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Architectural–landsystem analysis of a modern glacial landscape, Sólheimajökull, southern Iceland

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ABSTRACT

Glacial terrains are commonly recorded using a landsystem approach, which allows detailed documentation of the geomorphological evolution of the landscape. However, landsystem analysis of Quaternary subsurface stratigraphies in which landforms are not apparent or preserved is problematic, making delineation of the sedimentary architecture of a glaciated basin infill difficult. The purpose of this study is to delineate the sedimentary architecture of the Sólheimajökull (southern Iceland) glacial landsystem and to provide an architectural framework for allostratigraphy and modern analogue purposes. An integrated architectural–landsystem approach is applied here, which utilizes the principles from both architectural element analysis and landsystem analysis. A bounding surface hierarchy (fourth- to seventh-order surfaces) provides a framework within which the architecture is organized. Fieldwork was conducted at Sólheimajökull glacier in 2012 and 2013; and 22 different surface features (bounded by the fourth-order surfaces) were mapped, which were grouped into four different landsystem tracts (glaciofluvial, ice-contact, jökulhlaup, and colluvial slope; bounded by the sixth-order surfaces). Landsystem tracts were deconstructed into smaller architectural units (components; bounded by the fifth-order surfaces), which allowed the delineation of eight allostratigraphic units that record the evolution of the glacial landsystem from ~7000 YBP to A.D. 2013. The results of this study can provide insight to interpretation and delineation of the sedimentary architecture of other modern glacial landsystems and subsurface Quaternary deposits in North America and other formerly glaciated areas.

1. Introduction

Studies at modern glacier margins allow first-hand documentation of the geomorphology, sedimentology, and sedimentation processes active in these environments, which can be utilized to understand the depositional and paleoenvironmental history of older Quaternary glacial successions (e.g., Boulton, 1972; Evans et al., 1999). Glacial landforms, and the sediments they contain, are commonly recorded using a landsystem approach (e.g., Evans and Rea, 1999; Evans et al., 1999; Andrzejewski, 2002; Delaney, 2002; Evans and Twigg, 2002; Spedding and Evans, 2002; Benn and Lukas, 2006; Golledge, 2007; Evans et al., 2008), which involves grouping genetically related sediment–landform assemblages into mappable units. The landsystem approach allows reconstruction of the geomorphological evolution of a glacial landscape (including its depositional and erosional history), based on the location, spatial relationship, and degree of preservation of sediment–landform associations (Evans, 2005). However, application of the landsystem approach for paleoenvironmental reconstruction of deeply buried subsurface deposits (in which the surface expression of landforms is not apparent or preserved) is problematic, making seamless delineation of the sedimentary architecture of a glaciated basin infill, from shallow to deep subsurface units, difficult.

Subsurface sedimentary geometries of glacial deposits are commonly delineated from exposed outcrop sections and by correlating units between boreholes and may be analyzed using formal stratigraphic methods (NACSN, 2005; Hughes, 2010) such as lithostratigraphy (e.g., Meyer and Eyles, 2007), sequence stratigraphy (e.g., El-ghali, 2005), and allostratigraphy (e.g., Eyles et al., 1998). The dynamic, and inherently erosional, nature of glacial depositional environments makes application of Walther's Law (Middleton, 1973) difficult; hence, the principles of lithostratigraphy and formal lithostratigraphic units (e.g., Willman and Frye, 1970) may not be the most appropriate methods for characterizing complex glacial successions (Räsänen et al., 2009; Hughes, 2010). Sequence stratigraphy has been utilized for the analysis of glacial successions deposited in marine-influenced (e.g., Powell and Cooper, 2002; El-ghali, 2005) and glaciolacustrine (e.g., Martini and Brookfield, 1995) depositional environments; however, sequence stratigraphy is based on identification of cyclic fluctuations in sea level, the delineation of highstand and lowstand system tracts, and identification of key surfaces (discontinuities and their correlative conformities) including a maximum flooding surface, which may not be applicable in glaciated terrain where marine influence is

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negligible or absent. Allostratigraphic principles are suitable for the analysis of the architecture of non-marine glacial successions (Hughes, 2010) because the delineation of discontinuities is not reliant on base level change. However, as a stand-alone method, allostratigraphy does not facilitate the characterization of the architecture and geometry of glacial deposits at various scales of resolution (e.g., facies associations to mappable units), and allostratigraphic units (and their bounding discontinuities) are often difficult to delineate between different depositional environments that have complex spatial relationships.

