SIX THOUSAND YEARS OF CHANGE IN THE NORTHEAST PACIFIC: AN INTERDISCIPLINARY VIEW OF MARITIME ECOSYSTEMS

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By

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Abstract

The goal of this thesis is to develop long-term records of North Pacific ecosystems and explore relationships between change in marine ecosystems and prehistoric Aleut culture through soil chemistry, isotope analyses of lake cores, and isotope analyses of bone from archaeological middens. Chemical analysis of soils yielded differences in soils of various archaeological features as well as middens of varying composition. Sites that had no middens were chemically distinguishable from sites that did have middens helping to define resource consumption in the local region. An important result of this study is that no single ecosystem (nearshore benthic, coastal pelagic or deep-ocean pelagic) experienced the same changes in $\delta^{13}C$ and $\delta^{15}N$ over the past 4,500 years. This suggests that changes in climate affected different ecosystems in unique ways. Only one change spans all species studied; the decrease in modern $\delta^{13}C$ in comparison to $\delta^{13}C$ of prehistoric specimens. According to these comparisons, the modern Gulf of Alaska may not be in the highly productive state that it was for the past 4,500 years, with the possible exception of the Medieval Warm Period. Lake core sediment analysis suggests an increase in salmon stocks in the Gulf of Alaska beginning ~6,000 years ago, with a decrease during the Medieval Warm Period. In fact, salmon stocks in the Gulf of Alaska appear to be healthiest during periods of atmospheric cooler and wetter climate over the past 4,500 years. In comparing my paleoecological records to the archaeological record of the area it appears that humans were affected by changes in their environment but, even in relatively small numbers, humans also influenced local ecosystems for the past 6,000 years. By building on our understanding of long-term climate change and long-term fluctuations in ecosystems and trophic dynamics of species in the North Pacific, and through considering humans in the ecological context, we can better understand present conditions in marine ecosystems.

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General Introduction

In order to understand present day change in the North Pacific, we need to understand past conditions and past variation more comprehensively than our current knowledge permits. This thesis considers the relationships between change in North Pacific marine ecosystems and prehistoric Aleut culture through studies including soil chemistry, isotopic analyses of lake cores, and isotopic analyses of bone from prehistoric middens focusing on the region located along the lower Alaska Peninsula (LAP)/eastern Aleutian Islands. Lake core sediments yielded data concerning Holocene paleoclimate and salmon returns from 6,000 calendar years before present (cal yrs BP). Bone isotope analysis returned information on changing environments and productivity starting ~ 4,500 cal yrs BP, and elemental analysis of archaeological soils helped elucidate changes in human resource consumption. Existing data suggest that this period has been marked by numerous climatic fluctuations and cultural changes (Maschner 1998; Jordan and Maschner 2000; Finney et al. 2002; Gedalof and Mantua 2002; Fitzhugh 2003; Anderson et al. 2005; D'Arrigo et al. 2005; Maschner and Jordan 2005). Thus the data provided abundant opportunities to study the response of marine ecosystems and humans to climatic variability.

Changes in climate have been linked to increases and decreases in both pelagic and anadromous fish stocks (Ware and Thomson 1991; Beamish and Bouillon 1993; Francis and Hare 1994; Roemmich and McGowan 1995; Welch et al. 1998; Mantua 2004) such as salmon and cod, important resources for pre-historic Aleut communities.

These changes in climate also affect other aspects of marine ecosystems, such as species composition, abundance and geographic distribution of shellfish, fish and sea mammals (Francis and Hare 1994; Hare and Mantua 2000). Paleoclimate records spanning millennia indicate that climate has changed both locally and globally (Bradley 1999). The Aleuts have been dependant on the ocean for thousands of years and fluctuations in marine ecosystems will have impacted Aleut communities (bottom-up processes), even if only at the local level. Conversely, preferential resource consumption may have influenced local ecosystems (top-down processes). Studies by both archaeologists (Jordan and Maschner 2000) and marine scientists (Finney et al. 2002) suggest that changes in the environment of the Northeast Pacific Ocean co-occur with changes in Aleut and Koniag house form and organization. This thesis aims to further test that hypothesis and gain a clearer understanding on the relationship between cultural change and climate change.

Chapter 1 presents the results of a multi-element weak-acid soils extraction study. Soil chemistry analysis has been used mostly as a prospecting technique to locate sites in areas with few or no visible archaeological features or materials. Recently, studies have attempted to isolate chemical enrichment of anthropogenic soils and chemical variation between different activity areas of a site (Griffith 1980;1981; Linderholm and Lundberg 1994; Schuldenrain 1995; Middleton and Price 1996; Middleton 1998). Multi-element analyses of soils from archaeological sites were used to help compare changes in house form, use of space, and resource consumption through time in the eastern Aleutians/LAP to changes in the marine ecosystem. A small study (Misarti unpub.) conducted on soil samples from archaeological sites in the Aleutians suggested that middens of differing composition (i.e. shell fish versus sea mammal) can be differentiated through chemical signatures. It was hypothesized that the multi-element analysis conducted here will help distinguish for example, between marine diets based mostly on salmon versus those based more on sea mammals. During the 2004 field season, 779 soil samples were collected from archaeological sites on the Sanak Island archipelago, Alaska for multi-element analysis. These were used in conjunction with 174 previously collected soil samples from Unalaska Island, Alaska to further evaluate the sensitivity of these elemental signatures to specific human activities. Off-site samples were also collected (both by coring and from open profiles) in order to understand the elemental composition of the natural soils in the area. Relative abundances of 11 elements (Al, Ba, Ca, Fe, K, Mg, Mn, P, Sr, Ti, and Zn) were analyzed on an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS). This chapter will attempt to answer the following questions. Will trends reported in past small studies continue in a study with larger sample size? Can these same trends be distinguished with coring techniques rather than large excavations? Do midden samples with more bone have a 2:1 ratio of Ca:P while midden samples with more shell have very little P as seen in a previous pilot study? Can this analysis distinguish between middens consisting mostly of salmon versus those based more on sea mammals versus those that are mostly shell? If so, does the chemistry vary over time or from site to site (seasonality)? How much do recent anthropogenic influences impact soil chemistry of sites?

The results of the lake core sediment analysis from two lakes are addressed in Chapter 2. Paleoclimate information and the levels of salmon-derived nutrients found in lake cores collected on Sanak Island, Alaska were derived from proxy data of stable nitrogen and carbon isotope analysis and carbon to nitrogen ratios. Recently, Finney (1998; Finney et al. 2000; 2002) has shown that stable nitrogen isotope composition of sediments from salmon system lakes is a useful tool to estimate fluctuations in salmon abundance over time. Climate change and ecosystem shifts were correlated across two cores, one from a salmon nursery lake and one without salmon. Use of a control lake was to determine if the proxy data utilized were sufficient to overcome the fact that lakes on Sanak are shallow and yearly precipitation is high and therefore there are high flushing rates in both lakes. Did changes in salmon-derived nutrients coincide with climate change data derived from the lake cores as well as previously published data for this geographic area?

