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Title: Looking for Fish of the Right Age: Developing Predictive Modeling for Submerged Sites Using GIS, Salmon Genetics, and the Human Ecology of Salmon

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Abstract

A major challenge to the study of the peopling of the Americas is that much of the Bering Land Bridge (Beringia), the geographic area that people migrating from Northeast Asia into North America would presumably have passed through, is now submerged due to sea-level rise since the last glacial maximum. The scale of this submerged land mass further adds to the challenge of how to search for archaeological evidence of the human migration. This thesis proposes an approach to submerged site discovery in Beringia intended to reduce the total area that needs to be considered in a predictive model by focusing on a key resource, salmon. The cultural importance of salmon to Indigenous peoples across the North Pacific is broadly acknowledged, and increasingly, that importance is being incorporated into hypotheses regarding the peopling of the Americas. The concept of salmon as a "magnet" resource is used here as a way to prioritize submerged areas for further analysis toward a predictive site discovery model. This paper incorporates studies of modern salmon DNA, ethnography, archaeology, and geo-spatial analyses into the preliminary phases of a predictive model. The framework of the

Danish Model (Benjamin 2010) for submerged site discovery is adapted here for

Beringia. The analyses discussed here are aimed at identifying areas within the larger

region that would be suitable for further phase III and IV investigation.

Looking for Fish of the Right Age: Developing Predictive Modeling for Submerged Sites Using

GIS, Salmon Genetics, and the Human Ecology of Salmon

by
Jon Krier

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APPROVED:

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Major Professor, representing Applied Anthropology

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Director of the School of Language Culture and Society

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Jon Krier, Author

ACKNOWLEDGEMENTS

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Introduction

The question of when the first people came to the Americas has long been a

central concern of North American archaeology (Fladmark 1979; Hoffecker, Powers, and

Goebel 1993; Horai et al. 1993; Meltzer 2003; Jackson et al. 2007; Potter et al. 2017).

Most theories regarding the peopling of the Americas posit the movement of humans

from Northeast Asia into North America for a variety of reasons, including

archaeological evidence, genetic studies, and geographic proximity (Bonnichsen et al.

2005; de Saint Pierre 2017; Dixon 1999; Erlandson and Braje 2015; Fladmark 1979; Hey

2005; Hoffecker 2013; Rouse 1976). Central to this dominant out-of-Asia-into-the-

Americas model (both geographically and theoretically) is the now submerged landscape

of Beringia (Potter et al. 2017; Hoffecker, Powers, and Goebel 1993; Hoffecker 2013;

Wickert et al. 2012; Llamas et al. 2016; Monteleone, Dixon, and Wickert 2013; Llamas,

Harkins, and Fehren-Schmitz 2017). However, archaeological evidence of the peopling

of the Americas from Beringia is difficult to locate due, in large part, to the fact that

roughly 2 million km^2 of Beringia was submerged beneath what is now the Bering Sea

due to sea-level rise since the Last Glacial Maximum, or LGM (J. Clark, Mitrovica, and

Alder 2014). This underwater landscape, so central to understanding the origins of the

first Americans, is truly vast (for comparison, the modern State of Alaska is 1.7 million

km^2). In order to make finding submerged archaeological sites within this vast land mass

more possible, this paper seeks to test a strategy using salmon as a simple single-factor filter to reduce the total area that needs to be considered in subsequent predictive modeling.

For much of the 20th Century, the dominant model for the initial peopling of the New World was the Clovis First hypothesis, which held that big game hunters walked across Beringia, in pursuit of large herd animals, and then down the ice-free corridor into North America roughly 13,000 years ago (Bonnichsen et al. 2005; Beck and Jones 2010; Faught 2017; Hoffecker, Powers, and Goebel 1993; Potter et al. 2017; Kelly 2003; Rouse 1976; Goebel, Waters, and Dikova 2003; Meltzer 2003). With the increasing recognition of archaeological sites that pre-date the ice-free corridor, such as Monte Verde (Dillehay et al. 2008; de Saint Pierre 2017; Erlandson, Braje, and Graham 2008) and Paisley Caves (Jenkins et al. 2012; Gilbert et al. 2008), alternative hypotheses of migration have been explored (Davis 2011; Erlandson 2013; Dixon 1999; Bonnichsen et al. 2005; Oppenheimer, Bradley, and Stanford 2014; Bradley and Stanford 2004). The Coastal Migration hypothesis, while not new (Fladmark 1979), has been the subject of a significant, and growing, body of literature (Erlandson et al. 2011; Erlandson and Braje 2015; Erlandson et al. 2007; ICF, Southern, and Davis 2013; Punke and Davis 2006; J. Clark, Mitrovica, and Alder 2014; Balter 2011; Erlandson et al. 2015; Erlandson and Fitzpatrick 2006; Bailey and Flemming 2008; Erlandson 2013; Sandweiss et al. 1998; Davis 2011; Des Lauriers et al. 2017; Erlandson and Jew 2009; Mackie et al. 2013; Monteleone 2013). The Coastal Migration hypothesis posits that the first humans to colonize the Americas may have traveled South by making use of ice free refugia along the Pacific coast, as opposed to navigating an ice-free interior corridor. The Coastal

Migration hypothesis generally assumes the presence of maritime adaptation and use of marine/coastal resources by first peoples (Erlandson et al. 2007, 2015). Evidence of late Pleistocene fish and marine resource use is rare but it has been found at some archaeological sites (Sutton 2017; Erlandson et al. 2011; Martinez 1979; Sandweiss et al. 1998; Des Lauriers et al. 2017; Erlandson and Jew 2009; Halffman et al. 2015; Choy et al. 2016; Goebel, Waters, and Dikova 2003).

In addition to the academic literature cited above, oral history and other traditional ecological knowledge, or TEK, provide important information for understanding how we might think about the Coastal Migration hypothesis. In 2012, the author had the opportunity to discuss parts of Haida oral history with members of the Haida Gwaii Watchmen program in Gwaii Haanas National Park. Of particular interest is a story in which the Haida people came to the archipelago now called Gwaii Haanas when the world was covered in ice. In this story, the people went West to escape the ice and found the Haida Gwaii ice-free (this means that according to Haida histories they were already present in North America during a time of glacial advance). The version the author was told was shared verbally; however, references to the story can be found attributing the story to Tribal Elder and Watchman, Captain Gold (Hume 2017; Gold 2004, 2014). This particular Haida story is significant because a key element to the Coastal Migration hypothesis is the presence of ice-free refugia that could have provided sufficient resources to support human populations along the Pacific edge of the ice sheet during the Last Glacial Maximun (LGM). A recent find of a potentially 13,800-year-old fishing weir off the coast Haida Gwaii further supports the idea that people in the Northwest were exploiting marine resources prior to the ice-free corridor (Moore 2014).

The Haida story also suggests that the peopling of the Americas could have been farther back in time toward or prior to the LGM than most peopling models suggest.

In thinking about how to operationalize the presence of human populations in the Americas prior to the ice-free corridor, this author decided to use the concept of salmon as a marker for resources sustaining human populations. Recently there has been an increasing acceptance of a long chronology for use of fish and marine resources extending to the Pleistocene (Butler and O'Connor 2004; Halffman et al. 2015; Choy et al. 2016; Thornton, Deur, and Kitka 2015; Sutton 2017). Salmon in particular are a key source of marine derived nutrients (MDN) for terrestrial ecosystems and have an outsized impact on the broader ecology of drainages in which they occur (Tiegs et al. 2011; Adams et al. 2010; Janetski et al. 2009; Cederholm et al. 1999; Aydin et al. 2005; Gende et al. 2004; Chaloner and Wipfli 2002; Gresh, Lichatowich, and Schoonmaker 2000; Gende and Quinn 2006; Chaloner et al. 2002; Cak, Chaloner, and Lamberti 2008; Hocking and Reynolds 2011; Naiman et al. 2002; Quinn 2011). As has been noted by Halffman et. al (2015), "the spawning behavior of anadromous Pacific salmon results in massive and predictable runs in freshwater streams over a short period, making these fish a potentially valuable human food resource… Although the degree of reliance on salmon by early Beringians is currently unresolved, historically in subarctic Alaska, salmon were taken in great numbers in summer to early fall for drying and storing through the winter." Studies of salmon DNA support the idea that the Haida Gwaii, as well as Beringia and Southeast Alaska, was a likely place to have served as a refuge for salmon species (Beacham et al. 2012; Beacham, Candy, Sato, et al. 2009; Beacham, McIntosh, et al. 2006; Beacham, Jonsen, et al. 2006; Hansen et al. 2011; C. T. Smith et al. 2001;

Beacham, Candy, Le, et al. 2009) The depth of Native connection to and knowledge of salmon (Hayden 1992; Thornton, Deur, and Kitka 2015; Arnold 2009; Roche, McHutchison, and Alexie 1998; May 2014) further suggests that salmon could serve as a marker of human subsistence in this region.

In order to define a salmon bearing drainage, the concept of a larger stream (larger catchment is used in this thesis as a first order approximation for stream order) was used (Quinn 2011; Beacham et al. 2012). Salmon spawning habitat is multivariate, and spawning site selection is influenced by factors such as stream depth, velocity, and substrate, additionally the incubating embryos require adequate flow of oxygenated water (Quinn 2011). Precisely which conditions were most important in those streams that salmon did spawn in through the LGM is unknown; however, whether the selection was most influenced by specific location variables (e.g. depth, flow, substrate) or simple presence of liquid water through the winter (i.e. flow large enough to prevent the stream from freezing solid), larger streams (of higher stream order) provide more opportunities for a drainage to meet those unknown requirements. The rationale for using stream size (represented through catchment or stream order) is based on the fact that salmon populations were subject to a population bottleneck at the LGM but were still present in multiple Northern refugia (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012). The Bering Sea region was the location of salmon home streams through the LGM, but although lower sea levels revealed a large area that could have supported salmon streams (if LGM Beringian streams supported salmon as ubiquitously as modern Alaskan and Siberian streams do) the genetic data suggests that salmon were not as abundant in

Beringia at the LGM as modern populations. This reduced abundance could simply be due to reduced productivity in the ocean areas where Beringian salmon matured; in which case, it is possible that salmon populations were widely dispersed in stream systems, but the runs may have been too meager to play a major role in human subsistence in Ice Age Beringia. However salmon stocks can mature far from home streams and their maturation areas can shift in response to climate shifts (Beacham, Candy, Sato, et al. 2009) and salmon show significant dietary flexibility (Tadokoro et al. 1996; Kaeriyama et al. 2004; Aydin et al. 2005) in response to climate events. This flexibility in the ocean portion of the anadromous life cycle of salmon, combined with the presence of populations of salmon in refugia along the glacial margin, indicates that stream conditions could have played a major role in where salmon populations remained viable in the North Pacific and Bering Sea during the LGM.

These drainages are identified as a starting point for the future gathering of higher quality data that can allow for the application of more elaborate predictive modeling and investigation methods (such as sub-bottom profiling and coring). A deeper understanding of the interactions between humans, salmon, and the environment can offer insight into where some of the earliest people in the Americas might have lived.

To be clear, the salmon-focused approach proposed here is not meant to entirely supplant or displace other predictive approaches or analyses (Mackie et al. 2013; Benjamin 2010; ICF, Southern, and Davis 2013; Monteleone 2013; Monteleone, Dixon, and Wickert 2013; Wickert et al. 2012). Rather, it is meant to focus further analysis on a spatially constrained subset of the total submerged landscape. If the likely location of drainages that bore salmon populations during the late Pleistocene could be located, it

would make sense to focus on those drainages for further analysis. Based on modern DNA studies, it appears that Salmon populations in the Bering Sea and along the glacial margin of the Pacific Northwest survived the LGM in three main refugia (Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012; C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006). The initial goal of this project was to identify the most likely Beringian drainages to have acted as salmon refugia. This meant that the research questions that guided this effort assumed that the data available was sufficient to actually answer the larger questions about the peopling of the Americas. The available data proved to be insufficient to answer the specific questions that were developed. This paper explores the limitations of currently available data, adapts the Danish Model (Benjamin 2010) for use in the predictive modeling of submerged sites in Beringia, reviews literature relevant to understanding the paleo-biogeography of salmon, and offers factors to consider in future attempts to build a predictive model for submerged site discovery relevant to the peopling of the Americas. At this time it is simply not possible to answer many of the questions relevant to the peopling of the Americas with the data that is available; however, the questions that are asked in this thesis are a useful conceptual model for the types of matters that would need to be addressed to evaluate the importance of salmon to the peopling of the Americas.

Some Limitations to consider

Overview

Identifying refugia locations is a large goal, and there are numerous efforts geared at locating and modeling ice-free refugia that could have supported early colonizers of

the Americas (Dixon 2015; Bailey and Flemming 2008; Monteleone, Dixon, and Wickert 2013; Monteleone 2013; Wickert et al. 2012; ICF, Southern, and Davis 2013; Mackie et al. 2013; Shugar et al. 2014). Identification of salmon bearing refugia along the entirety of the Pacific edge of the Pleistocene continental ice-sheets proved to be beyond the scope of this study; however, a greater understanding of the geography of Beringia is still important to understanding the peopling of the Americas. Toward that goal, this paper seeks to understand the changing landscape of the Bering Straits region from the LGM to the modern sea level regime.

For the purposes of this paper, more elaborate theoretical constructs for fine grained predictive modeling are collapsed into the idea of using salmon as a "magnet resource" (Sutton 2017); a magnet resource being understood as a resource that attracts people into a region, rather than a resource encountered randomly. This concept of treating salmon as an attractive resource that drew humans into new areas along the Pacific Coast can be compared with the classic image of big game focused Clovis hunters following animal herds across the land bridge. The idea is similar, but the resource type is different. Compared to large land herbivores like caribou that currently inhabit the arctic, the migratory patterns of salmon are relatively constrained from a terrestrial perspective. Caribou also migrate along largely predictable patterns, but the ranges in which the animals can be found can still be geographically large, and different populations have varied migration habits and densities (Fancy et al. 1989; Bergman, Schaefer, and Luttich 2000). Salmon live in the water, so they are restricted to rivers and streams. Salmon also return to the streams where they hatched. And salmon return to those streams on a fairly predictable schedule (Quinn 2011). Salmon also serve as a

source of MDN that increases the productivity of the nearby environment (Chaloner et al. 2002; Gende and Quinn 2006; Chaloner et al. 2007; Janetski et al. 2009; Tiegs et al. 2011). For all these reasons it is reasonable to argue that humans in a landscape that contained salmon bearing streams would be likely to utilize salmon resources and would likely seek them out.

Whether hypotheses for the peopling of the Americas focus on a specific keystone species (salmon in the case of this paper), classes of resource (Clovis big game hunters), or productive habitats (Kelp Highway), most hypotheses use the lens of some attractive factor that brings humans into a new area. Models that do not address resources, like the Beringian Standstill hypothesis that focuses on human DNA proxies for human population movements, sometimes assume migration driven by population pressure (Llamas et al. 2016). There is not a clear or supported body of theory that explains why humans initially migrated into the New World. Most modeling is developed working backward from the fact that people did indeed migrate into the Americas. Since humans did colonize the Americas in the deep past, the focus has been on what factors would have drawn people into new lands.

This project used Geographic Information Science (GIS) analyses to attempt to locate salmon bearing streams and evaluate the quality of various datasets.

A Brief Introduction to the GIS Products and Analyses Used in this Project

Broadly speaking GIS encompasses the myriad ways that geographic data can be converted into useful information (Boldstad 2012). There are a variety of data types and products that are commonly used (e.g. point data, line data, shapes, shapefiles, raster

data) to create the layers that are used in geoanalysis. For geodata to be fully utilized it has to be projected using an appropriate coordinate system. Projection is simply the process of taking coordinate data from a three-dimensional globe and representing it as accurately as possible on a two-dimensional map surface. Appropriate projection can be challenging in polar regions since most map projection systems are optimized for middle latitudes, and longitudinal coordinates become severely compressed the closer one comes to the poles.

For the purposes of this project the main data type employed was raster data. Rasters are grids of data in which each pixel contains a quantitative value (ESRI 2016). Digital images like JPEGs are familiar uses of rasters in non-geospatial settings (though image rasters are also commonly used in GIS). To keep the data manageable, individual pixels do not have spatial data associated, rather the entire raster is georeferenced by a single anchor pixel, and since the dimensions of the other pixels are known, the spatial projection of the rest of the pixels derive from their relationship to the anchor pixel. This means that if a raster is not properly georeferenced then it cannot be projected in a map to scale, other types of analysis are possible, and images can be generated, but accurate projection requires georeferencing. Additionally, if the dimensions of the pixels are set according to coordinate intervals (arc minutes/seconds), as many US Government rasters are, rather than setting the pixels to constant area, then the variability of actual pixel size can create a variety of errors when the raster is projected or analyzed.

The primary type of raster data that is used as the basis for the analyses in this thesis is Digital Elevation Model (DEM) rasters. DEMs provide continuous elevation data for each pixel in the coverage area. In terrestrial settings there are a variety of ways

that elevation data can be directly or remotely sensed. One of the highest resolution methods of gathering terrestrial elevation data is lidar (US Department of Commerce 2014). Lidar can provide elevation data at resolutions of less than one meter. Comparatively, underwater elevations (bathymetry) are harder to gather. Most remote sensing applications have limited efficacy for deriving bathymetry. For example, one of the few space based methods of detecting bathymetry is satellite altimetry (Sandwell and Smith 1995) which has a pixel resolution of 2 kilometers square. Green laser lidar can be used in shallow water, as long as the water is clear, but the depth is typically limited to less than 10 meters depth. The primary way that detailed bathymetry is gathered is with multibeam sonar (US Department of Commerce n.d.; Abraham and Willett 2002; Hughes Clarke, Mayer, and Wells 1996), but sonar surveys require ships to engage in systematic surveys that are expensive, and typically use methods that have difficulty accurately sensing depths less than 50 meters.

Once a DEM is identified for analysis there are a variety of analysis steps that are employed. These methods are discussed in depth later in the paper. One of the key types of analysis used in this project is drainage analysis, in which a DEM is used to model which way water is most likely to flow from a given pixel. Drainage analysis allows the creation of estimated stream paths for DEMs. This is useful for trying to understand where rivers may have been in Beringia.

Data Limitations

The scale of the area examined in this paper is vast. The currently submerged portions of the landbridge is approximately $2 * 106 \text{ km}^2$ (J. Clark, Mitrovica, and Alder

2014). And unfortunately, the bathymetric datasets available to use for the analysis of

that landscape are coarse grained and problematic. The well georeferenced Manley

(2002) DEM from INSTAAR has useful features, like being resampled to constant area

pixels (rather than Arc-minute pixels which have highly varied area values at high

latitudes), but those pixels are 2 kilometer squares, and the source raster, ETOPO2

(Center 2006), derives its 2 Arc-minute bathymetric cell data from satellite altimetry

(Sandwell and Smith 1995) which does not lend itself to finer resolutions. Additionally,

the Manley (2002) DEM is derived from the 2001 version of ETOPO2 which had

problems like a global one-pixel offset that were not corrected until the 2006 version. A

single pixel offset would not be a huge deal in a fine-grained raster, but when trying to

locate submerged streams, two kilometers is a large margin of error. The isostatically

adjusted DEM datasets from J. Clark, Mitrovica, and Alder (2014) represent a major

improvement in accurately modeling relative sea level in Beringia; however, the publicly

available datasets lack georeferencing data, and are derived from an undescribed subset

of the ETOPO1 (Amante and Eakins 2009) global relief model. This means that the J.

Clark, Mitrovica, and Alder (2014) data cannot be projected accurately which severely

limits the interoperability of the data, or the representation options. Additionally, the J.

Clark, Mitrovica, and Alder (2014) DEM was not resampled into a constant area cells, so

the distortions caused by the inability to project the data are not easily rectified. And

finally, the bathymetric data for the ETOPO1 was primarily sourced from GEBCO

estimated seafloor bathymetry, and it is unclear what data sources were used. The

ETOPO1 sourced bathymetry is also problematic for drainage analysis as is discussed

later. All of this adds to the difficulty of accurately modeling Beringia. The coarse

grained nature of the available DEMs also fundamentally reduces the utility of the datasets for predictive models designed to ascribe probability values to individual pixels based on multiple factors (ICF, Southern, and Davis 2013; Monteleone 2013), since factors like insolation being within 50 meters of a stream are problematic if the pixel size is more than a kilometer square.

As much as possible, these issues are addressed and discussed in the analyses described in this paper. The limitations described, in some cases proved to be insurmountable for success in achieving research goals. Despite the limitations there is still value in exploring the perspectives and approaches described in this paper. The conclusion of this paper addresses the relative successes and failures achieved in answering the research questions and suggests the ways that the lessons of this project can be applied to future research.

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Research Approach and Questions
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Research Approach

Following the example of Monteleone (2013) and others, this project adapts the Danish Model (Benjamin 2010) for submerged site discovery. The Danish Model is a six-phase discovery model for ancient submerged sites that has seen significant success in a variety of settings around the world. The phases of the model are: 1) regional familiarization: archaeology, geography, geology, geomorphology, oceanography, and hydrology; 2) ethnographic component: cultural parallels, historical research, and modern interviews; 3) map, chart and aerial imagery analysis, and location plotting; 4) observation of potential survey locations, physically and with sonar; 5) marking of

theoretical site with GPS and diving to investigate; 6) post-fieldwork analysis, interpretation and dissemination.

There are various methods that have been used for predictive modeling of submerged sites. Some methods use more pixel based (i.e. factors like slope or similarity to characteristics of known site locations) quantitative approaches designed to evaluate the likelihood of sites being present on given pixels of a DEM (Wickert et al. 2012; Monteleone, Dixon, and Wickert 2013; Monteleone n.d.). Other approaches focus more on the proximity of pixels to probable locations of resources (e.g. proximity to streams, coastal rugosity, etc.) (ICF, Southern, and Davis 2013), though it should be noted that in the cited example, Davis et al. also incorporate pixel characteristics like insolation into the model. As these models all work with rasters, the end product is a heat-map style layer that ascribes probability to pixels based on the selected matrix of factors. The Danish Model does not replace any of these methods, rather it is a conceptual framework, based on best-practices, that guides the development and iteration of analysis strategies; however, the specific methods discussed in Benjamin (2010), do focus on an approach that prioritizes specific landforms known to be likely sites of habitation/use based on locally relevant ethnography, history, and known archaeological sites. This project sought to use a specific culturally important resource (salmon) to prioritize a specific type of landform (streams) as a first level filter to reduce the total area for future exploration.

The Danish Model was developed out of a larger body of submerged site exploration. The Scandinavian examples are difficult to replicate elsewhere. The Doggerland region uniquely benefits from a confluence of high-quality datasets, concerted effort, and successful underwater explorations (Fleming 2008). North America

in general, and Beringia specifically does not have this same quality of datasets and comprehensive environmental reconstructions, and likewise do not have the same record of successful exploration. This thesis project sought to employ a Danish Model style approach, but there is no way to evaluate relative practical validity of different methods in the Beringian milieu since predictive modeling of submerged sites in this region is still largely conjectural.

