sediments and despite its relationship to surging cannot be used as a simple diagnostic for a surging glacier. Consideration of the complexity of glacial systems is required when evaluating a glacial landsystem due to the potential for repeated advances and retreats of the ice margin, which can overprint different landsystem signatures, destroy landforms, and alter the landscape. Process-form relationships are a key component of landsystem analysis in both modern and ancient glacial deposits. A single landform is not diagnostic of any one landsystem and the glacier forefield must be examined holistically.

Recent research at glacier margins has further emphasized the importance of incorporating morphological, sedimentological and structural evidence into interpretation of ice processes (Ingólfsson et al., 2015). This allows for the inclusion of factors such as till rheology, thermal regime, and geometry into the examination and interpretation of the processes occurring subglacially and ice marginally (Ingólfsson et al., 2015). Fieldwork is an important part of the landsystems analysis process and provides significant information on geomorphological and sedimentological characteristics of the forefields. The collection of sedimentological evidence is critical to identify landsystems that can model the subsurface distribution of sediments. Beyond the physical collection of data, fieldwork also allows for contextualization of aerial imagery, providing a different perspective on DEMs and aerial images.

With increased utilization of unmanned aerial vehicles (UAV) for scientific research, it is becoming increasingly common to forgo detailed field explorations and to use high resolution aerial imagery as the primary source of data (Evans 2011; Evans and Orton 2015b; Evans, Ewertowski, and Orton 2015a). UAV can be powerful tools to facilitate research in areas that are difficult to access and to expedite the gathering of high resolution photographs, aerial imagery and elevation data (Bemis et al., 2014). Despite these advantages, it is important to maintain expert-informed fieldwork within landsystem analysis and glacial geological studies to provide the needed sedimentological context.

Landsystems analysis is primarily a qualitative methodology where classifications are determined by the expertise of the individual researcher; this is exemplified by the multiple interpretations of similar landsystems that are made by different researchers (i.e. differentiation in zonation of the surge type glacier from Schomacker et al. (2014) to Ingólfsson et al. (2015). Creating parameterization or requiring additional input of quantitative data to landsystems analysis may reduce the range of interpretations made by researchers.

Landsystems analysis is most effective when applied to modern systems or landscapes affected by the last glacial advance where there remains adequate surface expression of landforms (Eyles, 1983a). Examining buried sediment can be difficult as the geomorphological features that are the focus of most landsystem studies are commonly absent. Incorporating more detailed sedimentological analyses in modern settings, including more complete outcrop, and subsurface examinations may increase the applicability of this method for buried sediments in paleoglacial deposits.

1.3.3 Examples of Icelandic landsystems

Landsystem analysis commonly applied to modern Icelandic glacial deposits with numerous studies exploring the various outlet glaciers draining ice caps around the southern coast (Fig. 1.4). Iceland is a frequently studied location due to a multitude of factors including the accessibility of the glaciers, the abundance of data available, and the wide variation in the types of glaciers found in close proximity. Two common landsystem types in Iceland are active temperate glacial landsystems (Evans and Twigg, 2002; Chandler et al., 2015; Evans and Orton, 2015) and debris-charged landsystems (Bennett et al., 2010; Krüger et al., 2010). Other landsystems present in Iceland include the plateau icefield landsystem at Eiríksjökull (Evans et al., 2015a); surging glacial landsystem present at Eyjabakkajökull (Benediktsson et al., 2010), Tungnaarjökull (Evans et al., 2009)and Brúarjökull (Schomacker et al., 2006) and; volcano centred landsystem of Snæfellsjökull (Evans et al., 2016a). Each of these systems is composed of characteristic landform-sediment assemblages reflective of the ice dynamics, climate, and topography of the glacier.

An active temperate glacier is a warm based glacier which spends at least some of the year at the pressure melting point with limited influence from the surrounding mountain topography including limited input of supraglacial debris (Evans and Twigg, 2002). The active temperate landsystem is thought to be similar to that of the southern margin of the Pleistocene ice sheets (Evans et al., 2015b). Based on multiple studies, there are three main landsystem tracts of the active temperate glacial landsystem: the subglacial, glaciofluvial, and morainic landsystem tracts, (Fig. 1.5; (Evans and Twigg, 2002; Evans et al., 2015b). This landsystem is present at multiple glaciers within Iceland including Breiðamerkurjökull (Evans and Twigg, 2002), Fláajökull (Evans et al., 2015), Heinabergsjökull and Skalafellsjökull (Evans and Orton, 2015).

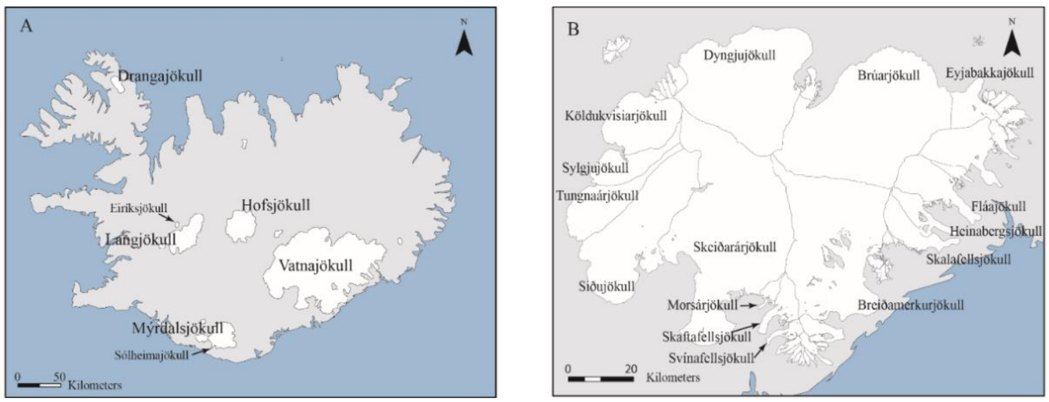

Figure 1.4: Map of Glaciers in Iceland including the five major Ice Caps Langjökull, Drangajökull, Hofsjökull, Mýrdalsjökull and Vatnajökull. Inset maps shows detailed locations of outlet glaciers of the Vatnajökull Ice Cap, the focus of many studies on Icelandic glacial systems.

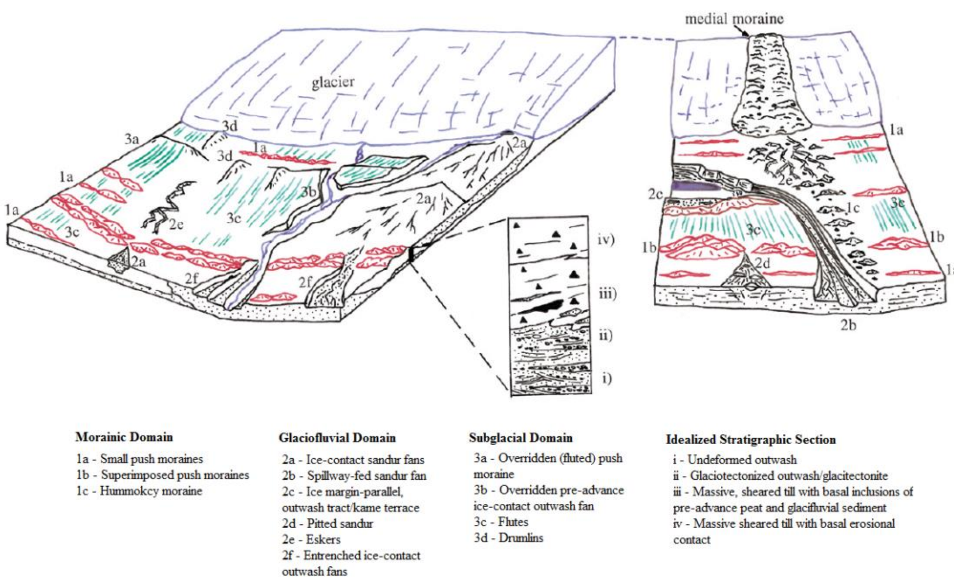

Figure 1.5: Schematic depiction of the active temperate glacier landsystem as proposed by Evans and Twigg (2002). Major components of this landsystem include moraines, overridden moraines, flutes, and glaciofluvial deposits.

Debris charged landsystems describe glaciers which have a high volume of debris-rich basal ice and englacial debris (Bennett et al., 2010). The large volume of debris can result from multiple processes including rock fall onto the glacier surface, passive debris pathways, entrainment of debris through thrusting and compression at the ice fall, and supercooling (Bennett et al., 2010). A commonality of debris charged landsystems is the presence of ice cored moraines which result in hummocky topography as the ice melts (Fig. 1.6; Bennett and Evans, 2012; Krüger et al., 2010). Debris rich landsystems have end moraines, large scale outwash plains, hummocky moraines, kettles and kame terraces, (Fig. 1.6; Krüger et al., 2010; Bennett and Evans, 2012). The composition of the moraines in these environments tends to be primarily supraglacial and proglacial sediments with only minor subglacial components (Bennett et al., 2010). Examples of debris charged landsystems within Iceland include Kviárjökull (Bennett et al., 2010) and Kötlujökull (Krüger et al., 2010). Overall, the debris charged landsystem reflects a greater input of sediments than the active temperate landsystem, creating larger features, more prevalent ice cored moraines, and more substantial areas of hummocky topography.

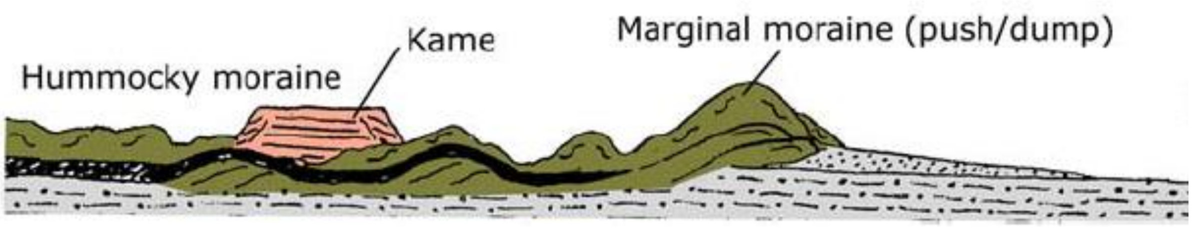

Figure 1.6: Schematic map of the final evolution of the debris charged landsystem taken from Krüger et al. (2010). Hummocky moraines are common within these systems due to an abundance of stagnating ice.

1.3.4 Comparison with Architectural Element Analysis (AEA)

The primary focus of landsystem analysis is on the process-form relationship between landforms and the glacier dynamics. A limitation of landsystem analysis is in its application to buried sediments where there is limited or no preservation of landforms. The incorporation of additional sedimentological data would increase its application to buried paleoglacial deposits.

Architectural element analysis (AEA), proposed by Miall (1985), focuses on sedimentological analysis of ancient deposits and is based on an established hierarchical classification of bedforms and bounding surfaces within clastic environments. An architectural element is a "a lithosome characterized by its geometry, facies, composition and scale" formed by processes related to a depositional environment (Miall, 1985) . To define an architectural element details on the internal geometry, external geometry, scale and bounding surfaces of a sedimentological feature are necessary. This creates the hierarchy of elements with successively larger scale and more complexity where the larger elements can be composed of smaller, simpler elements. Bounding surfaces separate architectural elements and are an important component of AEA providing information on the amount of environmental change that has occurred.

First used in fluvial settings, architectural element analysis is now applied to a range of other depositional settings. The method is not commonly applied in glacial settings, with only a few studies using the technique (e.g. Boyce and Eyles, 2000; Bennett et al., 2002; Slomka and Eyles, 2015). The limited use in glacial sedimentology may be due to lack of extensive outcrops required for this type of analysis. As a consequence, widely applicable architectural elements have not been established for all glacial environments and individual studies have proposed differing elements for different glacial environments (e.g. subglacial (Boyce and Eyles, 2000); glaciofluvial (Slomka and Eyles, 2015) and glaciolacustrine (Bennett et al., 2002)). Further use of this method to analyze glacial deposits will allow for the creation of more consistent and widely applicable architectural elements.

The combination of architectural element analysis and landsystem analysis may be beneficial for enhancing our ability to analyze and understand buried glacial deposits. Slomka and Eyles (2015) used these two methods at the margin of Sólheimajökull, an outlet glacier of the Mýrdalsjökull Ice Cap. In this study the hierarchical bounding surfaces defined in AEA were used together with the landform delineation of landsystems analysis to identify genetically related sediment-landform packages (Slomka and Eyles, 2015). Multiple scales of sediment-landform packages were used to define landsystem tracts (i.e. glaciofluvial, jökulhlaups) (Fig. 1.7; Slomka and Eyles, 2015) and architectural-landsystem models for ice-marginal, ice-proximal and ice-distal regions of a non-surging, temperate glacier were created. Integrating analytical methodologies that focus on different components of the glacial forefield can create a more complete understanding of the relationships between ice dynamics and deposition. Increasing the focus on sedimentological characteristics through the addition of methods such as AEA to

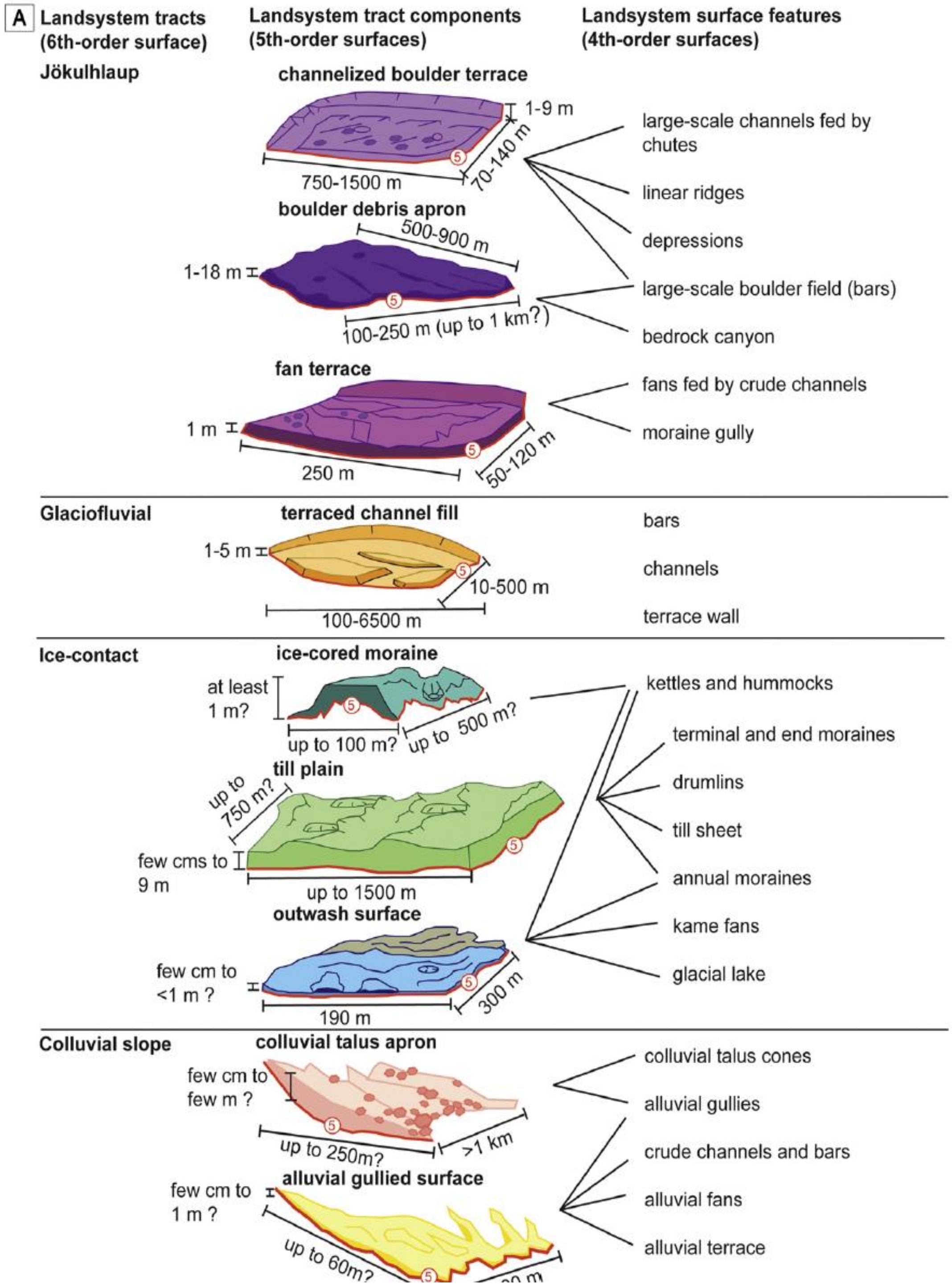

Figure 1.7: Hierarchical sediment-landform packages used by Slomka and Eyles (2015) to analyze the Sólheimajökull proglacial field.

landsystems analysis, improves the ability to understand and model the heterogeneity and complexity of glacial deposits in formerly glaciated terrain.