Chapter 3 addresses stable isotope analysis of over 300 bone samples from 6 species [Steller sea lions (*Eumetopias jubata*), Harbor seals (*Phoca vitulina*), Northern fur seals (*Callorhinus ursinus*), sea otter (*Enhydra lutris*), Pacific cod (*Gadus macrocephalus*) and sockeye salmon (*Oncorhynchus nerka*)] from middens spanning the past 4,500 years and compares them to modern samples from the same species. These species were chosen because they represent the benthic (sea otter and cod) and pelagic (pinnipeds and salmon) food webs. Cod may also reflect a more mixed diet, as they are known to prey on both fish and benthic invertebrates (Yang 2004). Stable isotope analysis is an extremely useful tool and can enhance past trophic dynamics and productivity of the ecosystems to be examined, a task conventional dietary studies can not accomplish (DeNiro and Schoeninger 1983; Post 2002). Samples of fish and marine mammals recovered in archaeological midden samples of differing time periods were analyzed using stable isotopes of nitrogen and carbon in order to determine if the base of the food webs that these organisms rely on shifted over the past 4,500 years. Variations in $\delta^{13}C$ in food webs may be related to fluctuations in primary productivity (Hirons et al. 2001) that in turn has been linked to climate shifts (Francis and Hare 1994). The $\delta^{15}N$ and $\delta^{13}C$ of the bones recovered in these middens were used to determine trophic relationships and how they fluctuate over time. Bone collagen is well suited for this type of study as it reflects a longer period in an organism's lifetime than tissues and hair and is not affected by seasonality (Koch et al. 1994; Hedges et al. 2005). Several questions were discussed in this chapter. Did the nearshore ecosystem undergo discernable changes over the past 4,500 years? Is individual variability within a species in a given time period less than the variability over time and are there distinguishable differences in stable isotope ratios of each species throughout the last 4,500 years? Is there an inverse relationship between $\delta^{13}C$ and $\delta^{15}N$ of organisms over time? What is the nature of any variability in terms of event frequency and modes of food webs (i.e. restructuring into different species assemblages such as the sea otter/kelp versus sea urchin alternate communities)?

Chapter 4 integrates all three data sets previously discussed and relates the conclusions to the regional prehistory of the Aleut along the western Alaska Peninsula and specifically to Sanak. Data from previous zooarchaeological studies from the lower Alaska Peninsula, eastern Aleutian Islands, and recently collected from Sanak Island, including specimen counts and weights, minimum number of individuals of species and age and sex of specimens, were also used to track changes in species represented through time. Since preferred resource consumption (a cultural choice not based on availability of a species) could influence materials recovered from middens, zooarchaeological data alone cannot determine climate-derived influence on numbers and types of species found in an area over long periods of time. It is hypothesized that Aleuts changed their lifestyles in direct response to climate change that affected the marine ecosystems they relied on by shifting village location and size over the past few thousand years. If changes in ecosystems are discernable, did they coincide with changes in the archaeological record of material culture, house form, and resource consumption (all lines of evidence believed to reflect sociopolitical change)? Did Aleut village location and size, house form and size, and resource consumption change over time in conjunction with changes in the marine ecosystem? Do zooarchaeological data and soil samples show restructuring of resource consumption at the same time periods when isotope ratios of organisms demonstrate a change in the marine ecosystem?

By answering all of the above questions this thesis will lend a better understanding of the processes that govern change. This will subsequently frame our modern data in a longer perspective. Few researchers are investigating the distant past to determine if some of the changes in the ecosystems being studied have occurred before and what that variability may mean for recent and future ecosystems. The three data sets discussed above are synthesized to yield a strong base of knowledge of changes in ecosystems with regards to changes in climate and the part humans played throughout this history. The past is a key factor to comprehending current and future change in the North Pacific.

References

Anderson L, Abbott MB, Finney BP, Burns SJ (2005) Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 64:21-35

Beamish RJ, Bouillon DR (1993) Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences 50:1002-1016

Bradley RS (1999) Paleoclimatology; reconstructing climates of the Quaternary, Second edn. Academic Press, New York

D'Arrigo R, Mashig E, Frank D, Wilson R, Jacoby G (2005) Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. Climate Dynamics 24:227-236

DeNiro M, Schoeninger MJ (1983) Stable carbon and nitrogen isotope ratios of bone collagen: Variations within individuals, between sexes, and within populations raised on monotonous diets. Journal of Archaeological Science 10:199-203

Finney BP (1998) Long-term variability of Alaska sockeye salmon abundance determined by analysis of sediment cores. North Pacific Anadromous Fisheries Community Bulletin 1:388-395

Finney BP, Gregory-Eaves I, Sweetman J, Dougas MSV, Smol JP (2000) Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. Science 290:795-799

Finney BP, Gregory-Eaves I, Douglas MSV, Smol JP (2002) Fisheries productivity in the Northeastern Pacific Ocean over the past 2,200 years. Nature 416:729-733

Fitzhugh B (2003) The evolution of complex hunter-gatherers: archaeological evidence from the North Pacific. Kluwer Academic/Plenum Publishers, New York

Francis RC, Hare SR (1994) Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science. Fisheries Oceanography 3:279-291

Gedalof Ze, Mantua NJ (2002) A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophysical Research Letters 29:2204-2208

Griffith MA (1980) A pedological investigation of an archaeological site in Ontario, Canada, I. An examination of the soils in and adjacent to a former village. Geoderma 24:327-336

Griffith MA (1981) A pedological investigation of an archaeological site in Ontoario, Canada, II. Use of chemical data to discriminate features of the Benson Site. Geoderma 25:27-34

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145

Hedges RE, Stevens RE, Koch PL (2005) Isotopes in bones and teeth. In: Leng MJ (ed) Isotopes in palaeoenvironmental research. Springer, The Netherlands, pp 117-145

Hirons AC, Schell DM, Finney BP (2001) Temporal records of $\delta^{13}C$ and $\delta^{15}N$ in North Pacific pinnipeds: inferences regarding environmental change and diet. Oecologia 129:591-601

Jordan JW, Maschner H (2000) Coastal paleogeography and human occupation of the western Alaska Peninsula. Geoarchaeology: An International Journal 15:385-414

Koch PL, Fogel ML, Tuross N (1994) Tracing the diets of fossil animals using stable isotopes. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publications, London, pp 63-92

Linderholm J, Lundberg E (1994) Chemical characterization of various archaeological soil samples using main and trace elements determined by inductively coupled plasma-atomic emission spectrometry. Journal of Archaeological Science 21:303-314

Mantua N (2004) Methods for detecting regime shifts in large marine ecosystems: a review with approaches applied to North Pacific data. Progress in Oceanography 60:165-182

Maschner HDG (1998) Salmon run volatility, subsistence, and the development of North Pacific societies. In: Hokkaido Museum of Northern People (ed) 12th International Abashiri Symposium: Salmon fishery in the north and its change through time. Association for the Promotion of Northern Cultures, Abashiri, Hokkaido, Japan

Maschner HDG, Jordan JW (2005) A new archaeological chronology for the eastern Aleut. In: Alaska Anthropological Association, Anchorage, AK

Middleton WD (1998) Craft specialization at Ejutla, Oaxaca, Mexico: an archaeometric study of the organization of household craft production. In: Department of Anthropology. University of Wisconsin-Madison, Madison

Middleton WD, Price TD (1996) Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using inductively coupled plasma-atomic emission spectroscopy. Journal of Archaeological Science 23:673-687

Post DM (2002) Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83:703-718

Roemmich D, McGowan J (1995) Climatic warming and the decline of zooplankton in the California Current. Science 267:1324-1326

Schuldenrain J (1995) Geochemistry, phosphate fractionation, and the detection of activity areas at prehistoric North American sites. In: Pedalogical perspectives in archaeological research. Soil Science Society of America, Madison, WI

Ware DM, Thomson RE (1991) Link between long-term variability in upwelling and fish production in the Northeast Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences 48:2296-2306

Welch DW, Ishida Y, Nagasawa K (1998) Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Canadian Journal of Fisheries and Aquatic Sciences 55:937-948

Yang MS (2004) Diet changes of Pacific cod (*Gadus macrocephalus*) in Pavlof Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995. Fishery Bulletin 102:400-405

Chapter 1: Reconstructing site organization using analysis of soil chemical composition in the eastern Aleutian Islands, AK.[1]

Abstract

This study presents the results of multi-element analysis of weak-acid extractions of 953 soil samples collected by coring on and around prehistoric village sites on two islands, Sanak and Amaknak, in the eastern Aleutians. Concentrations of Al, Ba, Ca, Fe, K, Mg, Mn, P, Sr, Ti, Zn were determined using an inductively coupled plasma-mass spectrometer (ICP-MS). Resultant elemental signatures allow the identification of site features and activity areas in the absence of large-scale excavation. All the archaeological sites showed similar and distinct chemical signatures regardless of site age or intensity of occupation. Site features such as houses, house berms, house floors and middens had distinct anthropogenic signatures and could be distinguished from one another. This approach may be used to identify sites that do not have distinct surface features and to target areas for excavation.