The Danish Model was chosen for this project for several reasons. The primary consideration that led to adopting this model was the desire to incorporate ethnographic data and cultural perspectives, as opposed to a more purely mechanistic approach like ideal free distribution (IDF) (Kennedy and Gray 1993). The attraction of a more quantifiable approach is certainly understandable (ICF, Southern, and Davis 2013; Merwin 2003); however, this author strongly prefers a model that assumes a greater level of human agency and cultural mediation of action. Both IDF based approaches, and the salmon based approach proposed here focus on subsistence resources; however, IDF assumes that organisms will distribute themselves where the most calorically advantageous constellation of resources are located (i.e. all things being equal, people will live where the most food is), while the selection of salmon is predicated on the understanding that salmon are a culturally key species (i.e. people choose where to live based on culturally based principles and values). Uncritical employment of IDF has been shown to be insufficient for predicting foraging habits of animals (Kennedy and Gray 1993), and humans with their elaborate cultures further complicate predictive modeling.

This project seeks to incorporate traditional ecological knowledge, traditional histories, and Native cultural practices into a predictive model. The Danish model,

developed outside of colonially-based archaeological paradigms, incorporates local

knowledge and practices as a fundamental step. Traditionally in colonial countries,

archaeology has been the province of the dominant (Western) culture and knowledge

system (Atalay 2006; C. Smith and Jackson 2006), and this has meant that knowledge

systems that were incompatible with Western systems (indigenous, oral traditions) were

treated as invalid for scientific use. In Old World archaeological settings, the histories of

the people who inhabit areas under archaeological exploration are incorporated into the

contextualization and understanding of the archaeological record. Comparatively, in the

New World (and other colonial countries like Australia), the absence of written records

from Western sources is too often treated as an absence of knowledge despite examples

of accurate traditional indigenous histories (Henige 2009). While the incorporation of

ethnography is not widely singled out as a feature of the Danish Model, it is worth noting

that in the Scandinavian milieu, where the investigators and the investigated are the same

people, the validity of traditional knowledge is assumed. This project seeks to also

incorporate the concept that indigenous knowledge is in fact knowledge and can be used

to develop and interpret scientific inquiry.

Additionally, the choice of the Danish Model was influenced by the fact that

Monteleone (2013) selected the model for her doctoral work, and the approach adopted

for this project was strongly influenced by her work. Finally, the most compelling reason

to adopt the Danish model is that it was developed out of best practices from successful

efforts (Benjamin 2010; Fischer 1995; Andersen 1985; Fleming 2008).

Within this framework, the primary focus of this paper can be seen as preliminary

Phase III analysis. Phase I is briefly addressed with an overview of the region and a

special focus on evidence for the presence of salmon through the LGM. Phase II is also

briefly addressed with a focus on the cultural importance of and human ecology of

salmon. The preliminary nature of the Phase III analysis explored in this paper is focused

on using the identification of major drainages to reduce the problem of modeling ~1.5

million square kilometers of submerged landscape to the problem of modeling specific

drainages within that greater landscape. Salmon are treated as a magnet resource to

simplify the challenge of identifying areas for future analysis.

Research Questions

Tangential to the overarching research structure of the Danish Model, this project

also sought to evaluate the feasibility of answering specific research questions. These

questions were originally formulated with the (incorrect) assumption that they would be

answerable using existing bodies of knowledge. While the questions themselves proved

to be largely resistant to resolution with currently available data, they are worthwhile

examples of the types of questions that would need to be answerable for future work on

predictive modeling of submerged sites. Introducing these questions, which map only

loosely onto the multiphase Danish Model, also allows us to evaluate the quality of

existing datasets.

Questions 1 and 2 are relevant to Phase I regional familiarization. Before strong

conclusions or arguments could be built along the lines laid out in this thesis, prerequisite

levels of knowledge would have to be established. In these research questions, there is

not a question that explicitly maps onto phase II, as familiarization with existing

archaeological and cultural knowledge is more a matter of literature review than

falsifiable hypotheses. Questions 3 through 5 relate to Phase III, and are examples of the types of questions that can be used to identify locations for future focusing research iterations.

Question 1 (Q1): Were there viable salmon populations in Beringia throughout the last 20 thousand years?

Question 2 (Q2): Can geospatial analysis incorporating drainage analysis of existing bathymetric datasets reasonably be interpreted as indicating the location of potentially salmon bearing paleodrainages in Beringia at the LGM?

Question 3 (Q3): With the understanding that there were salmon in Beringia through the LGM, can GIS analysis identify likely locations of salmon bearing drainages through the period of sea-level rise following the LGM?

Question 4 (Q4): Can locations still recognizable as specific landforms (such as valleys) be identified from the existing datasets?

Question 5 (Q5): Once areas of particular interest are identified through the answering of the previous questions, can existing available datasets be used refine and test the validity of the earlier analyses?

Phase I: Regional Familiarization

Were There Salmon in Beringia During the Late Pleistocene?

The Pleistocene to the Holocene:

At the LGM, eustatic sea levels were ~125 meters lower than modern sea-levels, though the relative sea level situation was highly heterogenous along the glacial margin due to isostacy (Shugar et al. 2014), and the complications of modeling glacial mass compound the challenge of accurately modeling local isostatic effects (Menounos et al. 2017). Despite the presence of extensive areas of exposed land in the region of Beringia, DNA analysis of modern salmon populations indicates that the majority of salmon survived in the regions south of the ice, Washington to California on the North American side of the Pacific, and Japan to Korea on the Asian side (Beacham et al. 2012; Beacham, Candy, Sato, et al. 2009; Beacham, McIntosh, et al. 2006; Beacham, Jonsen, et al. 2006; Hansen et al. 2011; Smith et al. 2001; Beacham, Candy, Le, et al. 2009).
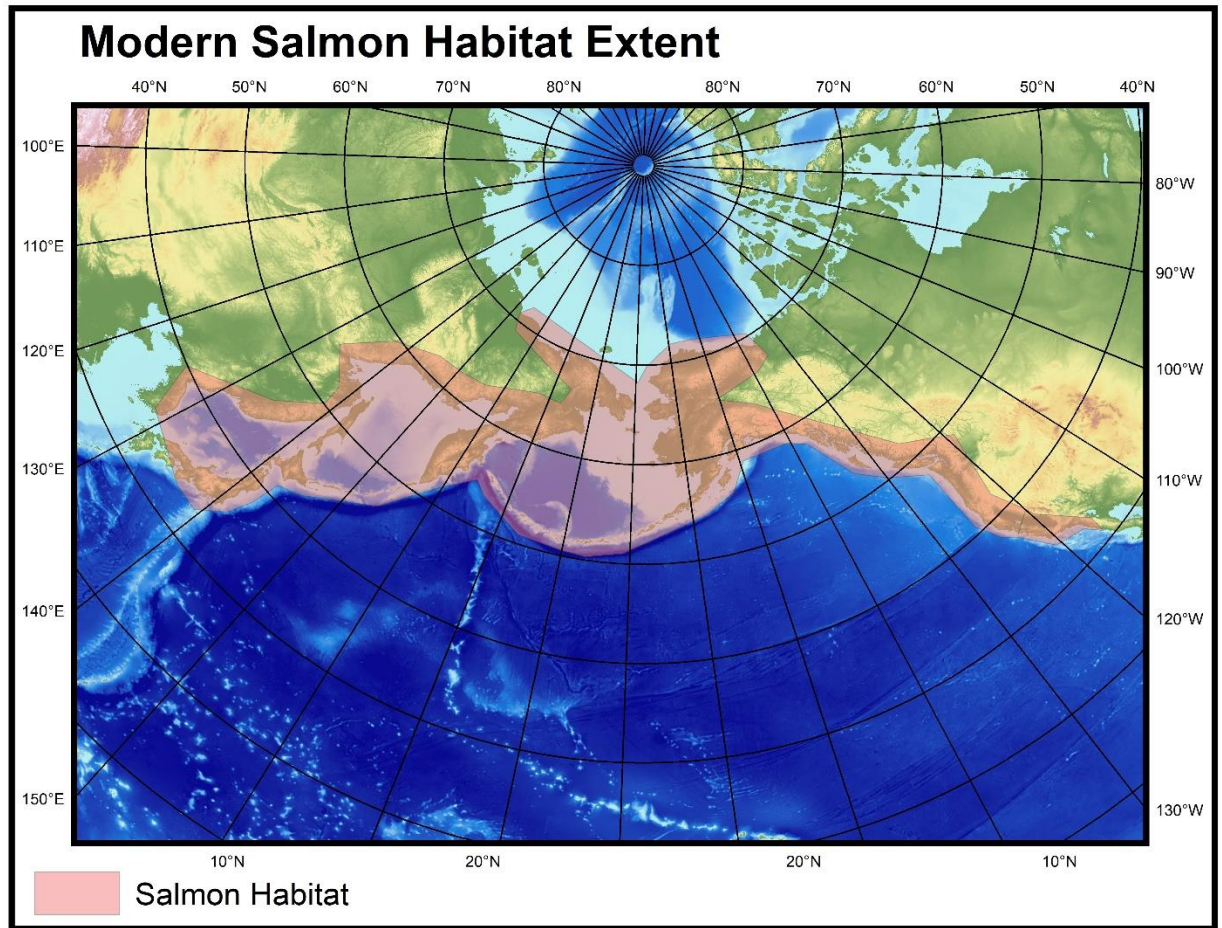
Figure 1: Modern Salmon Range. DEM ETOPO1 1 Arc-Minute Global Relief Model (Amante and Eakins 2009). Map created by Jon Krier. 2017. Projection: Berghaus Star AAG. This map is not intended to be a precise representation of the current distribution of salmon streams, it is provided simply as an aid to visualization of the area being discussed in this section of the paper. The general range for salmon used in this map is based on The Atlas of Pacific Salmon (Augerot and Foley 2005), but is simply a rough polygon rather than a basin delimited layer as in the Atlas. Note that as this paper is focused on the Beringian region the Berghaus Star AAG projection was chosen for reduced distortion in polar areas with less extreme distortion at lower latitudes than classic Polar Projections. The Berghaus Star AAG projection allows for the creation of a more familiar appearing map that still allows for clearer visualization of polar areas, but as with any polar centered projection it is impossible to provide a single North direction or consistent scale. The longitude and latitude graticule with coordinate labels is used in lieu of a North Arrow or scale.
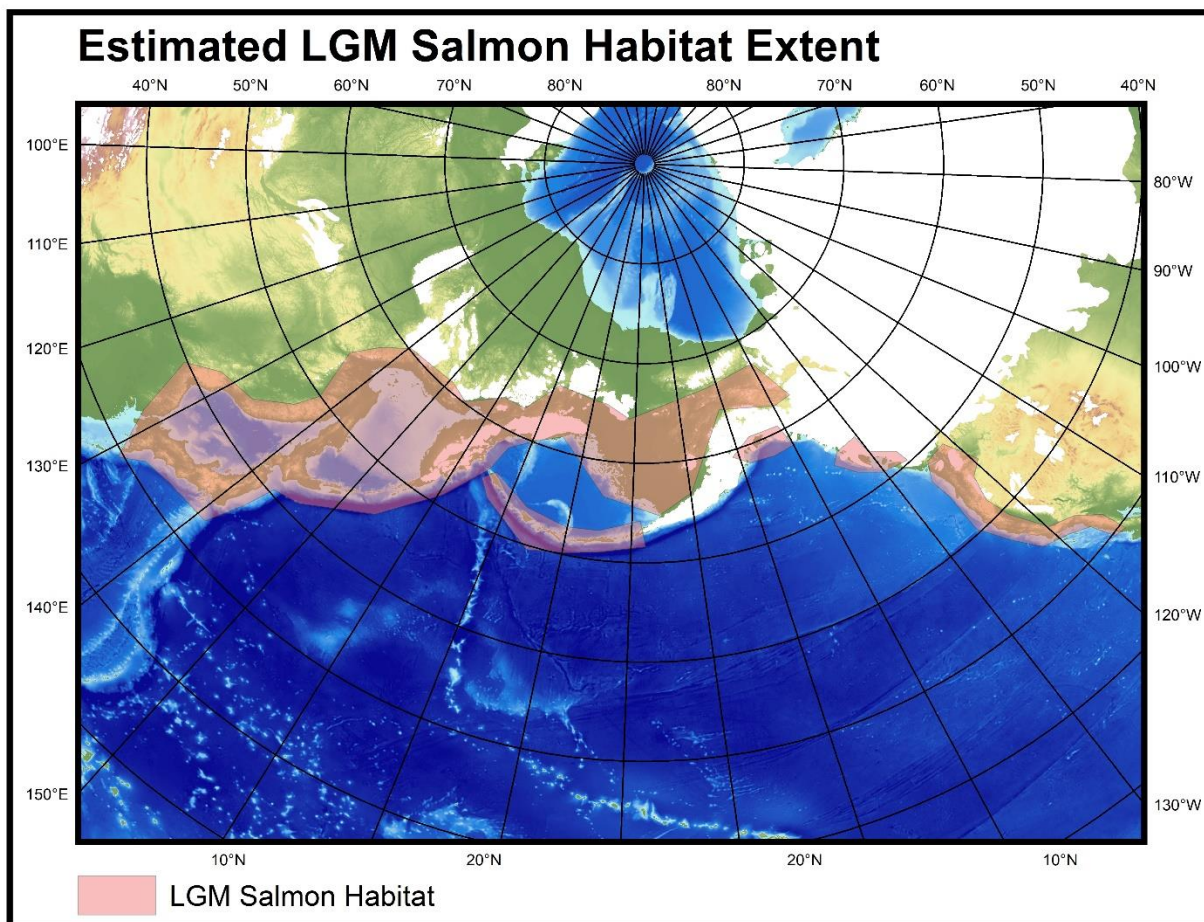
Figure 2: Estimated LGM Salmon Range. Sea-level 125 meters below modern sea-level (not isostatically adjusted). Glacial extent Ehlers, 2011. DEM ETOPO1 1 Arc-Minute Global Relief Model (Amante and Eakins 2009). *Map created by Jon Krier. 2017. Projection: Berghaus Star AAG. This map is not intended to be a precise representation of the current distribution of salmon streams, it is provided simply as an aid to visualization of the area being discussed in this section of the paper. The general range for salmon used in this map is based on The Atlas of Pacific Salmon* (Augerot and Foley 2005) *and a rough estimate of the general locations of salmon populations at the LGM based on DNA based biogeographic reconstructions* (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012). *The Southeast Alaska and Haida Gwaii regions are indicated generally based on the DNA based biogeographic reconstructions, but do not correspond to specific drainages. In Beringia the drainage of the Yukon is generally indicated because it was unglaciated, and in recognition of archaeological evidence of recurrent anadromous fish usage in the late Pleistocene at an interior tributary of the Yukon* (Halffman et al. 2015; Choy et al. 2016). *Note that as this paper is focused on the Beringian region the Berghaus Star AAG projection was chosen for reduced distortion in polar areas with less extreme distortion at lower*

latitudes than classic Polar Projections. The Berghaus Star AAG projection allows for the creation of a more familiar appearing map that still allows for less distorted visualization of polar areas, but as with any polar centered projection it is impossible to provide a single North direction or consistent scale. The longitude and latitude graticule with coordinate labels is used in lieu of a North Arrow or scale.

Over the ~19,000 years of sea level rise from the end of the Pleistocene there were three spikes in eustatic (not incorporating isostatic effects) sea level rise. The first period of extra rapid sea level rise was at 19,000-18,000 Before Present (BP), again at 14,000-13,000 BP, and a last rapid transgression at 12,000-11,000 BP. Even during the periods where sea level rose less rapidly, the average rate stayed over 6 meters per millennium throughout the Pleistocene/Holocene transition (International, Research, and Research 2013:21-22), though this average is based on Eustatic measurements and does not take local differences into account. This meant that for roughly the past 20,000 years the locations of most coastal habitation would have been moving steadily inland (though due to isostatic effects this is not uniformly true; in some areas the relative sea level stayed largely unchanged or even fell as the Earth's crust rebounded [Shugar et al. 2014]), and the majority of early evidence of people using salmon resources is likely to be submerged. This is especially true in the Bering Sea where this project is focused.

For salmon this also meant that their habitats were in a constant state of flux during the Pleistocene-Holocene transition from the LGM to modern sea levels (~20,000BP to 4,000BP). The retreating ice meant that increasing areas of salmon habitat were exposed, but simultaneously the shape and locations of watersheds capable of supporting salmon would have been fluctuating continuously for tens of thousands of years. The colonizing nature of salmon populations was doubtlessly key to allowing a species that needs both fresh and salt-water systems for reproduction to not only persist

through the period of warming, but in fact expand its territory to include all of the North Pacific up to the Arctic Ocean.

The Ecology of Salmon:

The earliest salmon fossils date to roughly 40 million years ago. As the mountains that ring the North Pacific grew into their modern arrangements, the salmon evolved and adapted along with the land. By the time of the Pleistocene (2.6 million years ago to 11.5 thousand years ago [Ehlers and Gibbard 2004])there were at least six species of salmon: Pink salmon, Coho, Sockeye, Chinook, Chum, and Smilodonichthys rastrosus (also known as Oncorhynchus rastrosus or Sabertooth Salmon). The largest of the salmon, Smilodonichthys, did not survive the ice-age; however, the other five species did survive (Arnold 2009).

At some point during the Pleistocene all of the salmon species were apparently extirpated through the northerly reaches of the modern range, though they recolonized prior to the LGM. During the LGM the various salmon populations were again restricted to more limited refugia. It is this double bottleneck effect that allows the identification of refuge regions using DNA analysis (C. T. Smith et al. 2001; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham, Jonsen, et al. 2006; Beacham et al. 2012).

Salmon display significant variability in life histories (even within species populations in a single drainage), but the anadromous nature of their reproductive cycle is a key element of their ecological importance (Quinn 2011; Arnold 2009; Hermansen 2006; Sutton 2017). The geologic history of their home range illustrates the magnitude

of disruptions that the salmon species have faced, and salmon display significant

interannual variation in the size of salmon runs, but the mechanics of their reproductive

cycle and nature of their systemic effects on their home ecosystems are tied to that very

variability. The vast majority of salmon in a given run return to their home streams. And

within those streams salmon reproduce in great numbers, with far more juvenile salmon

produced than are ever expected to survive (Arnold 2009). The eggs of spawning salmon

are deposited in home streams. Those eggs hatch and the juvenile salmon live through

the winter in their home streams and during the following year move out into the open

ocean to mature. After two to four years the salmon return to fresh water to spawn.

While the vast majority of salmon return to their home streams, a small fraction

goes to different streams as colonizers[1]. The large numbers of eggs that even a few

salmon deposit allow salmon to fill available habitat (Arnold 2009:19). The ability of

salmon to colonize new streams and fill the available capacity of those streams is far

from the totality of their ecological effect. In addition to expanding into available niches,

salmon actually expand the productivity and capacity of the drainages they inhabit.

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[1] Note Regarding Life History Variability: This paper focuses on description of the life cycle of stream type

salmon. There are also ocean type salmon who spend their first winters in the ocean after hatching in

headwaters, but ocean and stream salmon types are not genetically differentiated and are apparently

differentiated only by location of egg deposition, not as actual separate populations (Beacham, Jonsen, et

al. 2006). Additionally, there are populations of salmon that live entirely within freshwater systems (such

as naturalized Great lakes populations) but the author is unaware of any instances of this cycle that are not

the result of historic anthropogenic transplantations. These life history variations are not examined or

considered in this paper.

Salmon are an ecologically important source of marine derived nutrients (MDN), the caloric and nutritive contributions of marine systems to terrestrial ecosystems (Gende et al. 2004; Adams et al. 2010; Hocking and Reynolds 2011; Cederholm et al. 1999; Chaloner et al. 2007; Cak, Chaloner, and Lamberti 2008; Aydin et al. 2005; Chaloner et al. 2002; Gende and Quinn 2006; Tiegs et al. 2011). In the historic period, salmon runs in North American Pacific drainages accounted for an estimated biomass of 640 – 991 million kilograms per year delivered to river systems that had salmon runs. In contrast, modern North American runs, circa 2000, are in the range of 305 – 606 million kilograms, meaning that minimally approximately half of the historically available MDN is no longer returning to the continental ecosystem. This nutrient deficit is even more pronounced in the Washington to California range (the area where the majority of North American salmon survived the Pleistocene), where the historic drop in returning salmon biomass from 160 – 226 million kilograms is now down to 11.8 – 13.7 million kilograms, representing a more than 90% reduction in salmon derived MDN (Gresh, Lichatowich, and Schoonmaker 2000:18).

Salmon derived MDN is a systemically important, and self-reinforcing, element in the ecology of salmon bearing streams and their surrounding environment (Gende and Quinn 2006; Adams et al. 2010; Hocking and Reynolds 2011; Janetski et al. 2009). Salmon corpses feed a wide variety of taxa directly and indirectly. In addition to bears, humans, eagles, and other primary consumers, the bodies of salmon feed decomposers and plants. The decomposing corpses also indirectly feed the juvenile salmon when they hatch by nurturing the species that the fry feed on. The bodies of dead salmon literally feed future populations of salmon in a positive feedback loop. Thus the removal of

salmon from a stream can actually reduce the overall capacity and vitality of the drainage, as well as reducing the ability of the drainage to support larger salmon runs (Gresh, Lichatowich, and Schoonmaker 2000; Thornton, Deur, and Kitka 2015). In the context of this research, however, the positive feedback loop effect that salmon runs exert on drainages is of key interest.

Locating Salmon at the LGM:

The tendency for salmon to both primarily return to their home streams and also colonize new streams makes it possible to infer whence modern populations have spread. The method used to infer the salmon population dynamics of the LGM for this paper are based off of analyses conducted over the past decade and a half looking at variation in salmon microsatellite allele frequencies (C. T. Smith et al. 2001; Beacham, McIntosh, et al. 2006; Beacham, Jonsen, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012). Earlier studies of salmon genetics focused on mitochondrial D-loop sequences (as did Smith et al. [2001] in part) but it appears that microsatellite loci represented a more economic and effective method of analyzing large populations. While these analyses are complicated, and not unambiguous, they do provide a means for inferring the regions that contained refugia where salmon survived the LGM.

The results of analyses performed on populations of Coho salmon (C. T. Smith et al. 2001), Chinook (Beacham, Jonsen, et al. 2006), Sockeye (Beacham, McIntosh, et al. 2006), Chum (Beacham, Candy, Le, et al. 2009; Beacham, Candy, Sato, et al. 2009), and Pink Salmon (Beacham et al. 2012) were reviewed to better understand the paleo-biogeography of salmon species. The Coho study (C. T. Smith et al. 2001) analyzed

genetic data gathered from hundreds of specimens taken from 17 locations on the West

Coast of North America and up into Alaska. This study is less extensive than later

studies and does not incorporate Asian populations. The analysis of Chinook population

structures (Beacham, Jonsen, et al. 2006) analyzed genetic data gathered from 52,000

specimens taken from 320 locations across the Pacific from Korea to California. This

study was much more extensive than earlier studies, and provided additional depth to the

methods of using microsatellite analysis to identify refugia. Sockeye analysis (Beacham,

McIntosh, et al. 2006) continued the trend and scale of the 2006 study with analysis of

genetic data gathered from 48,000 specimens taken from 299 locations across the Pacific

from Japan to Oregon. The analysis of Chum populations (Beacham, Candy, Le, et al.