Architectural element analysis (AEA; Miall, 1985) is an informal stratigraphic method (NACSN, 2005) for the delineation and characterization of sedimentary geometry at different scales of resolution (e.g., bedform to major basin fill), which is nested in a framework of hierarchical bounding surfaces. The bounding surfaces represent unconformities of different scales and serve as a framework within which the sedimentary architecture is structured (Miall, 1988). The AEA methodology was developed for the analysis of ancient fluvial sediments exposed in outcrop sections (Allen, 1983; Miall, 1985) and has since been modified and applied for the analysis of sediments deposited in fluvial (e.g., Miall, 1994; Ghazi and Mountney, 2009), deep marine (e.g., Hubbard et al., 2008), deltaic (e.g., Eriksson et al., 1995), subglacial (e.g., Boyce and Eyles, 2000), and glaciofluvial (e.g., Slomka and Eyles, 2013) depositional environments.

The purpose of this study is to delineate the sedimentary architecture of the Sólheimajökull landsystem utilizing an integrated architectural–landsystem approach in order to (i) test the applicability of AEA in a modern glacial depositional environment; (ii) characterize the main architectural components of the landscape; (iii) understand the allo- and autogenic controls on the sedimentary architecture; and (iv) provide an architectural model of the Sólheimajökull landsystem for modern analogue and allostratigraphic purposes. Translation of landsystem units into hybrid architectural–landsystem units has significant implications for the delineation of the sedimentary architecture of other modern ice margins and subsurface glacial deposits within previously glaciated terrains and facilitates the construction of architectural models at various scales of resolution that may be utilized for other applications such as groundwater investigations and source water protection programs. The Sólheimajökull landscape is selected for the study because it is easily accessible for the collection of new data and has been extensively studied (hence, historical data are available), which aid in the characterization and reconstruction of the glacial sedimentary architecture. The depositional history of Sólheimajökull has been impacted by jökulhlaups and changing ice margin positions during the Holocene, which have resulted in a complex suite of landforms and sedimentary deposits in the ice marginal and proglacial areas; however, a comprehensive landsystem model of the Sólheimajökull landscape has not yet been delineated.

2. Study area and geologic history

Sólheimajökull is a non-surging, temperate outlet glacier of the Mýrdalsjökull ice cap located in southern Iceland (Fig. 1; Björnsson, 2002; Scharrer et al., 2008). The accumulation area (altitude of 1300 m asl) sits above the southwestern part of the Katla volcano caldera (Scharrer et al., 2008). Sólheimajökull is blanketed with supraglacial debris derived from the 1918 Katla eruption, the 1999 jökulhlaup event (a catastrophic release of glacial meltwater), and steep bedrock valley slopes (including Jökulhaus, a prominent bedrock outlier; Fig. 1). The Little Ice Age (c. A.D. 1750–1920; Dugmore and Sugden, 1991) glacial position is demarcated by a series of prominent end moraines from which the ice margin underwent punctuated retreat until about A.D. 1970 (Fig. 1). After this period of recession, the ice margin advanced to the 1995 ice margin position (Fig. 1), followed by continuous retreat (average of 50 m/y) to its present-day position (Maizels, 1991; Friis, 2011; Schomacker et al., 2012). The glacier snout is presently retreating into a bedrock trough that has been subglacially scoured in some places to 50 m below sea level and is presently occupied by an ice-contact lake (Mackintosh et al., 2002).

