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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.

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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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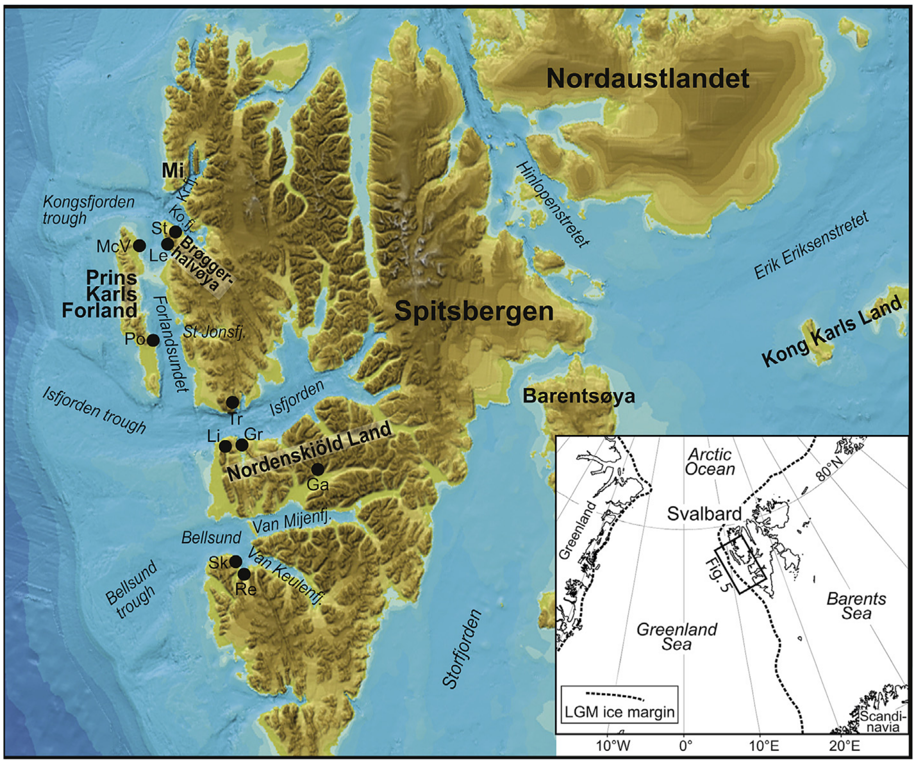

Fig. 1. Location map. Base map from IBCAO v. 3.0 (Jakobsson et al., 2012). Abbreviations used: Mi = Mitrahalvøya; Kr.fj. = Krossfjorden; Ko.fj. = Kongsfjorden; St = Stuphallet; McV = McVitiepynten; Le = Leinstranda; Po = Poolepynten; Tr = Trygghamna; Li = Linnédalen; Gr = Grønnfjorden; Ga = Gangdalen;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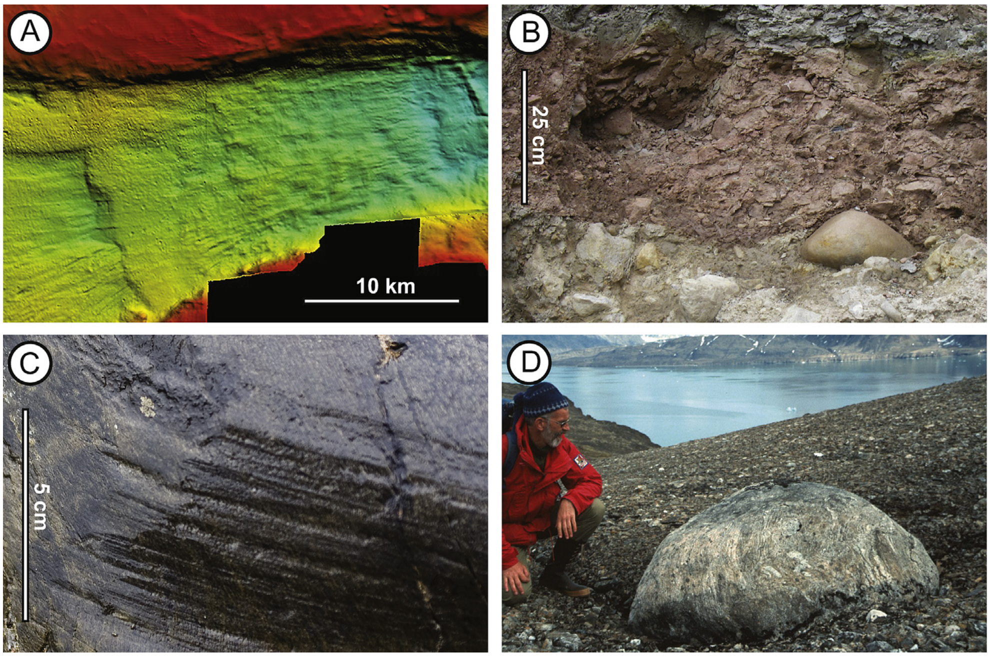

Fig. 2. Examples of ice-flow indicators utilized in this study. A. Seafloor lineations and grounding zone wedge (moraine) in the Kongsfjorden trough (modified from Ottesen et al., 2007). B. Subglacial till with petrographic and clast fabric information. The reddish till bed is from site Leinstranda (modified from Alexanderson et al., 2011a: Fig. 5C). C. Glacial striae along Kongsfjorden (Photo: Gustaf Peterson). D. Glacial erratic on Mitrahalvøya (Landvik et al., 2013).

2.1. *Maximum flow style*

Maximum flow style existed when at least parts of the ice sheet experienced topographically unconstrained ice flow, cf. Landvik et al. (2013) "maximum glaciation". For the most extensive glaciation in our records (the Late Weichselian), the maximum flow style reconstruction is primarily based on seafloor megascale glacial lineations (MSGL) in the fjords and troughs (Landvik et al., 2005, 2013; Ottesen et al., 2007) (Fig. 2A), often associated with terminal moraines on the continental shelf reflecting largely topographically unconstrained ice flow. In the fjords and troughs, the till deposition and MSGL formation suggest that ice-streams existed (Landvik et al., 2005; Ottesen et al., 2007), whereas the inter-fjord areas experienced a less active ice flow towards the ice-sheet margin (Landvik et al., 2005, 2013). Maximum flow style is also mapped from till fabric and provenance studies in stratigraphic records (Fig. 2B), glacial striae and erratics (Fig. 2C, D), as well as exposure age constrained minimum ice surfaces over some of the land areas.