2009) looked at 53,000 specimens taken from 380 locations across the Pacific from

Korea to Washington respectively and also was used to generate a better understanding of

the stock origins of open ocean Chum (Beacham, Candy, Sato, et al. 2009). The Pink

Salmon study (Beacham et al. 2012) was similar in scope, though the peculiarities of Pink

Salmon life histories made the specifics of the study different[2].

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[2] Despite working with similar sample sizes (46,500 samples at 146 odd-year and 116 even-year locations),

the Pink Salmon study (Beacham et al. 2012) differed most dramatically from the other studies. The 2012

study looked at Pink Salmon which have a pronounced separation between odd-year and even-year

broodlines. Pink salmon almost universally mature in two years, which has led to almost total genetic

isolation between broodlines. The interyear genetic variation within geographic population areas for Pink

salmon is 5.5 times the variation between geographic populations. This is compared to ranges of 13 to 18

times more variation between populations than interyear variation for the other species of salmon. The

different year broodlines also appear to have survived in different refugia during the LGM, with the even-

The analyses of salmon microsatellite loci examine allele frequencies and diversity to evaluate relationships between salmon populations across the Pacific Rim. The variation within populations and distribution of genetic diversity were used to understand population structures. The genetically based clustering was compared to regionally defined populations. The comparison of genetic grouping and geographic locations of populations was used to infer the dispersal patterns from refugia as the glaciers retreated.

Across the pacific, from the Korean peninsula to California, salmon display a generally similar clinal genetic tendency with greater genetic diversity in the southern extremities and less genetic diversity in the northern middle. Additionally, due to the earlier extirpation throughout the north during an earlier Pleistocene glaciation, it is possible to see which side of the Pacific supplied the majority of the seed stock for the northern areas which survived in refugia during the LGM. This resulted, in some cases, in centers of genetic diversity at the drainages where the recolonizing species met prior to the LGM. The interpretation of the subtleties of the DNA analyses is beyond the scope of this paper.

The key takeaway for the purposes of this project is the very general idea that salmon of all five species examined were present in Beringian refugia through the LGM (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006;

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year population persisting in Beringia, and the odd-year line only surviving in the south. To this day the even-year broodline shows increased viability following incubation at low temperatures (4°C). But while the reproductive life histories of Pink salmon make them genetically unlike the other four species, their genetics do tell a similar story in the broad strokes.

Beacham, Candy, Le, et al. 2009; Beacham et al. 2012).   There is also evidence that salmon populations persisted in other glacial refugia along the Pacific Coast of North America, but that picture is more complicated and less relevant to this thesis. The genetic analysis of modern populations of salmon does not seem to be sufficient for making definite claims regarding the presence or absence of salmon in specific drainages at the LGM, but it does indicate that salmon were present. Perhaps future analyses of ancient salmon DNA can be used to make stronger connections between archaeologically recovered specimens and modern populations; however, finding sufficiently intact ancient DNA samples for salmon will undoubtedly be challenging since the relatively short half-life of ancient DNA (521 years) limits the amount of data that can be gathered from samples more than 20 half-lives old (10.5 thousand years) (Kaplan 2012). Significantly, the presence of salmon through the LGM and on to contemporary times combined with their colonizing tendencies supports the inclusion of anadromous fish resources in future predictive modeling efforts. In view of the discovery of evidence of late Pleistocne era recurrent use of anadromous species at an interior tributary of the Yukon drainage (Halffman et al. 2015; Choy et al. 2016) the incorporation of salmon into future models is not limited to applicability to coastal or marine focused approaches. Salmon can be used as a factor in modeling habitat suitability for humans in Beringia whether the assumed subsistence strategy is terrestrially or coastally focused.

Beringian Glacial Geology

In order to understand the nature of the changing landscape of North America and Beringia over the last 20,000 years it is necessary to have some understanding of the

ways that glaciation has affected the geology of the region. An in-depth discussion of

Beringian glacial geology is beyond the scope of this thesis (Bailey and Flemming 2008;

J. Clark, Mitrovica, and Alder 2014; Shugar et al. 2014; Menounos et al. 2017) but this

section seeks to provide a basic overview of the significant factors. The issues of

determining precise sea-levels for different points in time are complicated beyond simple

disagreements on eustatic (global bathtub) sea level models by glacial isostacy. Isostacy

is the way that the crust of the earth floats on the mantle. When there are continental ice

sheets, the increased thickness and weight of the ice weighs down the continental plates.

The effects are not limited to direct sinking underneath the ice-sheets, isostatic flexure

also lifts portions of the crust adjacent to the depressions, and during periods of post-

glacial rebound those flexed areas are also subject to increased subsidence. Creating

models for this is complicated, but work by J. Clark, Mitrovica, and Alder (2014)

provides a pattern for modeling isostatic effects on relative sea level. The isostatically

adjusted datasets for Beringia, as well as eustatic versions of the same area, were made

available by J. Clark, Mitrovica, and Alder and are used for analysis here. The publicly

available J. Clark, Mitrovica, and Alder (2014) datasets for Beringia are an un-

georeferenced raster derived from an unspecified subset of the ETOPO1 (Amante and

Eakins 2009) global DEM which limits the broader utility of the dataset, but the J. Clark,

Mitrovica, and Alder data is sufficient for exploring the importance of isostatic

adjustments and the general utility and limitations of the source ETOPO1 dataset for

predictive modeling.

J. Clark, Mitrovica, and Alder (2014) does not examine Southeast Alaska and

Haida Gwaii, each of which has dramatically different geological and glacial factors at

play. There is an improved 24 arc-second bathymetric dataset for Southern Alaska

available, the Southern Alaska Coastal Relief Model (SACRM) (Lim, Eakins, and

Wigley 2011), which makes use of a large number of sonar and other remotely sensed

sources for the Aleutian and Southern Alaska coast areas. Unfortunately for the purposes

of this Beringia focused project, the SACRM primarily uses ETOPO1 as the datasource

for Bering Sea bathymetry. Even with a more detailed bathymetric model for Southern

Alaska, accurately modeling diachronic isostatic effects would be a very challenging

project along the coastal margin since the questions of mass loss and temporal extent are

still being answered (Menounos et al. 2017; Potter et al. 2017; Shugar et al. 2014).

Drainage analysis of areas along the glacial margin without adjustments for isostacy is

extremely problematic and is not included here.

For the analyses conducted here (discussed in greater depth in Phase III) a

simplified approach to glacial geology is adopted. For the purposes of modeling salmon

bearing drainages at the LGM, glacial extent is taken from (Ehlers, Gibbard, and Hughes

2011), and represented in maps by the LGM glacial extent polygons from that

publication. In the models for the LGM major Beringian drainages (Figure 9) the sea-

level is not adjusted for isostacy and is arbitrarily set at 125 meters below modern sea

level. J. Clark, Mitrovica, and Alder (2014) set the eustatic sea level at 20,000 years

before present at 131 meters below modern. Fairbanks (1989) puts the global eustatic

LGM sea-level at 121 ±5 meters below modern. 125 was selected as an intermediate

value within the Fairbanks range. For the purposes of modeling changes throughout the

time-series values derived from J. Clark, Mitrovica, and Alder (2014) were used and

glacial extents were not explicitly represented.

Phase II: Cultural Familiarization

The Time Depth of Salmon Usage

Historically there had been an assumption in archaeological literature that marine

resources have only been used by Indigenous peoples for a few thousand years (Lyman

1991; Arnold 2009)[3]; however recent scholarship has embraced a much longer

chronology for marine resource (Des Lauriers et al. 2017; Sutton 2017; ICF, Southern,

and Davis 2013; Davis 2011; Erlandson and Jew 2009; Butler and O'Connor 2004;

Erlandson et al. 2007; Erlandson and Fitzpatrick 2006; Erlandson, Moss, and Des

Lauriers 2008). Recent theories of the peopling of the Americas (Erlandson 2013; ICF,

Southern, and Davis 2013; Erlandson et al. 2011; Mackie et al. 2013; Davis 2011) have

focused on a potential coastal route for the first people entering the Americas. This

"Coastal Migration" hypothesis contrasts with the "Ice Free Corridor" hypothesis that

was used in the "Clovis First" model and some current hypotheses (Potter et al. 2017;

Morrow 2017). A key component to the Coastal Migration hypothesis is the idea that the

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[3] The reason for this long-standing assumption for the lack of antiquity for Native use of marine resources

was the lack of known sites predating the stabilization of modern shorelines. The dominant hypothesis to

explain the lack of marine resource use has been termed the "Ignorant Indigene" hypothesis (Lyman 1991).

It was thought that North American Natives simply did not understand how to utilize marine resources

prior to roughly 5,000 years ago. This was the explanation for the rarity of coastal sites indicating the use of

marine resources prior to 3,000 years before present. The period prior to the supposed development of an

understanding of marine resources was referred to as the pre-littoral period, and references to this idea can

persist in the literature (see Arnold 2009) though more recent archaeological efforts seem to be moving past

the pre-littoral concept.

earliest evidence of people moving into the Americas is likely to have been submerged by rising sea-levels at the end of the Pleistocene; this hypothesis also assumes that people understood how to use marine resources by the terminal Pleistocene.

While most approaches to the coastal migration hypothesis have avoided focusing on a particular resource, Sutton (2017) explicitly uses salmon as a "magnet" resource; a resource that attracts people into a region, rather than a resource encountered randomly. Sutton argues that salmonids were the primary resource (though not the only resource) that drew human populations along the coast as glaciers retreated. While the ethnographic and prehistoric use of salmon is very well documented and ubiquitous along the Pacific Coast of North America (May 2014; Arnold 2009; Roche, McHutchison, and Alexie 1998; Butler and O'Connor 2004; Sutton 2017; Hayden 1992; Thornton, Deur, and Kitka 2015) the actual time depth of salmon use is unknown. Because of the rise of sea levels, most likely early sites for using salmon are now submerged. Additionally, catastrophic flooding along the Columbia river could have destroyed any deposits from prior to the Missoula floods (15,500 cal yr BP [Sutton 2017]). And taphonomic processes as well as recovery issues caused by the small size of many components of fish remains could account for much of the absence of evidence of fish use. The success of Choy et al. (2016) in identifying salmonid use dating to ~11,800 cal y B.P. through chemical profiling of hearth features at the Upward Sun site supports the argument that element preservation and recovery bias has handicapped our understanding of the antiquity of salmon use.

One spectacular site that demonstrates the deep time depth of the connection between humans and salmon is the Dalles Roadcut Site (Butler and O'Connor 2004).

The Dalles, Oregon, was the location of Celilo Falls, which was an important center of Native salmon fishing until the falls were submerged in 1957 by the Dalles Dam. With a minimum time-depth of 10,000 years, the Celilo Falls area is the longest known continuously inhabited site in the Western Hemisphere[4].

But evidence for early use of salmon and other fish, while thin, is not limited to the Dalles Roadcut and Upward Sun. Sutton (2017: 6-13) provides a survey of archaeological evidence for the use of salmonids and other fish along the Pacific Rim of North America:

Western Beringia:

Diuktai Caves' faunal assemblage included fish bones in a site whose earliest components dated to 16,000 cal y B.P.. Ushki Lake also provides evidence of salmonid use in Kamchatka by 13,000 cal y B.P. Sutton additionally states that there are other old salmon use sites in Western Beringia, but none that date prior to 12,000 cal y B.P (Sutton 2017; Goebel, Waters, and Dikova 2003).

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[4] The actual age of the deepest deposits at the Dalles Roadcut site are not known because fishbone was not collected from the deepest parts of the excavation when it was initially excavated, and the deeper deposits are now below the water table. The more recent excavations and evaluation of curated material by Butler and O'Connor (2004)was able to confirm 9,000 years of continuous use even though the top two meters of the deposit were scraped away in the 1950's and the lower deposits were inaccessible due to the water levels caused by the Dalles Dam. It is noteworthy that the reexamination of the Dalles Roadcut site was conducted in part because of challenges to the anthropogenic origins of the deposits largely based on the assumption that Natives had not been using salmon for that long.

Eastern Beringia:

There are a quartet of Tanana River sites with early evidence of fish use: The previously mentioned Upward Sun site (Potter et al. 2014; Halffman et al. 2015; Choy et al. 2016), the Broken Mammoth site (Krasinski and Yesner 2008; Yesner 2001), Mead (Holmes 2001), and Swan Point (Kedrowski et al. 2009). All four sites contain at least some evidence of Pleistocene fish use. Additionally, late Pleistocene age sites in the Yukon (Bluefish Cave and Lime Hills Cave) contained fish remains. Other early sites with faunal remains did not contain identified fish elements; however, as Upward Sun demonstrates, chemical analysis could reveal fish usage in settings where identifiable fish remains are not located. It is also worth noting that the Pleistocene age sites in Eastern Beringia are far from the coast even today. It is not surprising that interior sites would reflect a focus on interior resources (Sutton 2017:7-8).

The Northwest Coast, Columbia River, and South of the Columbia:

As described by Sutton (2017:9), there are sites showing early fish use along the Pacific Coast, though there are few sites that demonstrate salmon use older than 10,000 years. Along the Northwest Coast (the areas that were along the glacial margin to the southeast of Beringia and northwest of the Columbia River system) there is scattered archaeological evidence of late Pleistocene habitation, including evidence of marine resource use (indirect evidence and shellfish remains), though the only direct faunal evidence of fish use described by Sutton is a single unidentified fish vertebra (2017:9) at Hidden Falls.

On the Columbia River system there is the aforementioned Dalles Roadcut Site, Marmes Rockshelter, and Buhl Burial Site. The Roadcut and Marmes sites contained direct faunal evidence of salmon use. Isotopic analysis of the Buhl burial, along the Snake River, indicated a diet of terrestrial resources and anadromous fish. Additionally Kennewick Man appears to have had a diet dominated by marine mammals and fish (Sutton 2017:10-11).

South of the Columbia River, archaeological evidence of salmon usage is scarce. Late Pleistocene sites, such as Indian Sands (Davis et al. 2002) are known, but lack fish bones. Sutton describes a number of Peistocene-age coastal sites, but none that contain salmon remains. Duncan's Point Cave, Cross Creek, and Diablo Canyon all contain evidence of fish use (2017:12), as does Daisy Cave (Erlandson et al. 1996; Erlandson and Jew 2009), but not salmon specifically. While the lack of evidence of salmon usage south of the Columbia could be partially explained by sea level rise (Southern Oregon and California were not subject to major isostatic fluctuations), given the fact that salmon migrate upstream suggest that there must be other factors at play. The lack of known evidence of salmon may be due to preservation issues, collection methods, or detection methods (the Upward Sun site indicates that salmon usage can be identified even if no fish bone is recovered [Choy et al. 2016]), but to build from these possibilities would be a fraught argument from absence. While it is this author's position that salmon were probably very important to early Americans, the possibility that salmon could have been ignored by late-Pleistocene people south of the Columbia must be acknowledged.

Traditional Ecological Knowledge

The Human-Salmon Relationship in the Pacific Northwest:

Archaeological evidence alone cannot illuminate the depth of connectedness between humans and salmon in the Pacific Northwest. There is little ambiguity regarding the significance of salmon to many Native cultures (Thornton, Deur, and Kitka 2015; Roche, McHutchison, and Alexie 1998; May 2014; Hayden 1992; Colombi and Brooks 2012). Salmon plays such a key role in the lifeways of some groups that they are referred to as "salmon cultures" (Colombi and Brooks 2012; Arnold 2009). Salmon cultures are so named because not only was salmon a major component of subsistence, and frequently a major figure in mythologies, but salmon resources are even a primary factor determining the locations of villages in Southeast Alaska for tribes like the Tlingit. In a very real way, the biogeography of salmon was directly reflected in the biogeography of humans living in salmon rich regions.

The use of subsistence resources is typically termed "exploitation" in archaeological literature; however, in the case of salmon resources in the Pacific Northwest the terms "harvest" and "cultivation" are perhaps more applicable. Thornton, Deur, and Kitka (2015) describe the intricacy of Native interactions with salmon, which they argue comprises deliberate cultivation, rather than simple use of an available resource. Native practices were not simply sustained for thousands of years prior to colonization, at fairly high population levels, they were actively conducted in ways that promoted conservation of salmon populations. Native practices included removing parts of weirs to ensure salmon could pass after harvest needs had been met, in-depth knowledge about the practice of transplanting populations of salmon, redd creation and

maintenance, and (in a particularly salient detail) even the way that salmon was processed promoted healthy salmon populations.

While the cultivation of salmon is perhaps best exemplified by practices like red creation, and transplantations, the details of harvest methods are also important. The dismantling of weirs, and other methods to limit the impact of harvesting were important. But the placing the bones and viscera of processed salmon back in the river they were taken from is a particularly noteworthy practice. This practice was explicitly aimed at conservation of salmon resources, though the framing of the practice was not put in the language of conservation, but rather described thusly: "We didn't really 'manage' them; we just took care of them by looking after the streams and making sure we handled them properly. (Tlingit elder quoted in Thornton, Deur, and Kitka 2015:190)." A key part of taking care of the salmon was putting their remains back into the river so that they could show the salmon where to return. While the conceptual framework for this practice may not have included the idea of MDN, the practice did ensure that vital nutrients were not removed from the river system and helped promote the health of the salmon runs.

In this way, traditional salmon practices could actually serve to moderate fluctuations and promote population health. As opposed to a purely extractive model in which all of the harvested MDN is removed from the system, in the traditional model nitrogen and phosphorous was deliberately reincorporated into the system. This cultivation of salmon contrasts with the extractive practices of modern industrial fishing. The Pacific Northwest is today running a roughly 5 – 7 million kilogram annual deficit of marine derived nitrogen and phosphorous as compared to historic levels (Gresh, Lichatowich, and Schoonmaker 2000). This modern deficit makes diminishing salmon

runs a negative feedback loop in which the reduced MDN makes it harder for the drainages to support future salmon runs.

The Human Ecology of Salmon:

Humans in North America have a long history of interaction with salmon (Roche, McHutchison, and Alexie 1998; Thornton, Deur, and Kitka 2015; Sutton 2017; May 2014), and the existence of salmon bearing refugia at the LGM (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012) indicates regions where early coastal people may have lived during the late Pleistocene. While the archaeological literature may not currently broadly support a long chronology for human utilization of salmon, ethnography (Thornton, Deur, and Kitka 2015) and at least some sites (Sutton 2017) do suggest a chronology extending back in time to the terminal Pleistocene. Additionally, the ecology of salmon creates a more productive environment where salmon runs thrive. These more productive environments would have represented more attractive habitats to early inhabitants of the Americas.

Much as contemporary and historic Native populations shaped their biogeography to accord with productive salmon bearing areas, it is likely that salmon would have influenced the locations chosen for habitation by early peoples. The interactions between humans and salmon are such that the ecology of one affects and influences the ecology of the other. The ecological practices of humans also impact the nature of the connection between the two. Where ecological practices promote sustained harvesting through cultivation, salmon and humans create a positive feedback loop. Where human practices

favor an extractive model of resource exploitation a negative feedback loop is created. But in either case, human and salmon ecologies are tightly linked where their ranges overlap.

Phase III: Preliminary Geospatial Analysis

Methodology:

Methods Introduction:

　　Salmon DNA evidence indicates that salmon were present in Beringia through the LGM (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012) (Q1). Starting from the perspective that salmon would have been an attractive resource that people in Beringia could be expected to pattern themselves around, the next step is to ascertain where in Beringia salmon bearing streams were located. The first analysis step in pursuit of salmon bearing drainage identification was using the Institute of Arctic and Alpine Research (INSTAAR) Bering Land Bridge DEM (BLBDEM) (Manley 2002)to identify LGM drainage basins (Q2). Next a diachronic examination of changing Beringian landscapes was performed using the J. Clark, Mitrovica, and Alder (2014) isostatically adjusted DEMs as well as the eustatic datasets. The J. Clark, Mitrovica, and Alder (2014) data is compared with the results of a time series using the same sea level curves with the Manley (2002) data (Q3). The products of the Q2 analysis were visually examined using slope and curvature in ArcGIS 10.3 (Buckley 2010a)to attempt to identify areas of interest (Q4). Finally, after St. Matthew Island was identified as an area for further analysis a new higher resolution DEM was generated using sounding depths from a 1952 hydrographic reconnaissance by the US Coast and Geodetic Survey (National Ocean Survey 1952b) and a similar survey for the Pribilof Islands was also analyzed (National Ocean Survey 1952a).

Spatial Data:

This analysis of the Bering Straits region was facilitated by the public availability of a 2km² resolution BLBDEM provided by INSTAAR at the University of Colorado (Manley 2002). The BLBDEM was developed from the ETOPO2 global DEM. The ETOPO2 DEM is a two arc minute resolution DEM with bathymetric data from the Sandwell and Smith dataset (Sandwell and Smith 1995; Center 2006). The Sandwell and Smith (1995) bathymetric data was created using satellite altimetry data. Because the Sandwell and Smith data is derived from satellite altimetry the resulting bathymetric data is continuous. Troublingly, according to the National Geophysical Data Center metadata (Center 2006), satellite altimetry is unreliable at depths less than 200 meters, but the source of data for shallower areas (all of Beringia is less than 200 meters below the modern sea level) is not stated. Additionally, the Manley (2002) DEM was created using the 2001 version of ETOPO2 in which all raster pixels were offset by one; this was corrected in the 2006 version (Center 2006). The Sandwell and Smith data was created as a two arc minute resolution, so even though there are ETOPO products with smaller cell size, the source bathymetric data is only resampled for smaller celled rasters, rather than more detailed source data. For the BLBDEM, Manley converted the ETOPO2 Dataset into a 2km² UTM projection.

The J. Clark, Mitrovica, and Alder (2014) datasets are divided into the isostatically adjusted Relative Sea Level (RSL) and unadjusted Eustatic Sea Level (ESL) rasters. These layers are derived from an un-georeferenced subset of ETOPO1, a one Arc Minute global DEM was also used for visualization purposes (Amante and Eakins 2009).

The bathymetric data for the ETOPO1 DEM was primarily derived from

GEBCO/Estimated Seafloor Bathymetry. GEBCO does not have a published description

of the data sources for their Estimated sea Floor Bathymetry. While ETOPO1 does offer

twice the resolution of ETOPO2, the bathymetric data for shallow areas remains

problematic, especially for Bering Sea depths less than 50 meters which are clearly

interpolated from very few data points. This is a particularly significant issue since the

time range represented from this data lacuna is roughly from 11,000 y B.P. to the present

day.

