The glacial geomorphology of the western cordilleran ice sheet and Ahklun ice cap, Southern Alaska

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ABSTRACT

During the late Wisconsinan, Southern Alaska was covered by two large ice masses; the western arm of the Cordilleran Ice Sheet and the Ahklun Mountains Ice Cap. Compared to the other ice sheets that existed during this period (e.g. the British-Irish, Laurentide and Fennoscandian ice sheets), little is known about the geomorphology they left behind. This limits our understanding of their flow pattern and retreat. Here we present systematic mapping of the glacial geomorphology of the two ice masses which existed in Southern Alaska. Due to spatially variable data availability, mapping was conducted using digital elevation models and satellite images of varying resolutions. Offshore, we map the glacial geomorphology using available bathymetric data. For the first time, we document >5000 subglacial lineations, recording ice flow direction. The distribution of moraines is presented, as well as features related to glacial meltwater drainage patterns (eskers and meltwater channels). Prominent troughs were also mapped on Alaska’s continental shelf. This map provides the data required for a glacial inversion of these palaeo-ice masses.

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1. Introduction

Approximately 70,000 km² (5%) of Alaska is currently glaciated (Molnia, 2008). During the late Wisconsinan (~30 to 10 kya) ice extent was approximately 10 times greater than this, with previous glaciations greater still in extent (Kaufman & Manley, 2004; Kaufman, Young, Briner, & Manley, 2011). The majority of this ice was contained within three ice masses; an ice cap over the Brooks range to the north of Alaska (Hamilton & Porter, 1975), a second ice cap over the Ahklun Mountains (Briner & Kaufman, 2000) and a much larger ice sheet in the south. The latter formed the Western edge of the Cordilleran ice sheet at its maximum (Booth, Troost, Clague, & Waitt, 2004) and covered the Aleutian Islands in the West, the Alaskan Peninsula and the Wrangell Mountains in the East (Kaufman et al., 2011; Mann & Peteet, 1994). As well as containing a large volume of fresh water, these Alaskan ice masses may have formed a barrier to human migration across the land bridge, known as Beringia, which existed between Alaska and Russia during the last glacial period (Mandryk, Josenhans, Fedje, & Mathewes, 2001; Misarti et al., 2012). Figure 1 shows the proposed extent of ice at different times across southern Alaska. This paper focuses upon the geomorphology left behind by the two principle ice masses in this area; the Ahklun Mountains Ice Cap and the Western Cordilleran Ice Sheet (Figure 1).

The maximum extent of the Alaskan ice masses has been proposed and mapped (e.g. Figure 1; Kaufman et al., 2011; Kaufman & Manley, 2004), but less is known about the pattern of the retreat of these ice masses. This is partially due to a lack of a map of the glacial landforms which this ice sheet left behind. The distribution of moraines, meltwater channels, glacial troughs, eskers and subglacial bedforms can be used to reconstruct ice sheets via a glacial inversion method (e.g. Clark, 1999; Kleman & Borgström, 1996; Stokes et al., 2015). This technique has proven informative for the British-Irish (e.g. Clark, Hughes, Greenwood, Jordan, & Sejrup, 2012; Greenwood & Clark, 2008; Hughes, Clark, & Jordan, 2010), Fennoscandian (e.g. Kleman, Hättestrand, Borgström, & Stroeven, 1997; Stroeven et al., 2015), Cordilleran (e.g. Margold, Jansson, Kleman, Stroeven, & Clague, 2013) and Laurentide ice sheets (e.g. Boulton & Clark, 1990; Trommelen, Ross, & Ismail, 2014). Here we present mapping of the glacial geomorphology for the Ahklun Mountains Ice Cap and the Western Cordilleran Ice Sheet across the area they each encompassed during the late Wisconsinan. This map will form the basis of an empirical reconstruction of these ice masses.