2.2. *Transitional flow style*

This is a topographically constrained ice flow, mainly in a fjord setting. It is based on the Landvik et al. (2013) "tributary ice-streams", but may also include the signatures of topographically constrained non ice-stream behaviour. Similarly to the maximum flow style, the signatures of transitional flow include seafloor MSGL and drumlins, recessional moraines and grounding zone wedges, and the flow direction is easily identified when it differs distinctly from the preceding maximum flow. For the last glaciation, the transitional flow style is also documented by land records from sites along the fjords: glacial striae, till fabric and provenance of erratic boulders. In fjords and valleys, maximum and transitional flow style may be parallel due the similar topographical constraints, and secondary criteria as glacier extent and thickness has been used to differentiate between the two. For example, whereas ice during the maximum ice-flow style mostly reached the continental shelf, it was limited to the fjords and sounds during transitional flow style. In the coastal areas the transitional ice flow does mostly reflect tributary ice-streams (Rignot et al., 2011) or ephemeral ice-streams (Kleman et al., 2006), initiated by the breakup of ice-streams and outlet glaciers in the major fjords.

2.3. *Local flow style*

This is topographically constrained ice-flow, predominantly in the terrestrial environment. The most important signatures are terminal moraines and tills deposited by ice flowing from local ice caps, piedmont glaciers, or valley and cirque glaciers (Landvik et al., 2013). Abundant geological signatures of local flow style from the last deglaciation overprint the older landscape and sediments. In the stratigraphic record, the local flow style is primarily represented by tills containing clasts of local provenance supported by preferred clast orientation and glaciotectonic structures, as well as proglacial meltwater deposits formed during periods of high relative sea level. The distinct neoglacial and surge moraines in front of many Svalbard outlet glaciers are not included in this study, as their geomorphic significance is not enigmatic. However, they do illustrate landscape evolution within the regime of local flow style.

3. Review of ice-flow data

We have compiled ice-flow data from various sources within seven different areas, encompassing both land and seafloor records (Fig. 3). All the ice-flow data presented, except those for Kongsfjorden glaciation K-2 and K-3, are from published studies. References to the sources of primary data are in the text and in Fig. 3. Glaciations in each area have been numbered in ascending age order, starting with the youngest glaciation. Each glaciation is

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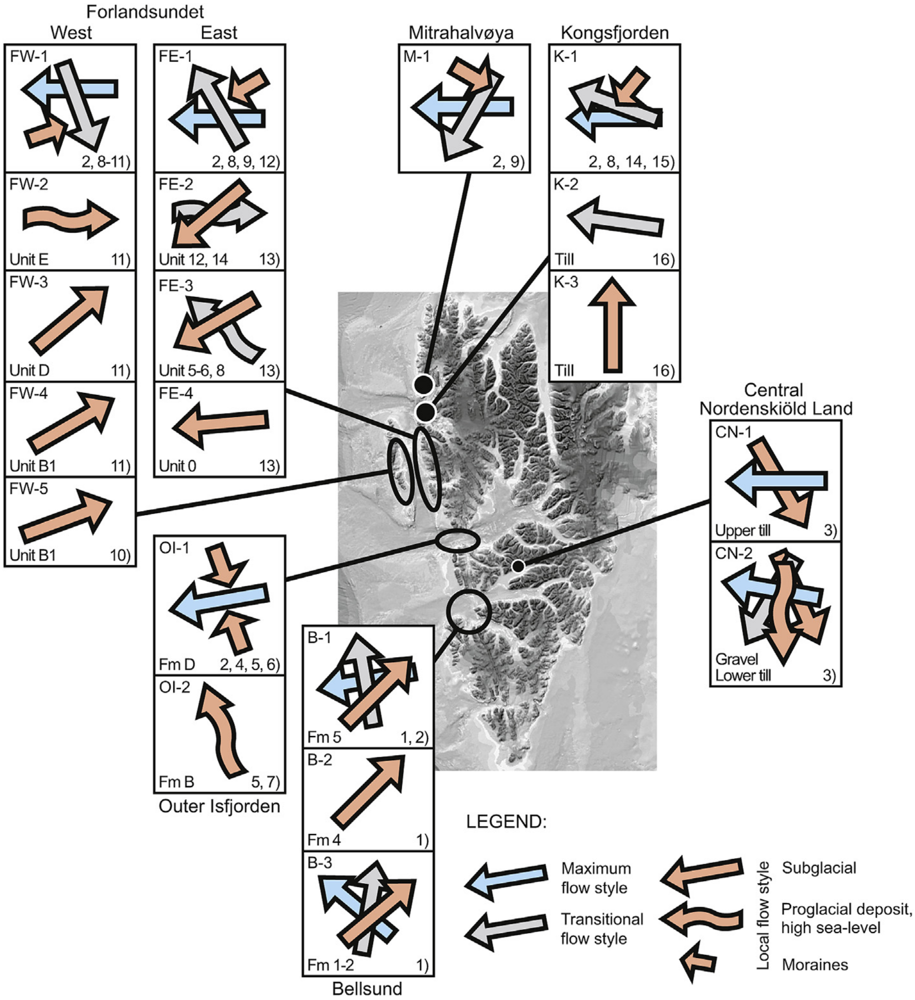

Fig. 3. Records of ice flow from the west coast of Svalbard. Different flow styles are shown from oldest (bottom) to youngest (top) at each site. Neoglacial and known surge advances are excluded. The boxes represent separate glaciations, relative ages have been established from stratigraphic and cross-cutting relationships. Upper left corner of each box: glaciation number; lower left: stratigraphic unit, when applicable; lower right: data reference. Glaciation numbers (e.g., FE-1) consists of an area prefix (e.g., Forlandsundet East = FE) and a number from youngest (1) to oldest (5). References: 1) Landvik et al. (1992); 2) Ottesen et al. (2007); 3) Landvik and Salvigsen (1985); 4) Svendsen et al. (1992, 1996); 5) Lønne and Mangerud (1991); 6) Forwick and Vorren (2009); 7) Lønne (1997); 8) Landvik et al. (2005); 9) Landvik et al. (2013); 10) Andersson et al. (1999); 11) Andersson et al. (2000); 12) Forman (1989); 13) Alexanderson et al. (2011a); 14) Lehman and Forman (1992); 15) Henriksen et al. (2014); 16) Alexanderson et al. (unpublished data).

based on a distinct lithostratigraphic unit from the cited study, and may contain a succession of different flow styles (Fig. 3).