Hillshade of Clark et al. (2014) Relative Sea Level Isostatically Adjusted Raster

Hillshade for 15,000 B.P.
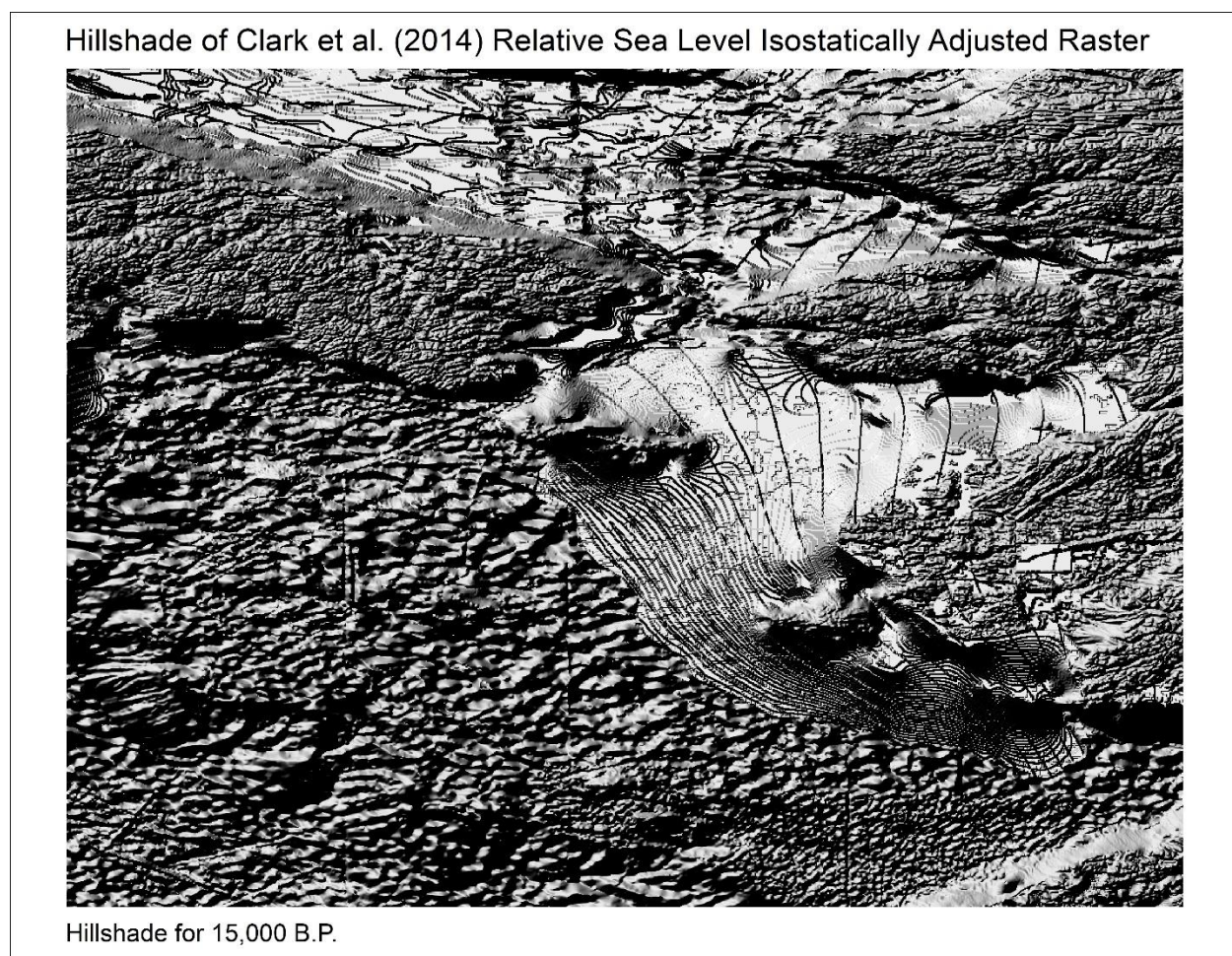
Figure 3: Unaltered hillshade of isostatically adjusted dataset derived from ETOPO1. DEM from J. Clark, Mitrovica,

and Alder (2014). This image was created by using the basic ESRI Hillshade function and is included to show the

digital surface created by the ETOPO1 DEM in Beringia. The standard hillshade function creates an apparent vertical

exaggeration which creates a confusing image but highlights the unnatural aspects of linear data artifacts and low-

data-point areas.
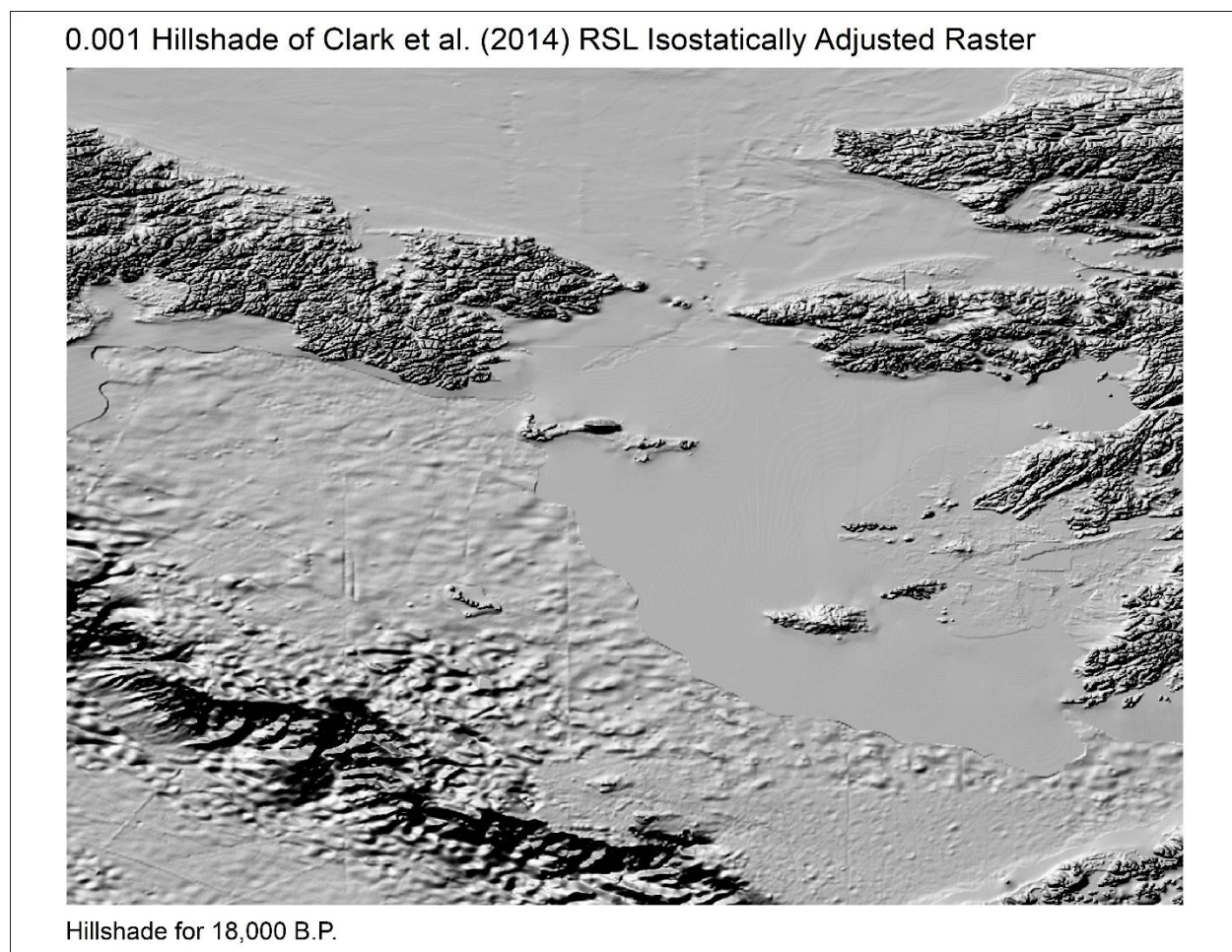
Figure 4: Hillshade with z-values multiplied by 0.001 of isostatically adjusted dataset derived from ETOPO1. DEM

from J. Clark, Mitrovica, and Alder (2014). This image was created by using the basic ESRI Hillshade function and is

included to show the digital surface created by the ETOPO1 DEM in Beringia. The standard hillshade function was

used with a multiplication of 0.001 to reduce the apparent vertical exaggeration to create a less confusing image;

however, while this layer is easier to understand visually it minimizes the visual impact of linear data artifacts and low-

data-point areas.

Bathymetric datasets using soundings suitable for generating a triangulated

irregular network (as a base dataset to develop DEM's from) from other sources were

sought for this project. Seth Danielson, at the University of Alaska Fairbanks has been

collecting sounding data, and he was kind enough to provide access to the data; however, the coverage is far from complete, and the DEM that has been generated has a roughly one-mile resolution with large areas defined through interpolation rather than remotely sensed data. NOAA provides access to a number of DEM datasets, though analysis revealed major limitations to the data available. The National Geophysical Data Center (NGDC) offers a data viewer that shows where NOAA has sonar survey data available to the public, which makes it clear that the vast majority of the Beringia region does not have sonar survey data available. There are sounding transects, but most of the Bering Sea does not have systematic sonar survey data available from NOAA.

Digitized smoothsheets from 1952 hydrographic surveys for the US Coast and Geodetic Survey in the areas of St. Matthew Island (National Ocean Survey 1952b) and the Pribilof Islands (National Ocean Survey 1952a) were located on the NOAA's NGDC website. The X,Y,Z data from these sounding surveys was converted into GIS data layers using ArcGIS 10.4. Because the hydrographic survey data was in .xyz format, the data had to be read into Excel spreadsheets before it could be read into ArcMap (Buckley 2010b). After being brought into ArcMap sessions, the survey data was exported into shapefiles. Then those shapefiles of the survey points were used to produce a number of other products. The points were used to generate TINs, and to interpolate continuous rasters for further analyses.

Ehlers, Gibbard, and Hughes (2011) shapefiles were used for LGM glacial extents.

Analysis

Analysis Introduction:

Once adequate datasets, and isostatic adjustments, have been generated the relatively straightforward process of identifying drainage boundaries and paleo-channels can be done. Fortunately, even in the absence of ideal datasets, or isostatic adjustments, rough estimates can be conducted relatively easily.

Drainage Boundaries:

The first step used in this analysis was to identify drainage boundaries. The flow chart for this analysis is presented here:
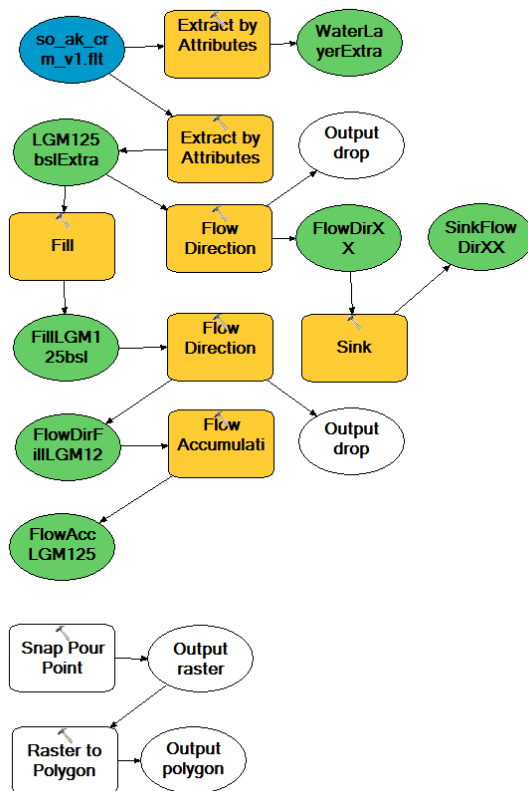
Figure 5: Drainage Boundary Analysis model

Following the initial process through flow accumulation, pour points are selected manually. It is after the points have been established that the pour point snapping and polygon generation is performed. The need to manually select pour points is the reason that this process could not be fully automated and incorporated into the integrated analysis model.

Stream Feature Generation:

The next major analysis was the generation of stream features. While this step is less vital for analysis purposes, it is vital for cartographic purposes, and facilitates visual interpretation of data. The additional steps of turning the stream segments into usable river layers is not described, but the generation of the stream feature layers followed this flowchart:
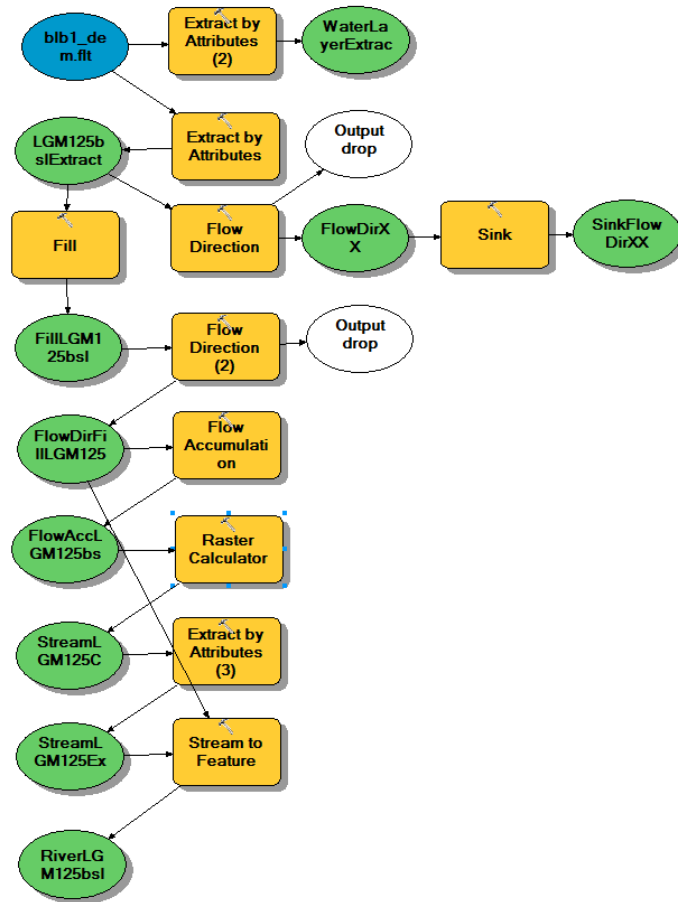
Figure 6: Stream Feature Generation analysis model

This a model produces stream features, though as mentioned, it does not produce complete rivers without additional processing. This means that the raw product is a number of discrete segments. If the user wishes to integrate the segments into rivers that is an option. However, since the generated stream features are simply best-guesses of where streams might have run based on available datasets, for most purposes the unintegrated streams are adequate.

Slope and Curvature Analysis:

Q4 (Can locations still recognizable as specific landforms (such as valleys) be identified from the existing datasets?) was based on the hypothesis that less heavily sedimented areas of the paleolandscape might be represented by greater surficial relief. This hypothesis is speculative and cannot be adequately tested in this case with available data. The reasoning behind the hypothesis is that during oceanic transgression the areas where rivers deposit the majority of their silt moves. When rivers reach the ocean, sediment precipitates out. For example, the Yukon- Kuskokwim Delta in Alaska is the size of the state of Louisiana and is itself a product of the rivers meeting the ocean at current sea levels, which have been around for roughly 4,000 years. This means that sedimentation can rapidly change the landscape over large areas and can result in deposits buried too deeply to be recovered. The rapid sedimentation of river valleys can be a significant obstacle to recovery of Pleistocene era as illustrated by the example of the Sixes River Valley in Oregon where coring indicated 27 meters of sediment was deposited over Pleistocene age sediments during the past ~10,000 years (Punke and Davis 2006). Since sedimented plains are typically quite flat, the hope is that areas identified with surficial complexity may represent locations that have not been deeply buried.

The analysis tools that were used look for surficial complexity are slope and curvature. In ArcGIS the curvature function measures the slope of the slope (Buckley 2010a). While this seems rather esoteric, it does allow for more precise representation of surficial complexity without sacrificing scale accuracy. Considering the 2km² pixel size of the BLBDEM used for this step of the analysis it is highly questionable to assume that

any revealed surficial complexity would correspond to actual human-scale complexity, but in the interest of gleaning as much information as possible from the available data it was attempted. Curvature is particularly useful for visualizations of DEM data when combined with hillshade layers, so the curvature datasets were used for qualitative visual examinations, not as quantitative data. The analysis model for this step was as follows:
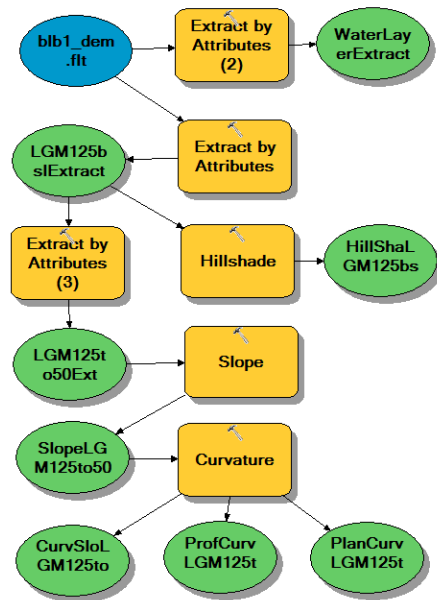
Figure 7: Slope and Curvature analysis model

Integrated Stream Slope and Curvature Analysis Model:

The successes of the initial analyses discussed in this paper led to continued iterations of analysis. New integrated analysis models were created by the author for a separate project using isostatically adjusted models. This integrated model was then reapplied to isostatically adjusted datasets generated by J. Clark, Mitrovica, and Alder

(2014) for the Beringian data. The integrated model includes a raster "times" step that is useful for dealing with z-value problems occur in some bathymetric datasets.[5]
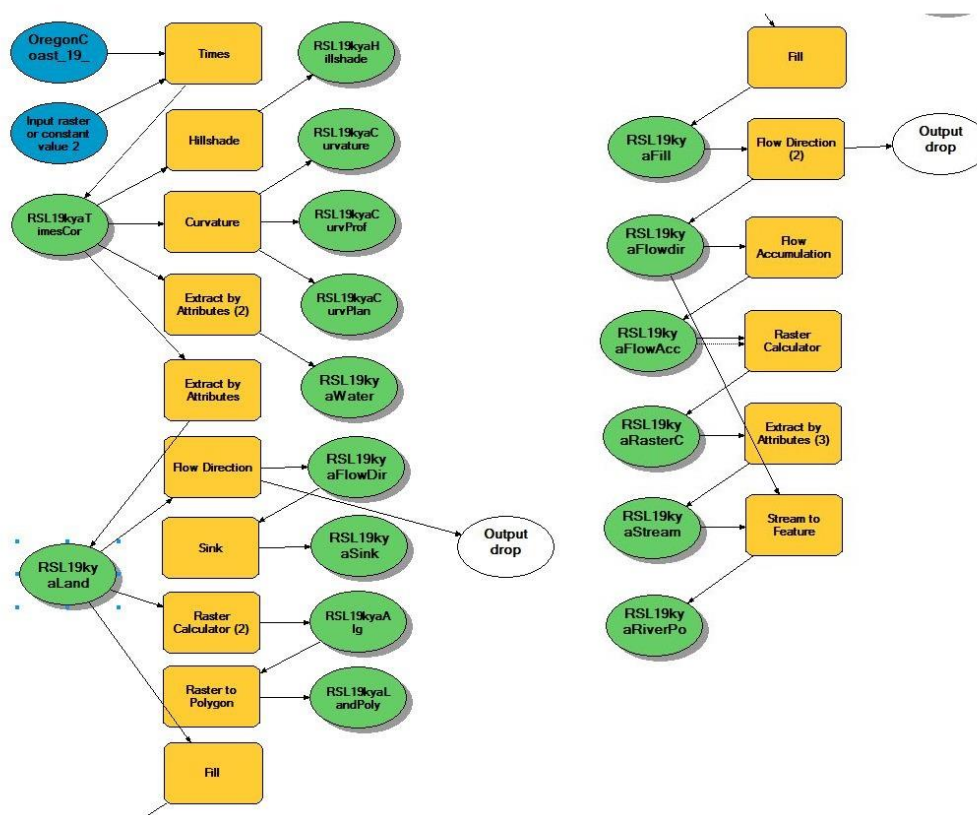
Figure 8: Integrated Analysis Model

Results

Paleo-Drainages at LGM:

Q2 looked specifically at identifying major drainages at the LGM in the hopes of identifying likely locations of salmon bearing waterways. Because the BLBDEM (Manley 2002) is rendered from a continuous bathymetric dataset, the drainage analysis

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[5] Methods Note: All of the shown data analysis models were tested and used to ensure that they actually performed the analysis desired.

produced a mostly believable appearing set of stream layers and drainage basins. While

the parent dataset (National Geophysical Data Center 2006) is not without linear artifacts

and limitations, allowing for the source and resolution limitations of available datasets,

the BLBDEM presents the best available guess for the general hydrology of LGM

Beringia at present.

Since the goal of the drainage analysis was to locate salmon bearing streams, and

there are many unknowns regarding the paleo-environment of LGM Beringia, and the

habitat requirements of salmon are complicated to model accurately, the proxies were

vastly simplified. Salmon require adequate stream depth, flow, substrate, and

temperature for spawning and embryo incubation (Quinn 2011) and accurately modeling

all of these factors for a submerged landscape would be a monumental challenge. The

simplest method to account for all relevant variables is to use stream order as a proxy

since the largest number of stream types in a system will maximize the chances of

appropriate habitat being present. Accurately modeling stream order requires knowledge

of probable stream locations, permeability, and precipitation. Since those factors were

not knowable, catchment size was used as a simple approximation of potential stream

order. The criteria for a drainage to appear in the Major Beringian Watersheds at LGM

map (see fig. 9) was to place the extraction threshold at 1,000 pixels. Since each pixel

represents and equal-area 2km² square, a 1,000-pixel extraction threshold means that each

pixel represented as a stream has a minimum catchment of 4,000km². Rather than

attempting to determine stream order, incorporate rainfall models, or other factors, setting

an arbitrarily high extraction threshold was used as a method to exclude smaller

waterways.

