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Glacial terrain zone analysis of a fragmented paleoglaciologic record, southeast Keewatin sector of the Laurentide Ice Sheet

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ABSTRACT

A highly fragmented subglacial landscape is recognized at the regional to sub-regional scales in northeastern Manitoba, Canada, in the southeast Keewatin Sector (a core region) of the Laurentide Ice Sheet. New field-based ice-flow indicator measurements, mapping of subglacial landforms (remote-sensing and aerial photograph), and a re-examination of previously published data from an 8100 km^2 area in northeastern Manitoba show that the preserved subglacial record reflects a complex and potentially long glacial history. Five streamlined landform flowsets are mapped. A much higher degree of inheritance in the field-based ice-flow indicator data, than previously reported, allows for recognition of multiple ice-flow phases. Analysis of the characteristics of the subglacial landscape combined with a relative-age chronology established with field-based indicators, led to the recognition of disjoint zones with internally-consistent glacial histories – termed *glacial terrain zones* (*GTZ*). These GTZ were then classified as (1) relict glacial, (2) palimpsest, or (3) deglacial in nature.

Our data suggest that while the southern Keewatin Sector was affected by regional ice-divide translocation, this alone cannot explain the fragmented, high inheritance landscape. We suggest that the subglacial landscape was continually evolving and subject to spatio-temporal variations in intensity of erosion, transportation and/or deposition throughout multiple glacial events (subglacial bed mosaic). Preservation of relict and palimpsest terrain likely occurred under large ‘sticky’ low-erosion regions. These regions could have formed by at least two different mechanisms: heterogeneous switch from warm-based to cold-based ice or within a warm-based subglacial environment from wet to stiff, dewatered till. Establishment of the regionally extensive (~700 km wide by at least 500 km long) dendritic esker channel-system may have caused rapid spatially-variable dewatering of the substrate far back under the ice sheet. The GTZ approach integrates all available data (e.g. flowsets and other landform data, striations) to advance our interpretation of the spatio-temporal evolution of subglacial dynamics in areas where the degree of landscape inheritance and overprinting is spatially highly variable. This mosaic may be a characteristic net-effect of landscape evolution beneath the core regions of ice sheets.

1. Introduction

The geomorphic landscape of glaciated terrain is a unique window into the subglacial environment (Stea, 1994; Kleman and Borgstrom, 1996; Clark, 1999; O Cofaigh and Stokes, 2008). The advent of remote sensing has brought about new ways of investigating this landscape at an unprecedented scale. New imagery, for example, has allowed for recognition of distinct and non-coeval regional groupings (flow stages, Boulton and Clark, 1990; flowsets, Kleman and Borgstrom, 1996; Clark, 1999) of streamlined landforms (Jansson et al., 2002; Greenwood and Clark, 2009b; Stokes et al., 2009). The mapping of these non-coeval ice flowsets across large regions is then used to recognize regional trends and spatio-temporal shifts in ice-flow patterns, which are then integrated in ice-sheet reconstructions (e.g. Kleman et al., 1997; Clark et al., 2000; Kleman et al., 2008; Greenwood and Clark, 2009a). In many cases, this approach has led to significant changes in our understanding of ice-sheet dynamics and evolution. Hence while it was once thought that the Keewatin Sector of the Laurentide Ice Sheet (LIS) was a long-lived stable ice centre (Shilts et al., 1979; Shilts, 1980; Aylsworth and Shilts, 1989), satellite imagery has now provided compelling evidence for a dynamic, migrating ice sector (Boulton and Clark, 1990; Kleman et al., 2010). The current flowset approach largely

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focuses on the characterization of streamlined landforms at vast regional scales (Boulton and Clark, 1990; Kleman et al., 1997; Clark et al., 2000; Kleman and Glasser, 2007; Stokes et al., 2009; Kleman et al., 2010; Smith and Knight, 2011). The success of this methodology has lead to application at smaller regional to local scales, where complications such as palimpsest (overprinted, Greenwood and Clark, 2009b) landforms, or relict (inherited, Finlayson et al., 2010) landforms emerge. Where cross-cutting relationships are difficult to decipher (Greenwood and Clark, 2009a,b), or where flowsets start/end adjacent to, but not crossing, other flowsets (this study), relative age is often difficult to determine. As one aspect of paleoglaciological reconstruction is a timeline of events, researchers need a multi-proxy set of tools (Kleman et al., 1997) to aid spatio-temporal interpretation of detailed, small-scale reconstructions. Other characteristics of the glacial landscape that may be indicative of different glaciological regime or non-coeval glacial records are also important (Greenwood and Clark, 2009a). These may include, for example, distinct clusters of other types of subglacial landforms (e.g. Rogen moraine, end moraines, De Geer moraines), field-based ice-flow indicator data and contrasting sediment dispersal patterns. It is thus critical for paleoglaciological ice-sheet reconstructions to not only recognize and describe distinct flowsets, but also to investigate the spatio-temporal relationships between all available data to identify evidence of inheritance (e.g. relict surfaces, mis-matched orientations, old ice-flow indicators, old sediment dispersal orientations) and/or the intensity of overprinting (e.g. palimpsest landforms, radiating lobate patterns, parallel conformity with esker ridges) (Greenwood and Clark, 2009a).