2. Methods

Onshore, glacial landforms were identified and mapped using three sources of data. All onshore sources were obtained from the USGS website (www.earthexplorer.usgs.gov). The data sets used and their resolution are listed in Table 1. A digital elevation
model (DEM) derived from interferometric synthetic aperture radar (IfSAR) provided the highest resolution data (5 m), but is not available across the whole of Alaska (Figure 2). Below 60°N the shuttle radar topography mission DEM (SRTM; 30 m resolution) was used (Figure 2). To fill the space where neither of these two data sets were available, glacial landforms were identified on Landsat ETM+ imagery (15 m pan-chromatic resolution), which is available globally. Offshore, elevation models of various resolutions were available (Table 1) from NOAA (https://maps.ngdc.noaa.gov/viewers/bathymetry/). Where high resolution bathymetric data were not available, a coarser resolution (500 m) elevation model was used. Only the largest glacial features such as glacial troughs or large moraines (several km’s in length and 10’s of m in amplitude) were visible on this DEM.

To maximise landform identification, we adopted a repeat pass approach to mapping, checking each area multiple times. However, our mapping is necessarily limited where high resolution offshore elevation models are unavailable. Where high resolution data was available, for example, the IfSAR DEM (Table 1 and Figure 2), this enabled a high level of identification and subsequent mapping of landforms. As a consequence, these areas are mapped in more detail than others. Therefore, we anticipate more detailed geomorphology may be revealed as higher resolution data sets become available, prompting future work. Landform preservation, burial and submergence also limit landform identification.

Glacial landforms were identified on hill-shaded relief models created from the available DEMs. Two

**Table 1. Resolution and source of data sets used.**

| Data set          | Horizontal Resolution (m) | Source                  |
|-------------------|---------------------------|-------------------------|
| Merged on and offshore DEM | 500                        | NOAA                    |
| SRTM DEM          | 30                        | Earthexplorer.usgs.gov  |
| Landsat ETM+      | 15 pan-chromatic          | Earthexplorer.usgs.gov  |
| IfSAR DEM         | 5                         | Earthexplorer.usgs.gov  |
| Adak Bathymetry   | 30                        | NOAA                    |
| Akutan Bathymetry | 12–200                    | NOAA                    |
| Chignik Bathymetry| 10–30                     | NOAA                    |
| Chenega Bathymetry| 12                       | NOAA                    |
| Cold Bay Bathymetry| 12–200                   | NOAA                    |
| Cordova Bathymetry| 10–90                     | NOAA                    |
| Dutch Harbour     | 15                        | NOAA                    |
| Bathymetry        |                            |                         |
| Homer Bathymetry  | 12–200                    | NOAA                    |
| Kachemak Bay      | 4                         | NOAA                    |
| Bathymetry        |                            |                         |
| Kingcove Bathymetry| 12–200                   | NOAA                    |
| Kodiak Bathymetry | 12–200                    | NOAA                    |
| Nikolski Bathymetry| 30                       | NOAA                    |
| Prince William Sound Bathymetry | 4–200 | NOAA            |
| Sand Point Bathymetry | 90                       | NOAA                    |
| Seldovia Bathymetry| 30–90                     | NOAA                    |
| Seward Bathymetry | 4–200                     | NOAA                    |
| Tatlek Bathymetry | 8                         | NOAA                    |
| Yakutat Bathymetry| 4–200                     | NOAA                    |
hill-shades were created from each DEM, illuminating from 45° and 315° to avoid azimuth biasing (Smith & Clark, 2005; Figure 3(a) and 3(b)). Hill-shades were made semi-transparent and overlaid on a DEM in order to avoid mapping hollows. False colour composite (bands 4, 3 and 2) Landsat images were enhanced using local image statistics in order to highlight subtle topography (e.g. Ely & Clark, 2016). The pan-chromatic band was used to further refine the imagery, to give a horizontal resolution of 15 m (Figure 3(c)). Features were mapped using a combination of hill-shade illumination angles and satellite data (Figure 3(d)).