Stream order can also be used as a method to exclude smaller streams; however,
setting the catchment basin threshold at 4,000km² achieved a very comparable result with
less effort.
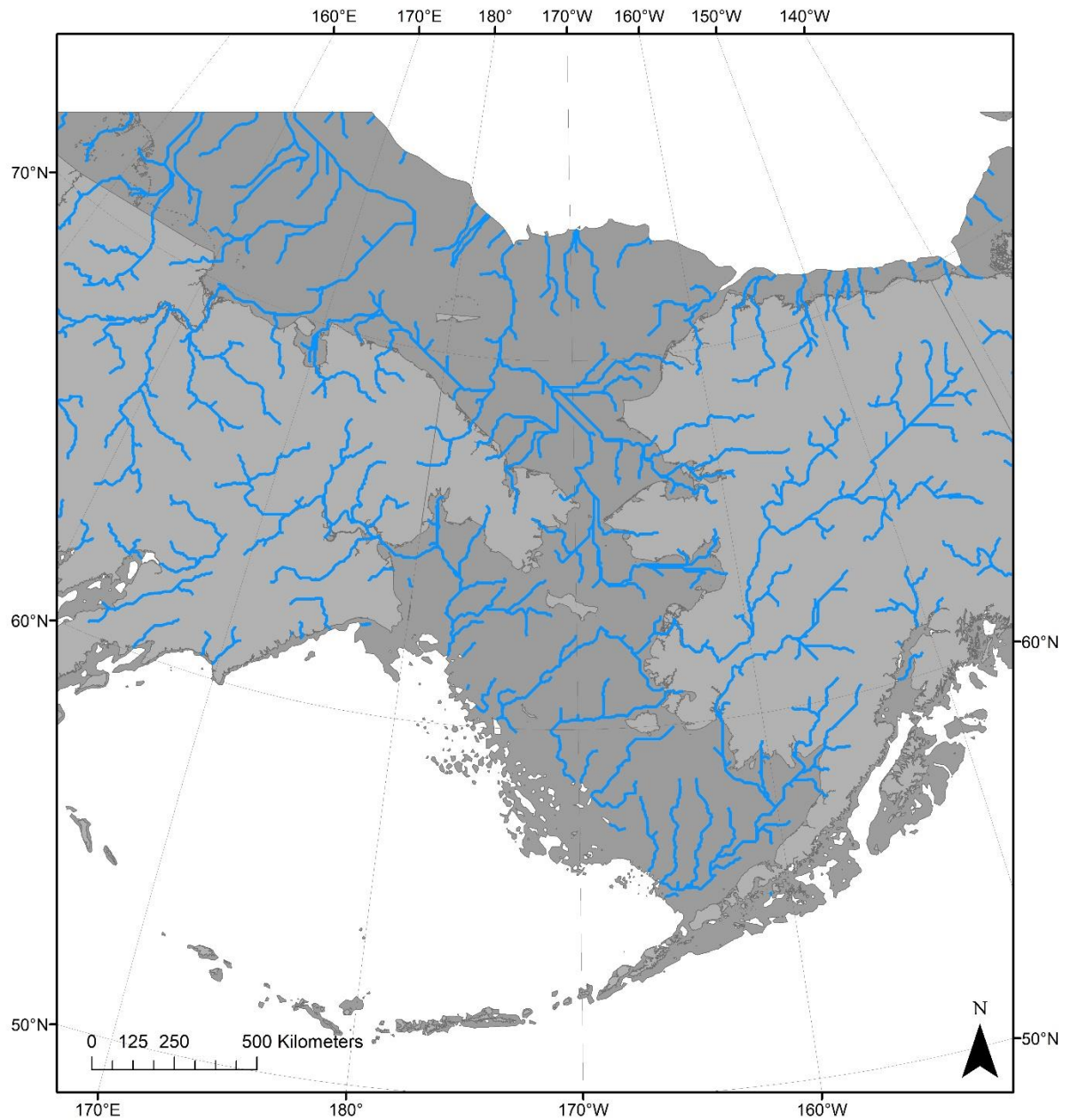
Figure 9: Results of drainage analysis using Manley (2002) DEM with an arbitrary threshold of 1000 pixels. This threshold means that the minimum catchment area for any pixel represented as a stream is 4,000 square kilometers.
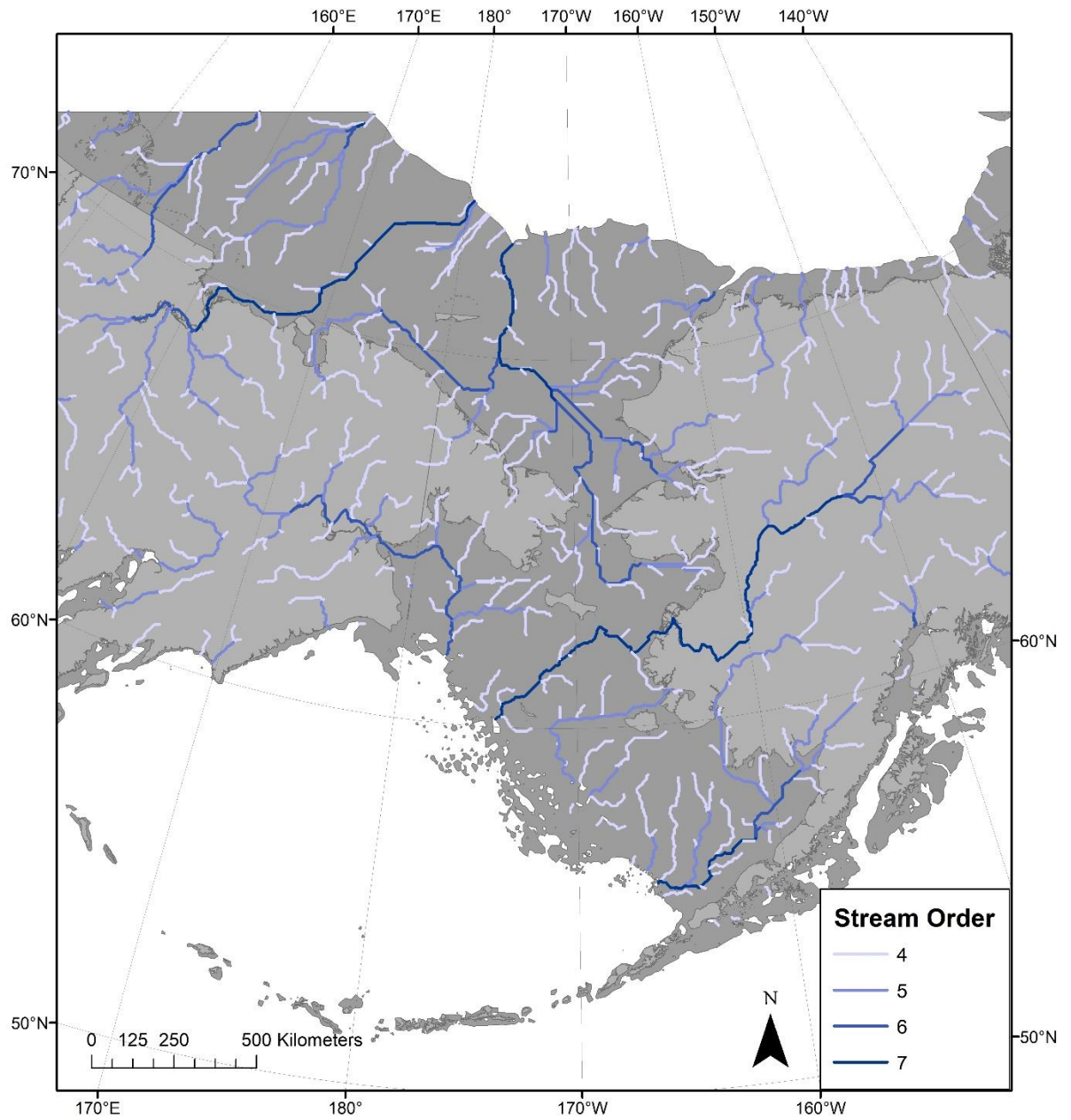
Figure 10: Results of drainage analysis using Manley (2002) DEM with a Strahler stream order analysis. This drainage analysis started with a threshold of 10 pixels for the first order streams, meaning the minimum catchment for a first order tributary was 40 square kilometers. In a Strahler stream order analysis, a stream only increases its order when it encounters an equal order stream. This map excludes lower order streams.
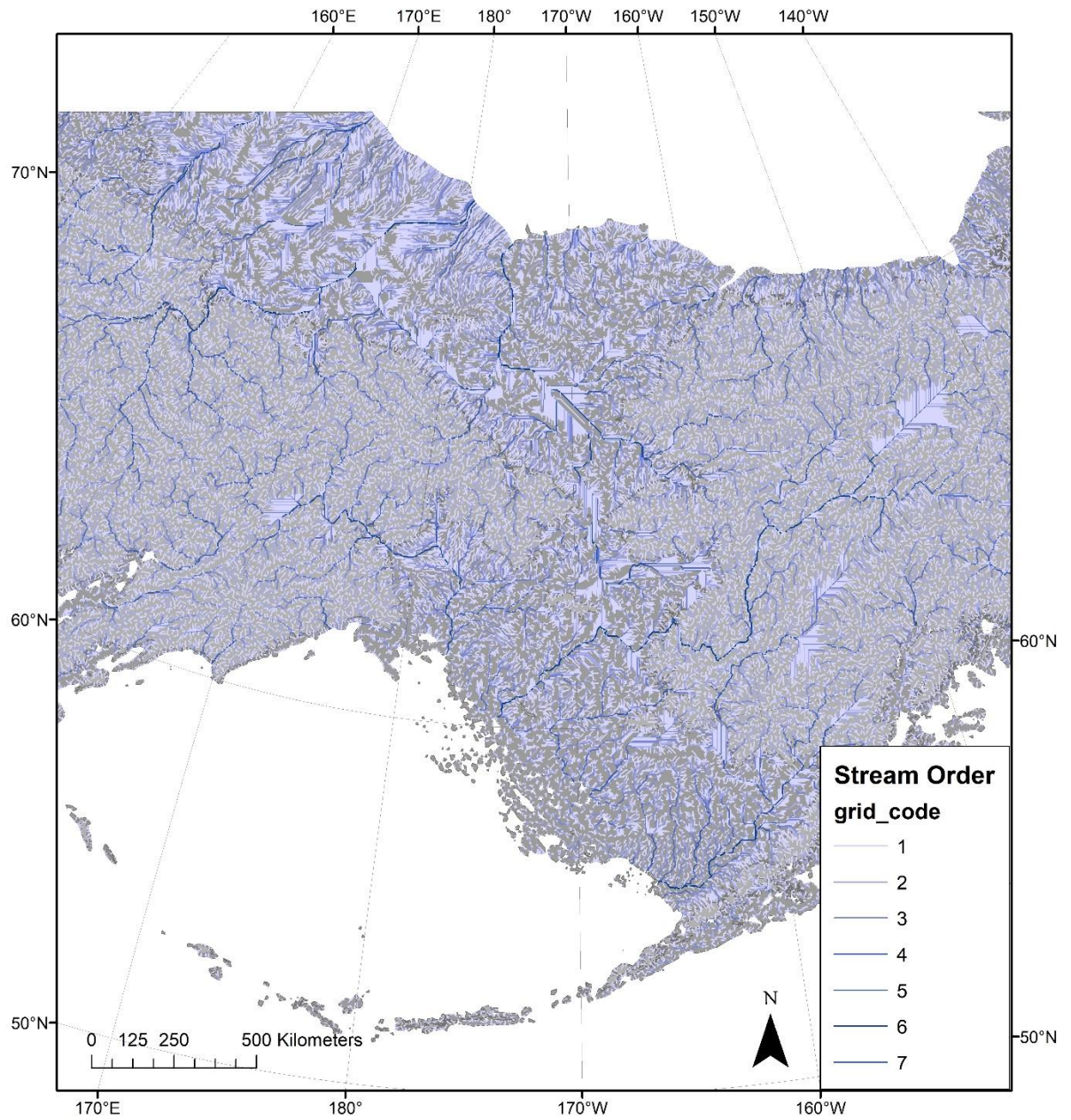
Figure 11: Results of drainage analysis using Manley (2002) DEM with a Strahler stream order analysis. This drainage analysis started with a threshold of 10 pixels for the first order streams, meaning the minimum catchment for a first order tributary was 40 square kilometers. In a Strahler stream order analysis, a stream only increases its order when it encounters an equal order stream. This map includes all streams.

Four primary drainage basins were identified in LGM Beringia. Of the four, three were extensions of major modern drainages: the Anadyr, Yukon, and Kuskokwim. The fourth major drainage basin is almost entirely submerged today, this basin was named the Nanvaruk Paleobasin.

The headwaters of the Nanvaruk Paleobasin are in the modern-day Baird Inlet. The Yupik name for the Baird Inlet is Nanvaruk (variable spelling), which means big lake. Since the paleobasin would have originated in the modern "Big Lake" and terminated in an even bigger lake at the LGM, "Big Lake" basin seemed an appropriate name, so the Yupik name was applied to the entire paleobasin. If this drainage model and bathymetric topology is accurate, this large internally draining freshwater basin is without modern analogue in the Beringian region.

All of the analyses conducted for this project, regardless of source DEM, indicate numerous large lakes. (Monteleone 2013) also estimates numerous lakes with surface areas in excess of 200 m² (the threshold used for lake extraction from a sink analysis). However, the Nanvaruk Paleobasin remains unique in scale and catchment, though it does not appear clearly in the ETOPO1 derived datasets. Indeed, the Nanvaruk Paleobasin does not show up in standard sink analysis because the four lowest sections of the basin lie below the LGM threshold, and the outline of the basin only becomes evident during time-series analysis of Beringia.
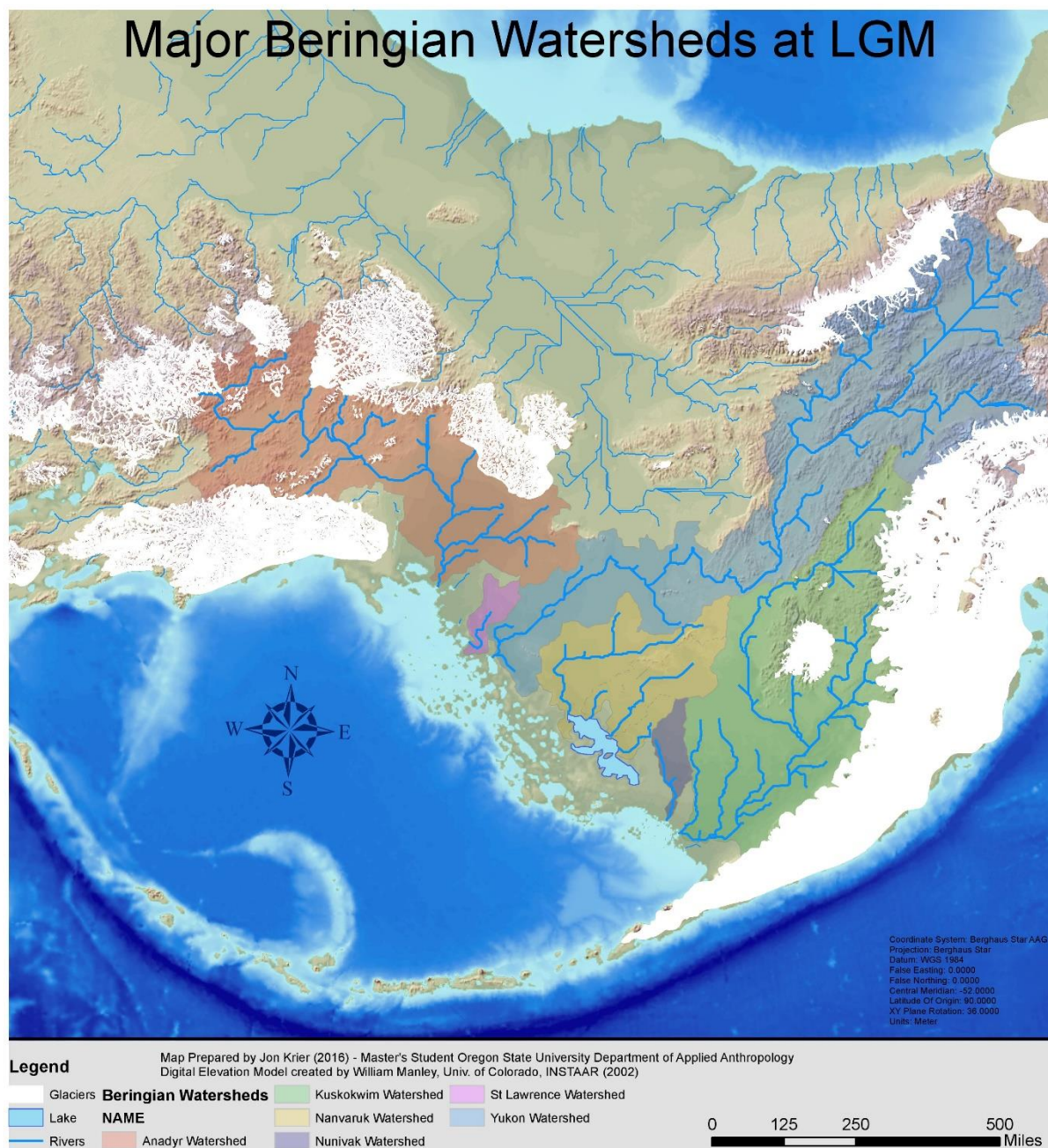
Figure 12: Major Beringian Watersheds at the LGM. Sea Level represented at 125 meters below modern. BLBDEM (Manley 2002). Glacial extent from Ehlers (2011). Map created by Jon Krier. 2017. Projection: Berghaus Star AAG.

The exceptionally large catchment of the modern and LGM Yukon drainage (the catchment area for the Yukon drainage in this analysis was 578,426 square kilometers) suggest that it could be a likely candidate for continuous salmon habitat through the

LGM. Since it is difficult to quantitatively estimate many of the factors that determine salmon habitat suitability from the BLBDEM dataset, sheer catchment size is used as a proxy for suitability here. If stream order is used as a proxy for salmon habitat suitability instead, then once again the Yukon drainage stands out with a stream order of 7 for thousands of kilometers.

Closeup of Possible Paleobasin at 95 Meters Below Modern Sea Level
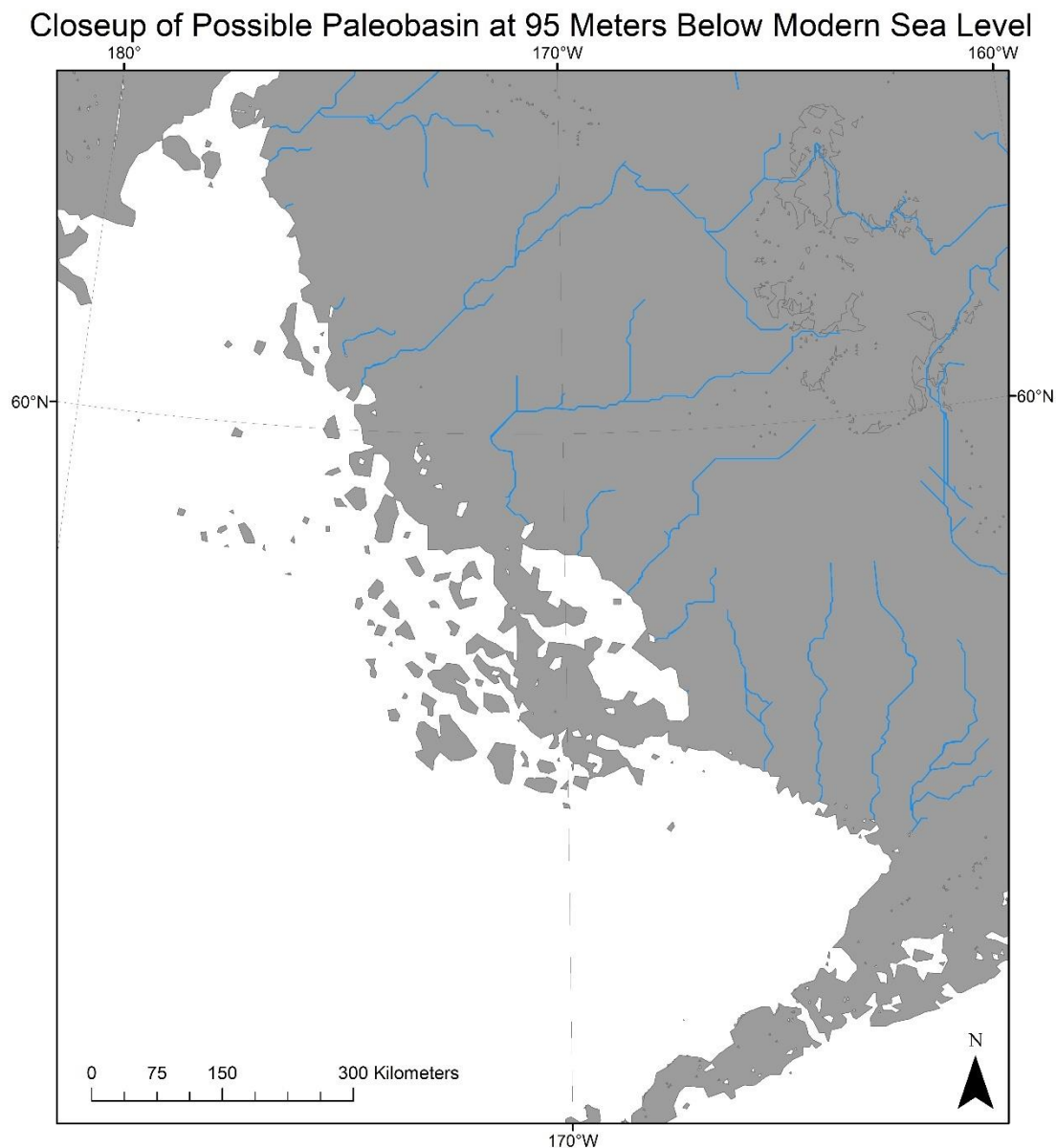
Figure 13: A closeup of the possible Nanvaruk Paleobasin as revealed by a sea level of 95 meters below modern, Manley (2002) DEM. At roughly 300 kilometers length the lake would have been comparable in size to Lake Ontario. This size estimate assumes that the basin would have filled and that the ETOPO2 DEM accurately represents the topography of the submerged landscape, neither assumption is strongly supported.

