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Manuscript Title: Asynchronous response of marine-terminating outlet glaciers during deglaciation of the Fennoscandian Ice Sheet

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1. Supplementary Methods: Dating and Correlating Ice Margin Retreat

The pattern and chronology of glacier retreat in northern Norway following the Last Glacial Maximum (LGM) has been known, in general outline, for several decades and up to eight major sub-stages have been identified in Finnmark (Sollid et al., 1973) and Troms (Andersen, 1968). These sub-stages are based on extensive and detailed mapping of marginal moraines that can be traced over considerable distances, together with raised shorelines cut into end moraines or extending beyond ice-contact deltas; further augmented by radiocarbon dates from marine sediments pre- or post-dating moraines (e.g. Marthinussen, 1962; Andersen, 1968; Sollid et al., 1973; Vorren and Elsborg, 1979; Corner, 1980). Much of this work laid the foundation for a regional ice margin chronology, compiled by Andersen and Karlsen (1986).

Andersen and Karlsen's (1986) map represents the only detailed attempt to both correlate and date ice-front positions across the entire region. It clearly demonstrates the asynchrony in ice margin retreat between different fjords, which is the focus of our investigation, but it requires updating. This is because several studies have carried out new mapping and collected new dates (Anderson et al., 1995; Fimreite et al., 2001; Olsen et al., 2001a, b; Forwick and Vorren, 2002; Vorren and Plassen, 2002; Eilertsen et al., 2005, 2006; Vorren and Mangerud, 2008; Winsborrow et al., 2010; Romundset et al., 2011; Rüther et al., 2011). Our objective, therefore, is to synthesise data from these studies into an updated ice margin chronology for each of our studied fjords (summarised in Table DR1). As in previous work, we do this by correlating major ice marginal positions across the region, constrained by moraines of known age (e.g. from radiocarbon dates) and based on previous work within individual fjords. Here, we briefly summarise this work, which underpins the chronology in Table DR1 (below) that is used in the manuscript (e.g. Figs 1-3).

1.1.Troms (Andfjorden, Malangen, Lyngen)

The chronology of ice margin recession is best known in the western part of the study area, in Troms, where most radiocarbon dates have been obtained (cf. Andersen 1968, Vorren and Elvsborg 1979; Corner 1980; Forwick and Vorren, 2002; Vorren & Plassen 2002; Eilertsen *et al*., 2005). Indeed, previous work has already produced time-distance diagrams for outlet glacier positions in Andfjorden-Vågsfjorden (Vorren and Plassen 2002) and the inner part of Malangen-Målselv (Eilertsen *et al.*, 2005), which we utilise. These depict phases of both glacier retreat and re-advance, interspersed with more stable ice margin positions of variable duration. Moraines have been correlated across the region based on their relationship to raised shorelines. Radiocarbon dates give maximum or minimum ages for these moraines or for deglaciation events (see Marthinussen, 1962; Andersen, 1968; Vorren and Elvsborg, 1979; Corner, 1980; Fimreite et al., 2001; Olsen et al., 2001a; Vorren and Plassen, 2002; Forwick and Vorren, 2002; Eilertsen et al., 2005; Romundset et al., 2011).

Glacier re-advances have been documented in several cases, in the form of overridden or over-consolidated sediments observed in sections (Andersen 1968, Corner 1980, Vorren & Elvsborg 1979) and on seismic profiles (Lyså and Vorren, 1997; Vorren and Plassen 2002; Eilerten et al., 2005), and their extent reconstructed in the form of time-distance diagrams. The largest re-advance occurred during the late Allerød (Tromsø-Lyngen re-advance), for which there is evidence of overriden moraines at least 25 km proximal to these moraines (Vorren & Plassen 2002, Eilertsen et al., 2005). Vorren and Plassen (2002) assumed a re-advance of at least 40 km at this time, comparable to conditions in western Norway (cf. Andersen et al 1995). To capture this uncertainty in our time-distance diagrams (Fig's 2 and 3), we have assumed a distance of 30 km (± 10 km) in the fjords in Troms.