3.1. Bellsund (outer Van Mijenfjorden)

The three fjords, Van Mijenfjorden, Van Keulenfjorden and Recherchefjorden, lead to the c. 20 km wide embayment of Bellsund at the head of the Bellsund cross-shelf trough (Fig. 1). The 700–800 m-high mountains along the coast are dissected by several wide valleys, and bordered by a well-developed strandflat to the west. The ice-flow reconstructions (Fig. 3) are based on stratigraphic studies of the Skilvika sediment successions at the south coast of Bellsund (Troitsky et al., 1979; Landvik et al., 1992), and seafloor morphology from the Bellsund trough and adjacent shelf (Ottesen et al., 2007).

Glaciation B-1 (Late Weichselian). A maximum ice-flow style is shown by MSGLs as well as a series of transverse recessional moraines in the Bellsund trough (Ottesen et al., 2007). A younger transitional flow style with a northerly flow constrained by the tributary Recherchefjorden is shown by till fabric and till petrography in the Skilvika sections (Fm 5: Landvik et al., 1992). Towards the top of the till bed, fabric and petrography show a switch to a northeasterly local flow style from the basin occupied by the present Scottbreen glacier (Landvik et al., 1992).

Glaciation B-2. Local ice-flow style from the Scottbreen basin is shown by prograding diamictic bouldery foresets, interfingering distally with shallow-marine sediments. The foresets were deposited directly from the ice margin at a time when relative sea level was c. 30 m higher than present (Fm 4: Landvik et al., 1992).

Glaciation B-3. Maximum flow style is inferred from two 5–10 m-thick till beds that rest on Palaeogene bedrock (Fm 1 and 2: Landvik et al., 1992). Till fabric and clast provenance show an upward switch from north-westerly maximum flow style to a transitional northerly flow style out of Recherchefjorden, and terminating with a local ice-flow style derived from a glacier in the Scottbreen basin.

3.2. Central Nordenskiöld Land

A sediment section in Gangdalen, a tributary to the large Reindalen valley (Fig. 1), provides a unique record of glacial inception in an inter-fjord area. All ice-flow reconstructions (Fig. 3) are from

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Landvik and Salvigsen (1985) who reported a stratigraphy where striated bedrock is overlain by two tills separated by 15 m of glaciofluvial gravels.

Glaciation CN-1. At the base of the till bed (Gangdalen upper till: Landvik and Salvigsen, 1985), till fabric and petrography record a topographically constrained local ice-flow style out of a tributary valley to Gangdalen. A switch to a maximum flow style is recorded by till fabric, showing a topographically unconstrained ice flow across Gangdalen.

Glaciation CN-2. Glacial striae on bedrock show an older phase of topographically constrained local ice-flow style out of a tributary valley west of Gangdalen. Cross-cutting glacial striae show a switch to transitional ice-flow style from the mountains to the east. Till fabric and petrography in the overlying till bed (Gangdalen lower till: Landvik and Salvigsen, 1985) reveal a younger WNW maximum ice-flow style across the Gangdalen valley. The subsequent local ice-flow style is inferred from a 15 m-thick bed of sandur deposits which show meltwater flow from a retreating glacier in the inner part of the Gangdalen valley (Gangdalen gravel: Landvik and Salvigsen, 1985). Based on reconstructed sandur gradients, Landvik and Salvigsen (1985) concluded that sea level was 40–80 m higher than present during deposition, indicating deposition subsequent to glacio-isostatic loading.

3.3. Outer Isfjorden

Isfjorden (Fig. 1) continues westward as the Isfjorden cross-shelf trough, which has repeatedly acted as an ice-stream conduit (Landvik et al., 1998; Vorren et al., 1998; Ottesen et al., 2007) during what we classify as maximum ice-flow style phases. The coastal mountain range reaches 600–800 m a.s.l., and coast-parallel fjords and valleys (e.g., Grønfjorden, Linnédalen, Trygghamna) have constrained transitional or local flow style. The ice-flow data (Fig. 3) are obtained from studies in the Linnédalen valley on the south coast of outer Isfjorden (Lønne and Mangerud, 1991; Mangerud et al., 1992) as well as from sediment cores (Svendsen et al., 1992, 1996; Forwick and Vorren, 2009) and seafloor morphology (Ottesen et al., 2007) from outer Isfjorden and the Isfjorden trough.

Glaciation OI-1 (Late Weichselian). A maximum ice-flow style (Fig. 3) is inferred from trough-parallel MSGLs on the seafloor (Ottesen et al., 2007) and subglacial till in sediment cores from the Isfjorden trough (Svendsen et al., 1992, 1996; Forwick and Vorren, 2009). Studies on land have failed to detect the same ice flow (Mangerud et al., 1992), but subglacial till (Fm D: Lønne and Mangerud, 1991) and glacial striae (Mangerud et al., 1992: Fig. 2) in Linnédalen show a period with a local ice-flow style towards the north. Seafloor studies also show topographically constrained local ice-flow style out of Grønfjorden to the east, and Trygghamna on the north side of the fjord (Forwick and Vorren, 2010).

Glaciation OI-2. A local ice-flow style towards the north, out the Linnédalen valley, is shown in the sediment successions along the Linnéelva river (Fm B: Lønne and Mangerud, 1991; Lønne, 1997), where ice marginal conditions were inferred from a proglacial fan formed during a sea level > 28 m higher than today.

3.4. Forlandsundet

The Forlandsundet strait (Fig. 1) in the inter-fjord area between Isfjorden and Kongsfjorden has been excavated along a Late Palaeogene graben (Hjelle et al., 1999) and separates the island of Prins Karls Forland from Spitsbergen. Past ice-flow data are provided by several sediment successions recording Late Quaternary glacial events along the coastlines of Prins Karls Forland (Salvigsen, 1977; Andersson et al., 1999, 2000; Alexanderson et al., 2013) and Spitsbergen (Forman, 1989; Miller et al., 1989; Alexanderson et al., 2011a,b).

Glaciation FW-1 and FE-1 (Late Weichselian). The entire Forlandsundet strait experienced a phase of maximum ice-flow style (Fig. 3). Seafloor moraine ridges and stratigraphy west of Prins Karls Forland (Landvik et al., 2005; Ottesen et al., 2007; Vanneste et al., 2007) show that glacial ice extended to the shelf edge, in agreement with westerly glacial striae and Spitsbergen erratics on the island itself (Landvik et al., 2013). The ice-sheet surface reached an elevation of >470 m a.s.l. on Prins Karls Forland as shown by ^{10}Be exposure age dated erratics (Landvik et al., 2013).

The maximum ice-flow style was succeeded by a transitional flow style with strait-parallel ice flow, both towards the NNW and SSE (Fig. 3). The transitional flow style is mapped from MSGLs (Ottesen et al., 2007: Fig. 3A) as well as from glacial striae along the Spitsbergen coastline, e.g. Engelskbukta (sites EG7 and EG8: Forman, 1989). Grounding zone wedges at both north and south entrances to the strait (Ottesen et al., 2007) show that the transitional flow style was active after breakup of ice in both Isfjorden and Kongsfjorden.