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[1] Misarti N, Finney B, and Maschner H. 2007. Reconstructing site organization using analysis of soil chemical composition in the eastern Aleutian Islands, AK. Prepared for the Journal of Archaeological Science.

Introduction

This study was undertaken to determine if the chemical analysis of soils collected using sediment coring methods is useful for distinguishing distinct areas within sites in the absence of excavation in the eastern Aleutian Islands of Alaska. If successful, such an approach would be useful in a number of different contexts, including those that characterize the study area; the region is remote, the field season is short (May through August), and sites are often difficult to locate. For example, in the Aleutians, while some sites have observable and visibly distinct features such as house and storage pits, many others are less apparent - obscured by post-occupational soil development, sometimes up to several meters worth, and other processes [14]. Exploratory test pits every few meters in such conditions are not always feasible or affordable and often yield very limited data.

The use of soil chemistry as an aid in archaeological investigations is well established, mostly as a prospecting technique to locate sites in areas with few or no visible archaeological features or materials. In the early 1900's, Arrhenius used elevated phosphate levels in soils to locate prehistoric villages in Sweden [1], while Woods [42] and Cavanagh et al.[5] have used soil samples to distinguish site boundaries. More recently, there have been attempts to isolate chemical enrichment of anthropogenic soils and identify chemical variation among different activity areas of a site [8,9,10,16,20,26,27,28,35,41]. Results indicate that several chemical elements occur in enriched or depleted amounts as a result of specific human activities (Table 1.1) and that the analysis of multiple elements can pinpoint site activity areas despite well-known issues with site formation processes [8,9,17,20,21,23,24,26,27,31,32,33,35].

Study Area

Climate

The soil samples used in this study were collected from two islands, Sanak and Amaknak, part of the Aleutian Island chain, Alaska (Figure 1.1). Cool summers and mild winters with high winds and rain characterize the climate of this region [11,31]. In the winter the Aleutian Low, a weather index of extremely low pressure that affects the eastern North Pacific, the Bering Sea and Sea of Okhotsk, dominates [30]. Summertime atmospheric temperatures are between 5° and 10° C while average winter temperatures are around 0° C. Annual precipitation varies from 530 mm to 2080 mm [30]. Vegetation is mostly tundra and shrubs or stunted trees.

Geology and sedimentology of Sanak and Amaknak Islands

The Aleutians are located on the edge of the North American tectonic plate and formed in response to the subduction of the Pacific plate [12]. The Aleutian Island arc originated in the Eocene [12,34,37]. Of volcanic origin and part of the "Ring of Fire", the oldest known exposed rocks (basaltic lavas) are circa 37.4 ± 0.6 m. y. [12]. Sanak Island is located at the eastern-most part of the Aleutian chain, 55 km south of False Pass in the North Pacific Ocean (Figure 1.1). The bedrock geology consists of a thick Mesozoic flysch sequence introduced by dioritic plutons that includes dark gray sandstones and black shales and siltstones [3]. The soils, however, are volcanic in origin and not weathered from bedrock. The soils associated with most archaeological sites on Sanak are Typic and Dystric Cryandepts; andisols that occur in areas of volcanism [36]. Both soil types are well-drained and loamy with fine volcanic ash occurring on nearly level to rolling landscapes. They have aluminum (Al) producing organic enriched horizons that fix phosphorous (P), are strongly acidic, very dark, and contain a high percentage of organic matter. Soil samples from natural and anthropogenic soils were tested for pH on Sanak Island, where the natural soil mean was 5.81 and the anthropogenic mean 5.63 (Huntley pers. comm.). Several sequences of surface horizons developed and were subsequently buried between periods of volcanic tephra falls. Tephras typically consist of black and reddish brown layers, and range from coarse to fine sandy/cindery ash (Figure 1.2a). The cool summers, mild winters, and heavy year-round precipitation sustains mostly grassy tundra with some crowberry tundra on exposed hills and grass-sedge marsh in low-lying wet areas.

Amaknak Island, a small island on the north side of Unalaska Island, is one of the Fox Islands, also in the eastern Aleutians (Figure 1.1). The soils associated with Amaknak are Typic Cryandepts, well-drained loamy soils with repeated deposits of volcanic ash and buried surface horizons (see description above)[36]. The cool summers, mild winters, and heavy year-round precipitation sustains dwarf willows and shrubs, crowberry tundra and grassy tundra. The vegetation type depends on elevation, wind exposure, and local animal species.

Cool wet climates, like that of the North Pacific, can reduce the rates of chemical weathering helping to retain even more mobile anthropogenic elements in the soils. A previous, small, study conducted in the Aleutian Islands revealed strong anthropogenic soil signatures and demonstrated that the area is an ideal location for chemical analysis of soils [10].

Anthropogenic and biological influences on soil chemistry

Amaknak Island and Sanak Island soils and soil chemistry have been influenced by human-related activities for millennia, although the most profound impacts probably occurred within the last several hundred years. For example, the introduction of arctic foxes (*Alopex lagopus*) for the purposes of fox farming to islands of the Aleutian archipelago not previously colonized by foxes is believed to have changed the soil chemistry and plant species composition [6,22]. Fox predation decreased the populations of ground nesting seabirds, subsequently decreasing the amount of guano and reducing nutrient transport from sea to land. The resulting nutrient-impoverished soils have three times less P and much lower marine-derived nitrogen than soils on islands that remain fox-free. Plant composition shifted from mainly grasses and sedges to shrub tundra.

This change in soil chemistry could clearly affect Sanak and Amaknak islands as arctic foxes were introduced in the early 1900's when fox farming in many areas of the

Aleutians began. Early Russian accounts describe red/cross foxes (*Vulpes vulpes*) inhabiting Sanak and Amaknak when the Russians first explored the island in 1771 [2,15,39] and recent archaeological excavations recovered pre-historic red fox remains (Betts, pers. comm.), so red foxes were indigenous to the islands. However, the numbers of foxes in the Aleutians were drastically reduced by the early 1800's due to trapping [2,15]. Foxes were subsequently imported to various islands including the Sanak and Unalaska archipelagos [2], considerably increasing fox populations.

Cattle were introduced to Sanak in the late 1880's although their numbers were small for the next 60 years [2]. In the mid 1900's the first commercial beef production started and by the 1960's there was a large herd of nearly 500 cattle [2]. A number of horses were brought to the island at this time. Many feral cattle and a small herd of horses still roam on Sanak and the grasses are cropped short, even during the summer months (Figure 1.3). There are presently no cattle on Amaknak Island. The introduction of cattle to some Aleutian islands had a dramatic effect on plant communities and possibly also on soil chemical composition. Non-native plant species on Sanak now include Kentucky blue-grass (*Poa pratensis*) and dandelion (*Taraxacum officinale*) both of which are abundant (Huntley pers. comm.; Figure 1.3b) and could have been introduced with cattle and horse feed. Studies elsewhere show that in grazed areas there is often higher P and N in the soils from manure although long-term grazing and overgrazing can eventually lower P levels in soils [18,25,38].

