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The role of the cryosphere in source-to-sink systems

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ABSTRACT

Glacial erosion and sediment production are of interest to diverse scientific communities concerned with the interaction of climatic, tectonic and surface processes that influence the evolution of orogens and with the climatic signals archived in glacigenic strata. We review the current state of knowledge on the generation, transfer, and accumulation of glacigenic sediment from land to sea. We draw from geomorphology, marine geology, geochronology, numerical modeling of surface processes and landscape evolution, and experimental and field observations of glacier erosion and deposition, and the interaction of ice with its bed and the ocean boundary. Our primary goal is to examine glacial systems using a holistic source-to-sink approach, with a focus on describing a) how glacial motion produces sediment, b) how the sediments (sink) record the dynamic nature of glacial systems under different climatic (thermal) regimes, c) the challenges in using the sedimentary record to interpret these dynamics in space and time, and d) the approaches still needed to further our understanding of how ice and associated sediment fluxes respond to climatic and other perturbations. The dynamic state of ice, i.e., the ice flux and ice extent, is defined differently between the source and sink communities, reflecting the challenges of establishing a stratigraphic signal that volumetrically constrains glacigenic sediment production as a function of the ice response to climate. Advances in marine geophysics have greatly assisted our understanding of mass transfer pathways and of former ice extents as a measure of ice dynamics, and have identified the primary depocenters and key lithofacies of glacial sinks. Sediment fluxes associated with the dynamic state of the ice are best constrained where sediment volumes derived from key lithofacies and seismic reflection isopachs can be temporally partitioned, of which there are few examples, rather than from discrete point measures of sediment flux that are subject to sediment transfer biases. Forward numerical modeling of sediment fluxes as a function of ice dynamics agree with observational data at the continental-margin scale, but finer time/space scale ice-dynamic models do not yet recreate observed ice extent or flowpaths. Future source-to-sink work in glaciated systems should focus on refining empirical relationships between ice velocity and sediment production, and expand the application of existing methods to develop sediment volumes and fluxes in known depocenters of former and modern ice streams.

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1. Introduction

A principal goal of examining a sediment routing system is to understand how it responds to, and preserves a record of, the dynamic processes that drive sediment production and transfer. This is especially important in settings where the principal geomorphic agent that produced the sediment is no longer present or challenging to work with under modern conditions. Global climate during the Quaternary Era is distinguished by the periodic intensification of glacial conditions on land and along continental margins (Larsen et al., 1994; McKay et al., 2009; Lourens et al., 2010; Jakobsson et al., 2014). The onset of widespread glaciation is viewed as responsible for the global increase in sedimentation that coincided with a change to a cooler and more variable climate beginning ~2–4 Myr ago, creating clastic wedges on continental margins that are up to 5 km thick (Eyles et al., 1991; Vorren et al., 1991; Eidvin et al., 1993; Faleide et al., 1996; Elverhøi et al., 1998a; Solheim et al., 1998; Laberg et al., 2010). The majority of mid- and high-latitude landscapes, from the land to the deep sea, reflect extensive Quaternary glacial influence (Bingham et al., 2010; Champagnac et al., 2014; Pedersen et al., 2014), including large-scale depositional and erosional landforms such as voluminous loess and paraglacial terrestrial deposits (e.g., Derbyshire, 2003), scablands carved by meltwater (e.g., Hanson et al., 2012), ice-gouged seafloors (e.g., Dowdeswell and Bamber, 2007; Dowdeswell et al., 2007; Batchelor et al., 2011; Cofaigh et al., 2012; Dowdeswell et al., 2014), and thick accumulations of glacimarine sediments both on land and in the ocean (e.g., Eyles et al., 1991; Dahlgren et al., 2005; Laberg et al., 2010). Glacial source-to-sink systems consequently are a primary archive of past and present global change.