Closeup of Possible Paleobasin at 82 Meters Below Modern Sea Level
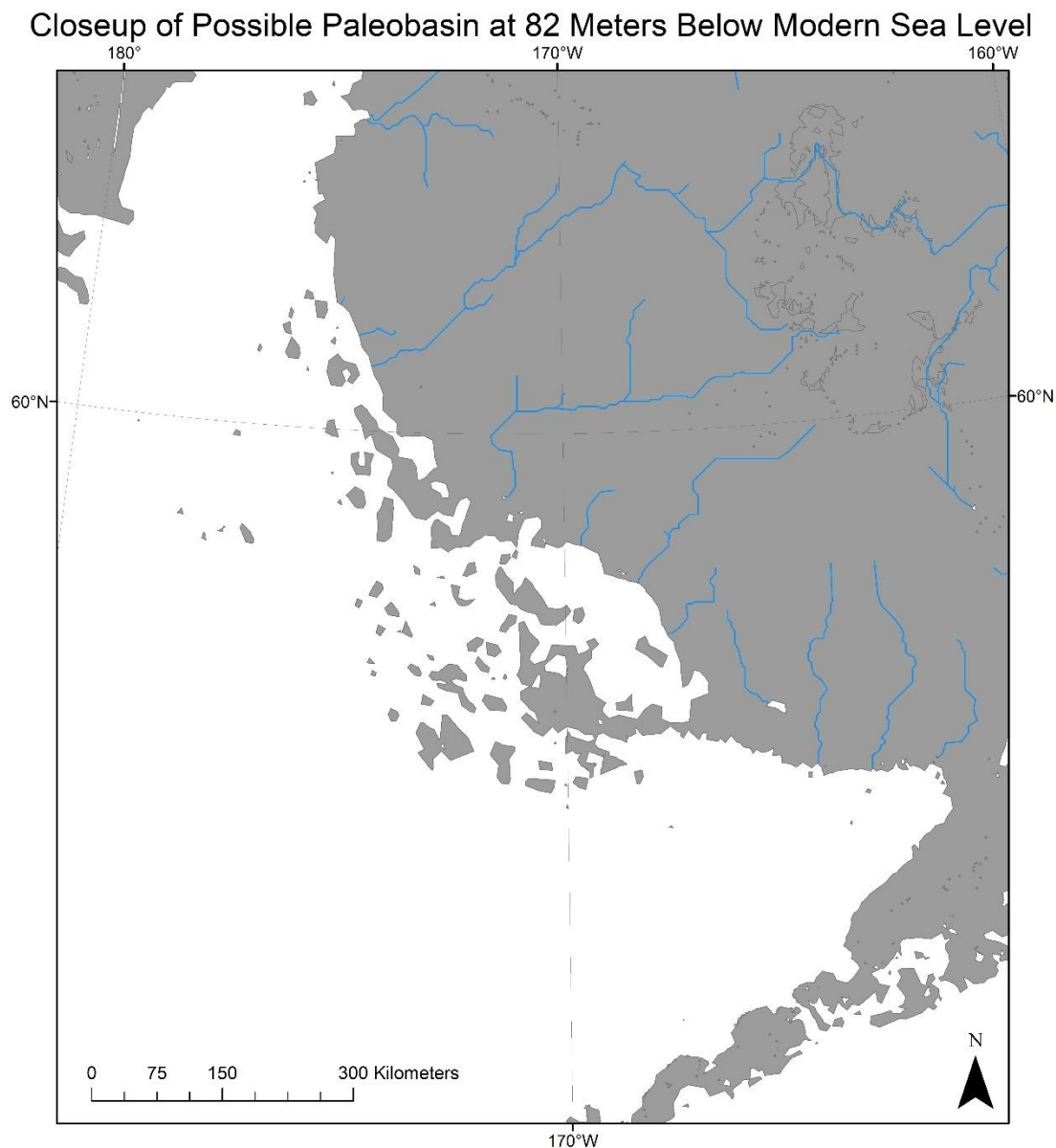
Figure 14: A closeup of the possible Nanvaruk Paleobasin as revealed by a sea level of 82 meters below modern (which corresponds to the J. Clark, Mitrovica, and Alder (2014) estimated relative sea level at 15,000 BP. Manley (2002) DEM. At this sea level (assuming the ETOPO2 source was accurate) the paleobasin would have been a bay three times as long as San Francisco Bay or twice as long as Puget Sound.

Closeup of Possible Paleobasin at 95 Meters Below Modern Sea Level
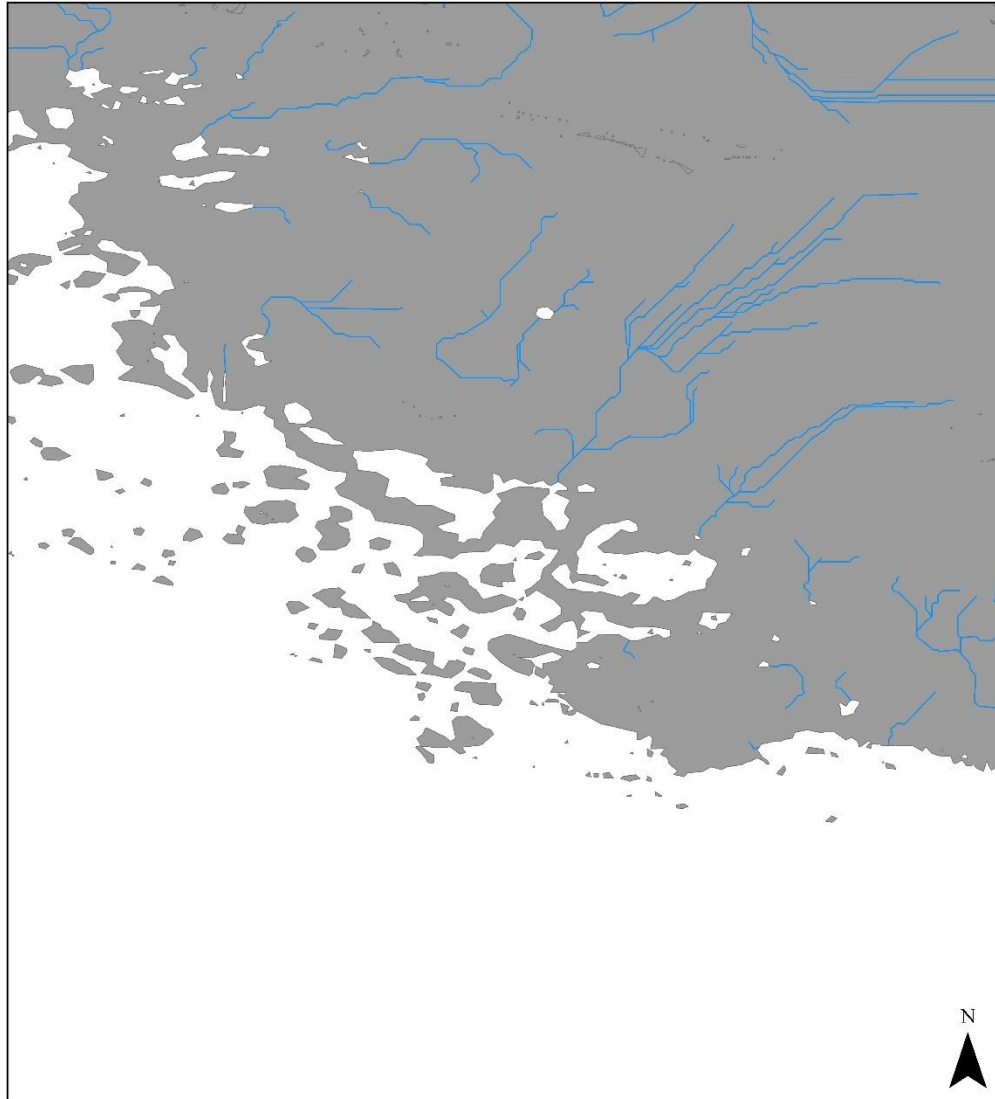
Figure 15: A closeup of the possible Nanvaruk Paleobasin as revealed by a sea level of 95 meters below modern using the unadjusted J. Clark, Mitrovica, and Alder (2014) DEM. Clearly the area in question still displays large lakes and inlets, but the landscape is dramatically different from the ETOPO2 derived Manley (2002) DEM. Note that since the J. Clark, Mitrovica, and Alder (2014) DEM. is ungeoreferenced the layer cannot be projected, and because the ETOPO1 layer was not resampled into equal area pixels, there is no valid way to estimate scale.

Closeup of Possible Paleobasin at 95 Meters Below Modern Sea Level (RSL)
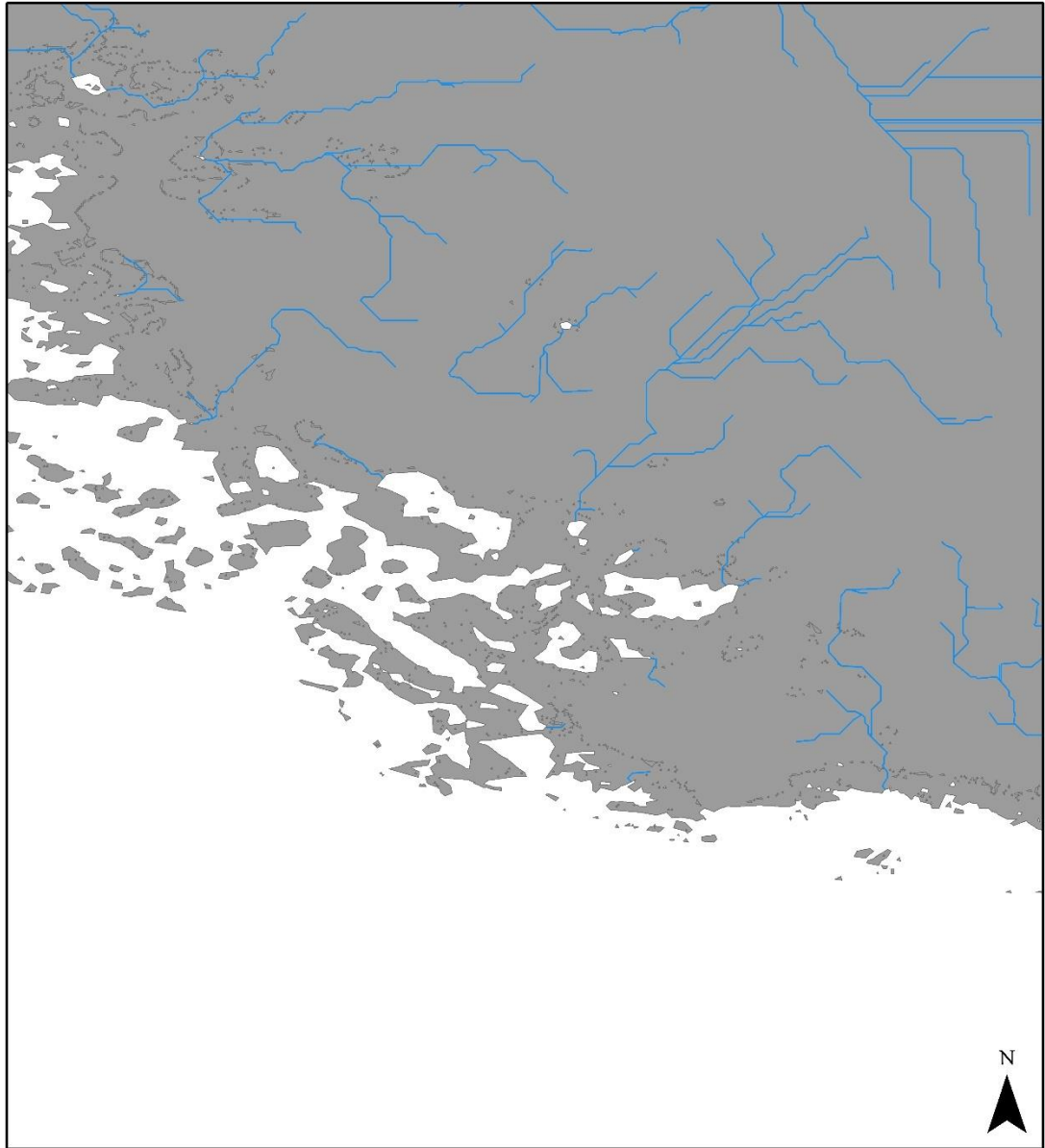
Figure 16: A closeup of the possible Nanvaruk Paleobasin as revealed by a relative sea level of 95 meters below modern using the isostatically adjusted J. Clark, Mitrovica, and Alder (2014) DEM. Clearly the area in question still displays large lakes and inlets, but the landscape is dramatically different from the ETOPO2 derived Manley (2002) DEM. Note that since the J. Clark, Mitrovica, and Alder (2014) DEM. is ungeoreferenced the layer cannot be projected, and because the ETOPO1 layer was not resampled into equal area pixels, there is no valid way to estimate scale.

Time Series Analysis:

Q3 is concerned with changes in landforms and drainages through time. Drainage analysis of the isostatically adjusted dataset (J. Clark, Mitrovica, and Alder 2014) appears to indicate that the Yukon and the majority of modern drainages did not drain into the Bering Sea from the LGM to around 11,000 B.P. The Eustatic models used by Clark et al. also shows the same drainage patterns. The area of the raster that represents the depths of 50-0 meters depth does not interface cleanly with the more rugose deeper areas, and additionally the ETOPO1 derived bathymetries seem to have a large number of deep holes that result in drainages simply terminating in small basins at the sharp edge at 50 meters depth.

Perhaps this ETOPO1 derived bathymetry is more accurate than the satellite altimetry derived values of the Manley (2002) DEM, but evaluating the relative accuracy of the bathymetry of the two datasets is not possible without better regional data. Regardless, the ETOPO1 bathymetry is not very useful for trying to understand the overall hydrologic picture of Beringia. The effects of the large unnaturally flat areas can be seen in rows of straight parallel streams on the plains.

Although the drainage analysis was problematic it was still conducted on the Clark et al. datasets. Though the 1 arc-minute cell size of the ETOPO1 derived bathymetry is significantly smaller than the 2 km² cell size of the Manley (2002) DEM the stream extraction threshold was left at 1000 cells. This results in a busier hydrologic image, but since the SACRM data does not indicate large drainage basins the smaller catchment threshold allows for a more complete stream image.

The main focus of the analysis of the J. Clark, Mitrovica, and Alder (2014) datasets was to gain a clearer image of the changes in landforms through time. Even if the drainage issues do limit the applicability of the dataset to a salmon focused survey, the broader changes through time can be useful to other modeling approaches. Time-series analyses were conducted for the isostatically adjusted RSL datasets and the unadjusted ESL datasets from Clark et al. Additionally a time-series was created for the Manley (2002) dataset using the same sea-level intervals.

All of the modeled sea levels in these analyses were based on the J. Clark, Mitrovica, and Alder (2014) isostatically adjusted RSL values where possible. J. Clark, Mitrovica, and Alder (2014) did not create RSL datasets for dates prior to 15,000 BP because when using the SACRM DEM there is little difference in exposed area from 82 meters below sea level to 131 meters below sea-level. In order to have a time series that continued back to the LGM the ESL values used by J. Clark, Mitrovica, and Alder (2014) for 15,000-20,000 BP were used. Due to the divergent nature of the sea level curves for the RSL and ESL values this resulted in a 26-meter jump in values from 15,000-16,000 BP. Since this jump was caused by switching between value sources an additional intermediate value was added as 15,500 BP. This added interval should not be viewed as reflecting actual chronologically consistent sea-level data, it is simply used to provide more consistent visualization of sea-level changes (see table 1).

Table 1: Sea-level values used in this analysis, from Clark et al. (2014) datasets.

	RSL Value	ESL Value	Difference
4,000 BP	0	0	0
5,000 BP	-1	-1	0

6,000 BP	-2	-1	+1
7,000 BP	-4	-2	+2
8,000 BP	-9	-6	+3
9,000 BP	-19	-14	+5
10,000 BP	-39	-37	-2
11,000 BP	-50	-49	-1
12,000 BP	-58	-57	-1
13,000 BP	-67	-75	-7
14,000 BP	-73	-87	-14
15,000 BP	-82	-102	-20
15,500 BP	--	--	-95
16,000 BP	--	-108	--
17,000 BP	--	-111	--
18,000 BP	--	-116	--
19,000 BP	--	-121	--
20,000 BP	--	-131	--

The RSL values as compared to modern sea-level values were calculated by
subtracting the high point of the modern area raster from the high point of the RSL raster.
Because the RSL values reflect different levels of transformation due to crustal
deformation due to glaciation, this method of calculating the RSL value is not accurate
for the entirety of the raster area, but it does allow for a closer analogy with the
unadjusted dataset. J. Clark, Mitrovica, and Alder (2014) compare eustatic sea level

curves against their relative sea level curves. In order to avoid simply reproducing their work this analysis compares the adjusted dataset to sea-level curves based on the RSL values (See table 2).
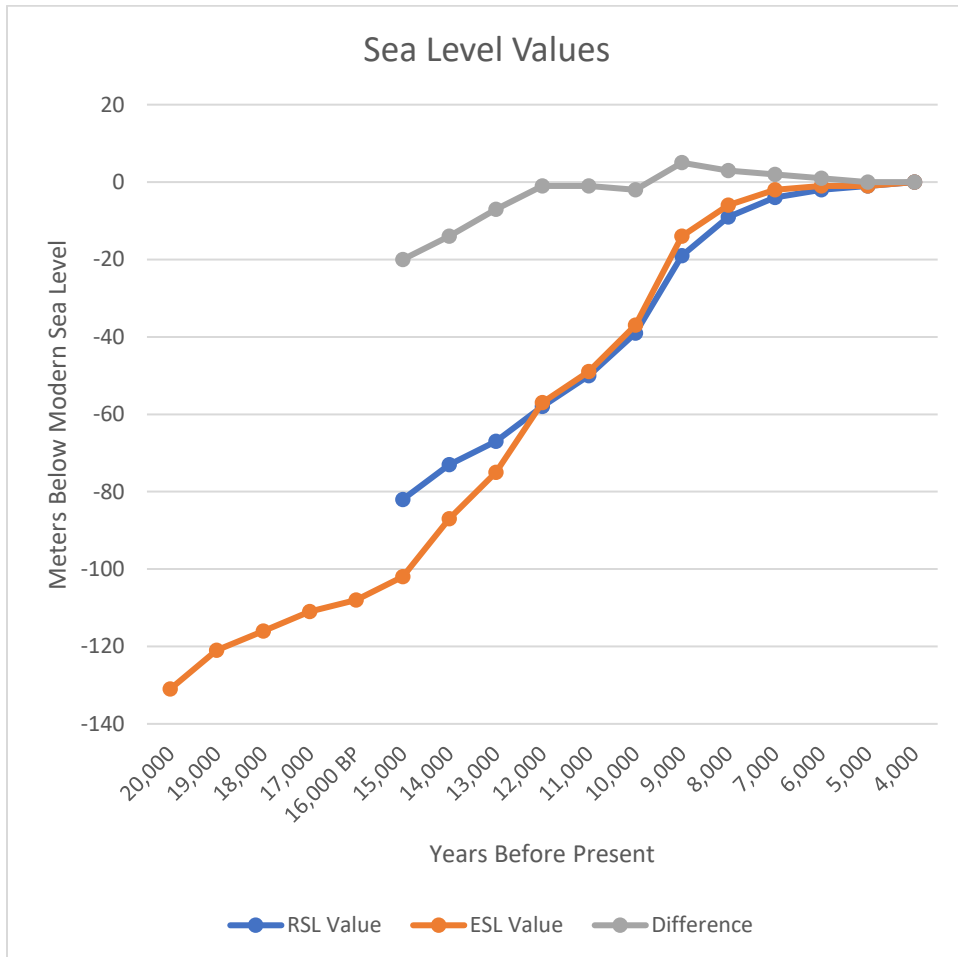
Figure 17: Graph illustrating the values of the RSL and ESL curves to modern sea-levels as well as the difference between the two over time.

Isostatically Adjusted Clark et al. (2014) DEM Time Series:
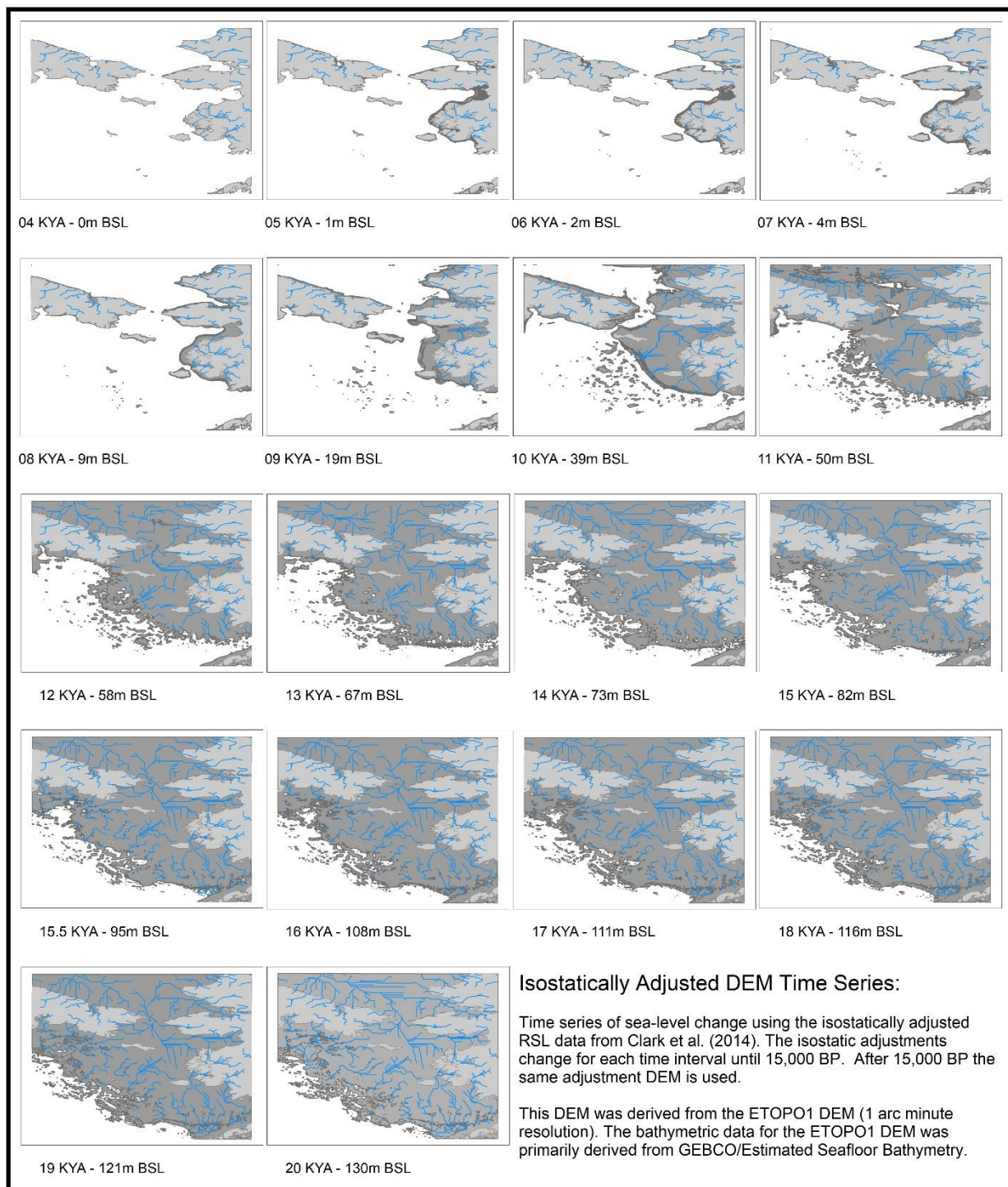
Figure 18: Time series of sea-level change using the isostatically adjusted RSL data from Clark et al. (2014). The isostatic adjustments change for each time interval until 15,000 BP. After 15,000 BP the same adjustment DEM is used.