Materials and Methods

In order to understand what activities are represented by chemical signatures of soils from particular areas on a site, a database characterizing natural and anthropogenic soils needs to be constructed for the Alaska Peninsula and the Aleutian Islands through archaeological and ethnoarchaeological research. Analysis of the 953 soil samples from archaeological sites described in this project is the first step towards this end. Previous archaeological research in this area utilizing chemical characterization of soils is limited to a minor portion of a PhD dissertation [10]. Natural soils have been characterized by USGS and Department of Agriculture studies though not in any great detail for the geographic area under study [7,36].

Materials

Soil samples from Sanak and Amaknak Islands were collected from known archaeological contexts including middens, house floors and other features located through test pitting and area excavations. Additional samples were also collected from geological profiles to assess possible impacts of pedogenic processes on buried residues [28] and to determine the chemical composition of the natural soils. On Sanak Island samples were also collected by auger every meter along a transect crossing a site and from well-defined house pits. Samples were collected from Sister's and Elma Islands, islands of the Sanak archipelago that did not have introduced species such as foxes or cattle (although Elma may have had foxes for a short period of time). In total 779 samples from natural and archaeological soils were recovered from the Sanak archipelago, although most samples originated from 5 sites, three of which were sampled in one meter intervals along a transect (Figure 1.4). Supplemental soils from 19 sites were sampled opportunistically from particular site and soil profile locations. One hundred and seventy four samples were also collected from one site (UNL-050) on Amaknak Island.

Soil analysis

The well-established methodology of weak-acid element extraction of soils was used in this study [4,10,16,26,27,28,41]. All samples were dried in an oven at 120°C for 48 hours and were then sifted through a 2 mm geologic screen in order to remove large pieces of bone, charred wood, and basalt that may have been present in the sample, as well as any grains larger than sand. All removed materials were noted for each sample. 2.0 mg of soil were extracted at room temperature for two weeks in 20 ml of 1N HCl. The supernatent was then poured off, using filters to ensure isolation from soil particles. The extractions were analyzed by an Agilent 7500ce Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) for concentrations in parts per billion (ppb) of 11 elements [Aluminum (Al), Barium (Ba), Calcium (Ca), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Phosphorous (P), Strontium (Sr), Titanium (Ti), and Zinc (Zn)]. The instrument was calibrated with commercially available standards and the standards were analyzed as a check every 10 samples. Duplicates of 100 samples were analyzed to determine long-term reproducibility (analytical precision ≥ 10 ppb for all elements except Fe, whose analytical precision ≥ 100 ppb).

Chronology

Radiometric samples of charcoal from archaeological middens (n = 44) indicate site age ranges from 4,000 cal yrs BP to 150 cal yrs BP (Table 1.2). Radiocarbon dates are from Beta Analytic (BETA) and the Center for Atomic Mass Spectroscopy (CAMS) and were calibrated using Calib5.02 [29].

Data analysis and display

All statistical analyses were computed in 'R'. Box plots show medians (represented by a line or dot), quartiles (the central box) and extremes (the whiskers). As elemental concentrations ranged over several orders of magnitude, ppb concentrations were converted to base 10 logarithms for ease in analysis and visual display of data. Soils from known locations and features were grouped and analyzed in descriptive categories (Table 1.3) by discriminant function analysis (DFA) with sample group as the independent variable to the 11 elements. In order to evaluate the accuracy of soil sampling to distinguish archaeological site features and activity areas utilizing the coring method an initial set of 374 samples from test pits and open excavations only was analyzed using DFA and compared to the entire data set including samples taken from transects

Results

Chemical composition of natural and archaeological soils

Percentages of correctly classified samples changed little when comparing the initial 74 samples to the entire data set (Table 1.4). Concentrations of elements did not decrease as sites aged (Table 1.5) although the intensity of occupation in an area affects the concentrations of most elements (Table 1.6) with Sr and P positively correlated ($r = 0.82$). There was a weak negative correlation between Ca and Sr ($r = -0.41$) over the last 4,500 years.

"On site" versus "off site" (see Table 1.3 for description) samples produced typical/distinct signatures for anthropogenic and natural soils. Consistent with other studies, Fe and Ti were lower on site than in natural soils but there was no discernable difference in Al [8,9,10,16,20,26,27,28,35,42; Figure 1.2b]. Sr and P were elevated in the anthropogenic soils as compared to natural soils (Table 1.6). In comparison to Elma and Amaknak Islands, mean P was lower overall on Sanak Island (Figure 1.5). Mean concentrations of K were lower on islands with cattle and foxes (Figure 1.6).

Principal component analysis (PCA) was performed on all elemental variables. The first component (explaining 38% of the variance) identified differences in soils between the Sanak archipelago and Amaknak Island (Figure 1.7), with Ba, Mn, P, Sr and Zn as the most important in the component. The second factor (explaining 23% of the variance) identified differences between natural soils and anthropogenic soils with Al, Ba, K, Mg, Ti and Fe as the most important elements within the second component. When means from only natural soils were calculated, very little difference was found in most element concentrations between the two islands, with the exception of the slight differences found in P and K discussed above (Figures 1.5 and 1.6).

Despite the apparent distinction in soils from the different islands, the relative concentrations of elements in soils from human activity areas across sites was definitively discernable by DFA (Table 1.4). Distinctions between anthropogenic (on site) soils versus natural (off site) soils are clear with 97% of "off site" and "on site" samples being correctly classified. The anthropogenic soil samples that were incorrectly classified are technically within site boundaries but represent soil layers between or below site occupations defined here as the "non-cultural" group. The elements that contribute most to the distinction between natural and anthropogenic soils are Fe, Ti, P, Sr, and Zn (Figure 1.2b).

House pits were easily distinguished from other "on site" soils using DFA; of 373 house feature samples 309 were correctly identified (83% accuracy; Table 1.4). These samples were further subdivided to distinguish possible occupation levels, thin layers of middens within house pits and the berms which often form around house pit features. DFA can classify the berms of houses versus other types of soils within a site with 90% accuracy. Thin layers of middens within houses and possible occupation surfaces (referred to here as house middens and house floors) are also distinguished by DFA, though defining house floors is less certain (88% and 68% accuracy, respectively).

Using a total of 246 midden samples, DFA classified midden soils with 80% accuracy (Table 1.4). Some of the misclassified soil samples were marginal midden samples often taken from below areas with midden remains and classified as middens. When these samples were removed 90% of middens were correctly classified (Table 1.4). Midden samples have elevated concentrations of P, K, Zn, Sr, Ba and Ca and slightly elevated levels of Mn (Table 1.6). These results are consistent with previous published studies utilizing chemical characterization of soils containing shell, bone and other food refuse (Table 1.1).

Middens containing both bone and shell were correctly classified 85% of the time while middens containing bone were only 64% correctly classified and about half (53%) of the samples from shell middens were correctly identified (Table 1.4). When the middens were divided into two main island groups (Amaknak and Sanak) the accuracy was improved overall. On Sanak Island bone middens were described with 82% accuracy, bone and shell middens with 94% accuracy and shell middens with 66% accuracy (Table 1.4). On Amaknak, bone middens were described with 82% accuracy, bone and shell with 85% accuracy and shell with 62% accuracy (Table 1.4). These results suggest that it is possible to determine composition of middens with some confidence within a local geographic area.

Discussion

Previous research has linked changes in concentrations of particular chemical elements in soils to human activities (Table 1.1). The preliminary step in this study was to determine if these same patterns could be discerned in archaeological sites in different locations with different landscape histories using different methods of sample collection, and regardless of site age. In general, the results from this study are consistent with patterns discovered in other archaeological studies [8,9,16,17,19,20,26,27,28,35,41].