The following features were identified and mapped: subglacial lineations, streamlined bedrock, moraines, eskers, meltwater channels and glacial troughs. Subglacial lineations were mapped as polygons around their break of slope. Break of slope was identifiable on hill-shaded DEMs (Hillier et al., 2015; Hughes et al., 2010; Figure 3(a) and 3(b)). On satellite imagery these breaks of slope were visible as changes in reflection or vegetation (Spagnolo et al., 2014). On the higher resolution IfSAR DEM (Table 1), many streamlined features were qualitatively different in appearance, giving the impression that they were predominately composed of bedrock (e.g. Bradwell, 2005; Lane, Roberts, Rea, Cofaigh, & Vieli, 2015; Figure 4). Differentiation of these features was aided by a surface geology map. Where possible, moraines were also mapped as polygons. Often, moraines were composed of several ridges comprising a moraine complex. Where this was the case, the smaller ridges were mapped as polylines and the moraine complex as a polygon (Figure 5). Furthermore, some smaller moraines were mapped solely as polylines along their crest. Eskers were also mapped as polylines along their crestline. Glacial meltwater channels were mapped as polygons along their thalweg. These were identified as glacial in origin due to their discordance with modern day fluvial drainage patterns (cf. Greenwood, Clark, & Hughes, 2007). However, it is reasonable to expect that a channel may have been occupied by both a glacially dominated source of water and by a fluvial or glaciofluvial water source at a later stage. Finally, glacial troughs were mapped as polylines along their banks, using 3D profiles and hill-shading to define their edges (Spagnolo & Clark, 2009). Unlike other ice sheets (e.g. Hättestrand & Kleman, 1999; McHenry & Dunlop, 2016; Trommelen & Ross, 2010), no examples of subglacial ribs, which form transverse to flow direction, were noted.

3. Map description

The Main Map was produced using Esri ArcGIS 10.1. It is comprised of 12,846 digitised polylines and polygons. The background for the map is a merged bathymetric and terrestrial elevation model downloaded from the National Oceanic and Atmospheric Administration (NOAA, www.ngdc.noaa.gov). The extent of modern day glaciers, available from the Randolph Glacier Inventory (version 5, www.glims.org/RGI/), is also
Figure 3. Subglacial lineations (drumlins) near Becharof Lake. (a) SRTM hill-shaded DEM, illuminated from the NW. Arrow denotes approximate palaeo-ice flow direction. (b) SRTM hill-shaded DEM, this time illuminated from the NE. (c) Landsat false colour composite of the same drumlins. (d) Mapped subglacial lineation outlines.

Figure 4. Examples of glacially streamlined bedrock. Arrows denote approximate palaeo-ice flow direction. (a) Hill-shaded IfSAR DEM of bedrock lineations West of Talkeetna, Matanuska-Susitna Borough. (b) Hill-shaded IfSAR DEM of a mixture of streamlined bedrock, crag and tails, and sediment lineations, near McKinley Fall, Matanuska-Susitna Borough. Regions of bedrock highs correspond to subglacial lineations with a qualitatively different morphology, thought to be streamlined bedrock.
Figure 5. Examples of moraine mapping. (a) Hill-shaded SRTM DEM of prominent moraines of both the Cordilleran Ice Sheet and the Akhlun Mountains Ice Cap. (b) Derived mapping. Note how the areas of looping moraines denoted by polygons also have prominent ridges mapped as polylines. Kvichak Bay begins to the south east of these images.

Figure 6. Examples of Alaskan subglacial lineations. Arrows denote palaeo-ice flow direction. (a) Lineations within McCarthy Borough, dissected by the Chitina River. (b) Elongate lineations near the confluence between the West and East Forks of the Yetna River. (c) Hill-shaded STRM DEM of subglacial lineations (drumlins) on the valley floors of the Akhlun ice cap. This example depicts the area near lakes Nerka, Aleknagik and Nunavugaluk. (d) Hill-shaded bathymetry of submerged subglacial lineations, SE of Mitrofania Bay.
included on the map in order to contrast with landforms created by more extensive glaciers. The map is designed to be printed on 2A0 paper, at a scale of 1:1,000,000. The distribution, frequency and characteristics of the mapped glacial landforms are discussed below.