As noted above, eight moraine sub-stages have been recognised between the shelf break and the innermost fjords in Troms (Andersen 1968; Vorren and Plassen 2002). They are (from oldest to youngest): Egga II, Flesen, D-event, Skarpnes (late Bølling-Allerød), Tromsø-Lyngen (Younger Dryas), and Stordal I, II and III (Preboreal). The most complete chronology has been obtained from Andfjorden-Vågsfjorden, where Vorren & Plassen (2002) combined evidence of early deglacial sub-stages (Egga II, Flesen, D-event) recognised in marine sediments, with evidence of younger glacial sub-stages (Skarpnes, Tromsø-Lyngen and Stordal I, II and III) identified on the basis of regional terrestrial evidence (Andersen, 1968). Their resulting chronology spans the time of glacier retreat from the shelf edge to the innermost fjords. We have adjusted this chronology for the Preboreal (Stordal I, II and III), based on more detailed radiocarbon and shoreline correlation dating of Preboreal moraines in Lyngen-Storfjord (Corner, 1980) and Malangen-Målselv (Eilertsen et al., 2005), where two major, and one minor, climatically controlled moraine sub-stages and several topographically controlled ice-front accumulations have been recognised. Based on this body of work, the resulting chronology (in cal. ka BP) for moraine sub-stages in Troms is as follows (cf. Table DR1):

1. Egga II	17.8 (± 0.3)
2. Flesen	17.3 (± 0.2)
3. D-Event	16.2 (± 0.3
4. Skarpnes	14.2 (± 0.3)
5. Tromsø-Lyngen	12.1 (± 0.2)
6. Stordal I (= Ørnes in Lyngen, Kjerresnes in Målselv)	11.4 (± 0.2)
7. Stordal II (= Skibotn in Lyngen, Bardu-Storskog in Målselv)	10.8 (± 0.2)
8. Stordal III (= Nyli in Lyngen-Storfjord, Alapmoen in Målselv)	10.4 (± 0.2)

This chronology has been applied to all three fjord systems in Troms included in this study. It is estimated (conservatively) to be reliable to within ±200-500 yrs. The uncertainty increases with increasing age and, for pre-Skarpnes ice front positions, distance from the reference area in Andfjorden-Vågsfjorden. Ice-front positions corresponding to the Skarpnes and younger events have been positively identified in all three fjord systems. Pre-Skarpnes glacier positions in Malangen and Lyngen have not been identified and their position is inferred from comparison with Andfjorden-Vågsfjorden. Malangen is situated fairly close to Andfjorden and has a similar setting with regard to topography and distance to the shelf edge. Its early deglaciation history, therefore, is assumed to be similar to that of Andfjorden (cf. Rydningen et al., 2013). Lyngen, however, is located much farther from Andfjorden and much farther from the shelf edge, and probably has more in common with Finnmark than Troms regarding its early deglaciation history (see below).

1.2. Finnmark (Altafjorden, Porsangen; Laksefjorden; Tanafjorden and Varangerfjorden)

In Finnmark, the dynamics and timing of glacier retreat and re-advance are less well known than in Troms. Fewer radiocarbon dates are available, and the chronology of glacier retreat is based largely on morpho-stratigraphic correlation of marginal moraines and raised shorelines (Sollid et al., 1973). The following regional moraine succession (from oldest to youngest) has been established: Risvik, Outer Porsangen, Korsnes, Repparfjord, Gaissa, Main, and up to two successive Preboreal moraines (Lampe-Jordall in Altafjorden (Follestad, 1979), Rotnes and Bjørnnes in Porsangen, and Korselv in Tanafjorden). At least one glacier re-advance is indicated by the way in which the Younger Dryas ('Main') sub-stage moraine overrides the Gaissa moraine in some areas (Sollid et al. 1973). This indicates a glacier re-advance of at least several kilometres, possibly corresponding to the late-Allerød re-advance in Troms (see below).

The 'Main' sub-stage can be reliably correlated with the Tromsø-Lyngen (Younger Dryas) sub-stage in Troms on the basis of raised shoreline correlation and moraine continuity. An age of 12.1 ± 0.3 cal. ka BP is assumed for this sub-stage. Younger moraine sub-stages (Lampe-Jordall in Alta, Rotnes and Bjørnnes in Porsangen, and Korselv in Tanafjorden) are assigned a Preboreal age, approximately equivalent to the Stordal I, or possibly Stordal II in Troms, on the basis of shoreline correlation (cf. Sollid et al., 1973), i.e. ca. 11.4 ±0.5 cal. ka BP. The Repparfjord sub-stage has been correlated with the Skarpnes sub-stage in Troms based on raised shoreline evidence (cf. Marthinussen 1962) and is consequently assigned an age of 14.2 ± 0.3 cal. ka BP, although a younger age has also been suggested (discussed below).