The high concentration of Sr in the archeological soils examined here is likely due to the incorporation of marine materials (Figure 1.2b). Hoffman [10] obtained similar results for Al concentrations in soils (no significant difference between natural and anthropogenic) analyzed from a prehistoric village site on Unimak Island, less than 60 km distance from Sanak Island. The natural soils in the Aleutians, Typic and Dystric Cryandepts, characteristically have high levels of Al^{3+} that form strong bonds with phosphates. The aluminum phosphate bonds likely reduce the amount of soluble Al^{3+} leaching from the soil.

The large decrease in P discovered by Croll et al. [6] and Maron et al. [22] in natural soils on islands with foxes was not evident in this study (Figure 1.5), though it must be noted that the laboratory methods and analyses for these two studies were different. In fact, it is unlikely that the decreased P on Sanak is related to fox presence/absence. Amaknak Island, which has an indigenous fox population, has the highest overall P values (mean = 7.057 ± 0.43 log ppb) in natural soils while Elma Island (mean = 6.875 ± 0.07 log ppb), not presently inhabited by foxes, has increased concentrations of P when compared to Sanak, which has foxes (mean = 6.602 ± 0.21 log ppb) (Figure 1.5a). The increase of natural soil P from Sanak to Elma was approximately 0.25 log ppb, less than three times as high as reported by Croll et al. [6] and Maron et al. [22]. Low P values from natural soils on Sanak Island are more likely due to the presence of cattle and the significant level of grazing that occurs across the entire island (Figure 1.5b).

There is some export of K in grazed systems [18] and so the reduced levels of K in Sanak soils compared to Elma (Figure 1.6a) could be due to heavy grazing. However, this does not explain why Amaknak has the relative lowest amounts of K of all the islands. As both Amaknak and Sanak also have foxes it is possible that their presence in some way affects the concentration of K in soils. These differences in natural soils do not appear to affect the relative changes in chemical signatures of soils on archaeological sites.

It appears that the differences determined by PCA between islands (Figure 1.7) are primarily in the archaeological soils. This is not surprising as the soils collected from Amaknak Island were from house floors and defined pit features within houses in an open excavation. These were all areas of intense and long-term human activity so element concentrations tended to be a little elevated in comparison to overall Sanak Island samples collected from a variety of site and feature types (see discussion below).

Chemical composition of site feature soils

Berms around house pit features are created during construction of semi-subterranean houses as dirt from the excavation was scattered around the outside of the pit [13]. Structural supports of driftwood or whalebone were then used as a roof frame and sod blocks were laid over the frames. If a house was abandoned and scavenged for structural supports, the berm would probably consist of the soils from sod used for roofing as well [13]. Therefore, house berm soils, although altered by excavation, should resemble natural soils more than anthropogenic ones. There are several elements (Ti, Fe, Ca, Sr, Mg and Mn) that contributed to the distinctions of house berm soils (Table 1.6). Mean Ti was higher than any group of anthropogenic site soils but not quite as concentrated as natural site soils (Table 1.6). Fe concentration in berms was higher than in possible occupation layers, middens and middens within a house, and was as high as that in natural soils (Table 1.6). House berm samples also had slightly elevated levels of Al when compared to samples within house pits (Table 1.6). These chemical signatures demonstrate that despite being "on site" berm soils do resemble local natural soils confirming archaeological theories about methods of semi-subterranean house construction. Relatively high concentrations of P prevented misclassification of house berm samples as natural soils although P concentrations were slightly lower than most other anthropogenic soils analyzed at these sites (Table 1.6). Three elements had surprisingly high or low concentrations in house berm samples. Mean levels of Mg were higher in berm samples than in any other group analyzed in this study. Increased levels of

Mg are associated with wood ash and bone (see Table 1.1) but only 5 house berm samples had any cultural materials associated with them. It is possible that refuse from house floors was deposited outside the house but lacked shellfish and therefore no trace of visible refuse remains. However, Ca and Mn concentrations (also associated with food refuse) in these soils were lower than any other on site soils (Table 1.6). All berm samples were collected from Sanak Island and Ca and Mn were lower in Sanak natural soils than other islands (Figure 1.6b). However, means of these two elements in berm samples were slightly lower than in natural soils from all islands combined, including Amaknak (Table 1.6).

A number of house floor samples contained food refuse and were often misidentified as "middens". The highest concentrations of mean group P and K of anthropogenic soils were found in soils from middens within a house and on possible house floors (Table 1.6). The only group of anthropogenic soils to contain higher concentrations of Sr than house middens and floors was the more encompassing group of "middens" (see Table 1.3 for group descriptions). Concentrations of Zn in soils from possible house floors were as high as any soil samples from midden locations (Table 1.6). Hoffman [10] found elevated levels of Zn on house floors and in hearths. High levels of Mg have been associated with fish and shell remains but house floors and middens did not reflect any elevated levels of Mg (Table 1.6). Ca was elevated on possible house floors and in house middens, even when compared to overall middens, and was as high as levels of Ca in shell middens (Table 1.6).

Chemical composition of archaeological midden soils

DFA was unable to distinguish with accuracy between the three groups of middens (as described in Table 1.3) when all islands were included in the analysis (Table 1.4). In a pilot study conducted on Amaknak Island, middens with more bone had roughly a 2:1 ratio of Ca:P while shell middens had negligable amounts of P (Misarti, unpub.); therefore, the expectation was to be able to distinguish between midden types. Analyses of middens from this study revealed a reduction in P concentration from midden samples with only bone relative to samples containing only shell, but did not have a clear distinction in Ca levels (Figure 1.8). Mg, although found to be related to bone and wood ash refuse in other studies, did not increase significantly in midden soils compared to other soil groups (Table 1.6).

Means of almost all chemical elements in midden soils differed between islands (Table 1.6). Differences in Ba, P and Zn between the three midden types on Amaknak were highly significant (single-factor ANOVA $p < 0.001$ for all three elements) but not significant (single-factor ANOVA $p > 0.1$ for all three elements) for middens on Sanak Island. These differences between islands may be due to several factors. It is possible that the differences reflect different species composition within the middens, different localized soil properties or different stages of decomposition of fauna. Only one site was considered from Amaknak Island while many sites, from various locations were considered from Sanak Island. The numerous factors involved in samples collected from Sanak may have mitigated the differences between midden types.

Chemical signatures of soils were different between sites that had middens and sites without any middens. On Sanak Island, Washwoman Creek (XFP-078), which contained no middens, was cored along a transect and soil samples were compared to all soil samples collected along a transect from two sites (XFP-057 and XFP-063), which did contain middens (Figure 1.4). DFA was able to distinguish all soils collected from Washwoman Creek when compared to soil samples collected from the two sites with middens with 94% accuracy. Only nine soil samples out of 137 from Washwoman Creek were misclassified as originating from the two sites that had midden remains. When compared individually all elements considered to be related to human activities (Ba, Ca, K, Mg, Mn, Sr and Zn) were statistically different (single-factor ANOVA, $p < 0.001$ in all cases) when Washwoman Creek samples were compared to samples from XFP-057 and XFP-063 together. In contrast, elements associated in high levels with natural soils had no statistical difference (Ti and Fe) or a weakly significant difference (Al, single-factor ANOVA, $p = 0.02$) when soil samples from sites with middens were compared to Washwoman Creek. This suggests that natural soils across Sanak Island do not differ and are not the reason why Washwoman Creek soils were significantly different from soils at other sites. Instead the differences could be due to the presence of shell middens altering soil chemistry significantly across an entire site (not just in areas where middens are located) when compared to a site with no middens. An alternative hypothesis is the differences are due to the human activities themselves that occurred at sites that have middens versus sites that do not.