### 3.1. Subglacial lineations and streamlined bedrock

Despite their frequency both in the literature and upon previously glaciated landscapes, the subglacial bedforms of Alaska have hitherto received little to no mention within the literature. Here, 5878 subglacial lineations, which are formed aligned with flow direction, were mapped from the 4 main sources of data (Table 2). Exemplars were found near Becharof Lake (Figure 3), within McCarthy Borough, Valdez-Cordova (Figure 6(a)) and at the confluence between the West and East Forks of the Yetna River (Figure 6(b)).

#### Table 2. Number of subglacial lineations and streamlined bedrock features per data set.

| Landform type       | Data source | Number of landforms |
|---------------------|-------------|---------------------|
| Subglacial lineations | Landsat ETM+ | 541                 |
|                     | IfSAR DEM   | 3150                |
|                     | SRTM DEM    | 1749                |
|                     | Offshore Bathymetry | 460  |
| Streamlined bedrock | IfSAR DEM   | 1239                |

#### Table 3. The number of mapped moraines per data set.

| Data source                  | Number of moraine features |
|------------------------------|----------------------------|
| Landsat ETM+                 | 514                        |
| IfSAR DEM                    | 949                        |
| SRTM DEM                     | 1135                       |
| Offshore Bathymetry          | 403                        |

Figure 7. Examples of Alaskan moraines. Arrows denote palaeo-ice flow direction and terminate at the moraines. (a) Hill-shaded SRTM DEM of moraines at the heads of Morzhovoi Bay (left) and Cold Bay (east). (b) Hill-shaded SRTM DEM of moraines north of the Alleutians, north of Mother Goose lake. (c) Hill-shaded SRTM DEM of concentric looped moraines, related to the Akhlun ice cap, east of Tikchik Lake. (d) Hill-shaded IfSAR DEM of moraines north of Mt. Denali.
(Main Map; Figure 6(c)), where they record a radial flow pattern outward from the centre of the mountain range and along valley floors. Furthermore, subglacial lineations were also observed on offshore bathymetry (Figure 6(d)).

Subglacial lineations form a morphological continuum of landforms spanning those typically referred to as drumlins, to mega-scale glacial lineations (Ely et al., 2016). The majority of Alaskan subglacial lineations would fall into the shorter end of this continuum, having low length–width ratios and thus conforming to the part of this continuum which is typically referred to as drumlins (Clark, Hughes, Greenwood, Spagnolo, & Ng, 2009). However, a few drumlins are remarkably long, elongate and parallel, reaching lengths above 6 km, exceeding the size of bedforms typically found on ice stream beds (e.g. Figure 6(b); Spagnolo et al., 2014). Future work is required to establish the potential role of palaeo-ice streaming across Alaska.

Additionally, 1239 examples of subglacially streamlined bedrock landforms were mapped (Table 1). These are typically 500 m long and a few metres high: exemplars are shown on Figure 4. These landforms can also be used to infer past flow direction and possible ice streaming (e.g. Bradwell, Stoker, & Krabbendam, 2008; Lane et al., 2015), but likely form by a separate set of processes to other subglacial bedforms (Dionne, 1987), hence their separation on our map. Streamlined bedrock is especially prominent on the mountains to the west of the Copper Basin (Figure 4). This suggests that at some point the Cordilleran Ice Sheet covered these mountains.

Figure 8. Examples of eskers and meltwater channels on hill-shaded IfSAR DEMs. (a) A large esker, passing through Lower Tangle Lake, Paxson. (b) An esker which grades into a meltwater channel, west of Dickey Lake, Valdez-Cordova. (c) A series of meltwater channels, located along the Denali Highway, east of Alpine Creek Lodge.
3.2. Moraines

Moraines were mapped as polylines and polygons \((n = 4101)\) from the different data sources \(\text{(Table 3)}\). A large range of moraine sizes were observed, the smallest being less than a metre high and a few metres wide, with the larger moraine complexes several tens of metres in height and kilometres wide. Some of the most impressive morainic patterns were found on the northern sides of the Alaskan Peninsula \(\text{(Figure 7(a))}\), the Aleutian Range \(\text{(Figure 7(b))}\) and the Alaska Range \(\text{(Figure 7(c))}\). Impressive moraines were also noted to emanate from the Akhun mountains \(\text{(Figures 5 and 7(d))}\). Comparatively few moraines were noted offshore, at least partially due to sparse data coverage or burial by post-glacial sediment. Many of the moraines form concentric, looped patterns \(\text{(Figures 5 and 7)}\) suggesting along valley margin standstills as the ice retreated.