1.4 Conclusion

Landsystem analysis has been widely applied within glacial environments throughout modern systems and paleoglacial deposits. The focus on process-form relationships between the landform-sediment assemblages and glacier dynamics has enhanced understanding of the effects of glacial and environmental factors on the development of the forefield. An important application of landsystem analysis in modern systems is to document the characteristics of analogue systems that can improve models used for reconstruction of paleoclimate and past glacial dynamics in formerly glaciated terrains.

The methodology has been widely applied in Iceland resulting in the definition of many landsystems including: active temperate landsystem (Evans and Orton, 2015; Evans and Twigg, 2002), debris charged landsystem (Bennett et al., 2010; Krüger et al., 2010), surging landsystem (Evans et al., 2009; Schomacker et al., 2014), ice plateau landsystem (Evans et al., 2015a) and volcano-centred landsystem (Evans et al., 2016a).

Landsystem analysis currently focuses on the geomorphology of deposits to determine the relationships, limiting its applicability to buried sediments. Inclusion of more detailed sedimentological evidence, the increased application of quantitative analyses and focus on integration of multiple data types will improve the utility of the methodology. Landsystem analysis has proven to be an effective method for examining process-form relationships within glacial sediments and continues to be a valuable tool for understanding these complex systems.

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Chapter Two

2.1 Introduction

The study of modern glacial deposits provides important information about their sedimentology and geomorphology and can be applied to paleoglacial deposits to understand their depositional and environmental history (Evans et al., 1999; Slomka and Eyles, 2013). Landsystems analysis is a commonly applied methodology which has been used in modern settings such as Iceland (e.g. Bennett et al., 2010; Evans and Twigg, 2002; Evans et al., 2009), Greenland (e.g. Lane et al., 2016) and Norway (e.g. Evans et al., 2012; Ewertowski, 2014) as well as in paleoglacial deposits (e.g. Alexanderson et al., 2002; Evans et al., 1999; Kehew et al., 2012). Focusing on the process-form relationships between glacial deposits and the characteristics of the glacier and surrounding environment, landsystem analysis can be applied in modern systems to facilitate the use of these settings as analogues for paleoglacial deposits and to improve paleoenvironmental reconstructions (Evans, 2003; Slomka and Eyles, 2013). The use of modern landsystems to enhance paleoglacial studies is further improved by the continuously growing knowledge base of different glaciological settings and glacier types (Evans, 2011).

This study compares the proglacial fields of three closely located outlet glaciers of the Vatnajökull Ice Cap in southeast Iceland (Fig. 2.1) and determines their landsystem types. Comparison of the glacier forefields will improve understanding of the influence of a variety of factors, such as bedrock, topography and ice distribution on the landforms and sediment distribution within the fields. Further understanding of process-form relationships in these settings can be applied to future studies of paleoglacial deposits.

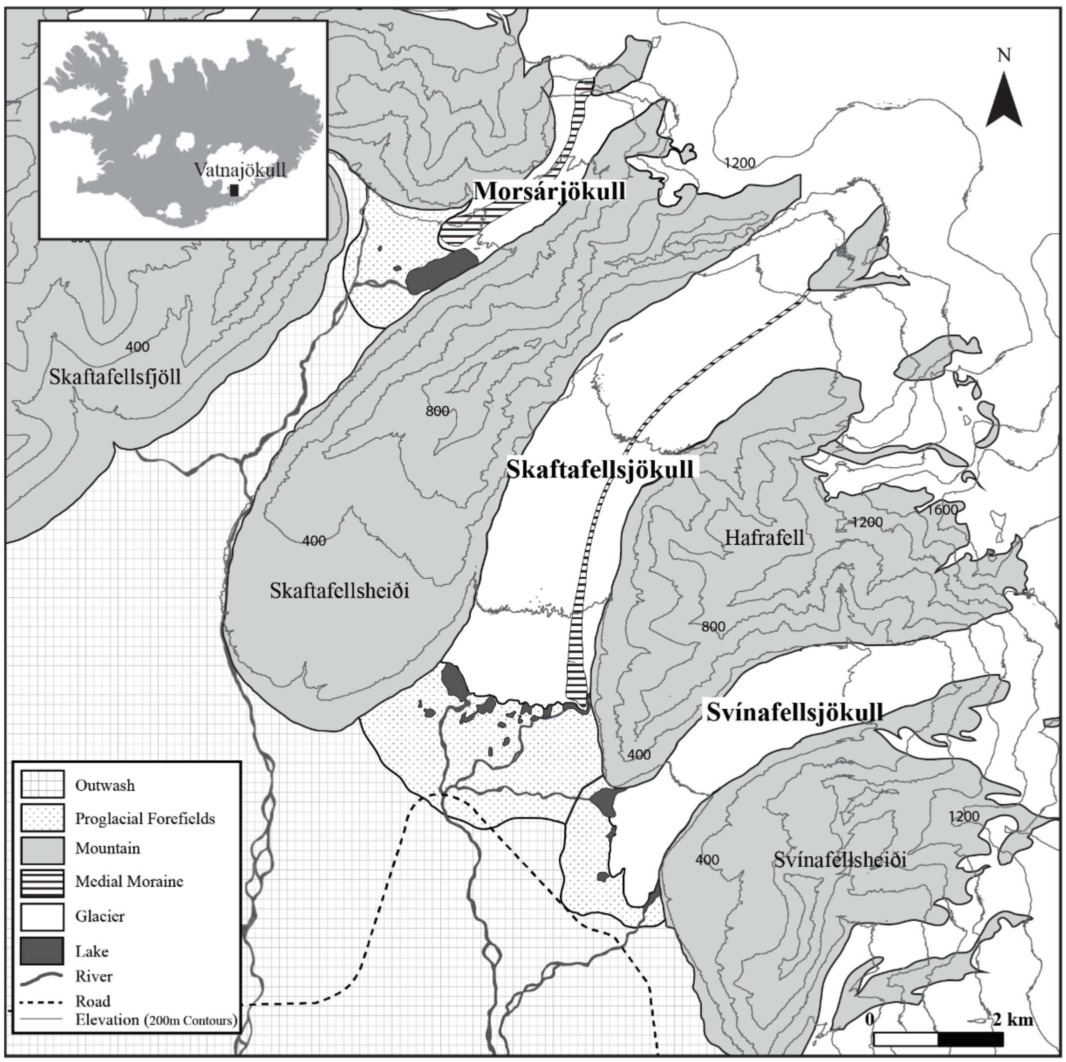

Figure 2.1: Map of the study area comprising the proglacial area of Morsárjökull, Skaftafellsjökull and Svínafellsjökull, three outlet glaciers of the Vatnajökull Ice Cap and Öræfajökull Ice Cap. The glaciers are located in southeast Iceland on the southwest margin of the ice cap, shown in the inset map.

The three glaciers, Morsárjökull, Skaftafellsjökull and Svínafellsjökull are located within close proximity of one another (Fig. 2.1) and are each sourced by the Vatnajökull

Ice Cap. This minimizes the impact of factors such as climate and ice source when comparing the proglacial fields of each of the glaciers and determining factors that may influence variability in the landforms and deposits. Reducing the number of variables that may influence glacial processes is useful for identification of the most important factors. There is limited literature focusing on the forefields of any of these three glaciers, with the majority of the work completed in the 1980s (e.g. Thompson and Jones 1986; Thompson, 1988). However, the glaciers and glacier dynamics have been well studied and there is ample information relating to bedrock characteristics (Jóhannesson and Sæmundsson, 2009), topography (Magnússon et al., 2012), and glacier dynamics including presence of supercooling zones (Cook et al., 2011b, 2007).

2.2 Study Area

Vatnajökull is the largest ice cap in Iceland and is composed of multiple ice centres, including Öræfajökull, the ice centre on which the three glaciers lie (Björnsson and Palsson, 2008). Morsárjökull, Skaftafellsjökull and Svínafellsjökull are outlet glaciers on the southwestern margin of the Vatnajökull Ice Cap located in southeast Iceland (Fig. 2.1). These glaciers lie within adjacent valleys draining Öræfajökull, a stratovolcano composed primarily of basalt and hyaloclastite (Jóhannesson and Sæmundsson, 2009). Although all three glaciers lie within close proximity, they exhibit varying rates of retreat, glacial size and topographical characteristics (Table 2.1, Fig. 2.2).

There have been two periods of major glacier expansion since the climatic optimum approximately 7000 ybp (Björnsson and Pálsson, 2008). The first occurred approximately 2500 ybp during which time Vatnajökull merged into a single ice cap with

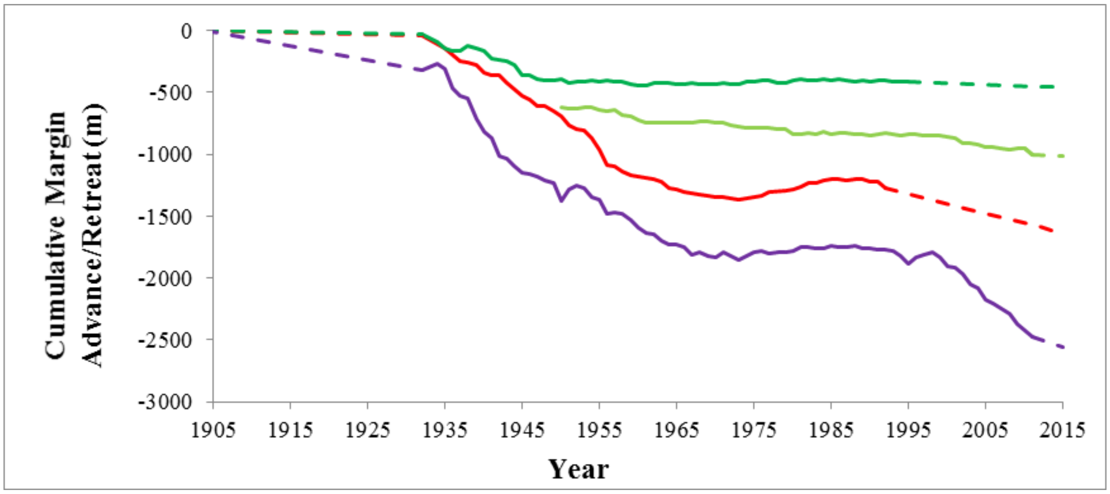

Figure 2.2: Cumulative retreat of the glacier margin for Morsárjökull (Red), Skaftafellsjökull (Purple) and Svínafellsjökull (Green) between 1905 and 2015. Svínafellsjökull has experienced asymmetrical retreat of the glacier margin starting in the 1940's (shown by the light green line representing the northern side of the glacier margin which has retreated 500m more than the southern margin of the glacier). Margin positions are based on glacier margin measurements from 1932 – 2012 (WGMS, 2012), aerial imagery and the Danish Geological Survey (Danish General Staff, 1904). Estimated margin retreat prior to 1935 and after 1995 at Morsárjökull and Svínafellsjökull are represented by dashed lines.

the surrounding ice centers of Öræfajökull, Grímsfjall, Bárðarbunga, Kverkfjöll, Esjufjöll and Breiðabunga (Björnsson and Pálsson, 2008). The Little Ice Age (LIA) was the second period of advance, and occurred between the Middle Ages and the end of the 19th century (Hannesdóttir et al., 2015). Glaciers in Iceland have been retreating since the end of the Little Ice Age at approximately 1890 (Chenet et al., 2010; Hannesdóttir et al., 2015) and have experienced variable rates during this period with more rapid retreat occurring between 1930-1960 and since 1995 (Björnsson and Pálsson, 2008). Between 1960-1995 there was stagnation or slight advance of the ice margins on the southeast side of the Vatnajökull ice cap in response to a period of cooler summers (Hannesdóttir et al., 2015).

Table 2.1: Glacier characteristics of Svínafellsjökull, Skaftafellsjökull and Morsárjökull. Measurements are based on data from 2010 (adapted from Hannesdóttir et al., 2015).

	Morsárjökull	Skaftafellsjökull	Svínafellsjökull
Glacial retreat since Little Ice Age Maximum (km)	1.8	2.7	0.8
Average Slope (°)	6.3	3.8	9.0
Area (km^2)	28.9	84.1	33.2
Volume (km^3)	6.0	20.3	3.6
Length (km)	10.8	19.3	12.0
Elevation of terminus (m asl)	170	95	100
Volume lost since 1890 (%)	20	20	30
Hypsometry Type	B	B	E
Supercooling at terminus	No	Yes	Yes
Overdeepened basin at margin	No	Yes	Yes
Equilibrium line altitude (ELA)	1065 ± 65	1080 ± 80	1060 ± 60

Morsárjökull is a valley glacier located between the mountains Skaftafellsheiði on the southern margin and Miðfell on the northern margin of the glacier. It is sourced by two separate ice streams connected to the Vatnajökull Ice Cap, which has resulted in the formation of a large medial moraine (Fig. 2.1). Morsárjökull has retreated 1.8km since the LIA maximum with an advance between 1970 and 1990 (Fig. 2.2 and 2.3; Hannesdóttir et al., 2015). Morsárjökull has had no recorded surges or jökulhlaups since the LIA maximum (Björnsson and Pálsson, 2008; Ingólfsson et al., 2015). Bedrock in the surrounding mountains is highly variable and consists predominantly of rhyolite, hyaloclastite and basalt (Huddart, 1994). There was a large rockfall onto the glacier surface from Skaftafellsheiði in 2007, which deposited approximately 4 x 10^6 m^3 of debris (Decaulne et al., 2010). This is the only recorded large rockfall to occur at this glacier and may have caused significant changes to the glacier surface and sediment input (Decaulne et al., 2010).

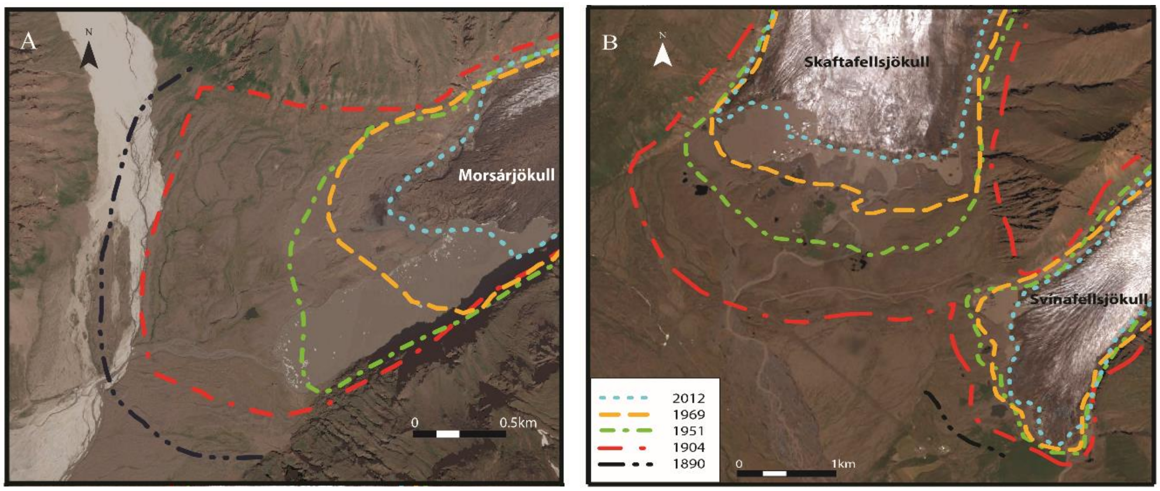

Figure 2.3: Historical glacier margin position overlain on Google Image at Morsárjökull (A), Skaftafellsjökull and Svínafellsjökull (B). These maps show the general pattern of retreat since the Little Ice Age maximum and the positions of the margins which can be related to the timing of landform deposition within each forefield. The 1890 margin position at Svínafellsjökull is not fully known for that time period with all but the remaining moraines having been eroded. Margin positions are obtained from lichenometric dating (Thompson, 1988), the Danish Geological Survey (1904), Army Map Services Map (1951) and LiDAR data from the Icelandic Meteorological Office and Institute of Earth Sciences (2013).

Skaftafellsjökull is sourced by Öræfajökull and the Vatnajökull Ice Cap and terminates on a lowland plain (Cook et al., 2010). Since the glacial maximum during the LIA, Skaftafellsjökull has retreated 2.7 km and lost 20% of its volume but experienced a period of advance between 1970 and 1990 (Fig. 2.3; Hannesdóttir et al., 2015). The terminal moraine at Skaftafellsjökull was deposited in 1904 with older moraines from the LIA being reworked by jökulhlaups from Skeiðarárjökull, an outlet glacier to the northwest (Hannesdóttir et al., 2015; Thompson, 1988). There have been no recorded surges or jökulhlaups from Skaftafellsjökull since the LIA maximum (Björnsson and Pálsson, 2008).

Svínafellsjökull is sourced from the Öræfajökull Ice Cap, with an icefall approximately 6 km from the margin (Cook et al., 2011b) and terminates on a lowland plain (Cook et al., 2010; Larson et al., 2010; Thompson, 1988). Svínafellsjökull has undergone less extensive retreat compared to nearby glaciers, having a cumulative retreat of approximately 800m since the LIA maximum (Fig. 2.3; Hannesdóttir et al., 2015). The rate of retreat of the margin at Svínafellsjökull varies significantly, with the southern edge experiencing 500 m retreat compared with the 1000 m of retreat at the northern edge since the LIA (Fig. 2.2; Thompson, 1988). The terminal moraine is a composite feature that predates the 1362 eruption at Öræfajökull based on tephrachronologic evidence and has been dated using lichenometry to approximately 2500 years before present (Björnsson and Pálsson, 2008; Chenet et al., 2010; Hannesdóttir et al., 2015).