Chemical composition of burial soils

Eighteen soil samples from beneath burials in a burial chamber from House 7, UNL-050 were analyzed as well. Ba, Mn and Sr were found in extremely high concentrations. P and Ca were found in concentrations equal to those found in "midden" groups. Concentrations of Fe were fairly low while Al levels resembled those of bone and shell middens and K concentrations were no different from many other groups (Table 1.6). This is consistent with studies showing that Ca fluxes from bone into the surrounding soils while Fe, Al and K flux into bone [19]. Increased concentrations of Mg are associated with bone remains as well, however, mean Mg was lower than all other groups identified in this study (Table 1.6). Sr concentrations in samples of soils from areas beneath human burials were similar to levels in bone and shell middens, an expected result given the prehistoric marine-based diet. Ba and Mn in these samples had the highest concentrations of any group in this analysis. The reasons for this are not entirely clear. Houses have high concentrations of Ba and Mn, though not as high as those found in the soils beneath the burials. The burial chamber was a side room and part of the original structure so perhaps these concentrations reflect a signature more associated with occupation levels within a house.

Evaluation of the utility of the core sampling technique

Taking cores on transects across sites or within and around house pits is nearly as accurate as taking samples from well-excavated, known areas in an archaeological site. There is currently little data on the length of occupation of most sites, but all sites sampled were villages with semi-subterranean house pits of varying size and form. Because the average concentrations of elements were similar across all sites, the data suggest that the length of occupation is not a dominant attribute effecting chemical signature (Table 1.5). Ethnographic studies of fish camps on the Yukon-Kuskokwim Delta, Alaska, confirm that fish camps only in use for one year had detectable anthropogenic signatures [16] so even temporary or short-term habitations can demonstrate a discernable change in chemical signatures.

Despite the wide range in radiocarbon-based ages of the archaeological sites used for this research, there does not appear to be any systematic change over time in the chemical composition of soils associated with human occupation. Studies of P during pedogenesis have shown that there are still significant amounts of acid-soluble P in soils even after 22,000 years [40]. In the 4,500 year period encompassed by this study, site age does not appear to be a factor in controlling concentration of any of the chemical elements assessed (Figure 1.9, Table 1.5). Despite the high amount of rainfall and acidity of soils in the Aleutians and Lower Alaska Peninsula, it appears that pedogenic processes over a few thousand years do not significantly alter the concentrations of elements contributed to the soils by human occupation.

There was a weak negative correlation between Ca and Sr (r = -0.41) throughout the 4,500 year period but there are a few time periods that are noticeably high in Ca and low in P and Sr (Figure 1.9). This could be due to time periods when shellfish were more important (increased Ca, decreased P) to diet than sea mammals (higher P and Sr and lower Ca). These time periods do appear to coincide with times when fewer sea mammals are found in archaeological middens around the northeast Pacific Rim (Misarti unpub.). Alternatively these differences could be due to seasonality of site occupation. If a site was occupied at a time of year when shellfish were the dominant diet source, the same trends in element concentrations would be expected.

The intensity of occupation does appear to be important in concentrating many elements (Table 1.6). For example, P was higher in all anthropogenic versus natural soils with highest concentrations found on house floors and all middens. Means for Zn, Sr, Ba, Ca and Mn yielded similar results. Fe, Ti and Al were lowest in areas of intense occupation (Table 1.6) while Sr and P were positively correlated (r = 0.82) in all the anthropogenic soils. UNL-50, despite being one of the oldest sites assessed, had some of the highest concentrations of all the elements associated with human activity (Table 1.5). This could be due to the fact that it was an intensely utilized site with many levels of human occupation and house floors.

Conclusions

Archaeologists have already demonstrated the utility of chemical characterization of archaeological soils but the data presented here highlight the utility of using small diameter auger coring to collect useful samples for site characterization. Weak-acid multi-element extraction of samples collected with augers in combination with analysis of samples obtained from identified features made it possible to distinguish house pits, living surfaces within houses, house berms, and midden areas without the need for large excavations. Analysis of samples collected with an auger generated information about sites, such as intensity of occupation (i.e. concentrations of many chemical elements were higher in the soils of the highly occupied sites), despite the fact that investigations for Sanak Island were in an exploratory survey stage at the time the samples were collected.

Preservation of archaeological sites themselves is perhaps one of the major incentives to core sites rather than excavate them. Archaeology, after all, is a destructive science and excavation permanently damages a site and the information one can derive from it. Likewise, once test pits have been excavated, those areas of a site have been permanently disrupted. The Alaska Peninsula and the Aleutian Islands are remote, and with the exception of a few populated areas sites are generally not in danger of being removed. It would therefore be helpful and less destructive to be able to determine site features and activity areas without excavation.

This research has also been important in generating data on which chemical elements are related to various features or activity areas in the eastern Aleutians and western Alaska Peninsula. For example, I found an association of Ba, Zn and Sr in addition to the well-known connection of P and Ca with midden soils. High concentrations of Mn, Mg, and K were associated with house floors while high concentrations of K and Mg and low concentrations of Mn were associated with house berms. Although the cause of these associations may be as yet unknown they will still help identify these features in future research.

The date a site was occupied does not appear to influence chemical signatures but the intensity of occupation is important. It has been determined that the age of a site does not affect the strength of the anthropogenic chemical signatures for at least the last 4,500 years. Many of the sterile layers between site occupations and at the base of sites have chemical signatures that approximate natural soils. This suggests that the elements associated with anthropogenic soils are not migrating far, despite the precipitation and well-drained quality of the site areas soils.

This data set can be used with some confidence to assist in the identification of: 1) site boundaries and features including middens in areas where these aspects of archaeological sites are not readily apparent , 2) ephemeral sites or older sites that may not have obvious surface features and 3) midden matrix (bone, shell or mixed). It is important that future research include both archaeological and experimental studies in order to better understand the processes involved in creating the specific signatures for each group discussed here.

Figures

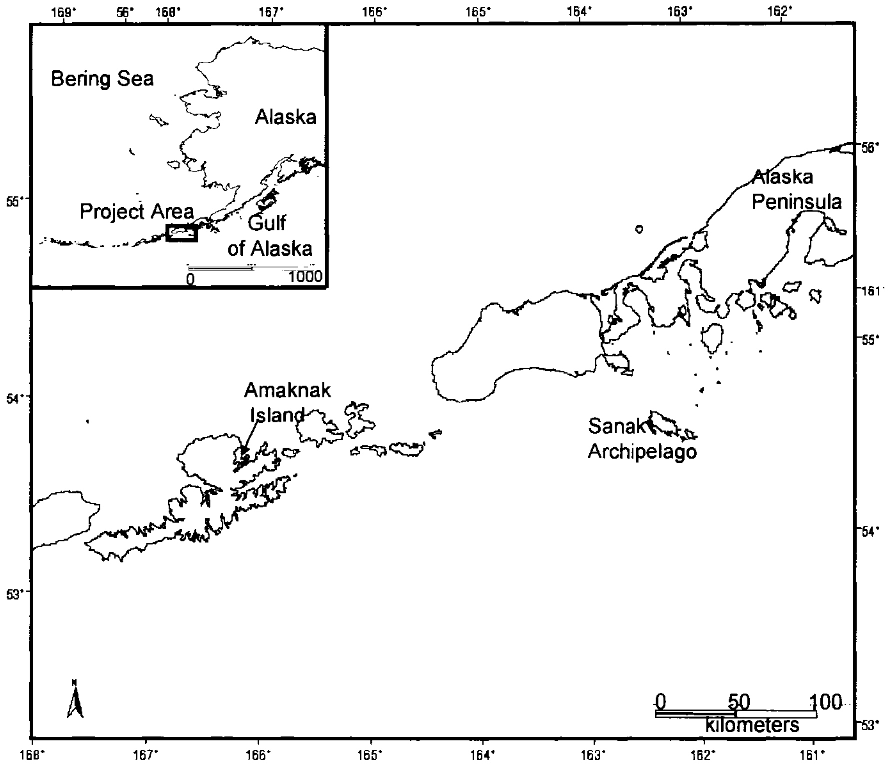

Figure 1.1. Map of project and island locations.

