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Landscape imprints of changing glacial regimes during ice-sheet build-up and decay: a conceptual model from Svalbard

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ABSTRACT

The behaviour of ice sheets and their geologic imprints in fjord regions are often multifaceted. Fjords, which were temporarily occupied by fast flowing ice-streams during major glaciations, and inter-fjord areas, which were covered by less active ice, show different signatures of past glaciations. The land and marine records of glaciations over the western Svalbard fjord region have been extensively studied during the last few decades. We have re-examined ice-flow records from stratigraphic and geomorphic settings, and propose a succession of ice-flow events that occurred repeatedly over glacial cycles: the maximum, the transitional, and the local flow style. The differently topographically constrained segments of the ice-sheet switched behaviour as glacial dynamics developed through each glacial cycle. These segments, as well as the different flow styles, are reflected differently in the offshore stratigraphic record. We propose that the glacial geomorphological signatures in the inter ice-stream areas mostly developed under warm-based conditions during a late phase of the glaciations, and that the overall glacial imprints in the landscape are strongly biased towards the youngest events.

1. Introduction

Marine-based ice sheets, as well as land-based ice sheets with marine margins, exist in a close interaction with the surrounding ocean. They are strongly influenced by changes in sea level, and represent major sediment sources for deposition along continental shelf margins as well as sources of meltwater and ice rafted detritus release to the adjacent ocean (Ottesen et al., 2005; Dowdeswell et al., 2010a). However, reconstructions of these interactions have not paid special attention to the complex nature and heterogeneity of the ice-sheet marginal dynamics, and considered ice sheets as large scale uniform systems (Landvik et al., 1998; Svendsen et al., 2004; Ingólfsson and Landvik, 2013).

One condition for understanding ice-sheet marginal dynamics is a better insight to the shifts in ice-flow directions over time. Reconstructions using spatial landform distribution data for ice-flow mapping have improved our understanding of palaeo ice-sheet dynamics. Boulton and Clark (1990a,b) used satellite imagery to identify regional scale glacial lineations that were grouped into flow-sets and flow switching is established from their cross-cutting relationships. Kleman and Borgström (1996) and Kleman et al. (2006) proposed an inversion model, where glacial lineations over large areas are grouped into swarm types, characterized by different glaciological controls as well as basal conditions during their formation. This method has demonstrated useful in recent glaciodynamic reconstructions of the Laurentide, British, Fennoscandian and southern Barents Sea ice sheets (Greenwood et al., 2007; De Angelis and Kleman, 2008; Greenwood and Clark, 2009; Stokes et al., 2009, 2012; Kleman et al., 2010; Winsborrow et al., 2010, 2012).

At its maximum, the Late Weichselian Svalbard–Barents Sea Ice Sheet extended to the Barents shelf edge in the west and north (Landvik et al., 1998; Svendsen et al., 2004), a position that had also been repeatedly attained by preceding glaciations (Mangerud et al., 1998; Vorren et al., 2011; Ingólfsson and Landvik, 2013) (Fig. 1). These essentially two-dimensional maximum ice-extent reconstructions have later been elaborated by a better understanding of the ice sheet's three dimensional geometry over the Svalbard archipelago (Landvik et al., 2003, 2013; Hormes et al., 2011; Gjermundsen et al., 2013), and largely confirmed by ice-flow patterns mapped from seafloor morphology (Ottesen et al., 2005, 2007; Winsborrow et al., 2010, 2012; Hogan et al., 2010a,b; Batchelor et al., 2011; Rebesco et al., 2011). These studies also show that the ice-sheet margins did not behave in a synchronous

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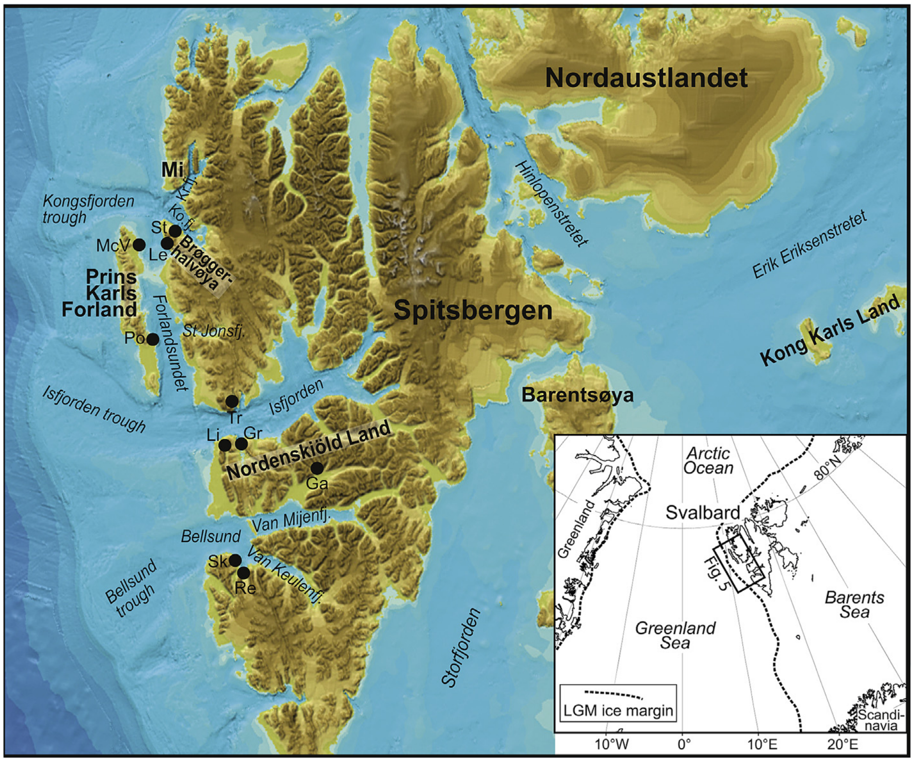