Among the older sub-stages, there are various ways to approach correlation. One approach, using a direct comparison with Troms, would be to correlate the prominent Outer Porsanger sub-stage with either the Flesen moraine (17.3 cal. ka BP) or the D-event (16.2 cal. ka BP) in Andfjorden. Accordingly, the Risvik event, represented by marginal moraines on the outermost coast at Porsangen, would be even older, suggesting coastal deglaciation around 17 cal. ka BP. Ages close to these dates or younger were suggested by Olsen et al. (1996; 2001a; b).

A second approach would be to correlate the Flesen and D-events in Andfjorden with deglacial stages recognised in the Barents Sea. Such a correlation seems more likely given that the coast of Finnmark is much farther from the shelf edge than the coast of western Troms. Thus, Winsborrow *et al.* (2010) tentatively correlated their Stages 2 and 3 in the Barents Sea with the Flesen and D-events, respectively. They suggested dates of 16 cal. ka BP for late stage (Stage 3) ice-stream activity off the coast of Finnmark, and 15 cal. ka BP for retreat of the ice margin to an onshore position. This is consistent with recent dating evidence from the southern Barents Sea (Juntilla et al., 2010; Rüther et al. 2011), e.g. an age of 16.6 cal. ka BP for the Stage 2 Outer Bjørnøyrenna sediment wedge.

A third approach was taken by Romundset *et al*. (2011). They used maximum ages of 14.1 and 14.3 cal. ka BP obtained from marine fossils in basal sediments in coastal lake basins to infer deglaciation of the outer coast of Finnmark (Rolfsøya) at around that time. Comparing these dates and glacial sub-stages in the fjords with cold events indicated by the NGRIP ice core (NGRIP Members, 2004), they correlated the Outer Porsanger sub-stage with the Older Dryas (Bølling-Allerød) cold period (ca. 14 cal. ka BP), and the Repparfjord and Skarpnes sub-stages with an inter-Allerød cold event (ca. 13 cal. ka BP). Their correlation makes these moraines more than 1,000 years younger than previously assumed. However, it should be noted that their dated lake sediments represent only minimum ages for the date of deglaciation of the outer coast, and other dating evidence suggesting an age of around 14 cal. ka BP for the Skarpnes event in Troms (see above) cannot easily be dismissed. Thus, assuming that the Skarpnes and Repparfjord sub-stages have the same age, which seems reasonable on the basis of raised shoreline evidence, we assign the Repparfjord sub-stage an age closer to 14 cal. ka BP than 13 cal. ka BP.

Because of the uncertainty regarding the age of sub-stages in Finnmark, the error estimates are larger than those for Troms. The Korsnes sub-stage is assigned an intermediate age closer to the age of the Outer Porsanger than Repparfjord, based on its position. Gaissa sub-stage moraines, which in places are overrun by moraines of the Main sub-stage, are tentatively assigned a late Allerød age based on a correlation with an early phase of the Tromsø-Lyngen event in Troms, for which there is some evidence (Andersen 1968; Vorren and Plassen, 2002). For inter-stadial ice front positions in Finnmark, we have assumed a similar age for the Allerød inter-stadial as in Troms, and a position estimated at 20 km (rather than 30 km) behind the ‘Main’ sub-stage moraines, based on the assumption that glacier fluctuations in the more continental setting of Finnmark were more subdued than in maritime Troms. Thus, our chronology (in cal. ka BP; cf. Table DR 1) is based on: (i) age constraints for coastal deglaciation and outer moraine sub-stages provided by recent data from the Barents Sea; (ii) correlation with Troms for Repparfjord and later sub-stages, and (iii), an inferred Allerød inter-stadial position:

1. Risvik	15.5 (± 0.5)
2. Outer Porsanger	15 (± 0.5)
3. Korsnes	14.8 (± 0.5)
4. Repparfjord	14.2 (± 0.5)
5. Allerød IS	13.5 (± 0.5)
6. Gaissa	13 (± 0.5)
7. Main	12.1 (± 0.3)
8. Rotnes	11.6 (± 0.5)
9. Korselv/Lampe-Jordfall	11.4 (± 0.5)
10. Bjønnes	11.2 (± 0.5)