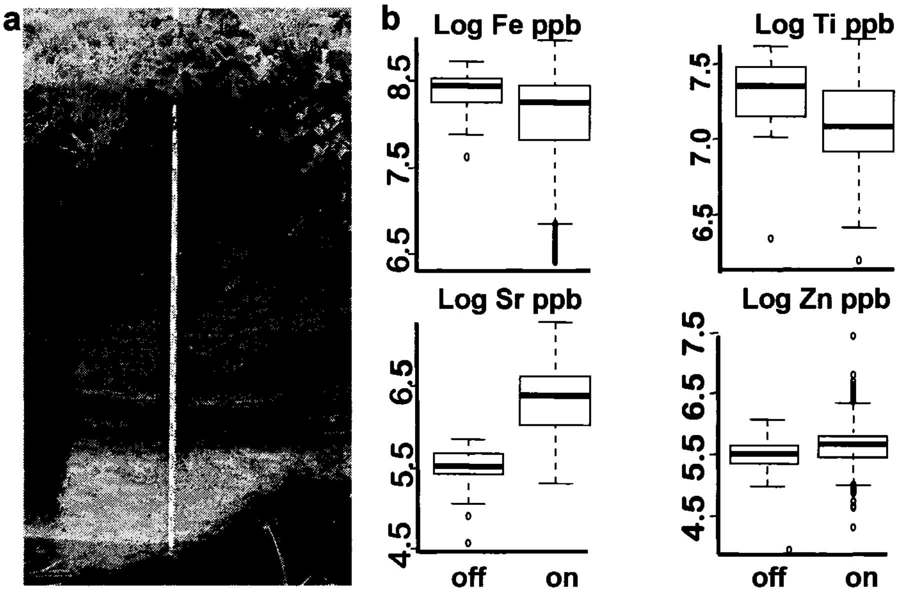

Figure 1.2. Natural soils of Sanak Island. a. Profile of natural soils on Sanak Island with bands of tephras. b. Concentrations of select elements in natural (off) versus anthropogenic (on) soils for all sites on all islands.

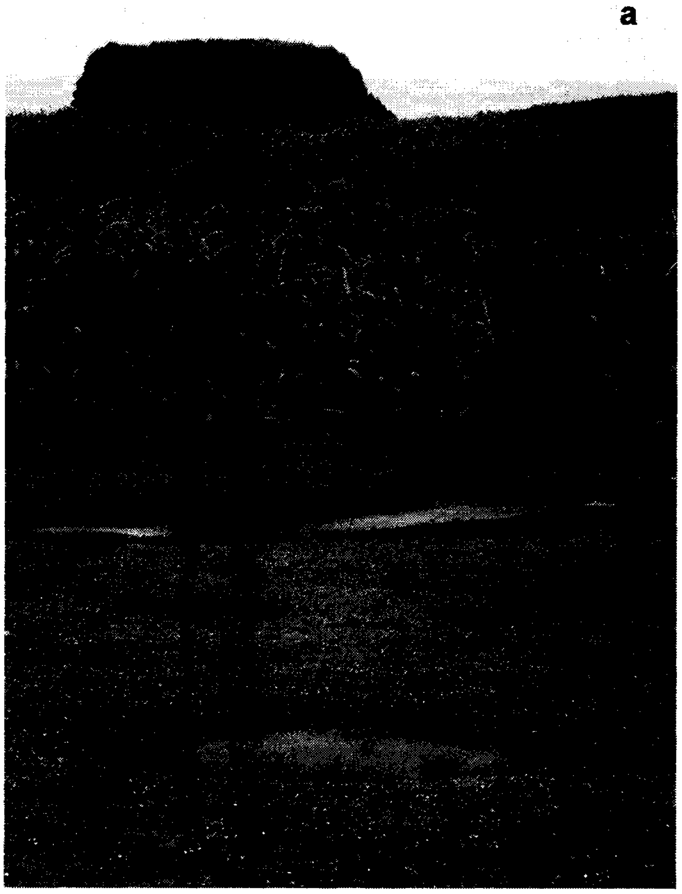

Figure 1.3. Comparison of vegetation types. a. Sister's Island (no foxes or cattle) and b. Sanak Island (both foxes and cattle).

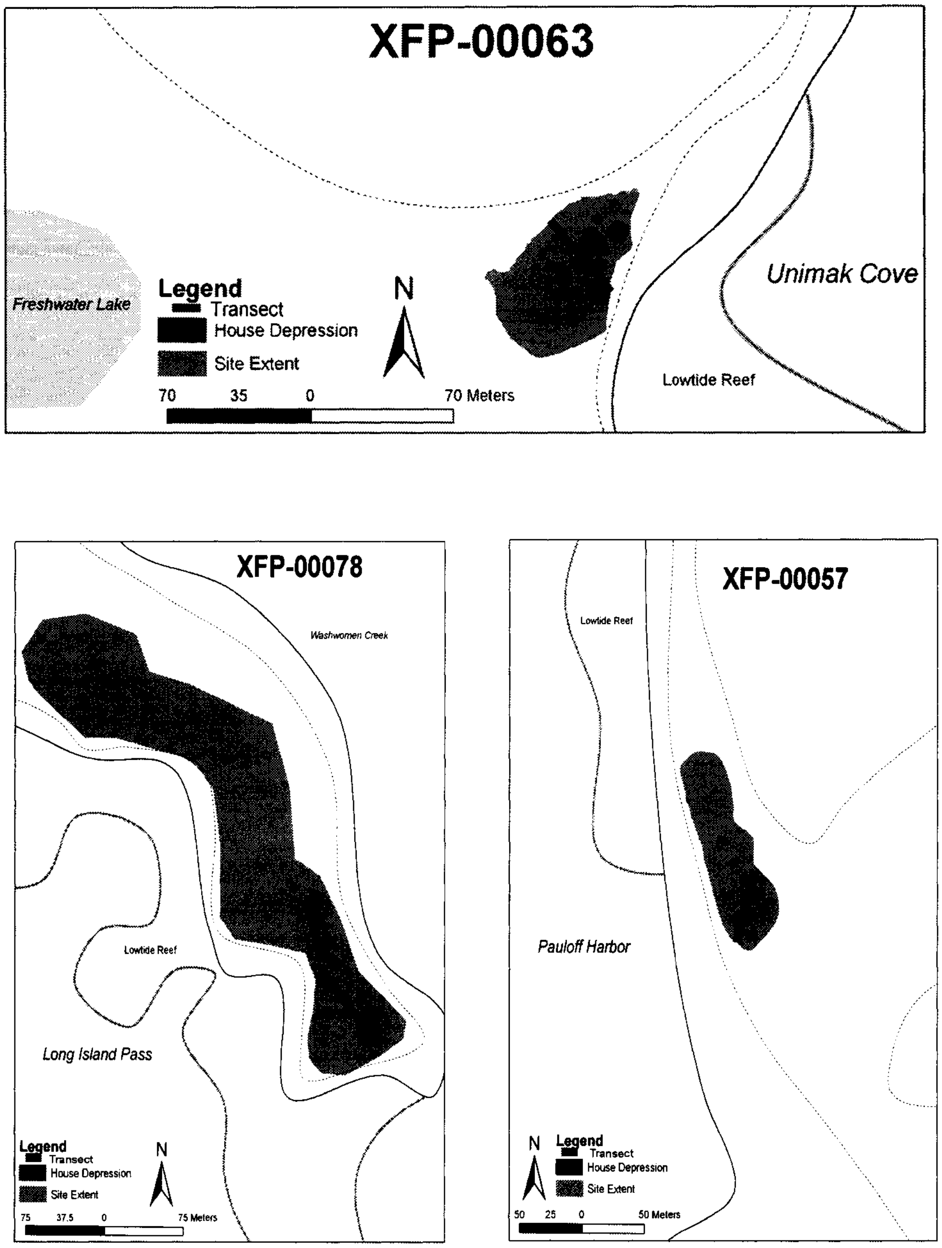

Figure 1.4. Map of archaeological sites with transect locations. Hillside (XFP-063)Washwoman Creek (XFP-078), and Pauloff Harbor (XFP-057).