Many Icelandic glaciers, including Skaftafellsjökull and Svínafellsjökull, terminate in overdeepened basins (Cook et al., 2011a; Marren and Toomath, 2014) which were created during the advances of the Little Ice Age (Björnsson and Pálsson, 2008). These basins generally range in depth from 50-100m below the proglacial field and commonly contain proglacial lakes, as in the case of Skaftafellsjökull and Svínafellsjökull (Fig. 2.1; Larson et al., 2010). The margins of both Skaftafellsjökull and Svínafellsjökull undergo basal supercooling, which is commonly associated with overdeepened basins at the terminus (Tweed et al., 2005). Margins undergoing supercooling often contain debris-rich and stratified basal ice (Cook et al., 2011a, 2010; Larson et al., 2010; Tweed et al., 2005), which can result in higher concentration of silt-sized sediments with preservation of the layering in the proglacial deposits (Cook et al., 2011b).

2.3 Methods

Initial mapping of the landforms in the proglacial areas of Svínafellsjökull, Skaftafellsjökull and Morsárjökull was completed through the use of a digital elevation model (DEM) and aerial imagery. The DEM was derived from LiDAR data surveyed in August 2011 and 2012 (Icelandic Meteorological Office, 2013). The elevation model was interpolated from the processed LiDAR data points in ESRI ArcGIS 10.3.1. The most recent Google Earth aerial image (Google, 2016) was draped on the elevation model and used to interpret landform type, morphology and spatial distribution within the proglacial regions. Historical maps (Army Map Services, 1951; Danish General Staff, 1904), aerial imagery and landform dating using lichenometry from previous research (Thompson, 1988) was used to determine landform ages.

Ground-truthing and sediment data collection was completed during a field season in summer 2015. The locations of landforms within the proglacial area were mapped in the field directly into a GIS, including those areas close to the glacial margin that have been exposed since the time of LiDAR data collection. Sketch maps, detailed notes and photographs were also used to record landforms within the proglacial field. Sediment characteristics such as grain size and sedimentary structures were recorded from surface pits and outcrops. Sedimentological logs were completed in each of the three proglacial areas along exposed outcrops from river cuts and river terrace levels. The three glaciers considered in this investigation are all within the boundaries of the Vatnajökull National Park, limiting the amount of disturbance of glacial features permitted in this region.

Landsystem analysis is a hierarchical methodology composed of three divisions: landsystem elements are the smallest division composed of a single landform type; landsystem tracts are composed of one or more landsystem elements and relate to larger scale processes and changes within the glacial system; and the landsystem, which is composed of landsystem tracts, and is defined on the basis of the overarching dynamics of the system (e.g. debris charged landsystem, surging landsystem) (Evans 2003).

A system of classification codes was used in this study to refer to landsystem elements (landforms) and simplify comparisons between areas. This is similar to the classification system applied to lithofacies in sedimentological studies (Miall, 1977; Eyles et al., 1983) that facilitates the organization and communication of sedimentological data from various environmental settings. The proposed landform codes (Fig. 2.4) are divided into the three general landsystem element divisions found within each of the three proglacial fields (moraines, glaciofluvial and glaciolacustrine) and further divided based on more specific characteristics (e.g. planform geometry, process). The use of these codes enables quick reference to the landforms, and in conjunction with consistent colours and symbology allows for easy communication of information. The code system can be applied to the analysis of the other proglacial areas in the future to create consistency of description.

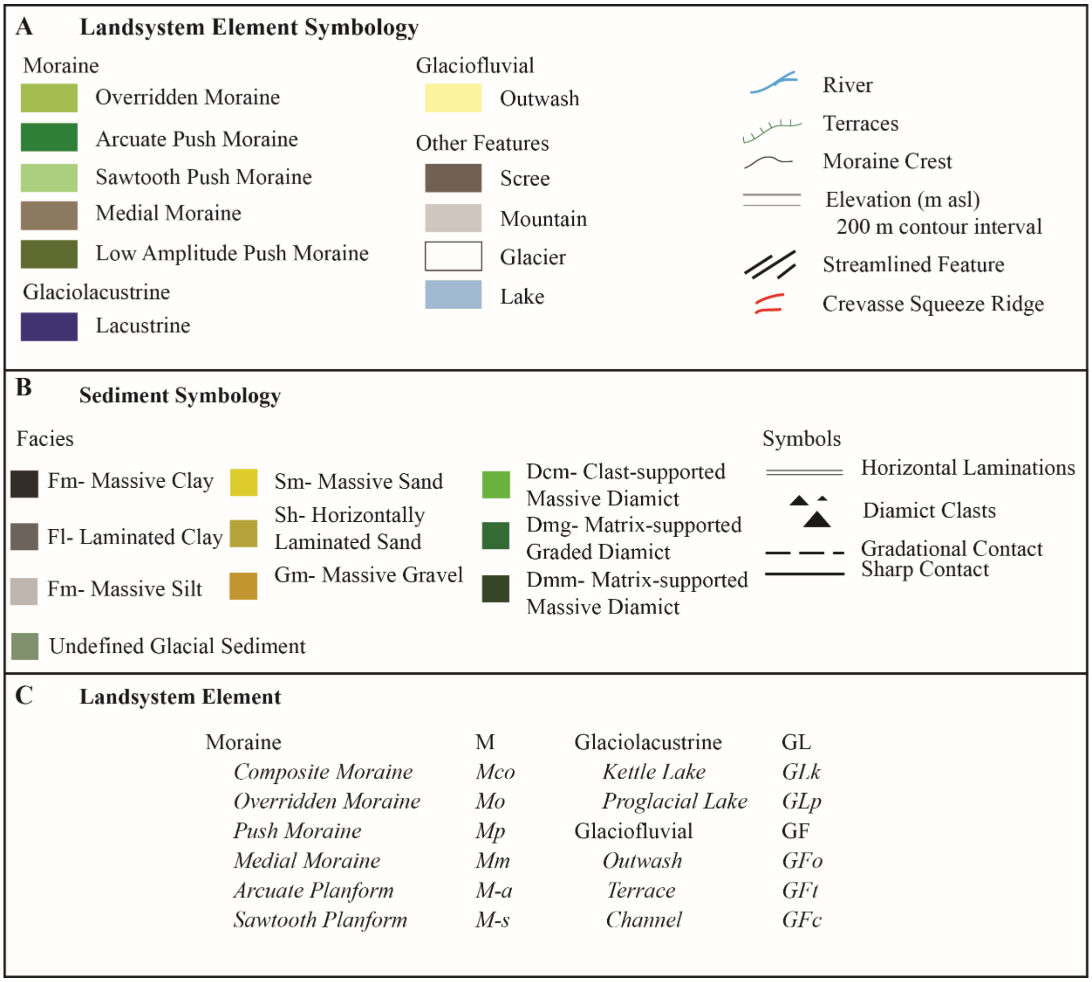

Figure 2.4: Symbology used in the figures of the forefields of Morsárjökull, Skaftafellsjökull and Svínafellsjökull. A) Symbols used for the landsystem tracts and landforms within the study area. B) Symbology for facies and sedimentary characteristics. C) Classification codes for the landsystem elements within the proglacial forefields. These are applied on all figures within this study.

The combination of field and remotely sensed data were utilized to classify the proglacial forefield into landsystem tracts. While the initial mapping and height measurements were completed using aerial imagery, field work has proved to be an integral part of the study. Field work provided contextualization of the aerial data, allowing for more informed and refined delineation of landsystem tracts. Field work also provides information on sedimentology which is pertinent to understanding the processes of sediment transport and deposition occurring at each of the glacier fronts. Field work allowed for examination of the areas proximal to the glacier that have been exposed since the LiDAR data was surveyed. Landsystem tracts were classified based on groupings of landsystem elements, the geomorphological and sedimentological characteristics of the elements such as planform and cross-sectional geometry; clast size and shape; landform height; and spatial distribution of the elements.

2.4 Landsystems Tracts

Each glacier shows differing characteristics in the size and the scale of landforms in the proglacial field which are used to determine the type of landsystem tracts within the forefields. Variability in the landsystem tracts found within the three fields relates to the dynamics of the glacier and characteristics of the topography. For this study the landsystems of Morsárjökull and Skaftafellsjökull will be discussed together as these two forefields display similarities in the scale and spatial distribution of landforms. All dates of landform deposition are based on aerial imagery, a map published by the Danish General Staff (1904), an American Army Survey Map (1951) and lichenometric dating (Thompson, 1988).

2.4.1 Morsárjökull and Skaftafellsjökull

The distribution of landforms on the proglacial forefields of Morsárjökull and Skaftafellsjökull are similar and have been divided into three divisions of landsystem elements can be identified: Moraines (M); Glaciofluvial (GF); and Glaciolacustrine (GL) (Fig. 2.4, 2.5, and 2.6).

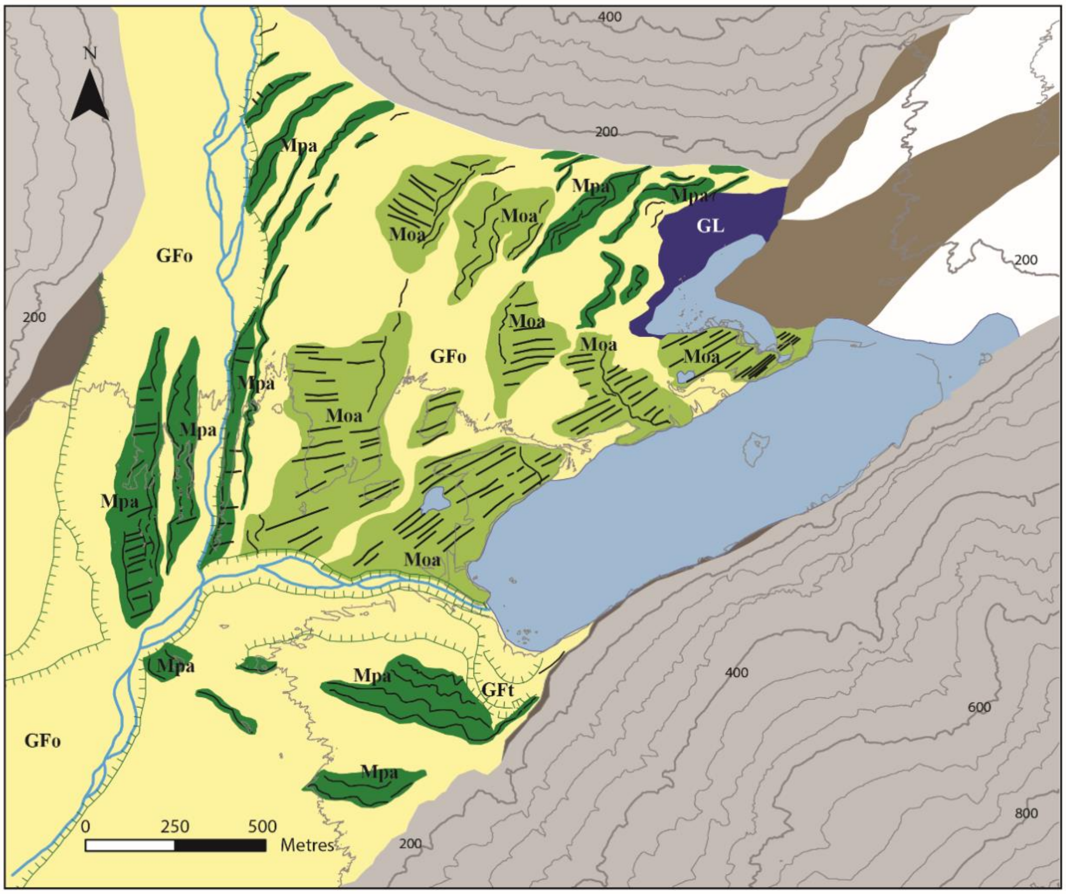

Figure 2.5: Map of the landsystem tracts at Morsárjökull showing the main landsystem tracts of the forefield including distal arcuate moraines (Mpa) and overridden moraines (Moa). Within this forefield glaciofluvial deposits (GFo) can be found throughout. See Figure 2.4 for symbology and classification codes.

2.4.1.1 Moraines

The morphology of a moraine can be used to determine the dynamics of the glacier at the time of deposition. The moraines have been classified based on their morphology into arcuate push moraines (Mpa), overridden moraines (Moa) and sawtooth push moraines (Mps).

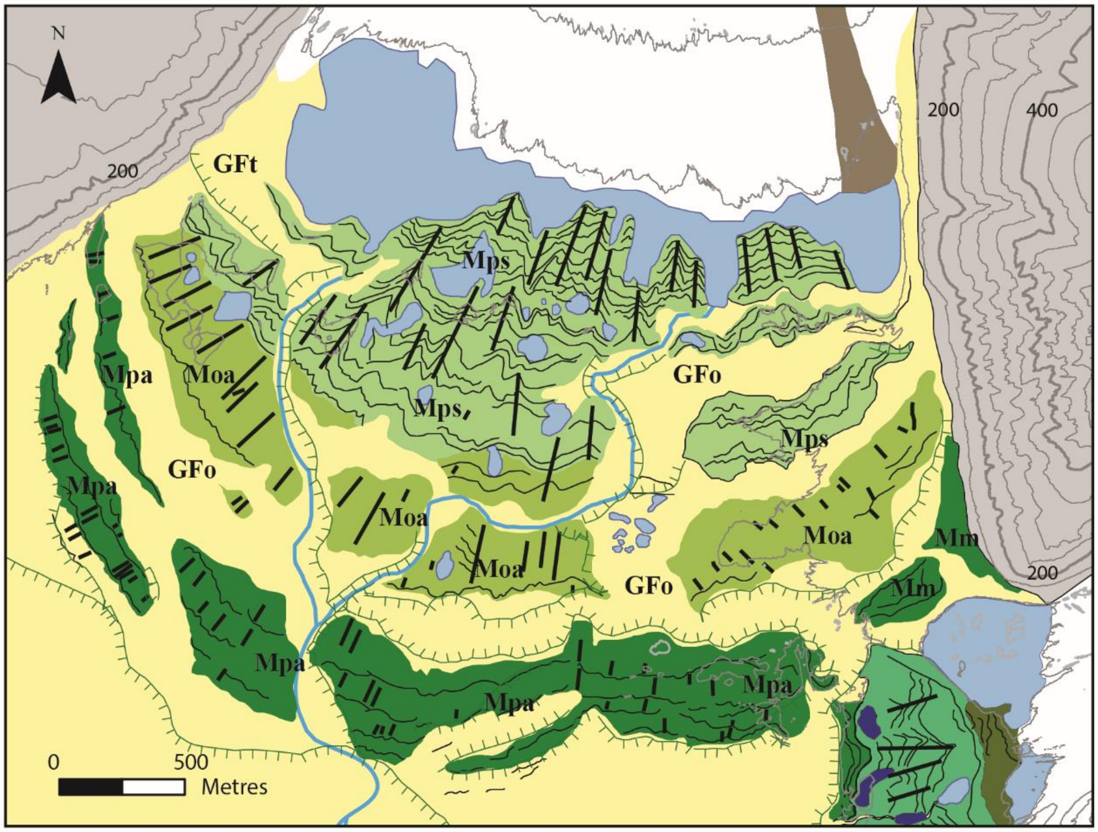

Figure 2.6: Map of the landsystem tracts identified within the forefield of Skaftafellsjökull. The arcuate moraines (Mpa), overridden moraines (Moa) and sawtooth push moraines (Mps) are the most prominent features of the forefield. Large proglacial lakes are located along the glacier margin and small lakes are found throughout the forefield. See Figure 2.4 for symbology and classification codes.

Arcuate Moraines (Mpa)

Arcuate moraines were deposited between 1904 and 1939 at Skaftafellsjökull and from approximately 1890 to 1910 and since 2002 at Morsárjökull. The number of moraines that have been preserved is less than the numbers of years elapsed at each glacier in the noted intervals; these moraines may represent annually generated push moraines (Bennett, 2001) but some may have been overridden and not preserved by periodic advance at the ice front. At each of the glaciers, arcuate moraines are located along the distal portion of the proglacial field and extend across the entire width of the field, representing the position of the glacier margin (Fig. 2.5 and 2.6).

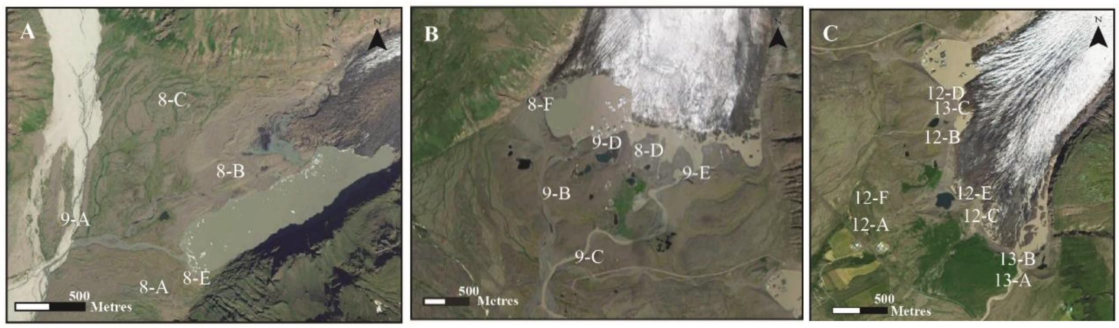

Figure 2.7: Google Earth images of each of the glacier forefields (A: Morsárjökull, B: Skaftafellsjökull, C: Svínafellsjökull) showing the approximate location of photographs shown in Figs. 2.8 and 2.11 and logs shown in Figs. 2.9 and 2.13.