A final phase of local ice-flow style, at some places glacier advances, is recognized at several sites (Fig. 3). From the Poolepynten area on Prins Karls Forland, Andersson et al. (1999) showed an expansion of the Archibald Geikie glacier during a period of high (c. 36 m a.s.l.) relative sea level. Along the northeast coast of Prins Karls Forland, both Boulton (1979) and Andersson et al. (2000) mapped a till cover of local origin along the mountain slope, assumed by them to represent the Late Weichselian maximum. From their descriptions we classify it as a local flow style, most likely derived from an advance of piedmont type glaciers. From several sites along the Spitsbergen coast, Forman (1989) showed a westward ice flow based on till fabric and glacial striae. At Engelskbukta, both glacial striae and till fabric show westward local flow style succeeding the transitional strait-parallel flow style (Forman, 1989: Fig. 2). He concluded an expansion of local glaciers into open strait environments during the Late Weichselian. Such a westward flow of the glacier in St. Jonsfjorden was also shown by Evans and Rea (2005). As for Prins Karls Forland, we conclude that this local ice-flow style occurred as a final phase after the deglaciation of the Forlandsundet strait.

3.5. Forlandsundet east coast (Spitsbergen)

All information on flow style changes is from studies of the sediment succession at Leinstranda in the NE part of the strait (Miller et al., 1989; Alexanderson et al., 2011a) (Figs. 1 and 3).

Glaciation FE-2. Ice proximal deposition towards the sector SE–NE during sea level > 22 m higher than present suggests the presence of a glacier in northern Forlandsundet (Unit 12: Alexanderson et al., 2011a), which we classify as a transitional flow style. A thin bed of beach gravel separates these deposits from a till (Unit 14: Alexanderson et al., 2011a) where both till fabric and petrography suggest a local ice-flow style off Brøggerhalvøya. The sandwiched beach sediments may indicate a drop in sea level and that considerable time occurred between the two ice-flow styles.

Glaciation FE-3. Transitional ice-flow style out of Engelskbukta is shown by ice proximal glaciomarine deposits formed during a sea level > 16 m higher than present (Units 5–6: Alexanderson et al., 2011a). The overlying till (Unit 8) shows a switch to a local WSW flow off Brøggerhalvøya.

Glaciation FE-4. A phase of local ice-flow style off Brøggerhalvøya is shown by glacial striae on the bedrock (Unit 0: Alexanderson et al., 2011a) underlying the Leinstranda sediment succession (Fig. 3).

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3.6. Forlandsundet west coast (Prins Karls Forland)

Pre Late Weichselian ice-flow data are recorded in the sediment successions north of Poolepynten (Andersson et al., 1999; Alexanderson et al., 2013) and at McVitiepynten (Salvigsen, 1977; Boulton, 1979; Andersson et al., 2000) (Fig. 1). All records show a local ice-flow style from Prins Karls Forland (Fig. 3).

Glaciation FW-2. An extensive glaciofluvial delta in the McVitiepynten sediment succession was deposited from a local glacier on northern Prins Karls Forland (Unit E: Andersson et al., 2000), and show local ice-flow style. Sea level was >15 m higher than present, and a distinct paleosol on the top of the unit show a subsequent relative sea level lowering, probably due to isostatic rebound, suggesting that the local ice flow followed a regional deglaciation (Andersson et al., 2000).

Glaciations FW-3 and FW-4. Two separate phases of local ice-flow style are recorded by subglacial tills in the McVitiepynten sections (Units D and B1: Andersson et al., 2000), both reflecting advances of local glaciers on northern Prins Karls Forland.

Glaciation FW-5. Local ice-flow style is also reported from Poolepynten where an expansion of local glaciers on Prins Karls Forland is shown by a subglacial till (Unit B1: Andersson et al., 1999) with a distinct till fabric and local petrographic content.

3.7. Kongsfjorden

The 200–300 m deep Kongsfjorden/Krossfjorden system, bordered by up 800–900 m-high mountains, and the extensive Kongsfjorden cross-shelf trough (Fig. 1) has repeatedly acted as a major conduit for past ice flow in NW Svalbard (Landvik et al., 1998, 2005; Vorren et al., 1998; Ottesen et al., 2007). The ice-flow data (Fig. 3) derive both from seafloor morphology from the trough and the shelf (Landvik et al., 2005; Ottesen et al., 2007), glacial geomorphology on land (Lehman and Forman, 1992; Peterson, 2008; Henriksen et al., 2014), as well as stratigraphic data from the Kongsfjorden coasts (Miller, 1982; Boulton et al., 1982; Alexanderson, unpublished data).

Glaciation K-1 (Late Weichselian). The westerly maximum ice-flow style is inferred from the MSGLs and recessional moraines in the Kongsfjorden trough (Landvik et al., 2005; Ottesen et al., 2007). A subsequent topographically constrained transitional flow style, with ice filling Kongsfjorden, is shown by the moraine along the northern shore (the Kongsfjorden moraine) (Lehman and Forman, 1992; Henriksen et al., 2014) as well as drumlins on the fjord floor inside the moraine (Howe et al., 2003: Fig. 3). A late phase of local flow style is shown by prominent moraine lobes left by valley glaciers cross-cutting the transitional style Kongsfjorden moraine (Peterson, 2008; Henriksen et al., 2014).

Glaciation K-2. From the southern shore of Kongsfjorden, a transitional flow style, parallel to the fjord, is inferred from till fabric in a reddish subglacial till in the Stuphallet sections (Alexanderson et al., unpublished data).

Glaciation K-3. Local flow style towards the north, off the Brøggerhalvøya peninsula, is inferred from till fabric in the Stuphallet sections (Alexanderson et al., unpublished data). However, the petrographic content may suggest a more transitional character.

3.8. Mitrahalvøya

Krossfjorden is separated from the ocean by the Mitrahalvøya peninsula, with it's up to 600 m-high mountains and 3–5 km wide strandflat to the west (Fig. 1). We address Mitrahalvøya as a separate area from Kongsfjorden, as it represents a coast/shelf setting in contrast to the adjacent Kongsfjorden fjord/trough.