In this paper we present a spatio-temporal *glacial terrain zone* (*GTZ*) approach, which combines the typical flowset mapping technique with terrain characteristics and data obtained during detailed fieldwork (e.g. topography, non-streamlined landforms, field-based ice-flow indicator record), and apply it to analyze the subglacial landscape (8100 km^2) within a core region (near-ice divide) of the LIS in northeast Manitoba, Canada. We then present previously unknown aspects of the glacial history of the southeast part of the Keewatin sector of the LIS, identify potential problems and knowledge gaps, and use new insights from this analysis to advance discussion of spatio-temporal subglacial landscape evolution.

1.1. Flowsets, landsystems and Glacial Terrain Zones

Flowset mapping began as a way to document complexity in the distribution of subglacial streamlined landforms, recognize consistent patterns, and inform reconstruction of ice-flow history in glaciated regions (Boulton and Clark, 1990; Kleman et al., 1994; Clark et al., 2000; Boulton et al., 2001b; Jansson et al., 2002). A flowset is defined herein as a discrete assemblage of subglacial streamlined landforms based on their pattern and the degree of internal consistency (e.g. parallel landforms with similar morphology), from which inferences about ice-flow history and basal thermal regime can be made (Kleman and Borgstrom, 1996; Kleman et al., 1997; Clark, 1999). Various attempts have been made to identify particular types of subglacial landform patterns and to relate them to specific subglacial conditions or ice-sheet phase (i.e. warm-based, cold-based, event-flow, deglacial) (Greenwood and Clark, 2009a; Stokes et al., 2009). For example, Clarhall and Jansson (2003) recognized that a fragmented glacial landscape in the Quebec-Labrador sector of the LIS, identified by partially superimposed flowsets, is evidence of temporally unrelated landform systems. They then suggested that subglacial landform generation may have occurred in discrete subglacial zones during restricted time periods. Likewise, De Angelis and Kleman (2008) identified several paleo-ice stream onset zones that are geomorphologically distinct from adjacent older palimpsest or relict terrain.

By grouping streamlined landforms into flowsets and by analyzing the spatial relationship between various flowsets, we note that the subglacial landscape may be described as a mosaic of distinct landform patterns (Ross et al., 2009; O Cofaigh et al., 2010) or structural elements (Boulton et al., 2001b). When other characteristics are introduced, such as topography, non-streamlined glacial landforms, field-based ice-flow indicators and sediment composition, it becomes apparent that these are actually sediment-landform assemblages or subglacial zones (Stea and Finck, 2001). We define these subglacial zones as Glacial Terrain Zones (GTZ), whereby a GTZ is a geologically distinct area that contains an internally consistent assembly history. This GTZ approach is further developed and detailed below (section 3.4) but here we argue that the partitioning of the glacial landscape into GTZ is an important step towards more complete paleoglaciological reconstruction models of past ice sheets. The concept of zonation was first presented by Stea and Finck (2001) for the Nova Scotian glacial landscape beneath Scotian Ice Divide of the Appalachian Ice Complex. These authors suggested each zone recorded a different signature of erosion and deposition, which led to a discrete sediment transport history. Similarly, warm-based fast-flowing ice-stream troughs are distinguished from slow, sluggish, often cold-based upland areas leading to the recognition of distinct zones on the landscape which record contrasting subglacial conditions (Briner et al., 2006; Kleman and Glasser, 2007; Ross et al., 2011). Indeed, paleo-ice stream research has evolved to the point where “paleo-ice stream landsystem” models (Clark and Stokes, 2003) can be identified from the subglacial landscape based on specific geomorphic criteria (O Cofaigh et al., 2002; Clark and Stokes, 2003; Anderson and Oakes Fretwell, 2008; De Angelis and Kleman, 2008; Ross et al., 2009). These glacial landsystems (Evans, 2003b) use geomorphic, sedimentological and stratigraphic data to create process-form models that then relate to specific glaciation styles and/or ice dynamics (Evans, 2003a). However, this type of zonal analysis has rarely been applied to the core regions of ice sheets in areas with subdued topography such as the Keewatin Sector of the LIS. Most landsystem models are concerned with spatial identification of specific units or elements, rather than partitioning of the *entire* glacial landscape into zones. These models are also often viewed as conceptual models synthesizing the diagnostic landscape features of a particular environment (e.g. paleo-ice stream landsystem, ice-marginal landsystem). We suggest that, due to translocation in ice-divide positions (McMartin and Henderson, 2004; Greenwood and Clark, 2009b; Finlayson et al., 2010), potential for high inheritance due to limited erosion, and possible changing thermal regimes (Kleman et al., 1999; Clarhall and Jansson, 2003; Kleman and Glasser, 2007), core regions of ice sheets are likely to be characterized by different zone types reflecting not only different erosion/transportation/depositional processes over short distances and through time, but also distinct subglacial thermal regime histories. GTZ analysis can be used to identify and classify these zones.

2. Regional setting and previous work

The study area is located in the northeastern part of Manitoba, on the Canadian Shield, with fieldwork completed in the Great Island-Kellas Lake and Churchill areas (Fig. 1). Elevation varies from sea level to 330 m above sea level (asl). Local relief is about 30 m high. The northern part of the area is characterized by extensive swaths of bouldery pristine and drumlinized Rogen moraine fields alternating with swaths of streamlined terrain and areas of bedrock outcrops (Trommelen and Ross, 2010). The remaining area is primarily a mix of till blankets and till veneers over bedrock with