Fig. 1. Location map. Base map from IBCAO v. 3.0 (Jakobsson et al., 2012). Abbreviations used: Mi = Mitrahalvøya; Kr.fj. = Krossfjorden; Ko.fj. = Kongsfjorden; St = Stuphallet; McV = McVitiepynten; Le = Leinstranda; Po = Poolepynten; Tr = Trygghamna; Li = Linnédalen; Gr = Grønnfjorden; Ga = Gangdalen; Sk = Skilvika; Re = Recherchefjorden.

manner and that different segments of the ice sheet responded differently to changes in the forcing mechanisms exerted on them (Landvik et al., 2005, 2013; Winsborrow et al., 2010). Consequently, our present perception of the Last Glacial Maximum (LGM) configuration of the Svalbard–Barents Sea Ice Sheet does neither allow for reconstructing regional variability in the timing of maximum extent (Clark et al., 2009) nor a clear understanding of its geometrical changes over a glacial cycle (Ingólfsson and Landvik, 2013).

We address these issues by proposing a conceptual model based on a review and re-examination of published stratigraphic and geomorphic records from western Svalbard (Fig. 1). Our aim is to look for patterns that can explain the often enigmatic stratigraphic and morphological fingerprints of past glaciations. Over the past three decades, numerous glacial stratigraphic and geomorphological studies on the west coast of Svalbard have aimed at gaining a better understanding of ice-sheet dynamics and glacial history (see Ingólfsson and Landvik, 2013). Paired with recent marine geological studies of seafloor morphology and stratigraphy from the western Svalbard continental shelf, troughs and fjords, they provide an opportunity to reconstruct ice-flow dynamics and geomorphic and sedimentary signatures of ice-flow switching through time. By applying a downscaled inverse modelling approach (Kleman et al., 2006) on these stratigraphic and geomorphic records, ice-sheet properties during different styles of ice flow can be reconstructed. Using mainly stratigraphic data, we accept that our generalized reconstructions rely on spatially limited observations. However, our stratigraphic approach provides undisputable age succession of the different ice-flow episodes within each area. Our approach is conceptual, focussing on successive changes in styles of ice flow and the associated consequences for landscape imprints. As these changes are transgressive in time and space, we do neither attempt regional correlations of flow-style changes nor attempt tying them to the Svalbard deglaciation chronology.

2. Ice-flow styles from the Svalbard west coast

In a recent study, Landvik et al. (2013) used the inter-fjord area of Forlandsundet and Prins Karls Forland and the adjacent Isfjorden and Kongsfjorden fjords to reconstruct a succession of three different glacial dynamic events for the Late Weichselian glaciation: the maximum glaciation phase, the tributary ice-stream phase, and the local ice caps and readvances phase (Landvik et al., 2013: Fig. 5). We have explored this concept further, going back in time and extending the spatial coverage, and present a refined definition of the phases to which we assign the term “flow styles”.

Three categories of ice-flow styles have been established based on the three phases suggested by Landvik et al. (2013): maximum flow style, transitional flow style and local flow style based, on stratigraphic records as well as geomorphic data (Figs. 2 and 3). The main criterion for the classification is the degree of topographic constraint on the flow, as defined and described below (see Sections 2.1–2.3). We cannot determine the exact lateral coverage of the three different flow style regimes over time. Our focus is instead on the ice-flow shifts in the stratigraphic domain, but the concept may be compared to modern flow-set reconstructions (e.g., Kleman et al., 2006; Stokes et al., 2009) that focus on the spatial domain.

We have reviewed seven areas (see Sections 3.1–3.7) from the west coast of Svalbard (Fig. 3), in both fjord and inter-fjord settings, where successions of past ice-flow directions can be reconstructed. Each flow style preserved in the geologic record at a site has been assigned a directional arrow in Fig. 3.

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