The moraines have an average height of 3.4 m and 3.6 m at Morsárjökull and Skaftafellsjökull respectively (Table 2.2). The planform geometry is primarily arcuate with an asymmetrical cross-sectional profile sloping more steeply up-glacier, Fig. 2.7, 2.8A and 2.9A). Parallel-sided flutes present in this landsystem tract terminate at the moraine ridge on the up-ice slope of the moraines at both Morsárjökull and Svínafellsjökull. The flutes average 0.5 m in height, 60 m and 72m in length at Skaftafellsjökull and Morsárjökull respectively.

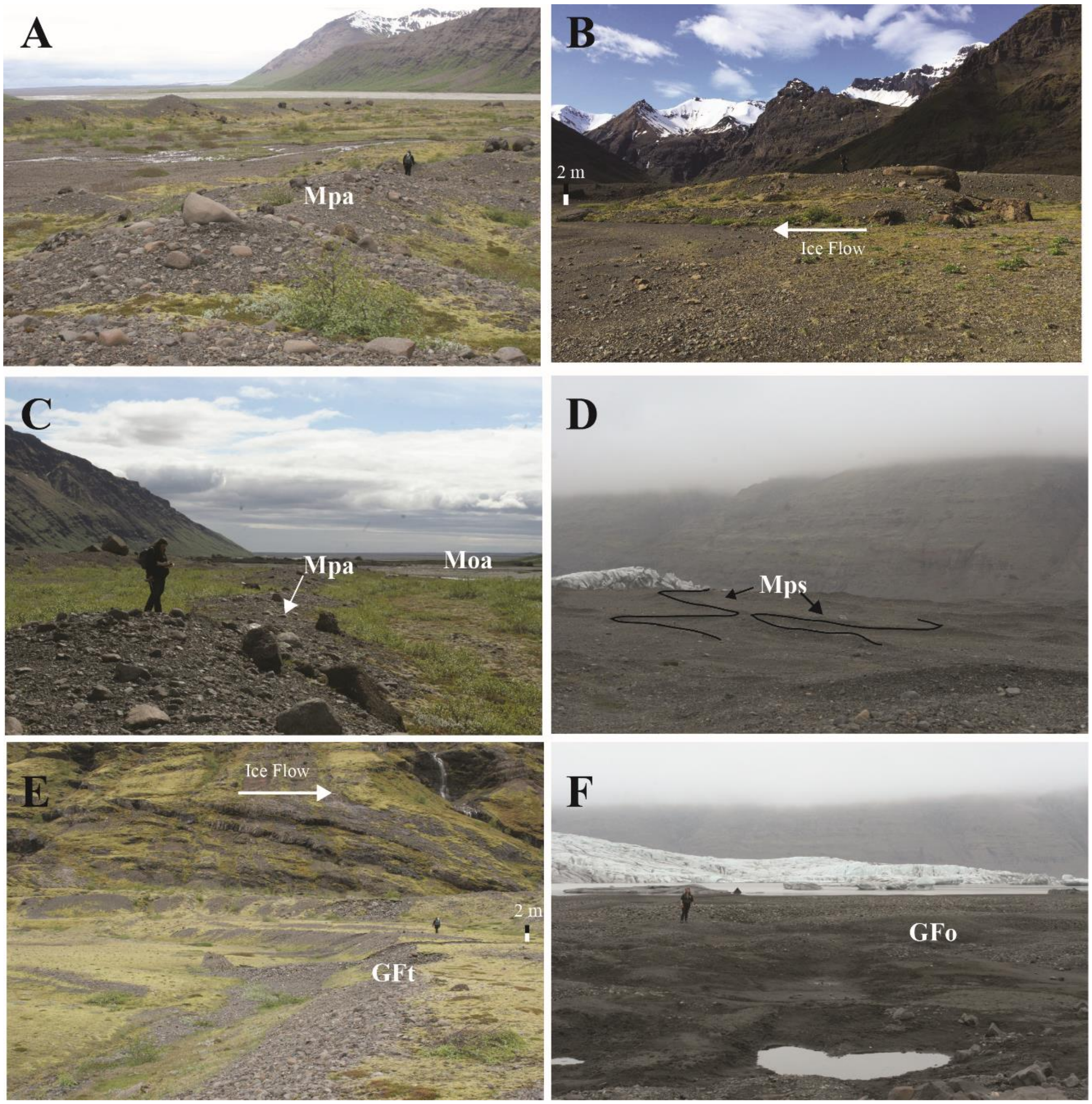

Figure 2.8: Photographs of the features of the landsystem tracts at Morsárjökull and Skaftafellsjökull. A) Arcuate moraine at Morsárjökull on the eastern edge of the proglacial field. Large hyaloclastite and basalt clasts visible on surface of the moraine. B) Streamlined feature at Morsárjökull contained within the overridden moraine landsystem tract. Ice flow direction indicated by black arrow. C) Push moraine overprinted on an overridden moraine on northeastern edge of proglacial field at Morsárjökull. D) Sawtooth moraines near glacier margin at Skaftafellsjökull. E) Glaciofluvial terraces at Morsárjökull, F) Pitted outwash with channels at Skaftafellsjökull. See Fig. 2.7 for location of photographs.

Table 2.2: The heights of the moraines within the three glacial forefields based on measurements from LiDAR derived DEM.

	Distal Arcuate Moraines		Overridden Moraines		Push moraine on overridden moraine		Sawtooth Push Moraines	
	Avg. (m)	Range (m)	Avg. (m)	Range (m)	Avg. (m)	Range (m)	Avg. (m)	Range (m)
Morsárjökull	3.4	0.3 - 12.4	7.0	2.9 - 14.2	1.6	0.6 - 3.5	1.9	0.25- 8.4
Svínafellsjökull	3.0	0.7 - 7.2	----	----	---	---	---	---
Skaftafellsjökull	3.6	1.5 - 6.5	5.8	3.2 - 7.2	1.1	0.8 - 1.3	---	---

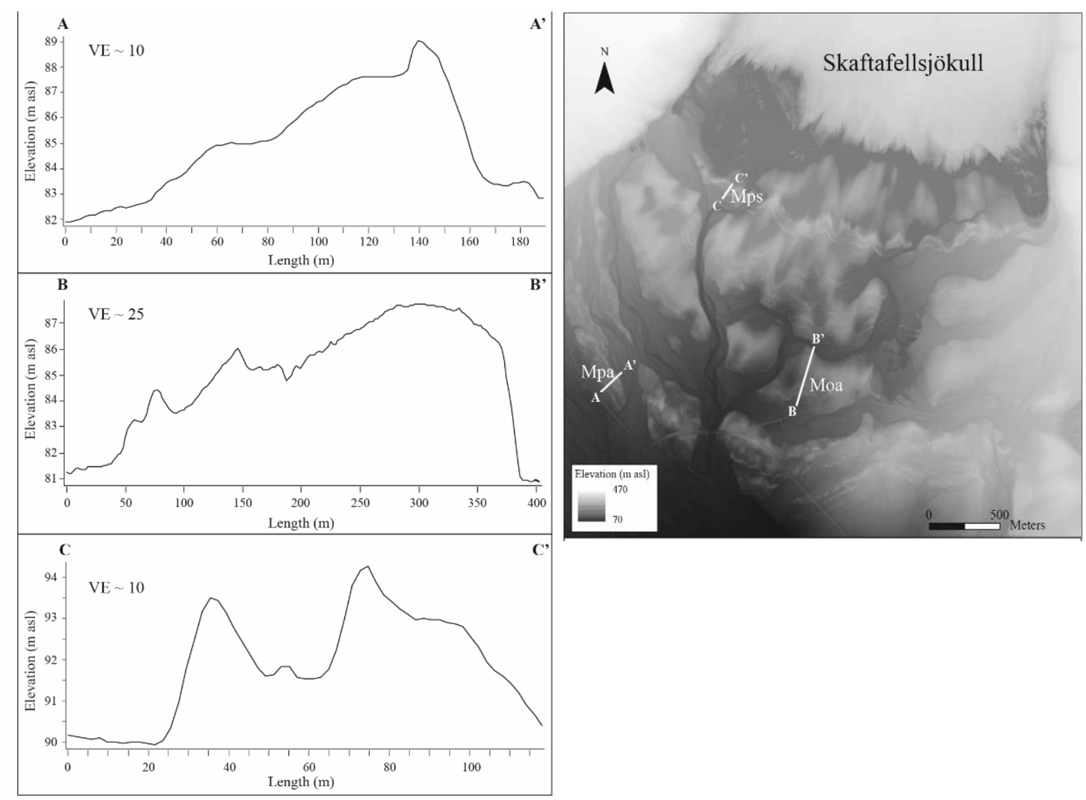

Figure 2.9: Cross-sectional profile of three landsystem elements within the Skaftafellsjökull proglacial field. A) Profile of distal arcuate moraines (Mpa) showing an asymmetrical cross-section with a steeper slope up-glacier. B) Overridden moraine (Moa) with an asymmetrical cross-sectional profile. C) Profile of two sawtooth push moraines (Mps) located proximal to the proglacial lake with shallower up-glacier profiles.

The arcuate moraines are composed generally of diamicts containing clay-fine sand matrix with basalt and hyaloclastite clasts. Clasts are poorly sorted with variation in size from <1 cm to >2 m and roundness from angular to well rounded. A river excavation through a moraine at Morsárjökull showed graded diamict at the base, exhibiting multiple sequences of diamict with increasing clast size. The diamict passes into a massive gravel layer containing coarse sand and gravel up to 2 cm and is topped by a thin layer of massive matrix-supported diamict (Fig. 2.10A).

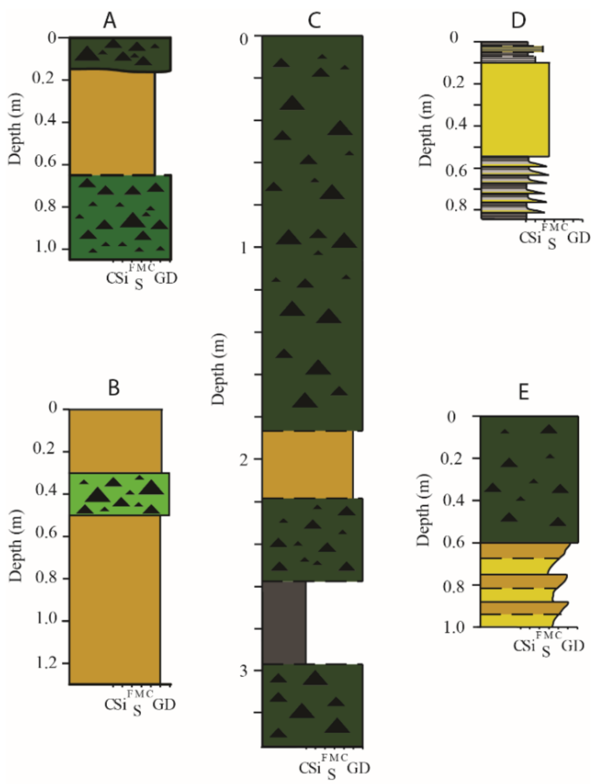

Figure 2.10: Logs of the excavations within the landsystem tracts of Morsárjökull and Skaftafellsjökull. A) Log through an arcuate moraine at Morsárjökull. B) Log of overridden moraines (Moa) located proximally within the Skaftafellsjökull forefield. C) Log of overridden moraines (Moa) located distally within the landsystem tract. D) Log through sawtooth moraines (Mps) at Skaftafellsjökull located proximal to lakeshore. E) Log through sawtooth moraines (Mps) at Skaftafellsjökull. See Figure 2.4 for symbology and classification codes, *Fig. 2.7 for photograph locations.*

Overridden Moraines (Moa)

Overridden moraines are located within the centre of the proglacial forefields of Morsárjökull and Skaftafellsjökull. Overridden moraines have a flattened top with streamlining evident along the surface including flutes with boulders on the up-ice side, (Fig. 2.8B). Streamlining is most prominent in the centre of the proglacial fields with overridden moraines along the margins exhibiting less distinct streamlining. The moraines have an asymmetrical cross-sectional profile showing a steeper up-glacier slope (Fig. 2.9B). On the shallow down-glacier slope, channels between streamlined features and active or abandoned lakes are common.

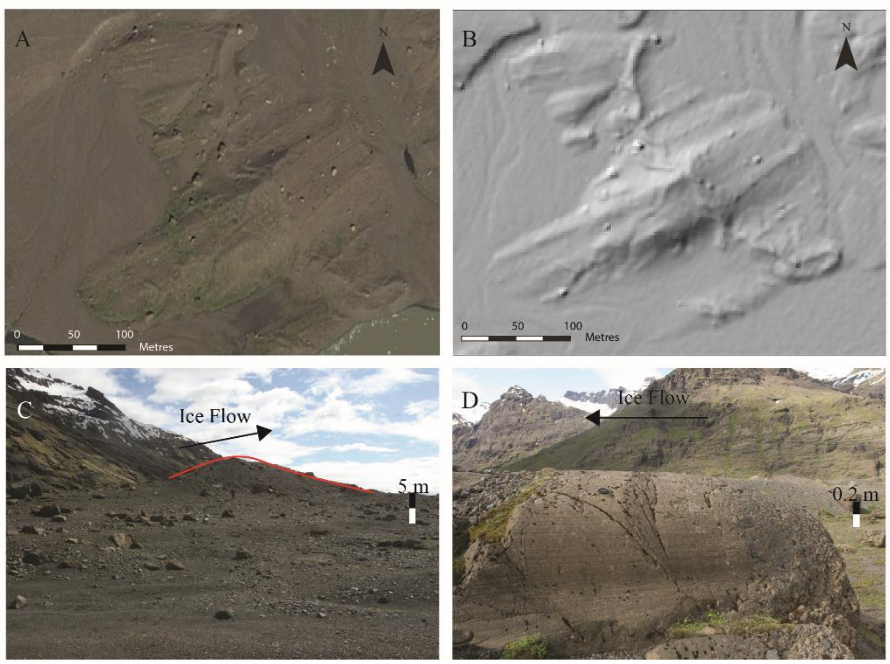

Figure 2.11: Photographs of the large streamlined ovoid feature found within the proglacial forefield of Morsárjökull. A) Aerial photo. B) Hillshade of ovoid streamlined feature shown in A. C) Side view of ovoid streamlined feature showing profile. D) Striated, bullet shaped boulder located on side of streamlined feature.

Arcuate shaped push moraines overlie the overridden moraines averaging 1 m and 1.5 m in height at Skaftafellsjökull and Morsárjökull respectively (Table 2.2; Fig. 2.8C). The push moraines were deposited from 1939-1950 at Skaftafellsjökull and between 1910 and 1975 at Morsárjökull. There are few push moraines preserved within the overridden moraine landsystem tract.

At Morsárjökull, included with the overridden moraines is a streamlined feature 14.2 m in height, double the height of the other landforms in this landsystem tract. This feature lies within the centre of the forefield in line with the medial moraine of the glacier (Fig. 2.5). It has an overall streamlined ovoid appearance in planform (Fig. 2.11A, B). Flutes located on the up-ice slope have a fine sand matrix with poorly sorted striated clasts ranging from <1 cm to 30 cm in size. Large clasts up to 30 cm in size rest on top of the flute and the surrounding streamlined feature. Bullet shaped boulders composed of hyaloclastite are commonly embedded within and rest on top of the landform (Fig. 2.11C, D). The down-ice surface of the feature has hummocky topography.

The sediment comprising the overridden moraines landsystem tract (Moa) is diamict composed of a clay-silt matrix with poorly sorted striated clasts (Fig. 2.10B, C). Two excavations within the Skaftafellsjökull forefield show characteristics of the internal composition of the moraines. In areas proximal to the glacier the overridden moraines show primarily massive gravel containing a thin layer of clast supported diamict (Fig. 2.10B). The excavation located ice-distally within the landsystem tract is composed primarily of massive diamict with layers of massive clay and gravel (Fig. 2.10C). There are abundant bullet shaped boulders found within overridden moraines at Skaftafellsjökull and Morsárjökull.

Sawtooth Moraines

Sawtooth moraines are defined based on their planform geometry which exhibits a zig-zag or "sawtooth" pattern with notches pointing up-ice and teeth down-ice (Fig. 2.8D; Burki et al. 2009). These moraines are located close to the glacier at Skaftafellsjökull, having been deposited between approximately 1950 to present based on aerial imagery (Fig. 2.3). Skaftafellsjökull experienced a minor advance between 1970 and 1990, which may have removed moraines deposited prior to this period of advance.