Glaciation M-1. The ice-flow switching over the Mitrahalvøya peninsula (Fig. 3) compares to the record from the Forlandsundet west coast (see Section 3.6). The topographically unconstrained maximum ice-flow style across Mitrahalvøya is suggested by the north–south trending moraines on the continental shelf to the west (Ottesen et al., 2007). The moraines' curvature towards the Kongsfjorden trough (Ottesen et al., 2007) suggests that maximum style ice-flow from Mitrahalvøya prevailed after the maximum flow style had ended in the trough. Subsequently, the transitional ice-flow style was constrained by the Krossfjorden basin as shown by glacial striae (Landvik et al., 2013) and erratics (Gjermundsen et al., 2013; Landvik et al., 2013), and probably existed after the breakup of the ice-stream in the Kongsfjorden trough. Glacial striae along the western shore of Krossfjorden (Landvik et al., 2013) show a last phase of local ice-flow style constrained by the valleys on Mitrahalvøya.

4. Discussion

4.1. Flow style successions and their geological characteristics

Based on the geological signatures left by different ice-flow styles over several glaciations (Fig. 3), we have reconstructed a generalized succession of ice-flow switching during ice-sheet build-up and decay. We have also evaluated the geological significance and characteristics of the different flow styles through this succession (Fig. 4).

4.1.1. Ice-sheet build-up

As glaciers and ice sheets grow, the zones of erosion and deposition will migrate over older glacial landforms and sediments, strongly reducing the preservation potential of pre glacial and early growth-phase sediments and landforms. The only records of western Svalbard ice-sheet build-up are from Gangdalen on central Nordenskiöld Land (Figs. 1 and 3). Two glaciations (CN-1 and CN-2) show growth of local glaciers before a switch to transitional and maximum ice-flow style (Fig. 3). As glaciers on Spitsbergen expanded, the shift to transitional ice-flow style suggests formation of valley or tidewater glaciers as outlets from local ice caps (Landvik and Salvigsen, 1985). Meltwater production is recorded by the deposition of sandur sediments and show warm-based conditions, but no ice rafted debris (IRD) delivery to the marine environment can be expected until tidewater glaciers have formed (Fig. 4). Further ice expansion caused a shift to maximum ice-flow style unconstrained by the topography.

4.1.2. Ice-sheet decay

The most complete record of ice-sheet decay derives from the Late Weichselian where the successively less extensive ice-flow events facilitate preservation of the older glacial landforms and sediments (Fig. 3). Thus, the preservation potential of different ice-flow phases is also skewed towards the younger events (Fig. 4). The regional correlation of the Late Weichselian glacial events (Landvik et al., 2005, 2013) enables a flow-set type reconstruction (Stokes et al., 2009) of both the lateral extent and the relative succession of flow styles (Fig. 5). At all coastal sites, both in the fjord/trough and inter-fjords areas (Figs. 3 and 4), the successions start with evidence for a maximum flow style, succeeded by the transitional flow styles, and a last spatially limited overprint by the local flow style (Fig. 5). We will discuss the ice-flow styles in more detail:

4.1.2.1. Maximum extent. During maximum extent, the ice sheet reached the shelf edge off the entire west coast of Svalbard (Landvik et al., 1998) (Fig. 5). However, two different modes of ice flow occurred in the fjord/trough systems and the inter-fjord areas,

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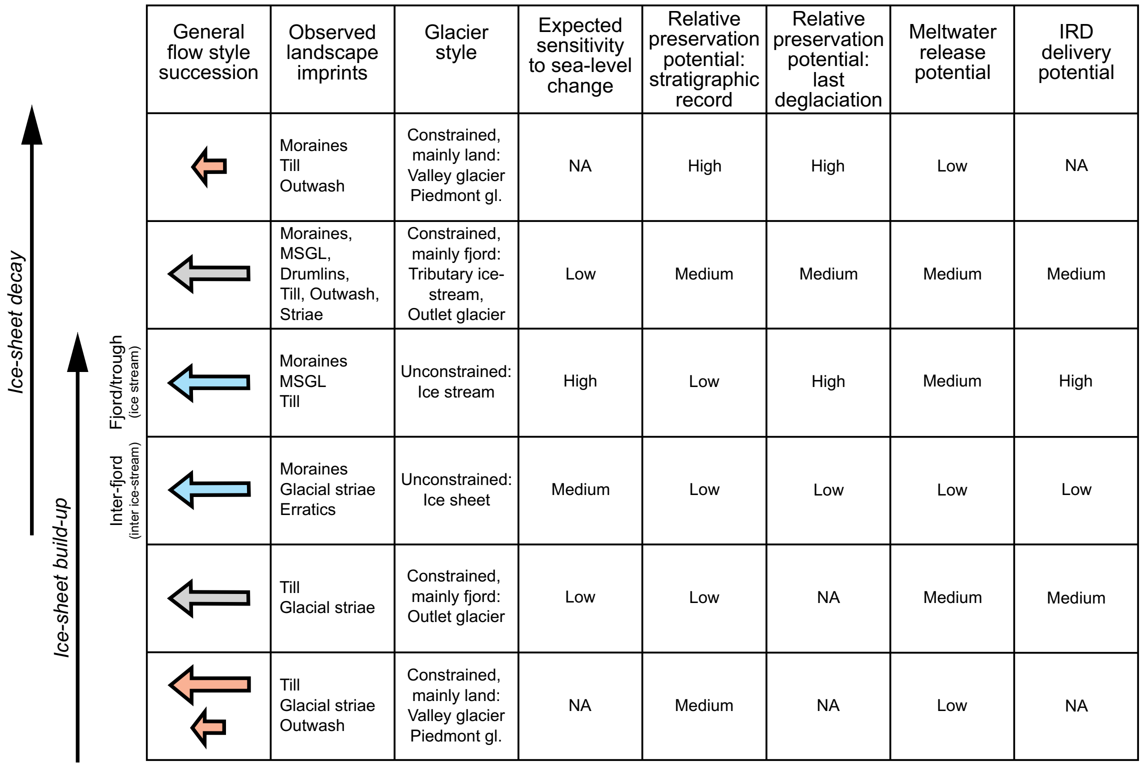

Fig. 4. Generalized succession of flow styles during one glaciation, their geological significance and characteristics. Flow style arrows are as in Fig. 3. See text for details.

respectively. In the cross-shelf troughs, the maximum flow style was characterized by fast flowing ice-streams (Fig. 5: thick blue arrows, in the web version), leaving behind a record of subglacial deposits and MSGLs (Landvik et al., 2005; Ottesen et al., 2007), and supplying sediments to the construction of the large trough-mouth fans (Vorren et al., 1998). These geological signatures suggest that warm-based conditions prevailed under these ice-streams. In the inter-fjord areas, glacial striae and erratics (Landvik et al., 2013) as well as end moraines on the shelf (Landvik et al., 2005; Ottesen et al., 2007) suggest evidence of an unconstrained westward maximum flow style (Fig. 5: thin blue arrows, in the web version). At the same time, there was limited sediment supply to the shelf edge (Dowdeswell and Elverhøi, 2002) as well as limited shelf progradation (Vanneste et al., 2007). Compared to the adjacent ice-streams, the inter-fjord areas experienced less active, perhaps periodically locally cold-based ice (Landvik et al., 2005, 2013).