3.3. Eskers and meltwater channels

Eskers were only observed on the IF SAR DEM, either due to the higher resolution of this data, or perhaps eskers were only formed in the region that this DEM covers \(\text{(Figure 2)}\). Polylines \((n = 592)\) included on the \textit{Main Map} represent individual esker segments \(\text{(e.g. Storrar, Stokes, & Evans, 2014)}\), the shortest of which were 10s m in length, but in places were traced for over 4 km. Compared to the Laurentide \(\text{(Storrar et al., 2014)}\) and Fennoscandian ice sheets \(\text{(Stroeven et al., 2015)}\) eskers are rare. This perhaps highlights differences in the drainage of these ice sheets, or points towards a poor preservation of eskers in Alaska. An example esker is shown in \textit{Figure 8(a)}. As has been reported for other palaeo-ice sheets \(\text{(Greenwood, Clason, Helanow, & Margold, 2016)}\), eskers were observed to switch into meltwater channels \(\text{(e.g. Figure 8(b))}\), but meltwater channels were also observed in isolation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Examples and profiles across glacially occupied troughs. Images are hill-shaded merged bathymetry and elevation data. \(\text{(a) The Shelikof Strait. (b) Troughs and fjords, south of Kenai Fjords National Park. (c) Profiles across lines Y–Y' and Z–Z', located on (A) and (B).}\)}
\end{figure}
from eskers (e.g. Figure 8(c)). In total, 1979 meltwater channels were mapped, again ranging from a few tens of metres to several kilometres in length. Future work is required to classify these meltwater channels before they can be used for glacial inversion (e.g. Greenwood et al., 2007).

3.4. Troughs

Polylines \((n = 135)\) marking the edge of troughs are included on the Main Map. The troughs are typically 50–300 m deep, and 100s m wide. The largest trough forms the Shelikof Strait, between the Aleutian Mountains and Kodiak Island, through which ice has been hypothesised to flow (Mann & Peteet, 1994). Further troughs are evident across the southern Alaskan continental shelf (Figure 9(c) and 9(d); Swartz, Gulick, & Goff, 2015). Elsewhere, ice streams form along such troughs (e.g. the Norwegian channel ice stream (Sejrup et al., 2003) and the Lambert Glacier-Amery ice shelf system (Hambrey & Dowdeswell, 1994)). However, a lack of high resolution bathymetry within the Shelikof Strait, and other troughs, prohibits any recognition of a possible palaeo-ice stream imprint (Stokes & Clark, 1999).

4. Summary and conclusions

The Cordilleran Ice Sheet and Ahklun Mountains Ice Cap left behind a wealth of geomorphological evidence during the late Wisconsinan in southern Alaska. Here we present the first systematic map of the glacial geomorphology across the areas formally occupied by these ice masses. Our mapping covers the terrestrial portion of these ice sheets, and, where bathymetric data exists, the submerged geomorphology. The map documents numerous subglacial lineations, which may represent the tracks of palaeo-ice streams. Large, looping moraine sequences record the recession of the ice masses. We also note features related to glacial meltwater, channels and eskers, as well as systems of glacial troughs offshore. This map provides the basis for a future empirical reconstruction of the ice masses in this area.

Software

Mapping and data manipulation were conducted in Esri ArcGIS 10.1.

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References

Booth, D. B., Troost, K. G., Clague, J. I., & Waitt, R. B. (2004). The cordilleran ice sheet. The Quaternary Period in the United States, 1, 17–43.

Boulton, G. S., & Clark, C. D. (1990). The Laurentide ice sheet through the last glacial cycle. The topology of drift lineations as a key to the dynamic behaviour of former ice sheets. Transactions of the Royal Society of Edinburgh: Earth Sciences, 81(4), 327–347.

Bradwell, T. (2005). Bedrock megagrooves in Assyst, NW Scotland. Geomorphology, 65(3), 195–204.