Unadjusted Clark et al. (2014) DEM Time Series
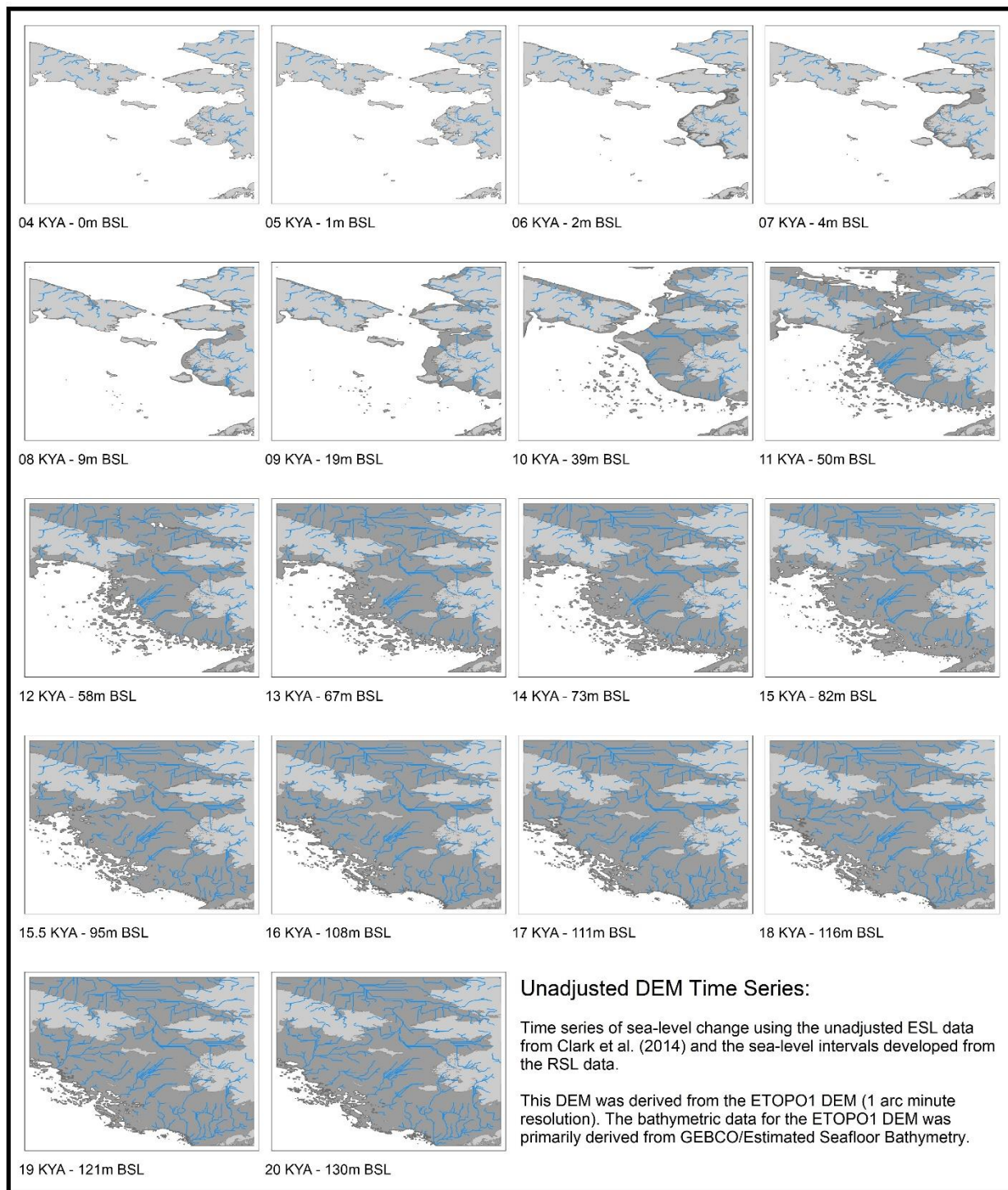
Figure 19: Time series of sea-level change using the unadjusted ESL data from Clark et al. (2014) and the sea-level intervals developed from the RSL data.

Unadjusted BLBDEM (Manley 2002) Time Series:
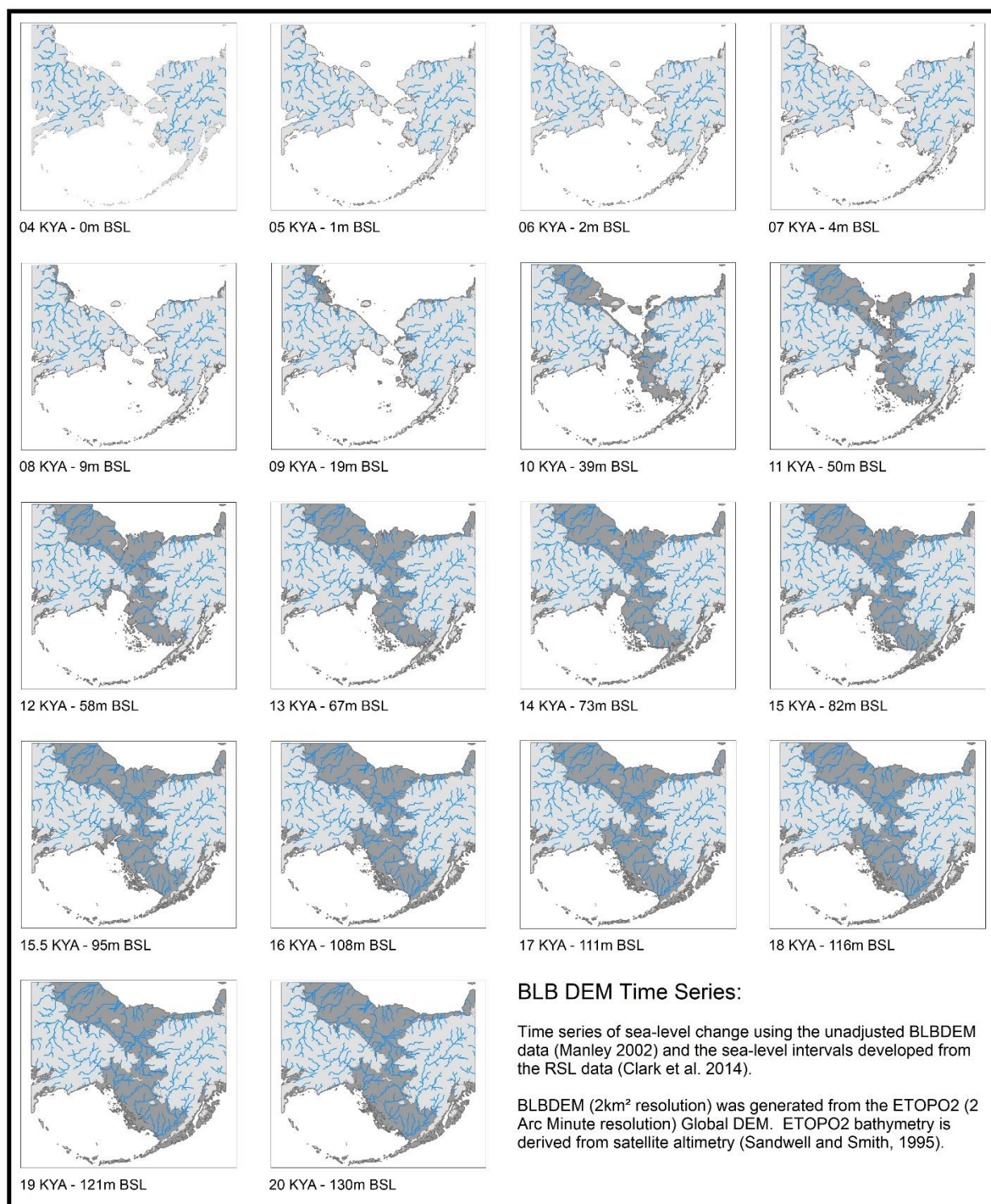
Figure 20: Time series of sea-level change using the unadjusted BLBDEM data (Manley 2002) and the sea-level intervals developed from the RSL data (Clark et al. 2014).

Discussion:

      J. Clark, Mitrovica, and Alder (2014) notes that in the eustatically modeled time series that substantial portions of the land-bridge become submerged by 11,000 BP, whereas the majority of the landbridge north of the modern-day Bering Strait stays above sea-level in the isostatically adjusted model. This observation remains true even when RSL derived sea levels are applied to the unadjusted datasets from the SACRM derived model and the BLBDEM dataset. Though the Bering Strait itself does not fully open until the 10,000 BP time-slice in all of the time-series scenarios, the rates of submergence north of the Strait remain the most visible changes between the RSL and ESL models.

      In the time-series using the Manley (2002) DEM with the J. Clark, Mitrovica, and Alder (2014) derived sea level intervals, the Nanvaruk Paleobasin becomes more visible around 16,000 BP as the lower portions of the basin drop below sea-level. At 15,500 BP the basin is at its largest enclosed extent. At 15,000 BP the Nanvaruk Paleobasin opens up to the Bering Sea and becomes more of a bay bounded by substantial islands. While this specific range of dates (16,000BP to 15,000BP) were selected purely because they made visualization of geographic changes easier, the dates are also relevant to the larger question of the timing of the peopling of the Americas. People were in the Americas at least by 14,500BP (Jenkins et al. 2012; Dillehay et al. 2008) and this timing corresponds to the hypothesized end of the Beringian Standstill (Llamas et al. 2016). A more detailed DEM of this region to determine whether this apparent paleobasin turned bay is real or simply due to the errors imposed by satellite altimetry is strongly desired. If the basin is real, even if it is not the size that the BLBDEM suggests, it could be very important to understanding the environment of Beringia.

For the purposes of predictive modeling for submerged site discovery, the more important differences lie along the southern margin of the landbridge. In all the models there is a complex archipelago in the Bering Sea from the LGM until at least 10,000 BP. At modern sea levels the only portions of that archipelago that are still emergent are the Pribilof Islands and St. Matthew Island. In the unadjusted models most of the islands become submerged by 9,000 BP. In the isostatically adjusted model many of the islands do not submerge until 8,000. The late Pleistocene southern coastline of Beringia is an extremely complex and dynamic landform in all of the models. For any refined predictive model (regardless of whether salmon are used as a key resource) the most accurate modeling of the complex coastline and changing archipelago are vital. This strongly demonstrates that more detailed modeling from improved bathymetric datasets will require isostatic adjustments for meaningful results.

Improved Data Needs:

The time series analysis of the various datasets demonstrates the need for improved data. The significantly altered rates of submergence of the Pribilof Archipelago in the different models need to be resolved for the development of more comprehensive site probability prediction. The potential Nanvaruk Paleobasin should be evaluated. If this internally draining basin without modern analogue is an actual landform and not simply a data artifact it would be an excellent area to explore further. While this paper focuses on salmon as a predictive proxy, the Nanvaruk Paleobasin could provide other information for environmental reconstructions. Coring the sediments of the paleobasin (if it exists) could be conducted for palynological evaluations of Beringian

ecology. Yet due to the quality of bathymetric data it is unclear if this paleobasin even existed, let alone how it could have been influenced by isostacy.

Slope and Curvature Analysis:

Following the initial analysis of the Manley (2002) DEM, slope and hillshade layers were generated to seek a clearer picture of the geography of LGM Beringia. As discussed in Q4, the operating hypothesis for this analysis was that evidence of surficial complexity could reveal areas where the paleo-landscape was more visible. The initial attempts to identify surficial complexity simply used slope and high visual contrast stretches of the bathymetric data (see figs. 21 and 22).

Slope analysis indicated that the region with the most rugosity was the area of the Pribilof Archipelago; however, none of the slope values were very high. The objective had been to identify steeply sided landforms like canyons. In retrospect this effort was trying to find features below the data resolution, but the next step was to apply a curvature analysis to aid the visualization of the Beringian landscape.

Curvature analysis was able to highlight the landscape of Beringia within the limitations of the Manley (2002) DEM. For the most part the resulting representation of Beringia remained low-relief, but it appeared that the sides of St. Matthew Island were an area where there could be valleys (see fig. 23). This evaluation was made purely visually. An area that apparently retains visible evidence of channeling minimally could present an area likely to have had predictably located drainages. While the underlying hypothesis is speculative, the area around St. Matthew Island is worth evaluating to see if the valleys are real or simply data artifacts.

Figure 21: Slope analysis of LGM beringia. BLBDEM (Manley 2002).
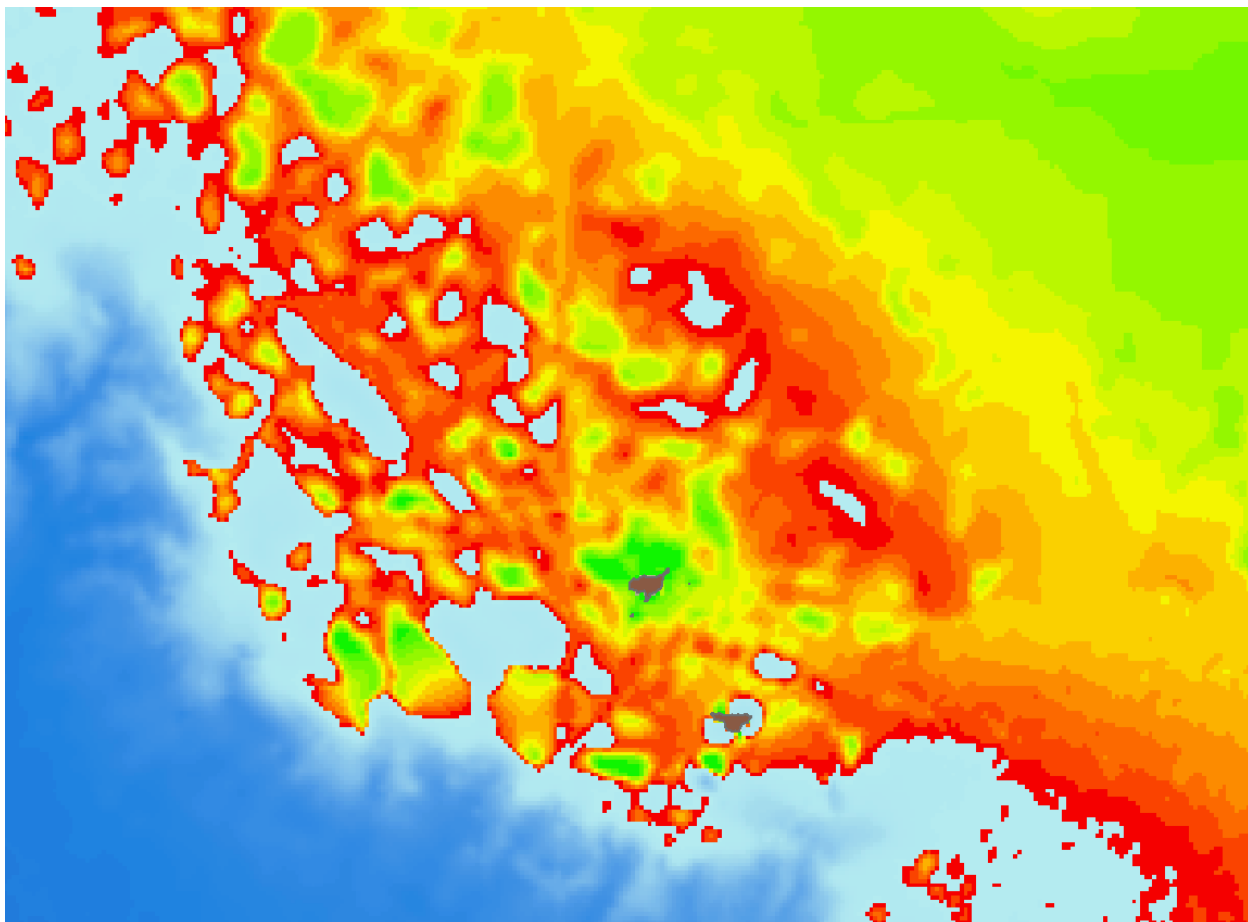
Figure 22: Screenshot of high contrast stretch of BLBDEM in the area of the modern Pribilof islands. The footprint of the Nanvaruk Paleobasin is visible as the redder area near the middle.
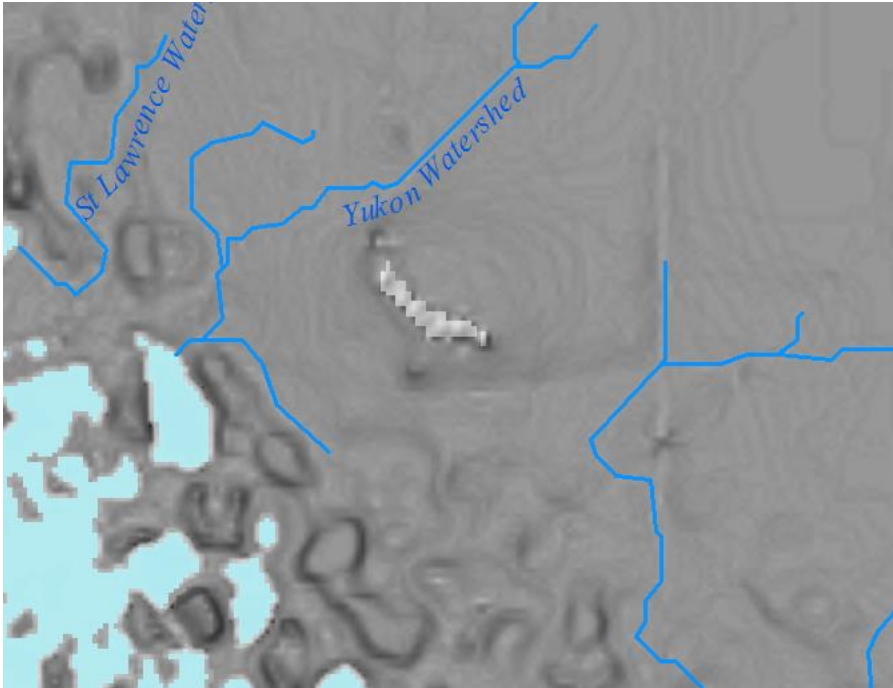
Figure 23: St. Matthew island closeup using curvature and hillshade to amplify surficial complexity. The Yukon Drainage to the north and Nanvaruk drainage to the south are visible, as is a linear feature that is clearly a data artifact. BLBDEM (Manley 2002).

Analysis of improved datasets:

The previous analyses all indicated the need for better bathymetric data. A search for publicly available bathymetric data for the Bering Sea revealed very few systematic surveys. There are soundings from individual tracklines that can be located, and some sonar derived Bathymtric Attributed Grids (BAGs) available on NOAA's NGDC website; however, none of the BAGs were for the Beringian areas of interest to this study. There were two 1952 hydrographic surveys in the form of digitized smoothsheets (see fig. 24) for St. Matthew Island (National Ocean Survey 1952b) and the Pribilof

Islands (National Ocean Survey 1952a).
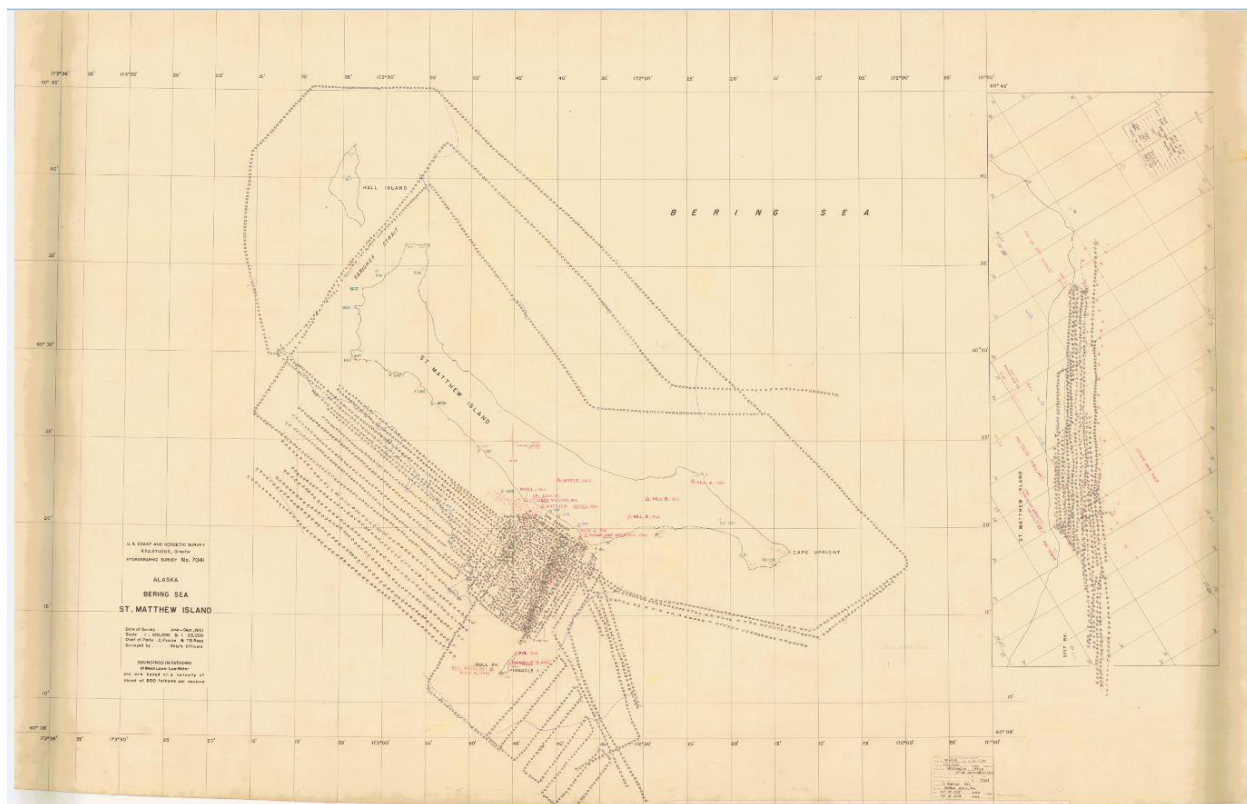
Figure 24: 1952 hydrographic survey smoothsheet for St. Matthew Island (National Ocean Survey, N.O.A.A. 1952a)

The X,Y,Z data from the digitized smoothsheets was used to generate a point cloud that was interpolated using kriging in ArcGIS 10.3 to create new DEMs of much higher resolution than the previously available datasets (see fig. 25).

Figure 25: Screenshot showing the footprints of the newly generated DEMs. The Basemap is the ESRI basemap.

The first improved DEM was for the area between the Pribilof Islands. The

resulting DEM is an improvement over existing layers but did not reveal any novel

landforms (fig. 26).
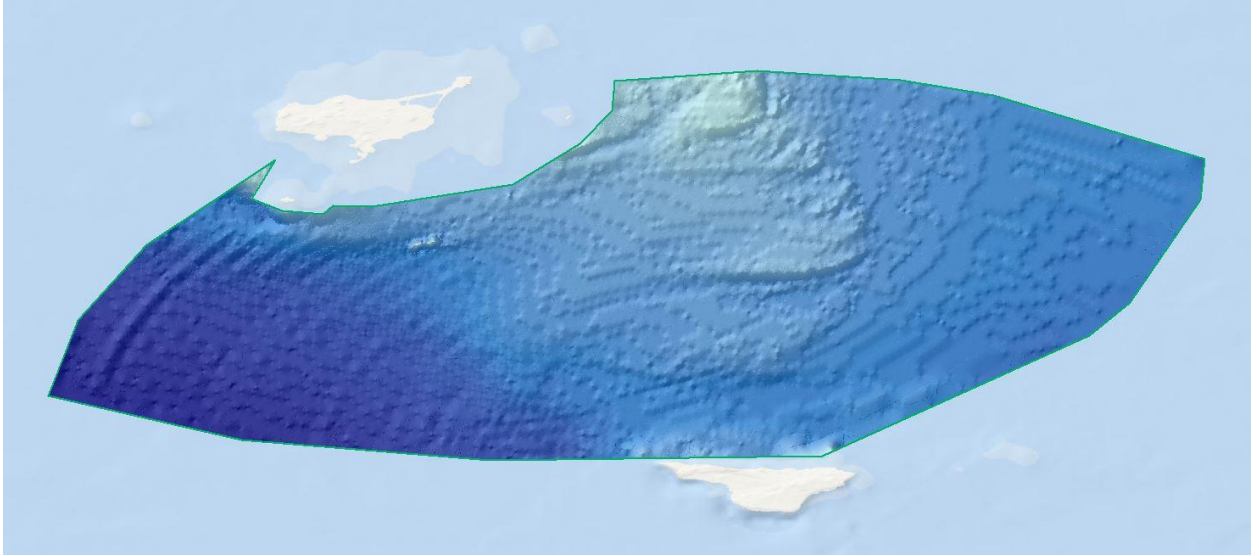
Figure 26: Screenshot closeup of composite image layering hillshade and colored stretch derived from the newly generated Pribilof DEM. The Basemap is the ESRI basemap.

