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Ribbed moraines in northern Manitoba, Canada: characteristics and preservation as part of a subglacial bed mosaic near the core regions of ice sheets

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ABSTRACT

Ribbed moraines are enigmatic glacial landforms for which different models, with contrasting paleoglaciologic implications, have been proposed to explain their formation. Despite the great deal of attention this type of landform has received over the last several decades, ribbed moraine fields in northern Manitoba, Canada are among the largest in the world but have been seldom studied. Ribbed moraines in this part of the world overlie the low-relief Canadian Shield, are not constrained by topography, and are part of a spatial subglacial-landform assemblage associated with drumlinoid ridges within palimpsest and relict-type Glacial Terrain Zones. Field observations herein provide new insights into the characteristics of these transverse-to ice-flow ridges at landscape (mapping and spatial analysis) and landform (internal structure using high-resolution shear wave (S-wave) seismic reflection surveys, sedimentological characteristics, clast-fabric analyses) scales. Two main types of ribbed moraine are recognized: 'pristine', high amplitude straight-crested ridges and secondarily-modified subdued 'drumlinized' ridges. Ribbed moraine in northeast Manitoba consist of massive, matrix-supported till at surface, which is similar in matrix texture and composition to the regional till sheet, though pristine moraines show a higher concentration of boulders. A seismic profile reveals subparallel-to surface layered stratigraphy with only minor folding and no major unconformities (stacking or faulting).

The demonstrated fragmentary nature of ribbed moraine fields, the inherited signature of the till within these fields, the secondary patchy drumlinization of the ridges, and the more abundant granitoid outcrops in areas of intense modification all suggest that subglacial ribbed moraine formed from pre-existing sediments and were later preserved and/or partially reworked through a regional mosaic of shifting subglacial bed conditions. We therefore make the case that pristine (unmodified) moraines were preserved beneath stable sticky spots. We support a link between ribbed moraine and widespread cold-based and/or dewatered subglacial conditions in inner-core regions of ice sheets, but for reasons of preservation, and not necessarily formation.

1. Introduction

The formation and paleoglaciologic implication of ribbed moraines is a question, posed throughout the last fifty years, that still remains largely unsolved (Lundqvist, 1969; Hättestrand and Kleman, 1999; Moller, 2006). Ribbed moraine, a geomorphic term without genetic connotation, was first defined (Hughes, 1964; Prest, 1968) as segments of gently arcuate to undulating ridges which trend normal or subnormal to a direction of ice movement. Some papers have classified these landforms based on morphology alone (Hättestrand, 1997; Hättestrand and Kleman, 1999; Dunlop and Clark, 2006), while others have considered their relationship to other subglacial landforms such as streamlined landforms (Cowan, 1968; Boulton, 1987; Aylsworth and Shilts, 1989; Bouchard, 1989; Lundqvist, 1997; Moller, 2006; Stokes et al., 2008), hummocky moraine (Fisher and Shaw, 1992; Marich et al., 2005) or ice-marginal proglacial landforms (de Geer moraines, Linden et al., 2008; controlled moraines, Moller, 2010). The presence and orientation of ribbed moraine has been used to reconstruct paleo-ice flow dynamics or to infer basal conditions in numerous studies (Kleman et al., 1997; Knight and McCabe, 1997; Kleman et al., 1999;

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Table 1
Hypotheses to explain the formation of ribbed moraine.