1.3. Age Uncertainties

It is important to acknowledge the inherent uncertainty in any reconstruction of palaeo-glacier behaviour and we acknowledge that subsequent dating may lead to revisions of the ice margin chronology depicted in this paper. However, we note that our work builds on a rich legacy of previous work, giving this region one of the most detailed ice margin chronologies available for any palaeo-ice sheet. Indeed, because of the extensive morpho-stratigraphic correlations, it is unlikely that new dates will lead to a radical revision of the broad pattern of retreat within each fjord. The time-distance diagrams from each fjord (e.g. Fig's 2 & 3) show error bars to clarify areas of uncertainty. Age uncertainties are based on an appraisal of: (i) the radiocarbon dating error, (ii) the number of dates, (iii) the correlation uncertainty and age relationships to older and younger events. They give a relative measure of uncertainty and are believed to be maximum estimates that span the complete range of 'known' uncertainty. Distance error bars are used in cases where the approximate, rather than precise, position of the ice front (substage) is known. Importantly, we note that these uncertainties are largely insignificant to our aim of reconstructing the broad patterns of ice margin recession in each fjord (e.g. relative, rather than absolute, changes in retreat rate, as shown by the vertical dashed bars that link sub-stages to neighbouring fjords).

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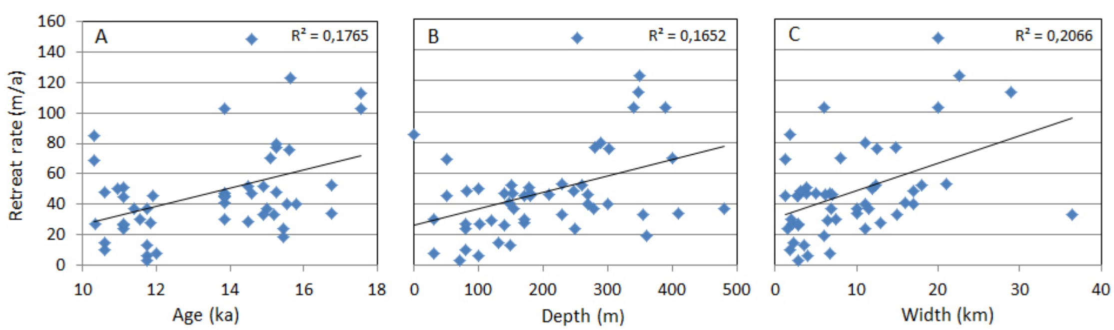

Figure DR1: Retreat rate versus time (**A**), depth (**B**) and width (**C**). Depth takes account of isostatic rebound and post-retreat sediment fill, where known.

Table DR 1: Correlated and dated moraine sub-stages (green) and inter-stadials (IS: red) from a synthesis of the literature used for calculating ice margin retreat rates in Troms and Finnmark. Estimated error limits for their age (ka) and position (km) in each fjord are given and used to assign uncertainty to the retreat rates in Figure's 2 and 3. Interpolated dates for ice margin positions at the mouth and end of each fjord (yellow: cf. Fig's 1, 2 and 3), or where correlation is more tentative, are shown in brackets. LJ: Lampe-Jordfall.

TROMS[1]						
Location:	Andfjorden[1,7]		Malangen[1,7,8]		Lyngen[9]	
Marine limit:	30-95 m		30-85 m		40-95 m	
Glacial event:	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*
Egga II	17.8	0.3/0	17.8	0.3/0		
Flesen	17.3	0.2/0	17.3	0.2/5		
F-D IS	16.8	0.3/5	16.8	0.3/5		
D-event	16.2	0.3/5	(16.2)	0.3/5	(16.1)	0.5/0
					(15.5)	0.5/0
Bølling IS	14.7	0.3/5	14.7	0,3/5	14.7	0.3/5
Skarpnes	14.2	0.3/2	14.2	0.3/0	14.2	0.3/0
Allerød IS	13.5	0.4/10	13.5	0.4/10	13.5	0.4/10
Tromsø-Lyngen[10]	12.1	0.2/0	12.1	0.2/0	12.1	0.2/0
Målsnes			11.7	0.2/0		
Stordal I	11.4	0.2/0	11.4	0.2/0	11.4	0.2/0
Stordal II	10.8	0.2/0	10.8	0.2/0	10.8	0.2/0
Stordal III	10.4	0.2/0	10.4	0.2/0	10.4	0.2/0
Final deglac.	(10.3)	0.2/0	(10.2)	0.2/0	(10.2)	0.2/0