Meltwater from the ice margin is drained by the Jökulsá á Sólheimasandi, which also receives meltwater discharged from Jökulsárgil (flowing from Jökulsárgilsjökull in the north; Sigurðsson and Williams, 1991), Hólsárgil (flowing southeast of Jökulhaus), and several other smaller streams (Russell et al., 2010a; Fig. 1). Along much of its length, Jökulsá is contained within a steep-walled valley incised by glaciofluvial erosion and widened by jökulhlaups. Older glacial sediments are exposed in the valley walls and preserved in a series of terraces (Fig. 1; Friis, 2011). Beyond the road bridge along Route 1 (Fig. 1), Jökulsá flows toward the North Atlantic Ocean in a valley train between two outwash sandar, Skogasandur and Sólheimasandur (Fig. 1). Maizels (1989, 1991) identified 13 stratigraphic units that make up the two sandar (Figs. 1A, 2) and dated the units using stratigraphic and geomorphic relationships, lichenometry, tephrachronology, and radiocarbon dating techniques (Maizels and Dugmore, 1985; Maizels, 1989, 1991). Both sandar are constructed from repeated jökulhlaups, glaciofluvial reworking, and alluvial fans (Figs. 1, 2A, D; Maizels, 1989).

Five jökulhlaups generated by volcanic activity of Katla (termed 'Katlahlaups'; Maizels, 1989; Russell et al., 2010b) have impacted Sólheimajökull in recorded history (Fig. 2B; Eliasson et al., 2006; Russell et al., 2010a,b), and at least eight major jökulhlaups have impacted Skogasandur and Sólheimasandur from B.P. 4500 to A.D. 1357 (Figs. 1A, 2A; Maizels, 1989, 1991). Minor jökulhlaups are also known to be generated from ice-dammed lakes in Jökulsárgil valley (Fig. 1), the most recent of which was recorded in 1936 (Thorarinsson, 1939; Maizels, 1991; Björnsson, 2002; Russell et al., 2010a). Active volcanic eruption sites on Katla are now most common and active in the Kötlujökull catchment (northeast of Sólheimajökull; Maizels, 1989; Eliasson et al., 2006; Scharrer et al., 2008); hence, most recent jökulhlaups at Mýrdalsjökull have impacted Kötlujökull and Mýrdalssandur (Russell et al., 2006). However, the most recent jökulhlaup to impact Sólheimajökull was on 18 July 1999 and was generated by volcanic activity beneath the Mýrdalsjökull ice cap (Russell et al., 2010a,b). Meltwater was routed down the western margin of the glacier ('Main Western Outlet') and formed an ice-dammed lake in the Jökulsárgil valley (Fig. 1). Smaller jökulhlaup routeways were located at the central and eastern areas of the ice margin, and most of the jökulhlaup flow was contained within the Jökulsá valley (Maizels, 1989; Lawler et al., 1996; Roberts et al., 2000; Roberts and Russell, 2002; Russell et al., 2002, 2010a). Draining of the ice-dammed lake resulted in the deposition of a boulder fan in the ice-marginal area, and retreat of the ice margin since 1999 has exposed a large esker that forms remnant ice-cored hummocks in the ice-contact lake (Schomacker et al., 2012).

3. Methods

Fieldwork at Sólheimajökull was conducted over a total of four weeks during May (2012 and 2013) and August (2013) on the east (north of Route 1) and west (south of Route 1) sides of Jökulsá (Fig. 3). Twelve transects recorded surface features and sediment types that were documented in hand-drawn sketch maps, photos, and in ESRI ArcPad using a handheld Thales MobileMapper CE global positioning system (GPS; Fig. 3). Transects originate from exposed bedrock surfaces (where available) on the valley walls and include data on relative change in surface topography (*y*-axis), distance (*x*-axis), surface features, sediment type, spatial relationships (e.g., over- and underlying, interfingering) and the nature of contacts (e.g., erosional, truncated, gradational, sharp, conformable) between surface features and associated sediments (Figs. 4–9).

The GPS data of surface features were integrated with 2010 LiDAR data (2-m resolution; courtesy of the University of Iceland), detailed sketch maps, transect data, and 2010 satellite imagery (from Google