Bradwell, T., Stoker, M., & Krabbendam, M. (2008). Megagrooves and streamlined bedrock in NW Scotland: The role of ice streams in landscape evolution. Geomorphology, 97(1), 155–156.

Briner, J. P., & Kaufman, D. S. (2000). Late Pleistocene glaciation of the southwestern Ahklun Mountains, Alaska. Quaternary Research, 53(1), 13–22.

Clark, C. D. (1999). Glaciodynamic context of subglacial bedform generation and preservation. Annals of Glaciology, 28(1), 23–32.

Clark, C. D., Hughes, A. L., Greenwood, S. L., Jordan, C., & Sejrup, H. P. (2012). Pattern and timing of retreat of the last British-Irish Ice sheet. Quaternary Science Reviews, 44, 112–146.

Clark, C. D., Hughes, A. L., Greenwood, S. L., Spagnolo, M., & Ng, F. S. (2009). Size and shape characteristics of drumlins, derived from a large sample, and associated scaling laws. Quaternary Science Reviews, 28(7), 677–692.

Dionne, J. C. (1987). Tadpole rock (rock drumlin): A glacial streamline moulded form. In J. Menzies & J. Rose (Eds.), Drumlin Symposium (pp. 149–159). Rotterdam: Balkema.

Ely, J. C., & Clark, C. D. (2016). Flow-strips and foliations of the Antarctic ice sheet. Journal of Maps, 12(2), 249–259.

Ely, J. C., Clark, C. D., Spagnolo, M., Stokes, C. R., Greenwood, S. L., Hughes, A. L., … Hess, D. (2016). Do subglacial bedforms comprise a size and shape continuum? Geomorphology, 257, 108–119.

Greenwood, S. L., & Clark, C. D. (2008). Subglacial bedforms of the Irish ice sheet. Journal of Maps, 4(1), 332–357.

Greenwood, S. L., Clark, C. D., & Hughes, A. L. (2007). Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: Application to the British ice sheet. Journal of Quaternary Science, 22(6), 637–645.

Greenwood, S. L., Clason, C. C., Helanow, C., & Margold, M. (2016). Theoretical, contemporary observational and palaeo-perspectives on ice sheet hydrology: Processes and products. Earth-Science Reviews, 155, 1–27.

Hambrey, M. J., & Dowdeswell, J. A. (1994). Flow regime of the Lambert Glacier-Amery ice shelf system, Antarctica: Structural evidence from Landsat imagery. Annals of Glaciology, 20(1), 401–406.

Hamilton, T. D., & Porter, S. C. (1975). Itkilik glaciation in the Brooks range, northern Alaska. Quaternary Research, 5(4), 497–497.
Hättestrand, C., & Kleman, J. (1999). Ribbed moraine formation. *Quaternary Science Reviews*, 18(1), 43–61.

Hillier, J. K., Smith, M. J., Armugam, R., Barr, I., Boston, C. M., Clark, C. D.,... Hättestrand, C. (2015). Manual mapping of drumlins in synthetic landscapes to assess operator effectiveness. *Journal of Maps*, 11(5), 719–729.

Hughes, A. L., Clark, C. D., & Jordan, C. J. (2010). Subglacial bedforms of the last British ice sheet. *Journal of Maps*, 6(1), 543–563.

Kaufman, D. S., & Manley, W. F. (2004). Pleistocene maximum and late Wisconsin glacier extents across Alaska, USA. In J. Ehlers, & P. L. Gibbard (Eds.), *Quaternary glaciations – extent and chronology, part II: North America. developments in quaternary science* (vol. 2, pp. 9–27). Amsterdam: Elsevier.

Kaufman, D. S., Young, N. E., Briner, J. P., & Manley, W. F. (2011). Alaska palaeo-glacier Atlas (version 2). In J. Ehlers, & P. L. Gibbard (Eds.), *Quaternary glaciations – extent and chronology. Developments in quaternary science* (vol. 2, pp. 427–445). Amsterdam: Elsevier.

Kleman, J., & Borgström, I. (1996). Reconstruction of palaeo-ice sheets: The use of geomorphological data. *Earth surface processes and landforms*, 21(10), 893–909.