These landforms exhibit asymmetrical cross-sectional profile with a shallower up-ice slope (Fig. 2.9C), similar to sawtooth moraines reported from other glacier margins (Burki et al., 2009). The sawtooth moraines are spatially related to the underlying streamlining of the sediment as well as the shape of the ice margin. The notches of the moraines are located on the topographical highs of the underlying streamlined diamict, and the teeth in the topographic lows. The average height of sawtooth moraines is 1.9 m (Table 2.2).

The surficial sediment on the sawtooth moraines is primarily diamict composed of a clay matrix with sub-angular to sub-rounded clasts. The clasts range from <1 cm to 60 cm in size, averaging 10 cm with striated and bullet shaped boulders are present. Sawtooth moraines contain different sediments based on their location within the landsystem tract. Close to the proglacial lakeshore the sediments are composed of layered silts, sands and clays (Fig. 2.10D). The excavated section located more distally within the landsystem tract, approximately 250 m from the proglacial lakeshore, progressed from multiple coarsening up sets of massive sand to gravel and massive diamict (Fig. 2.10E).

2.4.1.2 Glaciofluvial (GF)

The glaciofluvial landsystem tracts at each of the glaciers consist of rivers, abandoned channels, river terraces and outwash. At Morsárjökull there is a single river draining the proglacial lake ranging from 10 m to 30 m in width with an unknown depth (Fig. 2.6). There are two rivers draining the proglacial lake at Skaftafellsjökull (Fig. 2.6). The western river intermittently drains the lakes during periods of high water level and varies from a few metres to 40m in width; the eastern river ranges from 20m to 62m in width.

Proximal to Morsárlon is an area characterized by multiple glaciofluvial terraces (GFt; Fig. 2.8E). These terraces are composed of interbedded horizons of rounded gravel, coarse sand and cobble sized sediment. Glaciofluvial terraces are present at Skaftafellsjökull between the moraines (Fig. 2.6), representing different years of deposition and incision.

Glaciofluvial outwash (GFo) is located between the moraines at both Morsárjökull and Skaftafellsjökull (Fig.6). The outwash sediment is composed of well sorted sediments fining from gravels and coarse sands proximal to the glacier to medium and fine sand distally and is channelized with active and abandoned braided channels. At Skaftafellsjökull the proximal outwash is pitted with ice melt collapse features and contains more abundant striated and bullet shaped clasts (Fig. 2.8F).

2.4.1.3 Glaciolacustrine

Morsárlon, the proglacial lake at Morsárjökull is located along the eastern margin of the glacier and has been present since the 1960s. Lakes are present along most of the Morsárjökull margin, although these are intermittent and dependent on the amount of meltwater released by the glacier. Lacustrine deposits near the glacier margin are composed of layered clay and silt with diamict containing a clay matrix and abundant clasts ranging from <1 cm up to 30 cm.

A large proglacial lake is present along the entire margin of Skaftafellsjökull, lying within the overdeepened basin. The lake level has been lowering over the past decade, based on aerial photographs, observations of sediment deposits, and lakeshore location measurements performed during this study. Within the forefield there are multiple lakes ranging in size from 18 m to 291 m in diameter, averaging 90m. These lakes are remnants of either kettle lakes or previous proglacial lakes that have been isolated during glacier retreat and kettle lakes. Lacustrine sediments found in a drained lake within the moraines exhibit well sorted silt and clay interbed with few clasts.

2.4.2 Svínafellsjökull

Svínafellsjökull is the most southern of the three glaciers under investigation, residing in a valley adjacent to Skaftafellsjökull (Fig. 2.1). Svínafellsjökull has experienced asymmetrical retreat of the glacier margin, which has created considerable variability in landsystems across the forefield. The forefield of Svínafellsjökull is defined by 3 landsystem tracts: Moraines (M), Glaciofluvial (GF) and Glaciolacustrine (GL) (Fig.12).

2.4.2.1 Moraines

The moraines at Svínafellsjökull have been subdivided on the basis of their morphological characteristics. The categories include arcuate moraines (Mpa) and composite moraines (Mco) (Fig. 2.12).

Arcuate Moraines

Within the confines of the LIA maximum (Fig. 2.3), the most distal deposits are arcuate moraines with few streamlined features deposited between approximately 1890 and 1935. The average height of the arcuate moraines is 3m, ranging from 0.65m to 7.2m (Table 2.2). These landforms were deposited during the period when Svínafellsjökull and Skaftafellsjökull were combined as a single large piedmont lobe. The arcuate moraines are closely spaced, with several overprinting to form a palimpsest landscape. Along the southern margin only a single moraine ridge is visible (Fig. 2.12).

Composite Moraine

Beyond the LIA maximum (Fig. 2.3) is a composite moraine, locally known as Storalda, which has been dated to 2500 ka based on lichenometric dating making it over 2000 years older than the rest of the forefield (Chenet et al., 2010; Thompson, 1988). The 22m high composite moraine is completely covered with vegetation (Fig. 2.13A). It exhibits an asymmetrical cross-sectional profile with a shallow ice-up slope and multiple moraine ridges on the up-ice side of the feature. This composite moraine represents the distal boundary of the forefield and beyond it to the southeast is a large area of outwash, Skeiðarársandur, created by jökulhlaups at Skeiðarárjökull to the northwest.

Dominating the proglacial field at Svínafellsjökull is a large composite moraine. This feature reaches up to 46m in height above the surrounding outwash plain, with the

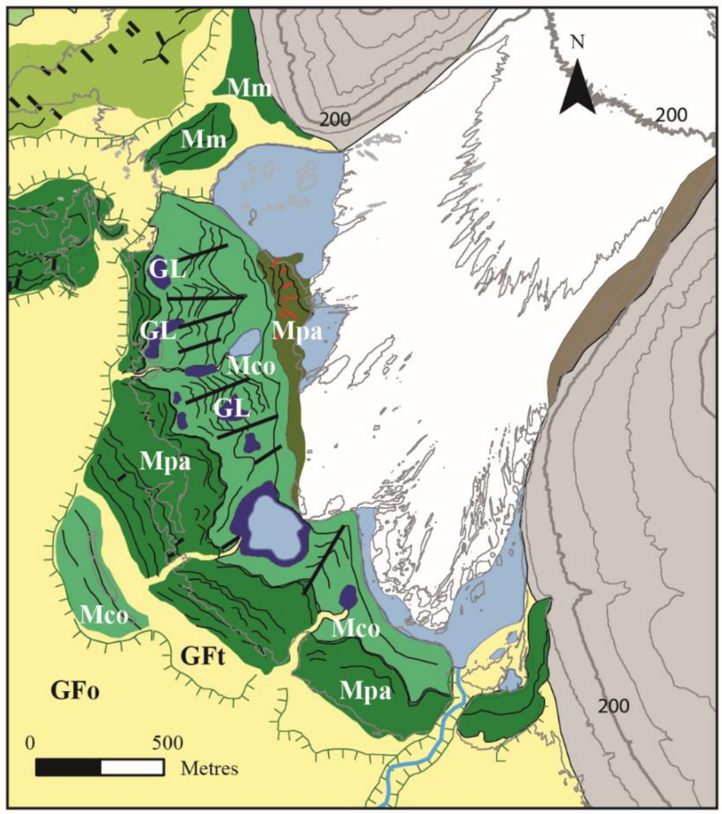

Figure 2.12: Map of the landsystem tracts at Svínafellsjökull which is dominated by the composite moraine landsystem tract. Also contained within the forefield are arcuate moraines, and proximal push moraines and crevasse squeeze ridges. Note asymmetry of landsystems tracts and limited glaciofluvial materials on the glacier forefield. See Figure 2.4 for symbology and classification codes.

highest point in the centre and sloping downward towards the eastern and western margins of the proglacial field. The moraine has an asymmetrical cross-sectional profile having a steeper slope up-glacier that grades into the overdeepened basin. On the down-ice slope there are sawtooth push moraines, hummocky topography and lakes (Fig. 2.12).

A sequence of push moraines (Mps and Mpa) overlies the large streamlined structure deposited from 1935 until approximately 1970 based lichenometric dating completed by Thompson (1988). These moraines are primarily sawtooth in planform geometry with few arcuate shaped moraines on the distal edge of the composite moraine. The sawtooth moraines (Mps) average 2.8 m in height, varying from 0.5 m to 7.3 m, (Fig. 2.13B) and are primarily composed of diamict with poorly sorted clasts with a clay-silt

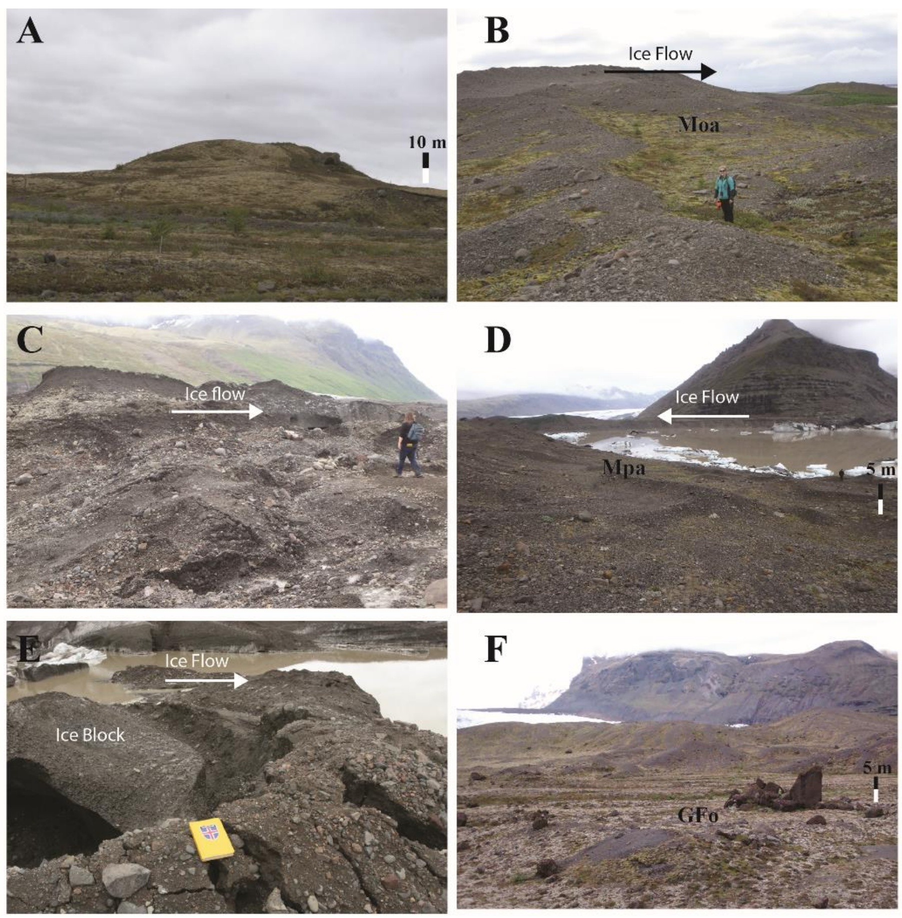

Figure 2.13: Photographs of features of the landsystem tracts at Svínafellsjökull. A) Storalda, the terminal composite moraine (Mco) at Svínafellsjökull. Glacier is located behind the photographer. B) Sawtooth moraine (Mps) overprinted on the composite moraine (Mco). C) Water filled depressions and crevasses located on the moraine near the glacier margin. D) Crevasse squeeze ridges (CSR) and push moraines (Mpa) located within the overdeepened basin at Svínafellsjökull. E) Push moraine (Mpa) being formed at the margin of Svínafellsjökull. F) Large hyaloclastite boulder group located on the outwash (GFo) surface between Storalda and the LIA maximum moraines. See Figure 2.4 for symbology and classification codes.

matrix. The clasts are subangular to subrounded and composed of basalt and hyaloclastite and do not appear to have a preferred orientation or fabric within the diamict. The form of the push moraines is influenced by the streamlining of the underlying sediment, wherein the notches of the moraines are located on the topographic highs and the teeth are on the topographic low.

The margin of Svínafellsjökull remained in approximately the same location between 1950 and 2000 (Fig. 2.2). A few distinct moraine ridges were deposited during this period. The glacier has pushed sediment into the composite moraine, further building the large feature. The areas of the composite moraine proximal to the glacier margin have crevasses within the sediment, water filled depression and channels on the top of the moraine (Fig. 2.13C). The sediment is composed of clay matrix with poorly sorted angular to round, striated and non-striated clasts ranging from <1 cm to 50 cm in size. Areas on the top of the composite moraine of sorted clay sediments and gravels indicate deposition in small ponds and channels.

The internal structure of the moraine complex varies across the field. Two sedimentological logs were taken within the forefield along the southern river. Close to the proglacial lakeshore the composite moraine is composed of units of massive diamicts, massive gravels and massive sands (Fig. 2.14A). Near the distal edge of the composite moraine the sediments consist of massive matrix supported diamict containing poorly sorted clasts ranging from <1 cm to 10 cm with a clay matrix (Fig. 2.14B).

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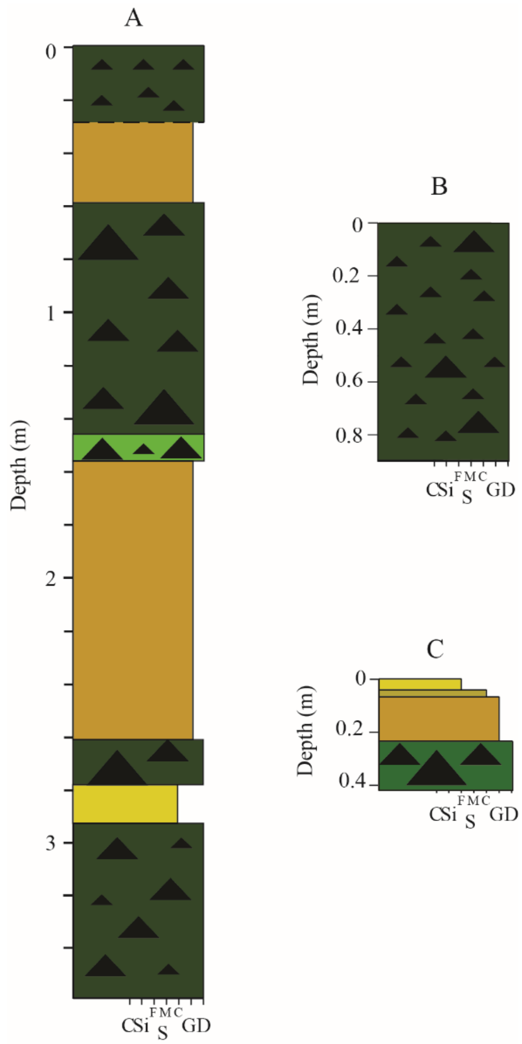

Figure 2.14: Sedimentological logs through different landsystem tracts at Svínafellsjökull. A) Log through the composite moraine (Mco) showing layers of matrix supported diamicts and gravels. B) Log through the composite moraine (Mco) located proximal to the glacial lake showing a massive matrix supported diamict. C) Log through a push moraine (Mpa) located within the overdeepened basin that contains a succession from diamict to a fining upwards sequence from gravels to fine sands. See Figure 2.4 for symbology and classification codes.

Low amplitude push moraines (Mpa)

Located within the overdeepened basin, adjacent to the proglacial lake is an area of small push moraines, averaging 0.8 m in height, ranging from 0.3 m to 1.5 m (Fig.

2.13D). The moraines are composed of silt matrix with poorly sorted sub-rounded clasts ranging in size from <1 cm to 30 cm with striations present on the majority of the clasts. The internal structure of this push moraine is composed of layers of diamict near the base with massive gravel and massive sand layers on top (Fig. 2.14C). Push ridges being formed are visible along multiple points of the glacier margin (Fig. 2.13E).

Between the push moraines are crevasse squeeze ridges which are arranged obliquely to glacier movement. The squeeze ridges are composed of a clay matrix with sub angular-rounded striated clasts. The crevasse squeeze ridges are less than 1m in height, averaging 0.6 m. There is no evidence of streamlined features within this landsystem tract.

2.4.2.2 Glaciofluvial

There are limited areas of outwash and fluvial deposits between the moraine landsystem tracts at Svínafellsjökull (Fig. 2.12). The glaciofluvial deposits, including terraces, rivers, and outwash (Fig.12) are confined primarily to two incisions into the composite moraine on the western margin, 19 to 30 m wide, and eastern margin, 20 to 63m wide (Fig.12). Within the channels the sediments consist of well sorted basaltic and hyaloclastite clasts which fine distally within the field. Between the arcuate moraines and Storalda is an area of vegetated outwash containing large angular to subangular hyaloclastite boulders (>1 m) (Fig. 2.13F).

2.4.2.3 Glaciolacustrine

At the margin of Svínafellsjökull is a proglacial lake residing in the overdeepened basin. Aerial imagery and remnants of previous lakeshores indicate a decrease in lake level over the past decade. Near to the current lakeshore the sediment is dominated by well sorted and well-rounded gravel with minimal clay. Within the composite moraine there are former and current lake bodies which are a mixture of kettle and proglacial lakes which range in length from 28 m to 329 m, averaging 113 m. The majority of these lakes are now drained and infilled by sediments that are well sorted, layered fine sands, silts and clays.