4.1.2.2. Transitional flow. A deglaciation of ice-streams in the cross-shelf troughs prior to the deglaciation in the inter-fjord areas has been shown both from the Isfjorden (Mangerud et al., 1992; Svendsen et al., 1996; Forwick and Vorren, 2009, 2010) and the Kongsfjorden troughs (Landvik et al., 2005; Ottesen et al., 2007; Henriksen et al., 2014). The deglaciation was probably induced by sea level rise (Landvik et al., 1998; Hormes et al., 2013), and allowed for the onset of the transitional flow style in the form of topographically constrained tributary or ephemeral ice-streams draining towards the ice-free troughs and outer fjords, or as tidewater outlet glaciers that stabilized in the inner fjords (Henriksen et al., 2014) (Fig. 5: grey arrows). The streamlined seafloor morphology (Fig. 3: FW-1, FE-1) (Ottesen et al., 2007) as well as glacial erosion and till deposition at several sites (Fig. 3: FE-1, B-1, M-1) (Forman, 1989; Landvik et al., 1992) suggest that predominantly warm-based conditions existed.

The marine-based ice-streams and outlet glaciers allowed for IRD delivery to the ocean (Fig. 4). In the stratigraphic record, sandur deposits formed during high sea-level (Fig. 3: FE-2, FE-3) are probably related to deglaciation events, showing that the transitional flow style had potential for meltwater release (Fig. 4).

4.1.2.3. Local flow. Evidence for the expansion of local glaciers succeeding major deglaciations is recorded in all coastal areas we have studied (Fig. 3). In the Late Weichselian/Early Holocene record, the local ice-flow phase is associated with subglacial till deposition and/or terminal moraine formation, suggesting active flow and predominantly warm-based conditions (Fig. 5: wide red arrows, in the web version). This ice-flow style is recorded in most areas (Fig. 3), but it was probably of relatively short duration.

4.2. Conceptual model of ice-flow styles and glacial imprints

The distinct contrast in geological records between the inter-fjord and fjord/trough areas can be understood in terms of lateral and temporal differences in glacial regime (Fig. 6). There is firm evidence that the Late Weichselian Svalbard–Barents Sea Ice Sheet extended to the continental shelf edge west of Svalbard (Landvik et al., 1998, 2005; Ottesen et al., 2007). However, the geological signatures left on the glacially inundated terrains, both seafloor and terrestrial, vary significantly with the change of flow styles through time, and with the fjord/trough vs. inter-fjord setting (Figs. 4 and 6).

4.2.1. Spatial and temporal variations in glacial imprints

In the inter-fjord (inter ice-stream) areas, only limited signatures of past subglacial activity can be observed (Landvik et al., 2013), despite a considerable duration of ice cover. The abundant preservation of pre Late Weichselian sediments (Landvik et al., 2005: Fig. 8) suggests that relatively limited glacial erosion occurred under all three flow style regimes. There was limited

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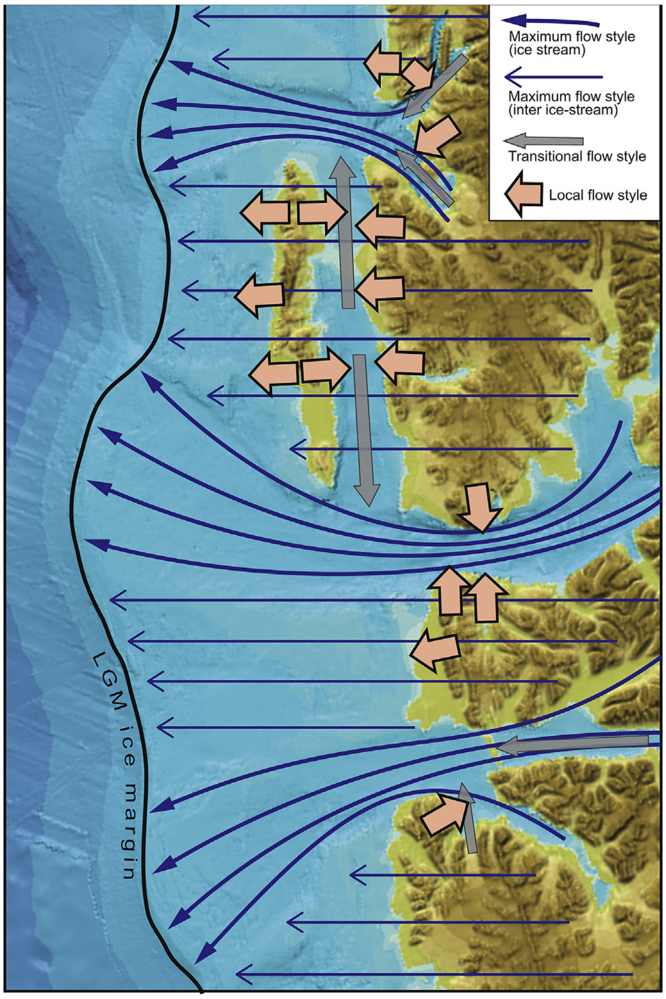

Fig. 5. Spatial distribution and succession of flow styles during the Late Weichselian maximum and subsequent ice-sheet decay (Fig. 3) along the west coast of Svalbard. See Fig. 1 for location. Base map from IBCAO v. 3.0 (Jakobsson et al., 2012).

sediment transport to the continental shelf edge during maximum flow (Vanneste et al., 2007), and the shelf is geomorphologically dominated by retreat moraines and transverse ridges (Landvik et al., 2005; Ottesen et al., 2007; Ottesen and Dowdeswell, 2009), in strong contrast to the streamlined morphology in the cross-shelf troughs. On land, however, scattered glacial erratics and tills of local provenance were deposited during a late stage of the last deglaciation (Boulton, 1979; Forman, 1989; Andersson et al., 1999, 2000), and clearly reflect local flow style. Consequently, we conclude that the landscape imprints of maximum and transitional flow styles in the inter-fjord areas have a low preservation potential (Fig. 4), and that the record of glacial signatures is skewed towards the younger events that left the strongest imprints on the landscape (Fig. 6).