Hypothesis	Fracture and extend	Subglacial modification – pre-existing ridges or hummocks	Natural instability	Shear and stack – dewatered stiff till patches or cold-based ice patches
Authors	Hättestrand and Kleman (1999), modified by Sarala (2006)	Boulton (1987), Lundqvist (1989, 1997), Knight and McCabe (1997), Moller (2006), Finlayson et al. (2010)	Aario (1977), Hindmarsh (1998), Dunlop et al. (2008), Fowler (2009), Chapwanya et al. (2011)	Shaw (1979), Bouchard (1989), Linden et al. (2008); Stokes et al. (2008)
Thermal Regime	Cold/Warm interface	Warm	Warm-based	Warm-based
Glacial stage of formation	Deglaciation–as interface between warm- and cold-based ice moves inward	Over multiple glacial episodes	Any time	Any time
Ice flow velocity	Increases down-ice	Increases down-ice	Constant/sheet flow	Decreases at Ribbed site
Ice movement	Fast-flow near margins causes extensive drawdown and sliding movement	Extensive/sliding	Deformation and sliding as guided by till rheology and effective pressure	Compressive/sticky spot
Sediment source	Pre-existing drift sheet together with the lower part of the ice sheet	Pre-existing ridges or rough topography	Pre-existing drift sheet; all sediment was effectively transmuted to the ridges	Pre-existing drift sheet OR continued subglacial deformation conveyor-belt stacking of debris-rich ice
Synopsis	At the transition from proximal frozen (non-sliding) conditions to distal melting (sliding) conditions, high tensional stresses and extensional ice flow will occur, as the basal ice velocity increases across the boundary of basal thermal regime. These tensional stresses lead to detachment and 'boudinage-like' fracturing of a pre-existing drift sheet into ribbed moraine.	1. Pre-existing transverse moraine ridges, originally deposited from ice-cored moraines, streamlined landforms or thrust ridges 2.Reshaping: sheath folds and shear bands indicate high strain at deformation. "compressional shortening of sediments would be combined with horizontal flattening and extension, gradually transforming a transverse element into longitudinal landforms".	Generated during basal sliding as a natural instability is initiated at the ice/substrate boundary. The instability takes the form of transverse two-dimensional rolls, which cause the resultant finite-amplitude waveforms (ridges). Factors that may initiate instability include substrate thickness, effective water pressure, textural variability, velocity variability, etc.	An obstacle to glacier flow* causes the development of shear planes in the basal part of the glacier through compressional ice flow and these, in turn, lead to the stacking of slices of debris-laden ice. Early models suggest this process repeats itself near the ice margin, where the stagnating margin creates an up-ice expansion of the obstacles to glacier flow *whereby the obstacle could be warm/cold interface, dewatered stiff till, bedrock topography
Sediment Provenance	Sediment within may have no relation to the landform	Sediment within may have no relation to the landform; composed mainly of ablation till, or proglacial sediments. May have a till carapace.	Sediment sourced from up-ice of the landform (transverse to ribbed moraine)	Sediment sourced from up-ice of the landform (transverse to ribbed moraine)
Relationship to other landforms	Variably overprinted by drumlins; not possible to transition back to ribbed.	Transitional to drumlins which are in turn transitional to ribbed moraines, etc	Transitional to drumlins	Variably overprinted by drumlins; overprints MGSL in the Dubawnt Ice Stream

Jansson et al., 2002; Raunholm et al., 2003; Van Landeghem et al., 2009).

As ridge formation is still contentious (Table 1; Hättestrand and Kleman, 1999; Dunlop and Clark, 2006; Moller, 2006; Finlayson and Bradwell, 2008; Chapwanya et al., 2011), inferences about basal thermo-mechanical conditions (e.g. link to widespread thawing cold-based ice, Hättestrand, 1997; Hättestrand and Kleman, 1999) remain uncertain. Most studies have focused on the formation of ribbed moraine (Cowan, 1968; Shaw, 1979; Bouchard, 1989; Lundqvist, 1989; Fisher and Shaw, 1992; Lundqvist, 1997; Hättestrand and Kleman, 1999; Sarala, 2006; Moller, 2010; Chapwanya et al., 2011), rather than why these fields of transverse ridges are restricted to certain inner-core region (Sollid and Sørbel, 1984; Hättestrand and Kleman, 1999), or other environments of strong basal-flow velocity gradients (Finlayson and Bradwell, 2008; Stokes et al., 2008). It was noted in Ireland (Knight and McCabe, 1997) and Scotland (Finlayson and Bradwell, 2008; Finlayson et al., 2010) that the crests of some transverse ridges are streamlined, cross-cut or overprinted by drumlins, whereas other ridges are unmodified and were not affected by later drumlinisation. In each of these cases, as well as in northern Manitoba, the subglacial landscape has recently been interpreted as a complex, patchy record of deforming and stable spots over multiple ice-flow phases, leading to a mosaic of inheritance and overprinting (Finlayson et al., 2010; Knight, 2010; Finlayson, 2012; Trommelen et al., 2012a, 2013).

Some of the largest fields of low-relief topography ribbed moraine in the world are situated near an inner-core region of the Laurentide Ice Sheet (LIS), in Nunavut and northern Manitoba, Canada (Prest et al., 1968; Aylsworth and Shilts, 1989; De Angelis, 2007; Kleman et al., 2010), yet they have not been studied. In this paper, we present the first study that combines remotely-sensed mapping of subglacial landforms across northern Manitoba, Canada, with field-based data from ribbed moraine ridges in northeast Manitoba. Incorporation of ribbed moraine data within a regional paleoglaciological context (Trommelen et al., 2012a, 2013) then allows us to consider what paleoglaciologic implications can be derived from the presence of ribbed moraine.

2. Study area

Northern Manitoba (58°–60, Fig. 1) is bounded by Hudson Bay in the east, and extends west to the Saskatchewan border, rising in elevation to about 500 m above sea level (a.s.l.). The entire region forms a uniform, gently-sloping plain with subdued topographic features. The northeast region falls within the continuous permafrost zone, while the remainder of the areas is within the extensive discontinuous permafrost zone (Sladen, 2011). In northeastern