2.5. Interpretations

2.5.1 Comparisons of the glacial forefields

The forefields of Morsárjökull and Skaftafellsjökull display many similarities in the type, scale and distribution of the landsystem tracts. The proglacial fields are both defined by their distal arcuate moraines, central overridden moraines and abundant fluvial deposits. A distinct difference between the two fields is the absence of sawtooth moraines at Morsárjökull which are found proximal to the Skaftafellsjökull margin.

The difference in morphology between arcuate and sawtooth moraines is the result of the shape of the glacier margin at times of deposition (Burki et al., 2009). Sawtooth moraines form at ice margins that exhibit closely spaced longitudinal crevasses and often poorly drained till (Evans et al., 2015a). The crevasses are formed as radial ice flow occurs in regions where the glacier enters a less confined space (Benn and Evans, 2010; Burki et al., 2009), such as moving from a valley to a lowland plain as in the case of Skaftafellsjökull. The sawtooth moraines at Skaftafellsjökull are located within the overdeepened basin created during previous advances (Magnússon et al., 2012). The basin changed the drainage pathways of the system and resulted in underlying till which was susceptible to squeezing and pushing, creating the distinctive sawtooth moraines.

Sawtooth moraines are commonly located proximal to the glacier margin and arcuate moraines more distal within the proglacial forefield (Burki et al., 2009; Evans et al., 2015a). This indicates that the sawtooth moraines may occur more prevalently along retreating, thinning glaciers where the margin is more susceptible to the formation of radial crevasses and impacts of backwasting compared with a thicker, advancing glacier that would deposit the distal arcuate moraines. The combination of a thinning retreating glacier and underlying streamlined sediment at Skaftafellsjökull combined to facilitate the deposition of the sawtooth moraines (Mps).

The forefield at Morsárjökull contains a 14m high streamlined ovoid feature which is not comparable to any of the features of Skaftafellsjökull. This feature is within the overridden moraine landsystem tract and it exhibits the fluted up-ice surface and push moraines that define this tract and indicates a primarily subglacial origin. This feature is almost twice the height of any of the overridden moraines contained within the Morsárjökull forefield and has hummocky down-ice surface which is more steeply sloped when compared with the rest of the landsystem tract. The feature is in the path of the medial moraine and may be a result of excess debris at this location or large boulders lying beneath the feature which act as a core onto which the sediment has been deposited. Further investigation of the sedimentology of this feature may provide the answer as to the process of formation.

Morsárjökull and Skaftafellsjökull both exhibit a distribution of landsystem tracts that is similar to that of a typical active temperate landsystem described from other localities in Iceland (Evans and Orton, 2015; Evans and Twigg, 2002; Evans et al., 2015a). The active temperate landsystem is dominated by three domains: low amplitude moraines formed through pushing, dumping and squeezing of sediment; glaciofluvial deposits; and flutes, overridden moraines and drumlins (Evans and Twigg, 2002).

The forefields of Morsárjökull and Skaftafellsjökull can be divided into three landsystem tracts representing differing dominant landsystem elements: distal fluted arcuate moraines (tract 1); central overridden moraines (tract 2); and proximal low amplitude push moraines (tract 3) with glaciofluvial landsystem tracts found throughout the proglacial field (Fig. 2.15). The three tracts are representative of changing depositional processes resulting in the variable sediment and geomorphological characteristics. Periods of differing glacial retreat patterns reflective of changes in climatic and glacial factors cause the variation between the landsystem tracts.

The distribution of sediments and landforms at Skaftafellsjökull is very similar to that of Fláajökull an active temperate outlet glacier lying on the southeast side of the Vatnajökull Ice Cap (Evans et al., 2015b), including the transition from arcuate moraines in the distal forefield to sawtooth moraines proximal to the glacier front. Active temperate landsystems, exemplified by the landforms found at these glacier margins, are applicable

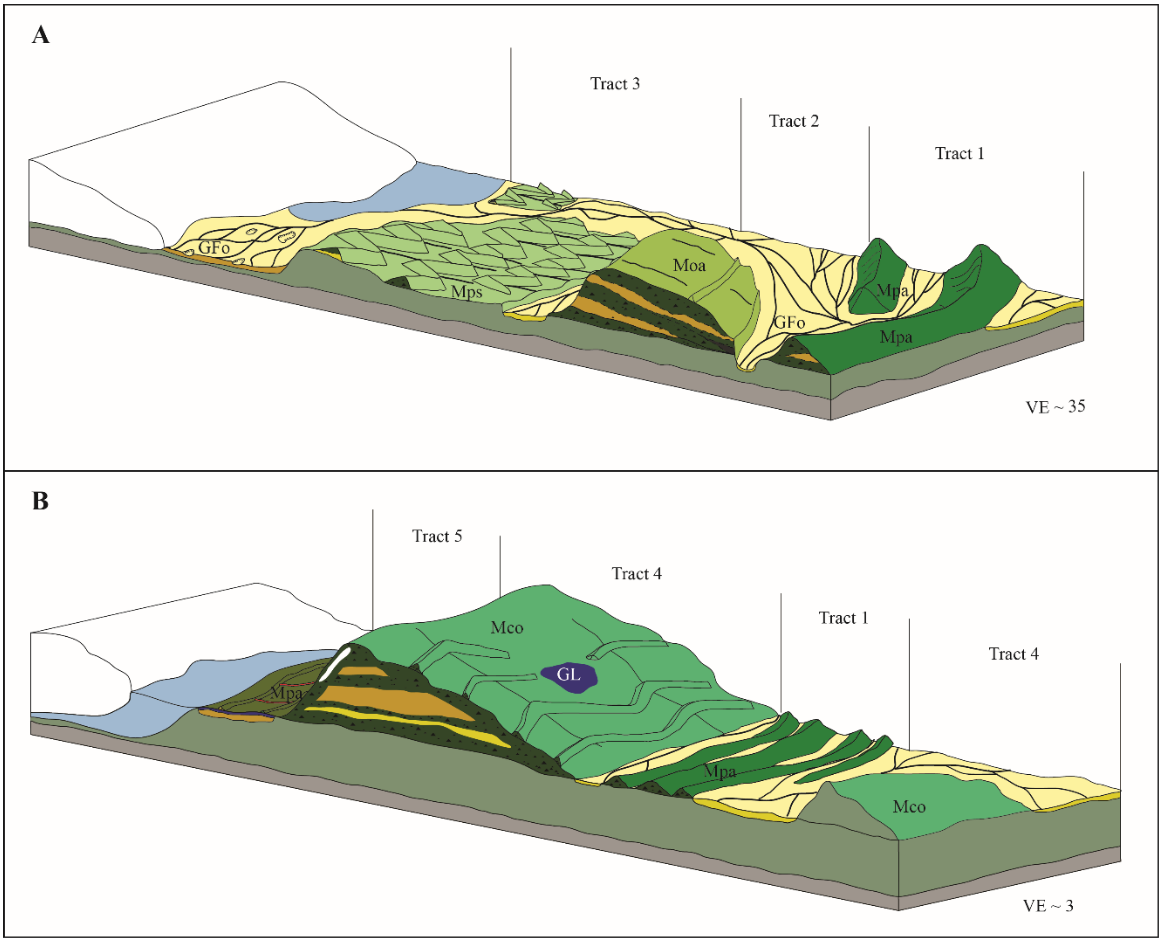

Figure 2.15: Simplified models of the landsystems of Skaftafellsjökull (A) and Svínafellsjökull (B). The tracts reflect different dominant processes occurring since the Little Ice Age Maximum (LIA). The sediments are simplified based on the excavated logs and sample pits throughout the forefield. There were no river cuts or excavations into the underlying sediment and it has been classified as undetermined glacial sediment. A) Simplified model of the forefield of Skaftafellsjökull divided into tracts based on the primary landforms found within each tract. These tracts reflect different processes occurring during the period since the Little Ice Age maximum. Tract 1: Arcuate Moraines (Mpa), Tract 2: Overridden Moraines (Moa) including the overprinted push moraines and Tract 3: Proximal low amplitude moraines with a sawtooth planform (Mps). Glaciofluvial landsystem tract is found within all three of the tracts at this field. B) Model of the landsystem tracts at Svínafellsjökull. Tract 4 consists of the composite moraine tract including the distal moraine Storalda, which was deposited 2500ka and the proximal composite moraine that includes the sawtooth moraines on the down-ice slope. The proximal composite moraine contains areas which indicate buried ice, depicted on this model as an area of glacier within the moraine. Tract 1 is composed of arcuate moraines deposited during the period between the LIA maximum and 1935 when Svínafellsjökull and Skaftafellsjökull were combined as a piedmont lobe. This tract is consistent with tract 1 of the Skaftafellsjökull model. Tract 5 proximal to the margin is composed of low amplitude push moraines and crevasse squeeze ridges. See Figure 2.4 for symbology and classification codes.

as analogues for the margin of Pleistocene ice sheets (Evans and Twigg, 2002), and can be used to improve modelling paleoglacial sediments and environments.

The forefield of Svínafellsjökull differs significantly from that of both Morsárjökull and Skaftafellsjökull. The rate of retreat of Svínafellsjökull is less than that of either of the other glaciers, having retreated approximately 800 m since the LIA maximum. This has resulted in a more compact forefield at Svínafellsjökull with larger height for the majority of the landforms and overprinted moraines and limited expanse of glaciofluvial deposits (Table 2.2; Fig. 2.12).

The dominant processes recorded by sediments and landforms differ between Svínafellsjökull and the other two proglacial forefields. Compared with Svínafellsjökull the sediments at Skaftafellsjökull and Morsárjökull are more prominently striated, rounded and contain more bullet-shaped clasts that indicate subglacial transport of material. Sediments at Svínafellsjökull contain both angular and sub-rounded clasts within the moraines which suggest that both supraglacial and subglacial sediments are present. The forefields of Skaftafellsjökull and Morsárjökull exhibit extensive streamlining and fluting of features, which are less common at Svínafellsjökull. This suggests that subglacial deformation and moulding of sediments is a prominent process at Skaftafellsjökull and Morsárjökull, while sediment at Svínafellsjökull has a greater supraglacial or englacial origin. This difference in landform and sediment types and the processes they record has been previously noted by Thompson (1988). The composite moraine within the Svínafellsjökull forefield shares some of the general characteristics of the overridden moraines that are found at Skaftafellsjökull and Morsárjökull although the overall morphology differs significantly. Overridden moraines are generally defined by a flattened top, heavily fluted surface, wide arcuate planform and are draped by push moraines (Evans and Twigg, 2002). The composite moraine at Svínafellsjökull exhibits streamlining and sawtooth push moraines overprinted on the down ice slope. However, the landform does not display the flattened topography or fluted surface expected of an overridden moraine indicating a different method of formation.

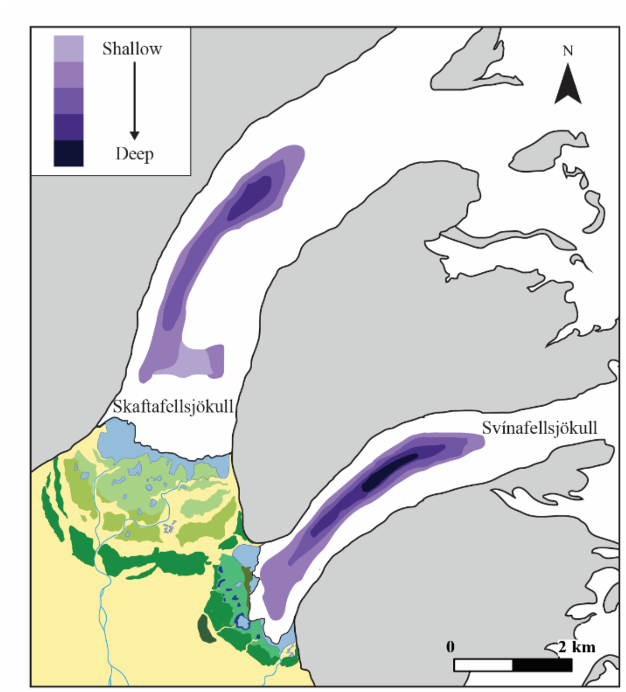

Figure 2.16: Schematic drawing of the overdeepened basins and troughs beneath Skaftafellsjökull and Svínafellsjökull which shows relative shallow and deep sections of the troughs. For further detail see Figure 6 in Magnússon et al. (2012).

Multiple processes are required to form the composite moraine that is a defining feature of the forefield at Svínafellsjökull. One component was likely the bulldozing of sediments excavated from the trough that is present beneath Svínafellsjökull by advancing ice (Fig. 2.16). During the LIA and earlier advances Svínafellsjökull excavated a trough and overdeepened its basin which is up to 320m deep (Magnússon et al., 2012). Some of the excavated sediment was deposited in the forefield during the LIA advance and overridden by the glacier; this is suggested by the streamlined features on the down-ice surface of the moraine and the presence of subrounded and striated clasts. The highest part of the composite moraine, located within the centre of the field, is in line with the trough (Fig. 2.16), further indicating that the excavation of the trough was an important process in the creation of the composite moraine. Since 1950, the glacier margin has remained stationary (Fig. 2.2) experiencing thinning rather than retreat of the margin as a response to increased temperatures and glacier volume loss. The stationary front has resulted in the buildup of debris and overprinting of push ridges on the up-ice slope (Fig. 2.12). Proximal to the glacier front there are indications of buried ice within the composite moraine including the presence of slumping, water filled depressions and channels (Fig. 2.13C). This buried ice core was likely deposited during the period of stagnation and covered by supraglacial debris. Svínafellsjökull may also have greater amounts of englacial and supraglacial debris compared to Skaftafellsjökull and Morsárjökull, aiding in the deposition of the composite moraine and reducing the rate of glacier margin retreat (Bennett and Evans, 2012). The icefall at Svínafellsjökull creates crevasses that can be filled with debris from the surrounding bedrock, which may contribute to the increased debris content of the glacier (Cook et al., 2011b) when compared with Skaftafellsjökull.

The composite moraine at Svínafellsjökull has influenced the distribution of the other landsystem tracts within the proglacial field (Fig. 2.12). The pattern of sawtooth moraines is closely linked to the underlying streamlining of the composite moraine with the teeth, the portion of the moraine pointing down-glacier, located in the topographic lows (Fig. 2.12). The presence of the large structure has limited the areal extent of the fluvial deposits within this forefield and is a significant control on the positioning of the rivers. Within the forefields of Morsárjökull and Skaftafellsjökull there are abundant areas of fluvial deposits including large swaths of outwash between the moraines (Fig. 2.5 and 2.6). The Svínafellsjökull forefield lacks this distribution of fluvial deposits with limited outwash within the confines of the LIA maximum. The area of outwash, located between the arcuate moraines and Storalda, is the largest area of outwash within the forefield (Fig. 2.12). Fluvial deposits have been confined to two incisions through the composite moraines which contain ribbons of outwash, terraces and the river channels. Within the overdeepened basin there are deposits of well sorted rounded gravel and sands, which were probably deposited by fluvial systems that formed parallel to the glacier margin, confined by the basin and the composite moraine.

A distinctive feature of the Svínafellsjökull margin is the asymmetrical retreat pattern, with the northern component having retreated further than the southern margin by hundreds of metres based on margin measurements (Fig. 2.2). This difference in retreat is reflected in the landforms present within the glacier forefield. Along the southern margin there are fewer moraine crests, with the most southern moraine containing a single ridge. The entire margin has experienced minimal retreat since the early 1950s when the glacier entered into the overdeepened basin (Fig. 2.2). There are many potential causes of this asymmetrical pattern of retreat along the margin. The southern area of the glacier is adjacent to the mountain Svínafellsheiði, which may contribute more debris to the ice surface. Debris cover of more than 1 cm to 2 cm on the glacier ice can reduce ablation and cause stagnation of the glacier (Bennett and Evans, 2012). Similar asymmetrical retreat of the glacier margin may be observed at Morsárjökull in the future, caused by the large debris fall in 2007 and the potential for insulation of the glacier. Increased marginal retreat on the northern side of the glacier may have been caused by the presence of a lake. Subglacial lakes along the terminus can cause an increase in the rate of margin retreat through the process of calving and thermal undercutting (Bennett and Evans, 2012). Multiple factors may have contributed to the distinct asymmetrical retreat of Svínafellsjökull which has in turn affected the proglacial field.

The distribution of landsystem tracts at Svínafellsjökull does not conform to any of the established proglacial landsystems within Iceland. The scale of the composite moraine and the evidence for stagnation of the glacier and slow retreat is more typical of the debris charged landsystems present at other Icelandic glaciers such as Kviárjökull (Bennett et al., 2010) and Kötlujökull (Krüger et al., 2010). Debris charged glacial landsystems typically exhibit an area dominated by processes related melting out of buried ice which results in hummocky terrain located within the confines of the distal arcuate moraine, as is occurring at Kötlujökull (Krüger et al., 2010). Svínafellsjökull lacks this area of hummocky terrain, though there is evidence of slumping, crevasses and water filled depressions within the composite moraine which suggest the presence of buried ice and the possibility that this terrain may develop over time. The glacier forefield can be defined as early stage debris-charged active temperate landsystem (Krüger et al., 2010).