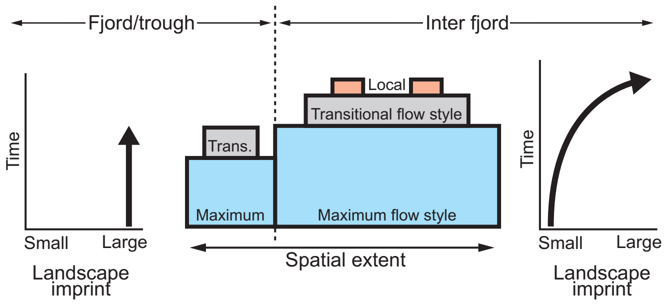

Fig. 6. Glacial landscape imprints in a fjord/trough vs. an inter-fjord area. The boxes show the relative spatial extent and duration of the different flow styles in the fjord/trough and inter-fjord areas. The diagrams on each side illustrate how the different flow styles contribute to the landscape imprints preserved in the geologic record. Note the contrast between the two areas.

The fjords and cross-shelf troughs (Fig. 6) constitute well defined ice-stream zones with till deposition (Svendsen et al., 1996; Landvik et al., 2005) associated with subglacial streamlining formed at the sediment/ice interface (Ottesen et al., 2007; Ottesen and Dowdeswell, 2009). This active glacial mode is also shown by the high glacial sediment flux to the shelf edge accommodating for the progradation of the extensive trough-mouth fans (Vorren et al., 1998; Butt et al., 2000; Dowdeswell and Elverhøi, 2002). Both in Kongsfjorden and Bellsund, the subsequent transitional flow style left significant deposits (Fig. 3). In the fjords and troughs, we conclude that there was a continuous high degree of landscape imprint exerted by the different ice-flow styles over time (Fig. 6).

4.2.2. Controls on the spatial and temporal variations in glacial regime

A key question remains: What were the main controls on the contrasts in landscape imprints between the two settings? From our compilation of ice-flow data, we propose a time-dependant model (Fig. 7) for the ice-stream vs. inter ice-stream areas along the west coast of Svalbard. As the geological controls are not location specific, we expect the model to also be applicable to other ice-sheet marginal fjord areas as e.g. western Norway, Greenland, Iceland, and the eastern Canadian Arctic.

In the fjord/trough ice-stream areas (Fig. 7A), the extensive deposits (see above) and MSGLs suggest that warm-based conditions prevailed throughout the duration of the ice-stream flow, both through the build-up and decay phase. The constant delivery of subglacial sediments as a source for debris flows on the trough-mouth fans suggest an active ice sheet, probably with warm-based conditions during the entire period from $T_{\mathrm{Inception}}$ to $T_{\mathrm{Deglaciation}}$ (Fig. 7A). Dowdeswell and Elverhøi (2002) studied marine sediment off the Isfjorden fan and in what they called the “inter-fan area”. They found uniform sedimentation rates along the whole margin during ice-sheet build-up, followed by a starvation of sedimentation in the inter-fan area at the glacial maximum, which they interpreted as caused by the onset of major ice-streams. Landvik et al. (2005) suggested that the difference in landscape imprint could be explained by the contrast between fast flowing ice-streams in the fjords and troughs, and dynamically less active (or of shorter duration) ice in the inter-fjord areas. From amino acid palaeothermometry in Linnédalen (outer Isfjorden), Mangerud et al. (1992) suggested the total duration of the Late Weichselian ice cover to be <5000 years, assuming it was warm-based. However, we now realize that this is a minimum estimate of total ice cover, as Linnédalen sits in the inter ice-stream area (Fig. 5) and probably experienced cold-based ice cover of an unknown duration.

In the inter ice-stream areas (Fig. 7B), the limited landscape imprints suggest less subglacial activity compared to the fjords and troughs (Fig. 7B) during most of the glaciation. This contributed to an increased preservation potential of older deposits, and limited the net glacial transport of sediments to the shelf edge. However, scattered evidence of glacial activity and extensive unconstrained maximum ice flow across the area do indicate periods of thawed bed conditions. Only a few observations highlight the build-up phase (Fig. 7B). Warm-based conditions during local ice-flow style in central Nordenskiöld Land (Fig. 3) indicate glacial inception as a result of the growth of local glaciers, and the sediment delivery

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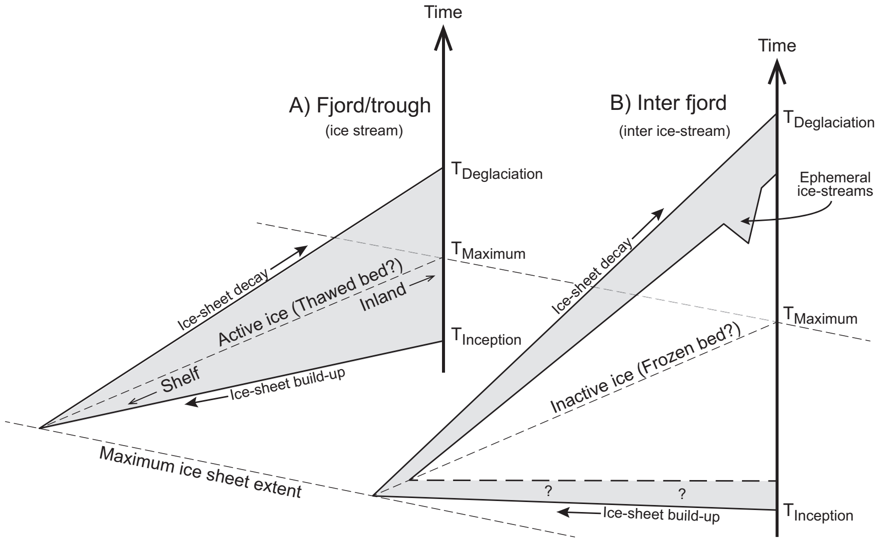

Fig. 7. Basal temperature conditions in the fjord/trough area (A) vs. the inter-fjord area (B) during ice-sheet build-up, maximum extent, and decay. See text for discussion.

to the shelf edge (Dowdeswell and Elverhøi, 2002) suggests that a warm-based phase persisted under parts of the ice sheet until it reached its maximum extent (Fig. 7). From this style of ice-sheet growth, we also expect the onset of build-up ($T_{\mathrm{Inception}}$) to be earlier in the inter ice-stream areas compared to the deeper fjords and troughs (Fig. 7).