Glacial erosion and sediment production are of interest to a wide variety of scientific communities concerned with the interaction of climatic, tectonic and surface processes that influence the evolution of mountain ranges, and with the interpretation of climatic and tectonic signals archived in sediments produced by the ice. Glaciated landscapes were one of the first depositional environments where sedimentary signals such as glacial drift, erratics, and moraines were formally interpreted to describe a series of dynamic ice processes that were either absent from or significantly reduced in scale in the current landscape. Since the mid-1800s, glacial chronologies have been developed for many regions where the ice was once more extensive (e.g., Agassiz, 1840; Lyell, 1840; Chorley, 1973), and past global ice volumes have been estimated from the oxygen isotopic record preserved in marine sediments (Imbrie et al., 1984; Lisiecki and Raymo, 2007). While the marine isotope stage (MIS) records have provided broad constraints on the timing of recent and Quaternary glaciations (e.g., Lisiecki and Raymo, 2007; Kawamura et al., 2008), less is known about the internal dynamics of former glaciers and ice sheets and their relationship to climate. Over a century later, we are still grappling with how to link dynamic glacial processes with their sedimentary and geomorphic products.

Landscape modification by ice is profound. Our ability to evaluate how glaciers and glacial erosion shape landscapes, produce sedimentary signals, and reflect climatic (or tectonic) variability is still limited by a dearth of information about what controls the rate of glacial erosion and sediment production. Climate drives a glacier's mass balance, which in turn determines the ice flux that erodes the landscape (e.g., Benn and Evans, 2010; Cuffey and Paterson, 2010). Terrestrial and marine subglacial and proglacial environments are among the most logistically challenging environments to work in, hampering our ability to develop first-order relationships between ice dynamics and sediment production. Moreover, generating a chronology on the timing and magnitude of glacial erosion and deposition has always been challenging (e.g., Balco and Rovey, 2010; Fastook and Hughes, 2013; Ingólfsson and Landvik, 2013; Cofaigh et al., 2014), often requiring multiple approaches (Livingstone et al., 2012; Fastook and Hughes, 2013), but has recently become more robust with evolving geochronometric techniques (e.g., Rosenheim et al., 2008; Balco and Rovey, 2010; Simon et al., 2012).

Glacial source-to-sink systems are unique in that ice, the primary erosional agent, can move through almost the entire length of a system, from the high mountains to the continental shelf edge, during one climatic period and then be entirely absent during others (Fig. 1). Moreover, ice responds to climate by adjusting its spatial extent and its internal flow dynamics (e.g., Raymond, 1987), which vary in space and time its capacity to do geomorphic work and produce sediment. In addition, the potential for ice to recycle its sedimentary record as it advances and retreats through the transfer zone results in an incomplete record of dynamics closest to the ice, and an integrated record beyond the last ice maximum extent (Fig. 1; e.g., Faleide et al., 1996; Hebbeln et al., 1998; Anderson, 1999; Cofaigh et al., 2002; Hemming, 2004). The most complete record often exists in the marine realm, but this setting is subject to its own internal dynamics that mute terrestrial ice signals, and often results in a record that is overprinted by oceanographic processes and tectonic preconditioning of the basin (Figs. 1 and 2; Cofaigh et al., 2002; Nygård et al., 2005; Reece et al., 2011; Andrews and Vogt, 2014; Walton et al., 2014; Romans et al., 2016–this volume). As such, the sedimentary record associated with both ice flux as well as ice sheet growth and decay can reflect both autogenic and allogenic forcing, complicating our ability to directly relate ice dynamics and sediment production to any particular climatic forcing.

Yet, given these limitations, we still are able to develop general conceptual and quantitative models of the role of ice in the production of a sedimentary signal (Figs. 1 and 2). On orbital time scales, the growth and decay of ice has a global signal (Lisiecki and Raymo, 2007; Lourens et al., 2010; Patterson et al., 2014). At higher temporal resolutions, the terrestrial and marine stratigraphic records of glacier and ice sheet dynamics contain a combination of local and regional processes and influences, including the climate, thermal regime of the ice, subglacial hydrology, bedrock lithology, drainage basin topography and size, oceanographic setting, sea level, and tectonic conditioning. For instance, both sediment and meltwater production vary by orders of magnitude over time (e.g., seasonally), as a consequence of the thermal regime of the ice (i.e., temperate versus polar glacial systems), and between