Klem, J., Hättestrand, C., Borgström, I., & Stroeven, A. (1997). Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. *Journal of Glaciology*, 43(144), 283–299.

Lane, T. P., Roberts, D. H., Rea, B. R., Cofaigh, CÓ, & Vieli, A. (2015). Controls on bedrock bedform development beneath the Uummannaq ice stream onset zone, west Greenland. *Geomorphology*, 231, 301–313.

Mandryk, C. A., Josenhans, H., Fedje, D. W., & Mathewes, R. W. (2001). Late quaternary palaeoenvironments of Northwestern North America: Implications for inland versus coastal migration routes. *Quaternary Science Reviews*, 20(1), 301–314.

Mann, D. H., & Peteet, D. M. (1994). Extent and timing of the last glacial maximum in southwestern Alaska. *Quaternary Research*, 42(2), 136–148.

Margold, M., Jansson, K. N., Kleman, J., Stroeven, A. P., & Clague, J. J. (2013). Retreat pattern of the Cordilleran ice sheet in central British Columbia at the end of the last glaciation reconstructed from glacial meltwater landforms. *Boreas*, 42(4), 830–847.

McHenry, M., & Dunlop, P. (2016). The subglacial imprint of the last Newfoundland ice sheet, Canada. *Journal of Maps*, 12(3), 462–483.

Misarti, N., Finney, B. P., Jordan, J. W., Maschner, H. D., Addison, J. A., Shapley, M. D.,... Beget, J. E. (2012). Early retreat of the Alaska Peninsula Glacier complex and the implications for coastal migrations of first Americans. *Quaternary Science Reviews*, 48, 1–6.

Molina, B. F. (2008). *Glaciers of Alaska*. US Geological Survey professional paper, (1386K).

Sejrup, H. P., Larsen, E., Halldíason, H., Berstad, I. M., Hjelstuen, B. O., Jonsdottir, H. E.,... Ottesen, D. (2003). Configuration, history and impact of the Norwegian channel ice stream. *Boreas*, 32(1), 18–36.

Smith, M. J., & Clark, C. D. (2005). Methods for the visualization of digital elevation models for landform mapping. *Earth Surface Processes and Landforms*, 30(7), 885–900.

Spagnolo, M., & Clark, C. D. (2009). A geomorphological overview of glacial landforms on the Icelandic continental shelf. *Journal of Maps*, 5(1), 37–52.

Spagnolo, M., Clark, C. D., Ely, J. C., Stokes, C. R., Anderson, J. B., Andreassen, K.,... King, E. C. (2014). Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. *Earth Surface Processes and Landforms*, 39(11), 1432–1448.

Stokes, C. R., & Clark, C. D. (1999). Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology*, 28(1), 67–74.

Stokes, C. R., Tarasov, L., Blomdin, R., Cronin, T. M., Fisher, T. G., Gyllencreutz, R.,... Jakobsson, M. (2015). On the reconstruction of palaeo-ice sheets: Recent advances and future challenges. *Quaternary Science Reviews*, 125, 15–49.

Storrar, R. D., Stokes, C. R., & Evans, D. J. (2014). Morphometry and pattern of a large sample (>20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews*, 105, 1–25.

Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O.,... Caffee, M. W. (2015). Deglaciation of Fennoscandia. *Quaternary Science Reviews*. Advance online publication.

Swartz, J. M., Gulick, S. P., & Goff, J. A. (2015). Gulf of Alaska continental slope morphology: Evidence for recent trough mouth fan formation. *Geochemistry, Geophysics, Geosystems*, 16(1), 165–177.

Trommelen, M., & Ross, M. (2010). Subglacial landforms in northern Manitoba, Canada, based on remote sensing data. *Journal of Maps*, 6(1), 618–638.

Trommelen, M. S., Ross, M., & Ismail, A. (2014). Ribbed moraines in northern Manitoba, Canada: Characteristics and preservation as part of a subglacial bed mosaic near the core regions of ice sheets. *Quaternary Science Reviews*, 87, 135–155.