FINNMARK[2,11] and Barents Sea[3,4,5]										
Location:	Altafjorden[2]		Porsangen[2]		Laksefjorden[2]		Tanafjorden[2]		Varangerfjorden[2]	
Marine limit:	40-85 m		40-75 m		40-70 m		45-75 m		75-95 m	
Glacial event:	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*	*Age cal.ka BP*	*Error ± ka/km*
Stage 1	(Barents Sea, shelf edge: c. 19)[3,5]									
Stage 2	(Barents Sea, Outer Bjørnøyrenna sediment wedge: 17.1 - 16.6)[3,4,5]									
Ende Stage 2	(Barents Sea, retreat from OBSW, c. 16.5)[3,4]									
Stage 3	(Barents Sea mostly ice-free, c. 16)[3,5]									
Coast deglaciation[5,6]	(15.8)	0.5/0	(15.8)	0.5/0	(15.7)	0.5/0	(15.6)	0.5/0		
Risvik			15.5	0.5/1	15.5	0.5/2.5	15.5	0.5/5	(15.4)	0.5/0
Outer Porsanger			15.0	0.5/0	15.0	0.5/2	15.0	0.5/1	15.0	0.5/5
Korsnes			(14.8)	0.5/2.5	(14.8)	0.5/1				
	(14.5)	(no plot)								
Repparfjord	(14.2)	0.6/10	14.2	0.4/1	14.2	0.4/1	14.2	0.4/5	14.2	0.4/3
Allerød IS	13.5	0.5/10	13.5	0.5/6	(13.9)	0.5/0	13.5	0.5/6	13.5	0.5/6
Gaissa			13	0.5/1.5			13	0.5/2	13	0.5/2*
Main	12.1	0.3/0	12.1	0.3/1			12.1	0.3/0	12.1	0.3/0
Rotnes			11.6	0.5/1					(11.9)	0.3/0
LJ/Korselv/Bjørnnes	11.4 (LJ)	0.5/0	11.2 (B)	0.5/1			11.4 (K)	0.5/0		
	(10.7)	0.5/0	(10.7)	0.5/0			(10.8)	0.5/0		

* Gaissa substage margin in Varangerfjorden located just inside (overridden by) the Main substage moraine.

Key data sources for correlating and dating glacial events:

[1]Andersen (1968): Moraine, shoreline and equilibrium line altitude correlations; biostratigraphy and **17 radiocarbon dates** (mostly shells from raised marine sediments)

[2]Sollid et al. (1973): Regional moraine mapping and shoreline correlation; shorelines used as 'dating lines'

[3]Winsborrow et al. (2010): Reconstructed flow patterns and dynamics (e.g. locationof ice streams) during deglaciation; compilation of **14 radiocarbon dates** from marine samples (foraminifera and macrofossils).

[4]Rüther et al. (2011) Seismic- and lithostratigraphy-based reconstruction of deglaciation; **6 radiocarbon dates** from marine samples (foraminifera and macrofossils)

[5]Junttila et al. (2010): Dating marine sediments and deglaciation; **6 radiocarbon dates** from foraminifera and macrofossils.

[6]Romundset et al. (2011): Raised coastal lake stratigraphy; **2 radiocarbon dates** (shell and algae) relating to deglaciation.

[7]Vorren & Plassen (2002): Marine stratigraphy and compilation of **44 radiocarbon dates** rlating to deglaciation of Andfjorden.

[8]Eilertsen et al. (2005): Litho- and seismic stratigraphy and mapping; **25 radiocarbon dates** (mostly shells from raised marine sediments).

[9]Corner (1980): Moraine and shoreline correlation; **3 radiocarbon dates** from raised marine sediments (shells).

[10]Fimreite et al. (2001): Pollen stratigraphy of lake sediments; **5 radiocarbon dates** from samples of gyttja.

[11]Olsen et al. (2001): **Radiocarbon dates** from glacigenic sediments containing low carbon content.