Svínafellsjökull's proglacial field can be divided into three landsystem tracts representing areas containing dominant landsystem elements that reflect similar depositional processes. The landsystem tracts include: distal arcuate moraines (tract 1); composite moraine including distally located Storalda and the proximal composite moraine (tract 4) and; proximal push moraines and crevasse fill ridges (tract 5; Fig. 2.15). Limited areas of glaciofluvial landsystem tracts are found throughout the other landsystem tracts within the proglacial field. The landsystem tracts represent distinct periods of ice movement at Svínafellsjökull caused by variations in the influences of climate and the surrounding bedrock on the landform deposition.

2.5.2 Factors contributing to differences in the characteristics of the proglacial fields

Although the glacial forefield of Svínafellsjökull is quite different to those of Skaftafellsjökull and Morsárjökull there are many similarities between the general characteristics of Skaftafellsjökull and Svínafellsjökull; each of the two glaciers has a pronounced overdeepened basin at their margin and beneath the glacier within the valley and they each experience supercooling at the terminus (Table 2.1; Cook et al., 2010). The glaciers are also sourced from a common mountain, Hafrafell, with a common source of sediment and they lie in closely spaced adjacent valleys. Skaftafellsjökull and Svínafellsjökull were formerly combined as a single piedmont lobe until approximately 1935 during which time both of the glaciers deposited arcuate moraines and a medial moraine within the forefield. Despite many similarities in glacial characteristics the proglacial fields of these two glaciers are vastly different, while those of Morsárjökull and Skaftafellsjökull are similar. There are multiple factors that may be causing these differences and similarities between the three fields including hypsometry, bedrock characteristics and the presence of supercooling.

2.5.2.1 Hypsometry

The three glaciers are all sourced from the Öræfajökull and Vatnajökull Ice Caps, which have been connected since the advance of the LIA. The two ice sources can have differing dynamics and may impact the development of landforms, although this is likely a minor controlling factor as the ice caps are currently connected. The hypsometry, which is the distribution of glacier ice based on elevation, is an important factor in how it reacts to changes in climate, and therefore the formation and distribution of landforms within the forefield of each glacier may have been affected by this. Morsárjökull and Skaftafellsjökull have a class B hypsometry which is defined by a unimodal distribution with the majority of the ice volume located above the equilibrium line altitude (ELA; Fig.17; De Angelis, 2014; Hannesdóttir et al., 2015). This hypsometry type has a high sensitivity to changes in ELA and mass balance which cause substantial changes in the terminus position (Quincey et al., 2009) as is seen at Morsárjökull and Skaftafellsjökull with 1.8 km and 2.7 km retreat respectively. The impact of the hypsometry on glacial response to climate changes can be observed in the similar pattern of advance and retreat for both glaciers (Fig. 2.4), including their minor advance between 1970 and 1990.

Svínafellsjökull has a class E hypsometry, which is a bimodal distribution with the ELA located between the two peaks (Fig. 2.17; De Angelis, 2014; Hannesdóttir et al., 2015). This type of glacier has a terminus which tends to be less sensitive to changes in ELA but has a mass balance that is more sensitive to changes in the ELA (De Angelis, 2014). Despite the relatively limited retreat of Svínafellsjökull, it has experienced 30% volume loss since the LIA maximum compared to the 20% volume loss of Morsárjökull and Skaftafellsjökull (Hannesdóttir et al., 2015). The loss of volume can be partially

The hypsometry of a glacier is an important factor in how it responds to climate change which relates to the position of the ELA and the distribution of ice above and below this point. A glacier with a B-type hypsometry, such as Skaftafellsjökull and Morsárjökull tend to have long, narrow low lying termini which causes even small changes in the mass balance to have large impacts on the margin location (De Angelis, 2014). Glaciers with type E hypsometry tend to exhibit less marginal change from climate change (Hannesdóttir et al., 2015); this is related to the higher percentage of glacier ice volume at lower altitudes requiring less retreat of the glacier margin position to maintain equilibrium as the ELA rises (Quincey et al., 2009). Although hypsometry is an important factor that controls the behaviour of modern glacial systems, this characteristic is difficult to determine for paleoglacial conditions.

attributed to the reaction of the glacier to climate change due to its hypsometry.

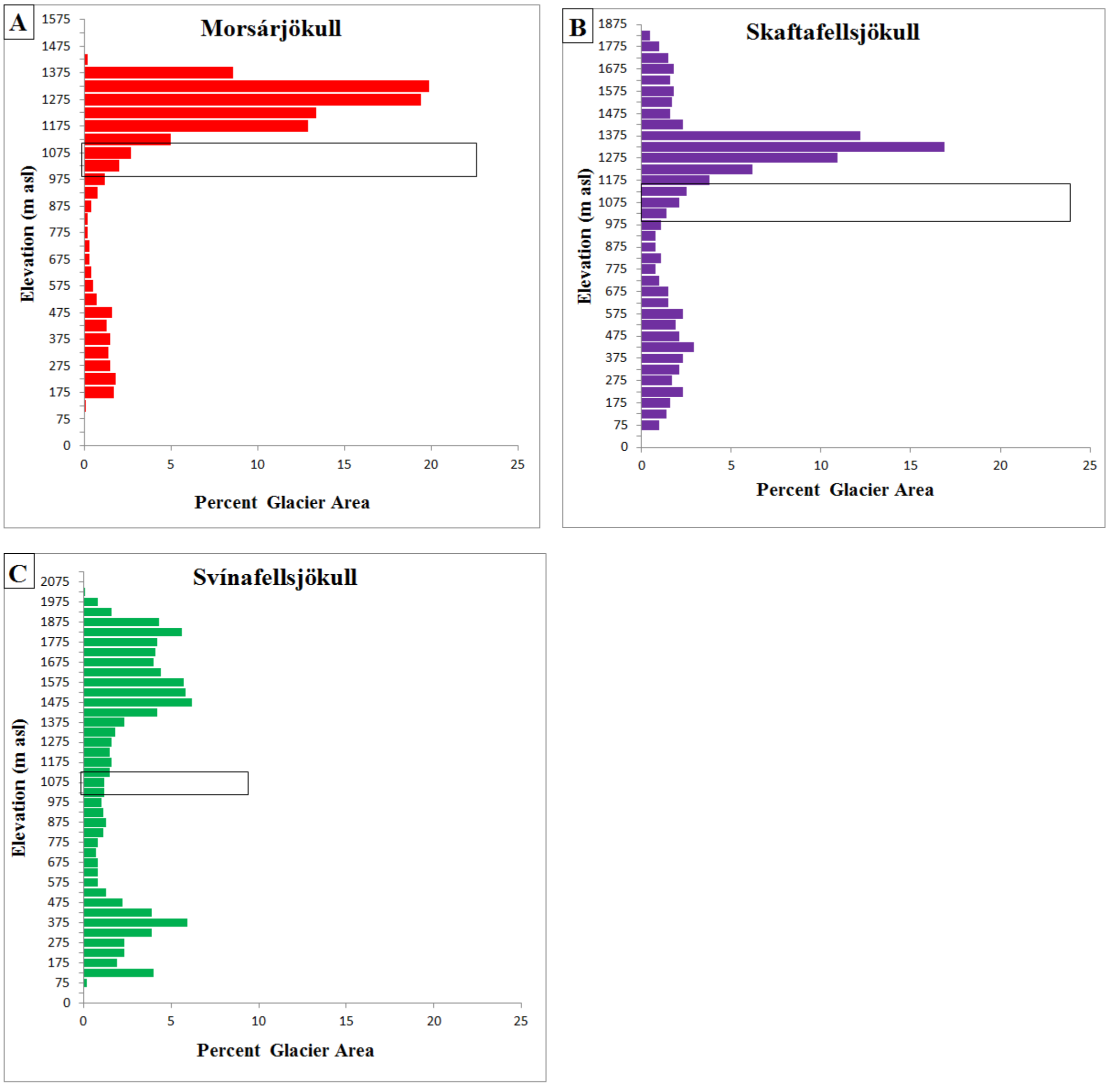

Figure 2.17: Graphs of the hypsometry of Morsárjökull (A), Skaftafellsjökull (B) and Svínafellsjökull (C). Morsárjökull and Skaftafellsjökull both display unimodal B type hypsometry while Svínafellsjökull has a bimodal E type hypsometry. The ELA range is depicted using the black box on each of the three graphs. Data obtained from GLIMS (2012).

2.5.2.2 Bedrock Characteristics

Bedrock characteristics and subglacial topography are important factors that affect retreat patterns, the types of sediment generated, and the morphology of landforms within the proglacial field (Adhikari and Marshall, 2013; Hannesdóttir et al., 2015). The bedrock of the mountains surrounding Svínafellsjökull, Morsárjökull and Skaftafellsjökull is composed of layers of basalt, hyaloclastite, pillow lava and sedimentary deposits (Fig. 2.18; Jóhannesson and Sæmundsson, 2009). The erodibility of the bedrock contributes to the debris flux of the glacier and to the development of subglacial topography. Based on the depth of the trough beneath Svínafellsjökull, the prominent lateral moraine on the southern margin, and reported minor rock falls onto the southern side of the glacier, it can be concluded that Svínafellsheiði, located south of the glacier, is more easily eroded than Hafrafell on the north (Fig. 2.1). Along the glacier margin Svínafellsheiði consists of mafic and intermediate hyaloclastite and pillow lava originating from the Upper Pleistocene (Jóhannesson and Sæmundsson, 2009). The erodibility of the bedrock may have contributed to the higher debris content of Svínafellsjökull, reducing the rate of retreat of the margin and allowing for deposition of the composite moraine.

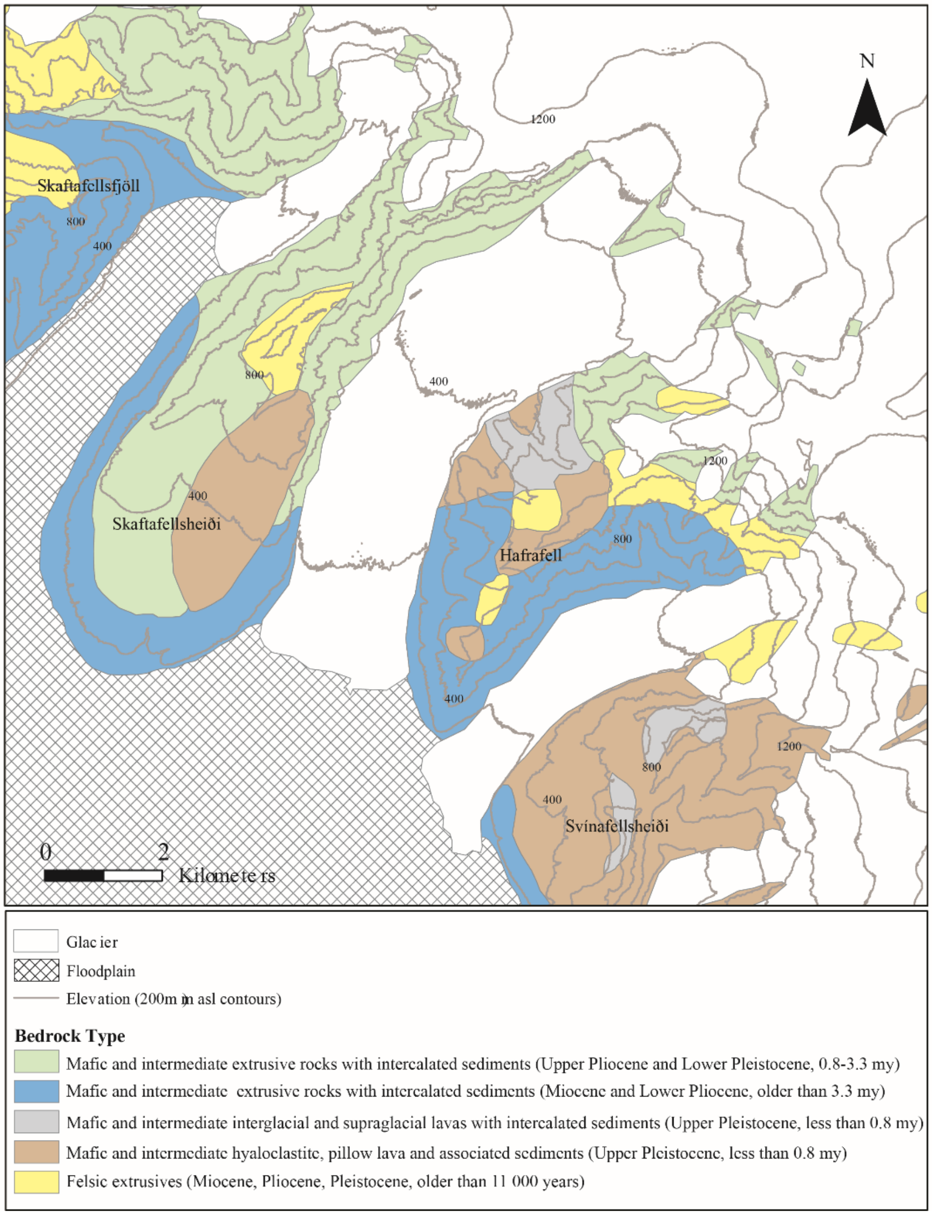

Figure 2.18: Bedrock map of the mountains surrounding the three glaciers. The mountains are composed primarily of basalt originating from multiple eruptions. Data obtained from Jóhannesson and Sæmundsson (2009).

Subglacial topography also affects a glacier's reaction to climate change and its pattern of retreat (Adhikari and Marshall, 2013). The overdeepened basin underlying the terminus at Svínafellsjökull is deeper than that of Skaftafellsjökull (Fig. 2.16 and 2.19;

Magnússon et al., 2012). Glaciers terminating into overdeepened basins have previously been recorded as responding to warming climate through thinning of the glacier, rather than retreat of the margin (Hannesdóttir et al., 2015). Based on simplified models overdeepened basins can cause a reduction in the horizontal movement of the glacier due to the slope which results in loss of mass through vertical changes (Adhikari and Marshall, 2013). This may have contributed to the minimal retreat of Svínafellsjökull since the 1940s, the period in which it lay within the basin.

The presence of a proglacial lake can cause thermal undercutting and calving which increases the rate of melting and retreat of the glacier margin (Evans and Twigg, 2002; Hannesdóttir et al., 2015). While the overdeepened basin at Svínafellsjökull may have contributed to its minimal marginal retreat, the overdeepened basin at Skaftafellsjökull has contributed to the increased retreat rate since 2000 when the glacier re-entered into the basin.

The different responses to the presence of the overdeepened basin is partially controlled by its shape and size (Adhikari and Marshall, 2013). The basin at Svínafellsjökull is deeper and has a steeper slope compared with that of Skaftafellsjökull (Fig. 2.19). This would result in more significant impedance for the ice movement furthering the tendency for thinning at Svínafellsjökull. The gentle slope of Skaftafellsjökull would only slightly reduce ice movement and therefore other factors such as the presence of the proglacial lake have more impact of the retreat pattern. Other factors such as hypsometry (De Angelis, 2014; Hannesdóttir et al., 2015; Jiskoot et al., 2009) and debris cover (Bennett and Evans, 2012)may have further impacted the variable response to the overdeepened basin. These factors alter the reaction of the glacier to environmental changes and contribute to the different pattern of retreat observed at the two glaciers.

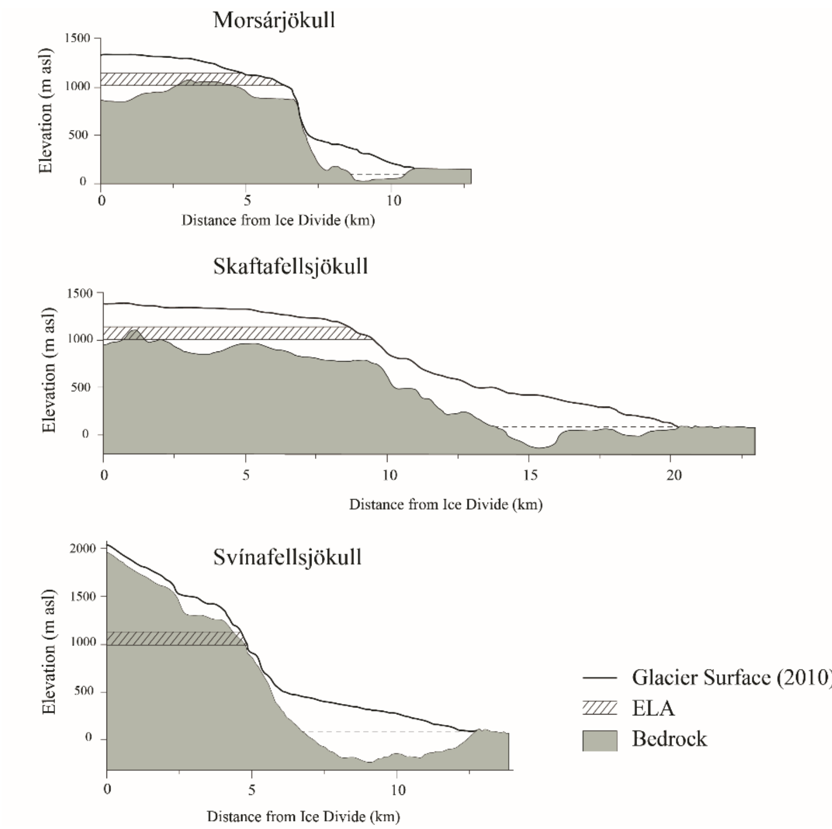

Figure 2.19: Adapted from Hannesdóttir et al. (2015) the bedrock topography for each of the three glaciers. The large overdeepened basin at Skaftafellsjökull and Svínafellsjökull are excavated below sea level.