We suggest that the inter ice-stream area was characterized by a zone of active ice (thawed bed conditions) that increased laterally through time, and migrated time transgressively over the landscape during the deglaciation (Fig. 7B). This can be seen from the strong bias of glacial signatures towards the later stages of the glaciation (Fig. 6). The extensive moraines on the continental shelf (Landvik et al., 2005; Ottesen and Dowdeswell, 2009) indicate that subglacial activity increased after the onset of the last deglaciation, and that warm-based conditions prevailed during ice-sheet retreat. The migration of the warm-based zone (Fig. 7B) implies that the maximum flow style signatures found in the inter ice-stream area (Fig. 4) did not form simultaneously. Switch-on of ephemeral ice-streams occurred during later stages of the retreat as the warm-based zone met the topographically constrained conduits channelling the transitional flow style (Figs. 4 and 7). A comparable time-transgressive model was proposed by Kleman et al. (2006) for the distribution of wet-based glacial landforms over the landscape during a deglaciation.

4.3. Regional consequences

The proposed model for changes in ice-flow styles and their associated geological imprints was made possible by the large number of studies covering the fjord region of western Svalbard, both spatially and stratigraphically. However, we expect the concept to have validity also for other areas. In recent studies from eastern Svalbard, marine geological investigations from the Erik Eriksenstretet between Kong Karls Land and Nordaustlandet (Fig. 1) (Dowdeswell et al., 2010b; Hogan et al., 2010b) and glacial geological studies from Nordaustlandet (Hormes et al., 2011) reported ice-flow observations compatible with the existence of local ice domes over south-eastern Hinlopenstretet and Nordaustlandet. This contrasts the reconstruction by Salvigsen et al. (1995) who used the regional pattern of glacial striae and other ice-flow indicators to infer a maximum, probably Late Weichselian, phase of ice flow from a centre over the northern Barents Sea (see also Ingólfsson and Landvik, 2013). These apparently contradicting ice-flow records and geological signatures may be resolved by our model, assuming they reflect the succession of both maximum and transitional ice-flow styles during the ice-sheet decay, and that their signatures are biased towards the younger records.

The model has important implications for our perception of past ice sheets, and the reconstructions based on their interaction with the marine sedimentary record. We suggest the ice sheet had a spatially non-uniform behaviour through its build-up and decay, where different flow styles resulted indifferent geological characteristics (Figs. 4 and 5). During maximum flow style, the major parts of the ice margin in the inter-fjord areas was relatively inactive (Fig. 4), whereas ice-streams along the fjords and trough conduits supported most of the sediment transfer to the continental margins and the adjacent ocean. This calls for caution in generalization of past ice-sheet behaviour from distal marine records.

We propose that the succession of flow styles that we have shown for western Svalbard could also be expected to have occurred over the entire Svalbard–Barents Sea ice sheet. Fig. 8 illustrates the time-transgressive nature of the different flow styles as a function of decreasing ice-sheet extent, thickness and volume. Maximum flow style dominated all over the ice sheet at the time of its maximum thickness/volume (T_{Max}). As the ice sheet decreased in size, the transitional and local flow styles became increasingly dominant and shifted towards the centre of the ice sheet (Fig. 8).

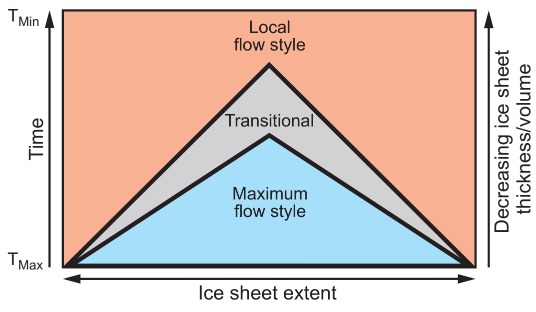

Fig. 8. Conceptual time–space distribution of the different flow styles across the entire ice sheet from the time of its maximum (T_{Max}) to its minimum (T_{Min}) extent. This illustrates the time-transgressive nature of the different flow styles.

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Only local flow style persisted as the ice sheet diminished to its minimum extent (T_{Min}). This time-transgressive concept may also be valid for other palaeo ice sheets, and contributes to explain the predominance of local flow-style signatures in the geological record.

5. Summary and conclusions

Enigmatic stratigraphical and morphological fingerprints of past glaciations in the Arctic have led to contradictory reconstructions of regional glacial history and ice-sheet behaviour over time (discussions in e.g. Miller et al., 2002; Landvik et al., 2005; Ingólfsson and Landvik, 2013). Our approach is to review and re-examine stratigraphic and geomorphic records from seven different areas on western Svalbard to look for patterns that can explain such apparent mismatch of different records, and to provide an understanding of the development of past glacial cycles. We have modified and further developed the three-stage glacial dynamic succession put forward for the Late Weichselian by Landvik et al. (2013), and we propose a new conceptual model that unifies the different records and describes the style of glaciations across western Svalbard.

The stratigraphic and geomorphic records reveal a succession of three different ice-flow styles that we classify from their degree of topographic constraints as maximum, transitional and local ice-flow styles:

1) The maximum flow style reconstruction is based on MSGL's and terminal moraines on the continental shelf as well as ice-sheet thickness reconstructions requiring largely topographically unconstrained ice flow.
2) The transitional flow style is partly topographically constrained. In fjord settings, the most important signatures are seafloor MSGLs, recessional moraines and grounding zone wedges, reflecting phases of ice-stream behaviour, whereas glacial striae, subglacial tills and proglacial outwash sediments reflect ice sheet or ice cap marginal zones over the land areas.
3) The local ice-flow style is characterized by strongly topographically constrained ice flow, predominantly in the terrestrial environment, and the most important signatures are terminal moraines and tills deposited by ice flowing from local ice caps and outlet glaciers.

Fjord/trough (ice-stream) and inter-fjord (inter ice-stream) areas exhibit different glacial landscape imprints, reflecting different flow styles and basal temperature conditions. Ice-streams in the fjords and troughs were probably dominated by thawed bed. The inter-fjord areas seems to have experienced thawed basal conditions only during a late phase of ice-sheet retreat, leaving the distinct glacial signatures of an active zone that migrated over the older landscape.

The composite western Svalbard glacial record shows that these ice-flow styles occurred in a preferred succession during both ice-sheet build-up and decay. Due to the higher preservation potential of the younger geological imprints, developed under warm-based conditions, most studies utilizing geomorphic data for ice-flow reconstructions have tended to be biased towards the latest ice-flow styles, usually the local or transitional flow style.

We suggest the succession of flow styles shown for western Svalbard occurred on a full ice-sheet scale and in particular that the transitional and local flow styles shifted time transgressively towards the palaeo centre of the ice sheet as a function of changing ice-sheet thickness and volume. This conceptual model should be valid also for similar palaeo ice-sheet settings in e.g. Greenland, western Norway, eastern Canadian Arctic and Iceland.

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