The St. Matthew Island DEM produced a particularly detailed look at bathymetry to the south of the island. The new DEM revealed a complex topography including what appear to be a stepped series of cliffs. If future predictive models suggest closer

examination of St. Matthew island this sort of detailed dataset could be used for more accurate modeling.
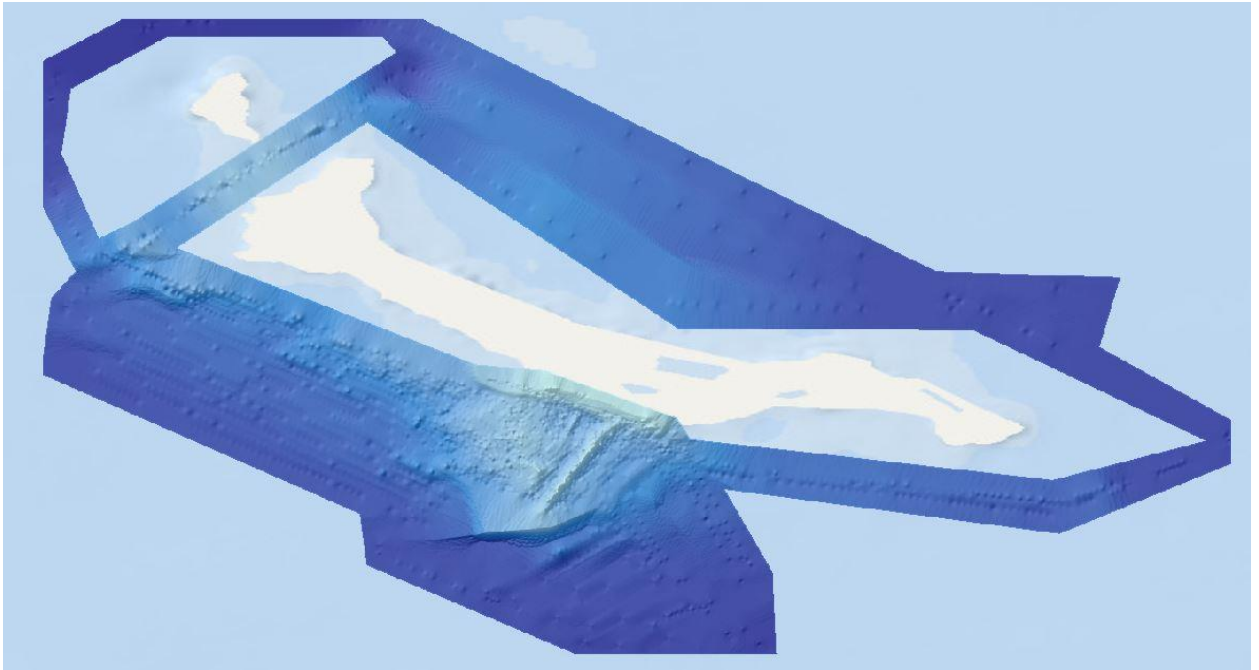
Figure 27: Screenshot closeup of composite image layering hillshade and colored stretch derived from the newly generated St. Matthew Island DEM. The Basemap is the ESRI basemap.
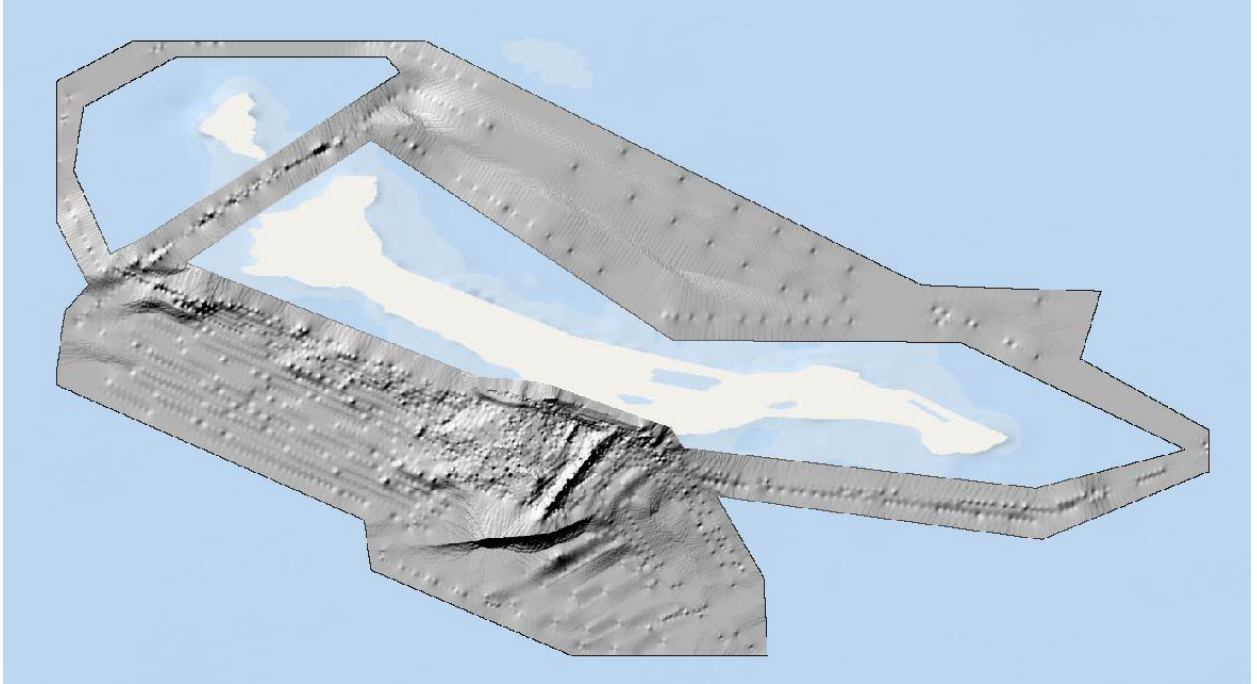
Figure 28: Screenshot closeup of the newly generated St. Matthew Island DEM Hillshade. The Basemap is the ESRI basemap.

Ultimately the newly generated DEMs are too limited in extent to evaluate the validity of the earlier analyses, but as a proof of concept they do illustrate the value of improved data. New bathymetric survey data can be turned into detailed DEMs to evaluate existing analyses and to develop improved predictive models.

Conclusions and Future Study

This paper represents a series of preliminary steps for developing a regionally focused predictive model for LGM-age submerged sites in Beringia. The Danish Model (Benjamin 2010) is adapted here as a framework to provide clear goals and benchmarks. One of the strengths of this approach is the incorporation of indigenous cultures and practices into the predictive modeling process. Specifically, the use of salmon as an attractive resource that would have encouraged human habitation of sites on salmon-bearing drainages is employed as a culturally based form of spatial patterning to prioritize certain areas of Beringia for more detailed future analysis.

Evaluating Research Questions

Question 1 (Q1): Were there viable salmon populations in Beringia throughout the last 20 thousand years?

This paper uses a series of salmon DNA analyses (Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012; Smith et al. 2001; Beacham, Jonsen, et al. 2006) to answer the question of where salmon were located. The data plainly indicates that there were salmon present in the study area, but the interpretation of where those populations were physically located is more difficult and equivocal. At this point it appears that the strongest claims that can be made as to the locations of salmon refugia are: 1) Salmon were present in the North Pacific in reduced numbers through the LGM; 2) There were at least two, and more probably three main refuge areas; 3) Beringia appears to be the only one of those three refuge areas that

probably supported all examined species of salmon; 4) The other two probable refuge regions likely did not each support all species throughout the LGM. The Yukon is a center of genetic diversity for salmon, and seems likely to have been a refuge, but the genetic data does not seem to be strong enough evidence to absolutely identify individual drainages.

The answer to the question is yes, there were viable salmon populations in Beringia throughout the last 20,000 years. Of course, this answer comes not from original research conducted for this project, but from review of existing marine biology literature. The primary limitation of using DNA data from modern populations is that it is by nature proxy evidence, not direct evidence of presence. The nature of the DNA evidence appears very strong, provided claims of undue specificity are avoided. The ideal way to evaluate the presence or absence of salmon would be to find direct evidence of salmon from Pleistocene era deposits. Following the example of Choy et al. (2016), isotope analysis of Pleistocene era deposits could be an effective way to build a more robust model of salmon distribution in the terminal Pleistocene. Perhaps coring of deposits of the right age could be used as a way to see if isotope analysis can reveal the presence of salmon in specific drainages in the past.

Question 2 (Q2): *Can geospatial analysis incorporating drainage analysis of existing bathymetric datasets reasonably be interpreted as indicating the location of potentially salmon bearing paleodrainages in Beringia at the LGM?*

This question is specifically focused on the period of the LGM. The exact timing of the actual LGM is subject to debate (Monteleone 2013); for the purposes of this paper, the LGM is treated as 20,000 BP. The drainage basins for this analysis were created using the INSTAAR (Manley 2002) Beringian DEM. The identification of drainage basins in the Beringian study area was conducted as a pour point drainage basin analysis (Parmenter and Melcher 2012) using ArcGIS 10.3. Further drainage analyses identified potential stream locations.

The answer to this question was negative. Existing bathymetric datasets were too problematic, and the resolutions were too coarse, to reasonably claim that they indicated the locations of submerged waterways. The question of stream suitability for salmon was simplified (in the Manley [2002] DEM) by the presence of three major Bering Sea draining basins, of which the Yukon was the largest. The Yukon paleodrainage catchment was estimated at more than half a million square kilometers, with thousands of linear kilometers of the drainage estimated as a 7th order stream. Considering the size of the Yukon in current times, as well as the known time depth of salmon use within the greater Yukon drainage, and the fact that the Yukon is a center of genetic diversity for modern salmon stocks, it seemed reasonable to assume that a clear indication of location of the Yukon Paleodrainage could be easily argued as being a likely salmon bearing drainage. This question was constructed with the expectation that the results of a drainage analysis would be compelling enough to indicate areas that should be targeted

for future sonar survey. Considering the ambiguous and contradictory results of drainage analyses using the various available datasets, it does not appear that the paleodrainage results are strong enough to warrant further reconnaissance on their own.

The primary data need for future analysis along these lines is higher resolution data with clear sourcing. For comparison, Landsat 7 has publicly available terrestrial resolution of 15 meters, and private satellites have finer resolution than this (Worldwide Mapping Inc. 2018), while the best data available for most of Beringia has a pixel resolution of roughly 1,000 meters and unclear sourcing. A dataset that encompasses the entirety of Beringia is unlikely in the near term without a marine remote sensing breakthrough. A more likely situation that could allow further modeling would be a relatively large sonar survey of the seafloor in the area of the now submerged Pribilof Archipelago. This region is useful to a variety of predictive modeling approaches, rather than solely for a salmon-based approach. Even a coarse-grained DEM with clear sourcing would allow for specific areas to be identified for focused multi-beam sonar survey and sub-bottom profiling.

Additionally, accurate modeling of paleo-shorelines and paleodrainages requires good quality isostatic adjustments that take the best current estimates of terminal-Pleistocene glaciations into account. For work in Beringia, this also requires that datasets be converted into formats that are optimized for the peculiarities of polar regions. Equal area rasters, rather than arc-minute/second pixels, are important for accurate visualizations. Georeferencing and clear meta-data are also important. Polar regions require special consideration of data formats because of the nature of coordinate systems,

and this is beyond the fact that environmental conditions and remoteness make data gathering more challenging to begin with.

Question 3 (Q3): With the understanding that there were salmon in Beringia through the LGM, can GIS analysis identify likely locations of salmon bearing drainages through the period of sea-level rise following the LGM?

Question 2 limits the chronometric applicability of this project to the specific window of the LGM and effectively ignores the ~20,000 years between that point and the present. In order to provide a diachronic utility to the products of this project, an additional series of analyses looking at the change in landforms and drainages through time was generated. These analyses compare the results of drainage analysis on a set of isostatically adjusted datasets as well as unadjusted datasets. This approach has the additional benefit of identifying areas that potentially remained significant for thousands of years that are within completely submerged landscapes now.

The answer to this question is negative for two reasons. Firstly, while salmon were present in the study area through the past 20,000 years, the genetic data that define the regions of refugia does not provide sufficient indications to determine in what sequence additional streams were colonized. The only argument that can be made, based on the data used in this project, is that larger streams probably had salmon. Even operating on the assumption that streams of some metric of largeness would have been likely to support salmon, the second reason this question is negative is again the ambiguous and contradictory results of drainage analyses using the various available datasets. Improved bathymetric data (finer grained, clear sourcing, adequately

georeferenced, etc.) would go a long way toward enhancing the quality and analytical utility of Beringian drainage analysis, but with regards to salmon, this model does not specifically indicate which streams had salmon.

In the modern Bering Sea region, salmon runs are ubiquitous, even in streams far smaller than the thresholds set in this paper. As such, it is not unreasonable to argue that streams are a good place to look for evidence of people using salmon in the past. Of course due to the multivariate needs for salmon spawning habitat (Quinn 2011) first order approximations of submerged salmon habitat are likely always going to be limited to stream order or catchment simplifications. With that in mind, improved bathymetric data would increase the chances of locating submerged river courses, and the evidence supporting the persistence of salmon populations and the time depth of salmon use in the Beringian region suggests that the usage of salmon resources by Pleistocene era people should be considered when developing a predictive model. Even if a salmon focused approach is not chosen for future models, the presence or absence of salmon in a given drainage has a significant impact on system productivity.

Question 4 (Q4): *Can locations still recognizable as specific landforms (such as valleys) be identified from the existing datasets?*

Slope and curvature analyses were also used to identify areas that appear to retain some terrain complexity. The hypothesis behind this question is that terrain complexity might be indicative of preserved paleolandscapes. If paleolandscapes can be identified that are neither obliterated by marine transgression, nor too deeply buried by depositional processes during sea-level rise, perhaps those areas could offer greater recoverability of

archaeological materials. This question is highly speculative, and problematic

considering the scale of the raster pixels used in the analysis, but exploring the question

allowed additional subtleties to be teased out of the INSTAAR (Manley 2002) DEM.

During this analysis the area around St. Matthew Island was identified as being of

particular interest.

The resolution and reliability of bathymetric data for the Bering Sea is simply

inadequate to identify specific landforms, especially on a human scale. The available

data is unreliable enough that it is unclear whether a basin large enough to contain Lake

Ontario actually existed or is simply the result of insufficient data points. Even when

hydrographic survey data was used to generate more detailed bathymetry around St.

Matthew Island, the areal extent of the data was insufficient to evaluate the presence or

absence of the canyon features that seemed to be indicated from analysis of the Manley

(2002) DEM. The sheer scale of the submerged landscape and the coarse-grained nature

of available data makes the identification of landscape features very challenging.

To borrow again from the Scandinavian example of Doggerland, creative

approaches to bathymetric modeling and partnerships could be fruitful. Researchers were

able to use seismic modeling sourced from both public and private (petroleum industry)

sources to create a DEM with a 12 meter resolution for their submerged landscape

(Gaffney, Fitch, and Smith 2008), which meant that the resolution for the Doggerland

DEM was a 33,000% improvement over the Manley (2002) DEM. This high grained

resolution allowed for detailed analysis of landforms, identification of faulting, and

strong arguments for other research possibilities. While Beringia provides numerous

additional challenges over the example of the much smaller Doggerland, creative

partnerships with ocean energy developments could lead to better data.

Question 5 (Q5): Once areas of particular interest are identified through the answering of the previous questions, can existing available datasets be used refine and test the validity of the earlier analyses?

        This final question is concerned with data quality and availability. Considering the coarse-grained nature of the data used for the regional level analyses, higher resolution data is key. Future research efforts following the examples of Davis (ICF, Southern, and Davis 2013; Mackie et al. 2013) and/or Monteleone (Monteleone 2013; Monteleone, Dixon, and Wickert 2013; Wickert et al. 2012) will need to incorporate more elaborate analytical models, as well as more detailed sensing methods like sub-bottom profiling, before any kind of direct sampling or physical survey could be considered. This thesis focused on the feasibility of using a single resource to constrain the total area for further research, whereas the models of Davis and Monteleone are much more developed in terms of identifying specific locations for underwater reconnaissance. Any attempts to identify submerged sites in Beringia will necessarily be iterative. Currently available data that can be used to evaluate the validity of the current model would be of interest. Bathymetric data that could more directly address the question of the drainage model validity was not located; however, as a proof of concept an improved bathymetry layer of the area around St. Matthew Island was created using sounding depths from a 1952 hydrographic reconnaissance by the US Coast and Geodetic Survey.

The answer to this final question is also no, but a more hopeful no. Existing datasets that were sufficient to test the validity of earlier analyses were not located; however, it is clearly possible to generate new GIS products that could be used to evaluate current analyses if new remote sensing data is created or made available. The creation of better quality remote sensing data for the Bering Sea is a challenging proposition. The Bering Sea is famously inclement (see the long running television show "Deadliest Catch"), and much of the area of interest to archaeology is less than 50 meters below modern sea-level. Depths of less than 50 meters pose a challenge for standard bathymetric multibeam sonar (Hughes Clarke, Mayer, and Wells 1996; Abraham and Willett 2002). Multibeam sonar is the dominant source for bathymetric data from the US government. It is possible to conduct sonar surveys in shallower water, but the equipment and methods are not the same as for deeper water. And aerial based remote sensing approaches are challenging since green laser lidar has limited utility in turbid waters. Since the general depth limit for scuba diving is 40 meters (PADI 2015), the challenges in getting relevant high quality bathymetric data compound the difficulty faced in any efforts to truth a Beringian predictive model. But if better data sources do become available, they can be used to evaluate current datasets.

Implications for Future Research

This project has provided valuable insights into the paleogeography of Beringia, as well as the nature and limitations of currently available data. Unfortunately for the goal of using this thesis as a launching point for further research into locating underwater

archaeological sites in Beringia, the results of this project do not support further efforts at the current time. In light of the limitations of the analyses presented in this paper, and the challenges to obtaining data of sufficient quality to improve the strength of these analyses, it is hard to argue that the expense and physical challenges of underwater archaeological investigation in Beringia is warranted based on this project. However, there are implications of relevance to other avenues of searching for evidence of the peopling of the Americas, as well as an example of a methodologically simple way to partially decolonize approaches to understanding the peopling of the Americas.

While the challenges posed by resolution and sourcing of current bathymetry for Beringia prohibits the type of drainage specific habitat identification that was hoped for, the isostatically adjusted bathymetric data (J. Clark, Mitrovica, and Alder 2014) is sufficient to define the scope of the area. By extending the maximum depth that the adjusted dataset was analyzed a maximum likely LGM extent for Beringia has been created. This means that it is unlikely that areas outside of the 20,000BP iteration of the time-series analysis would need to be considered in future searches for the earliest Beringians. For maximum utility this extent should be refined, but as a gross delimitation of the area of interest it is still useful both for purposes of archaeological and energy development.

Comparison of Beringia to Doggerland provides an example of the kind of modeling that is possible with high quality bathymetry. This thesis project was unable to strongly argue for specific locations of major drainages, but the 12 meter resolution of Doggerland bathymetry allowed for discerning erosional landforms from depositional landforms, and faulting that complicated the picture (Gaffney, Fitch, and Smith 2008).

With improved data it is certainly likely that the drainage-based approach explored in this paper could be fruitful. Additionally, such data and analysis could indicate areas for other types of environmental reconstruction research, like optimal locations for sediment coring for palynological and isotype analysis. Marine core analysis would also provide strong parallel lines of evidence for model refinement.

DNA studies of modern salmon populations indicate that salmon were present in Beringia at the LGM and through the present day. The precise location of those salmon refuges cannot be known based on current information, but the presence of a northern refuge in Beringia appears well supported by genetic data. The identification of paleo-drainages based on the BLBDEM (Manley 2002) bathymetric model indicated landscape level areas for focusing future efforts. The ultimate usefulness of this information is, however, limited by a lack of certainty about the accuracy and scale of the DEM. It is likely that the paleo-drainages identified in this paper are good starting points for refining the picture of what LGM Beringia looked like, but the lack of higher resolution bathymetric data limits the ability to test these results. Future bathymetric survey in the Bering Sea would go a long way toward resolving questions of the accuracy of the current model.

More importantly for research into locating ice-free refugia along the glacial margin, the DNA studies of modern salmon populations indicate that there were likely at least two refuges along the glacial margin that supported salmon populations through the LGM (C. T. Smith et al. 2001; Beacham, Jonsen, et al. 2006; Beacham, McIntosh, et al. 2006; Beacham, Candy, Le, et al. 2009; Beacham et al. 2012). The Southern Coast of Alaska and the Haida Gwaii remain promising areas for future analysis. The proximity

of the coast to the hinge line of isostatic effects from the ice-sheets (Shugar et al. 2014) means that the chances of finding Pleistocene era salmon streams near (above or below) modern sea level is vastly improved. Though the ongoing challenges of accurately modeling ice sheet extent and chronology (Menounos et al. 2017; Potter et al. 2017; Ehlers, Gibbard, and Hughes 2011; Ehlers and Gibbard 2004) mean that understanding the diachronic local effects of isostacy along the Pacific Northwest Coast is extremely difficult.

Analysis of isostatically adjusted bathymetric data demonstrated the importance of incorporating corrections into future studies of Beringia. The southern Beringian coast was a dynamic and complicated landscape through the terminal Pleistocene. Accurate modeling of this environment is vital to the creation of better high-probability site discovery models.

More generally, whether or not future efforts to locate early evidence of human occupation of the new world choose to place as much importance on anadromous fish, salmon can and should be factored into understandings of the environments that early North Americans inhabited. Salmon were present through the Pleistocene-Holocene transition. Salmon were, and continue to be, of great importance to Native American peoples along the Pacific coast, and well into the interior in some places. Humans interact with their environment in culturally mediated ways, and the significance of salmon to modern coastal populations is Pan-Pacific in modern distribution. While Pleistocene era evidence for salmon use is sparse, it is present, and sites like Upward Sun (Halffman et al. 2015; Choy et al. 2016) and the Dalles Roadcut (Butler and O'Connor 2004) indicate that salmon use was recurrent and in some cases sustained. By identifying

specific keystone species with broad geographic scale cultural relevance, it is possible to incorporate Indigenous knowledge, culture, and practice into scientific investigation of the deep past. Salmon may not be a magic bullet for locating submerged sites, but they are important to understanding the past and the peopling of the Americas.

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