2.5.2.3 Supercooling

Supercooling is a process which occurs beneath glaciers where subglacial water flowing through conduits moves up a steep slope; As the water moves from an area of high to low pressure, the geothermal heat and heat from friction is not sufficient to warm the water to maintain thermal equilibrium with the glacier and the water becomes supercooled. Supercooling occurs within the overdeepened basin at Skaftafellsjökull and Svínafellsjökull allowing the entrainment of sediment into the base of the glacier, creating stratified basal ice with high debris content (Cook et al., 2011b, 2010; Tweed et al., 2005). The process of debris entrainment increases the sediment flux to the glacier margin and can contribute to the formation of proximal landforms such as push moraines found at the margins of Svínafellsjökull and Skaftafellsjökull (Cook et al., 2010). The signature of supercooling at the glacier margin is difficult to discern, although stratification of sediment within the ice can be preserved in the marginal deposits and result in an increase in the concentration of silt entrained from the supercooled water (Bennett et al., 2004; Cook et al., 2011a; Larson et al., 2006). Typical sediments created through supercooling can include stacked debris flow deposits and melt out tills dominated by layered silts with clay and sand lenses and rounded clasts (Larson et al., 2006). These sediment are often affected by subsequent processes disturbing the original deposits (Cook et al., 2011a). The sediment at the margin of Svínafellsjökull along areas of push moraine formation was slightly more silt-rich when compared with other areas of the proglacial field although this may not be solely related to the supercooling at the base.

Understanding the impacts of supercooling on proximal landforms in modern systems is important in aiding the interpretation of paleoglacial deposits such as those from the Laurentide and Scandinavian Ice sheets as they are thought to have undergone this process (Larson et al., 2010). Based on observations of previous studies (Cook et al., 2011a, 2010) and the present field work there are areas at Svínafellsjökull and Skaftafellsjökull where stratification may have been preserved within the proximal push moraines. Further analysis of these landforms is needed to understand the impacts of the supercooling and potential signatures in the paleorecord.

2.5.2.4 Summary

The variability in the landsystem tracts between the three glaciers is probably caused by a combination of factors including differences in the hypsometry, the bedrock lithology and the bedrock topography. An important factor in the response of a glacier to warming climate is its hypsometry which impacts the reaction of the ice margin to changes in climate. The E type hypsometry of Svínafellsjökull causes less retreat of the margin of the glacier, instead resulting in loss of mass through thinning which allows for the deposition of multiple moraines in approximately the same location creating the moraine complex. The B type hypsometry of Skaftafellsjökull and Morsárjökull causes large marginal position variation when there is climatic change due to the long, narrow low lying tongues associated with this glacier type (De Angelis, 2014). This has resulted in the deposition of landsystem tracts that are separated with smaller landforms and less overprinting compared with Svínafellsjökull. The bedrock of Svínafellsheiði is more easily eroded when compared with Hafrafell and Skaftafellsheiði providing the higher debris flux of Svínafellsjökull. The high debris flux of Svínafellsjökull has also impacted the scale of the landforms within the proglacial field, as well as limiting ablation and causing a period of stagnation of the glacier margin which resulted in the large complex moraine at the glacier front. The overdeepened topography at the terminus of Skaftafellsjökull and Svínafellsjökull has impacted the retreat and the landforms at each of their margins. The steep sided basin at Svínafellsjökull has impeded the ice movement resulting in volume loss through thinning of the glacier resulting in minor variation of the ice margin position and the buildup of the composite moraine. At Skaftafellsjökull the shallow basin and significant proglacial lake has increased calving and retreat of the glacier margin over the past 15 years. This has resulted in a thin, crevassed ice margin which deposited low amplitude sawtooth push moraines (Mps) proximal to the lakeshore. Despite some evidence of sediments deposited through supercooling processes further investigation into the sedimentology of the proximal landforms is needed to understand the full signature of the supercooling at the base of these glaciers to increase their applicability as analogues for paleoglacial deposits.

2.5.3 Response to future climate warming

The changing climate has caused recession of the margins of Svínafellsjökull, Morsárjökull and Skaftafellsjökull, exposing the sediments and landforms of the modern proglacial forefields. Continued warming will have further impacts on the glaciers and will result in differing landsystem tracts within the valleys that the glaciers occupy. The warming climate will result in a rise of the ELA which will most significantly impact Morsárjökull and Skaftafellsjökull. These relatively low lying glaciers have the majority of their accumulation area located between 1100 m asl and 1400 m asl (Fig. 2.17). Once the ELA rises the glaciers will be cut off from their ice source and will stagnate in their valleys. The response of the glacier margin to climatic changes may be less immediate at Morsárjökull due to the presence of the ice fall, which delays response times to increased elevation of the ELA. After the ELA rises above 1400 m asl the glacier will be detached from the main ice source. The thickened area at the base of the ice fall will continue to feed the lower glacier for a period after this ELA rise creating an area of stagnating ice which may deposits landforms associated with de-icing which includes hummocky topography, kettle holes and gravity flows. The lower valley and currently exposed proglacial field will contain moraines deposited during the period when the glacier was still attached to the larger ice source allowing the margin to vary yearly. The overdeepened basin beneath Skaftafellsjökull will fill with meltwater and will act as a sediment trap in which lacustrine deposits will accumulate.

Svínafellsjökull will probably react more slowly than the other two glaciers to rises in temperature as the majority of its accumulation area lies at higher elevations (Fig. 2.17). The high debris content of the glacier and the icefall may also slow the response time to climate warming. Svínafellsjökull is likely to begin to show the typical debris landsystem characteristics such as hummocky terrain and kames (Bennett et al., 2010; Krüger et al., 2010) if the climate continues to warm, as the higher debris content will cause stagnation of the glacier tongue and the formation of de-icing structures.

2.6. Conclusions

- The landsystems at Morsárjökull and Skaftafellsjökull are similar in the distribution and scale of landsystem tracts, resembling the active temperate landsystem commonly found within Iceland (Evans and Twigg, 2002; Evans et al., 2015a). These glacial forefields can be used as analogues for the interpretation of ancient deposits on the southern margins of Pleistocene glaciers.
- The landsystem at Svínafellsjökull does not conform to that of other Icelandic glaciers (Evans et al., 2015a, 2015b, 2012; Ingölfsson et al., 2016), though it

shares similarities with the debris charged landsystem (Bennett et al., 2010; Krüger et al., 2010).

- The combination of remotely sensed data and field work has provided robust information for understanding the proglacial fields of Morsárjökull, Skaftafellsjökull and Svínafellsjökull.
- The classification code used in this study created consistency between the analysis of the three glacier forefields enabling comparisons to be made. This system can be applied in future landsystems studies to improve the consistency of terminology to describe glacial systems and therefore increasing the comparability of studies completed in different research locations and by different researchers.
- The proximal composite moraine at Svínafellsjökull was likely formed through a combination of processes including supraglacial deposition, bulldozing of sediments and the overprinting of moraines caused by the small marginal movement of the glacier. Further investigation into the sedimentological characteristics of the Svínafellsjökull composite moraine is necessary to understand the amount of impact each of the processes occurring and how it has resulted in the 46m tall feature.
- Exploration of the proximal landforms at the margin of Svínafellsjökull and Skaftafellsjökull will provide insight into the impacts of supercooling on glacial deposits. The process was likely commonly occurred beneath previous ice sheets, such as the Laurentide and Scandinavian Ice Sheets (Larson et al., 2006) and

recognizing these deposits will aid in refinement of models of previous glaciations.

- Multiple characteristics of the glaciers, bedrock and their topography contribute to the distinctive differences between the landsystem tracts of the three closely located glaciers of this study. The hypsometry of the glaciers plays a significant role in their response to climate, and therefore formation of their landsystem tracts. Morsárjökull and Skaftafellsjökull have similar hypsometry type which his prone to rapid movement of the glacier margin which; this is reflected in their proglacial fields as well as the similar pattern of retreat observed at these two glaciers. The hypsometry of Svínafellsjökull differs and is more commonly associated with slow retreat of the margin. The overdeepened basin at Svínafellsjökull has reduced forward movement of the glacier inducing thinning rather than retreat. At Skaftafellsjökull the shallower slope of the overdeepened basin causes limited impedance of the glacier and instead has resulted in a proglacial lake which inducing calving and thermal undercutting speeding up the retreat of the margin. The bedrock of Svínafellsheiði is more easily eroded compared to that of Hafrafell and Skaftafellsheiði resulting in higher debris content of Svínafellsjökull increasing the debris flux of the glacier. The combination of these factors has resulted in the variation between the three glaciers of this study.

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Chapter Three

3.1 Introduction

The proglacial landsystems of three outlet glaciers of the Vatnajökull Ice Cap in Iceland were defined in this study based on their geomorphological and sedimentological characteristics. A comparison of the landsystems defined for each proglacial field was used to understand the processes and environmental factors influencing the distribution, scale and type of landforms present. The methodology and classification system used within this study can be applied in other modern and ancient glacial settings to further understanding of the factors that influence the development of landsystems in these terrains.

3.2 Future Work

More detailed work at each of the three glaciers investigated, as well as an expansion of the project to examine other glaciers in a variety of climatic and tectonic settings would be beneficial for increasing the applicability of these systems as analogues for paleodeposits. The incorporation of more detailed sedimentological analysis would be a valuable addition to the project findings. This study focused on in-depth analysis of the available digital satellite data and supplemented this information with fieldwork completed during a single field season. The large size of these proglacial fields requires multiple field seasons to provide detailed analysis of the sedimentology of the landforms identified on satellite imagery. Further sedimentological work would allow for a more complete understanding of the processes occurring at these retreating ice margins since the Little Ice Age Maximum (LIA). An extended field season at each glacier would be required to obtain specific sedimentological information pertaining to the landsystem elements. With this, it may be possible to understand the connections between the landforms contained within the glacial forefields and the timing of changes in the glacial systems (which may be triggered by climate changes) increasing the applicability of this information to paleoenvironmental reconstructions. Any further understanding of these complex areas improves their utility as analogues for buried paleoglacial deposits.

Additional sedimentological research could be completed using architectural element analysis, which has been previously used by Slomka & Eyles (2015) in conjunction with landsystem analysis. This provides a framework for integrating the sedimentological and geomorphological information and creates a more useful analytical tool for application to other glacial systems. The completion of this analysis would require the compilation of sedimentological logs of more extensive outcrops within each of the three fields to create transects of the landsystem tracts and make clear connections between the sediment and the landforms. The exposure of sediment in landforms within many of the landsystem tracts is limited and excavation of outcrops might be necessary to complete such detailed work.

An additional area for future study is the composite moraine at Svínafellsjökull. The glacial forefield at Svínafellsjökull is not overly similar to any of the identified landsystems within Iceland and there is limited information available with which to link the landforms with associated depositional processes. A major component of the Svínafellsjökull forefield is the composite moraine, which likely formed due to multiple processes, including bulldozing of subglacial sediments and deposition of supraglacial materials. Extensive research on this feature would result in an increased understanding of the processes involved in its deposition and how those processes relate to changes in glacier behaviour. The size of the composite moraine, up to 46m in height and 485m in width, would require multiple outcrop studies to understand the processes responsible for its formation. Unfortunately, there are limited outcrops available on this structure as there are only two major river channels cutting through the moraine.

A focused study on the proximal landforms at Skaftafellsjökull and Svínafellsjökull could also be beneficial to the overall understanding of modern glacial systems. At Skaftafellsjökull and Svínafellsjökull the basal ice is undergoing supercooling (Cook et al., 2010); the impact of this and the potential for a signature recognizable in paleodeposits is not well understood. Previous work at these ice margins has established that there may be an increase in silt content within deposited sediments and there is potential for preservation of stratification in the landforms (Cook et al., 2010). Further research into the proximal landforms would constrain a signature of supercooling at glacier margins and the probability of preservation of this signature. Supercooling was likely occurring beneath the margins of the former Scandinavian and

Laurentide Ice Sheets (Larson et al., 2010) and understanding the potential impacts of this process would aid in the identification of its effects in buried deposits.

Expanding the study area to nearby glaciers would help in understanding the impact of the different factors, such as bedrock, topography and hypsometry, on the proglacial fields. From this study, it is evident that the type of bedrock, the hypsometry and the topography of the region are large contributors to the distribution of landforms within the proglacial field. The study of additional glaciers would help constrain the effects of these factors on the development of proglacial landsystems.

To the northwest of the study area lies Skeiðarárjökull a large outlet glacier of the Vatnajökull ice cap which is known to experience jökulhlaups (Hannesdóttir et al., 2015). Expanding the study to this glacier would provide an opportunity to increase knowledge of the impact of the hypsometry, bedrock and topography on landsystems while remaining within the same geographic area thus limiting the climatic differences. A comparison between the overprinting signature of the jökulhlaups characteristic of this glacier and the other non-jökulhlaup glaciers in this study would therefore be possible. There are many potential studies on these three fields and closely located glaciers that would add to the knowledge base on modern systems.

3.3 Conclusions

The integration of fieldwork and remotely sensed data in the analysis of three proglacial regions in Iceland has resulted in enhanced understanding of the landsystems characteristics of these three glaciers. Combining data sources provides a more complete picture of the landforms and their associated sedimentology, critical for understanding the process-form relationships. The creation of a classification system that can be applied across multiple studies allows for commonality, and therefore comparability between these studies. The application of the system of classification codes within this study allows more consistent comparisons to be made between study sites. This set of classification codes can be applied in future research to create a more consistent and effective method of identifying and denoting landsystem elements within proglacial fields.

The landsystems identified at Morsárjökull and Skaftafellsjökull are similar in the distribution and scale of the landsystem tracts they contain that include distal arcuate moraines, overridden moraines and abundant fluvial deposits. Minor variations in the landsystems, including the presence of sawtooth push moraines proximal to the glacier front at Skaftafellsjökull, probably relate to differences in the surrounding topography. These two glaciers have similar characteristics to other outlets of the Vatnajökull Ice Cap, and exhibit the succession of landsystem tracts typical of the active temperate landsystem (Evans et al., 2015; Evans and Twigg, 2002).

Svínafellsjökull is not directly comparable to any of the established landsystems in Iceland; however, it shares some similarities with the debris charged landsystem (Bennett et al., 2010; Krüger et al., 2010). There is evidence of buried ice in the composite moraine that may develop into the hummocky topography typical of a debris rich system as the forefield matures. Currently there are slumps, crevasses and water-filled depressions on the composite moraine, which are reflective of the first stage of ice melting and development of hummocky topography (Krüger et al., 2010).

At these glaciers, hypsometry plays a significant role in the response to climate and therefore the distribution of landsystem tracts within the forefield. Morsárjökull and Skaftafellsjökull have a similar, B-type hypsometry, and reflect that in their proglacial fields as well as in the similar pattern of retreat of each of the glacier margins. The hypsometry of Svínafellsjökull, an E-type hypsometry, has influenced the rate of retreat resulting in a lesser marginal retreat. Other characteristics that influence the landforms within the forefield include the bedrock type, the topography, and glacier dynamics such as supercooling. The relative impact of these factors is not well understood and requires further examples and study to determine which has had the most impact on the development of the forefield.

The landforms in the proglacial fields of Morsárjökull, Skaftafellsjökull and Svínafellsjökull are controlled to a large extent by bedrock characteristics, glacier hypsometry, and the surrounding topography. Despite the close proximity of the glaciers to one another, these factors have created differences between the scale and distribution of landforms with that of Morsárjökull and Skaftafellsjökull exhibiting similar characteristics and Svínafellsjökull differing. The process-form relationships found in these systems can be applied in future studies of paleodeposits and other modern systems to further understand these dynamic systems.

Understanding the complexity of glacial sediments in both modern and ancient deposits is important for resource management and disaster policy planning. Predicting the impact of climate change on water resources in modern glaciated mountain regions is dependent on determining hydrological pathways through glacial sediments (Viviroli et al., 2011). In these same areas there is the potential for catastrophic outburst floods of proglacial lakes due to collapse of natural dams created by glacial landforms (Carey, 2005). Within previously glaciated regions, such as southern Ontario, many communities rely on aquifers hosted in glacial outwash deposits (Slomka and Eyles, 2013). The ability to create three dimensional models of sedimentary packages for these regions is critical for the management of water resources and predicting and protecting against future disasters. Landsystem analysis can be applied to these areas to predict the distribution of glacial sediments and aid in refinement of models for glacial deposits. To increase the applicability of landsystem analysis as a methodology for understanding the three-dimensional distribution of subsurface deposits, continued study of modern glaciated regions is required (Evans, 2003). The importance of glacial deposits for water resources is undeniable and the understanding of their subsurface distribution is key to ensuring continued use of these resources for their surrounding communities.

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