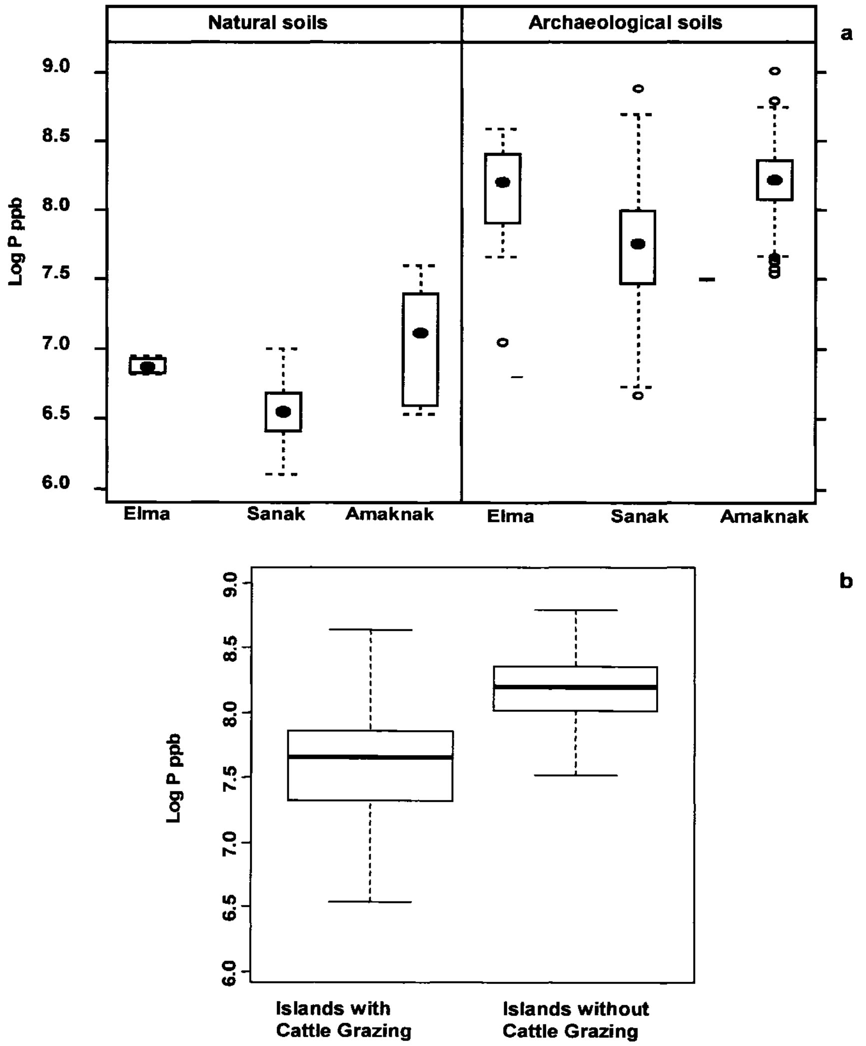

Figure 1.5: a. Comparison of P concentrations. a. Concentrations of P in natural and anthropogenic soils on islands with no introduced species (Elma), islands with cattle and foxes (Sanak) and islands with foxes only (Amaknak). b. Comparison of P concentrations in natural soils on islands with and without cattle.

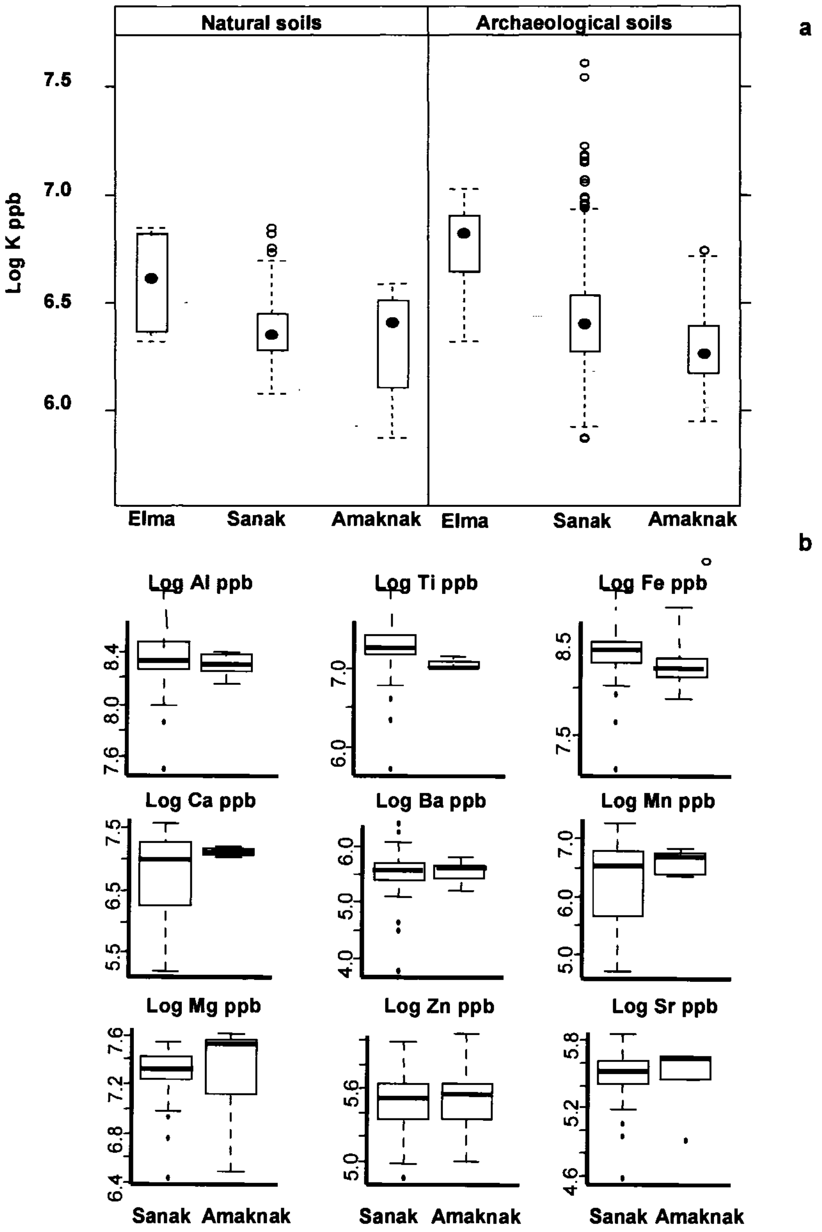

Figure 1.6: Concentrations of select elements in natural and anthropogenic soils. a. Concentrations of K in natural and anthropogenic soils on islands with no introduced species (Elma) versus islands with cattle and foxes (Sanak) versus islands with foxes only (Amaknak). b. Comparison of concentrations of select elements in natural soils from Sanak Islands and Amaknak.

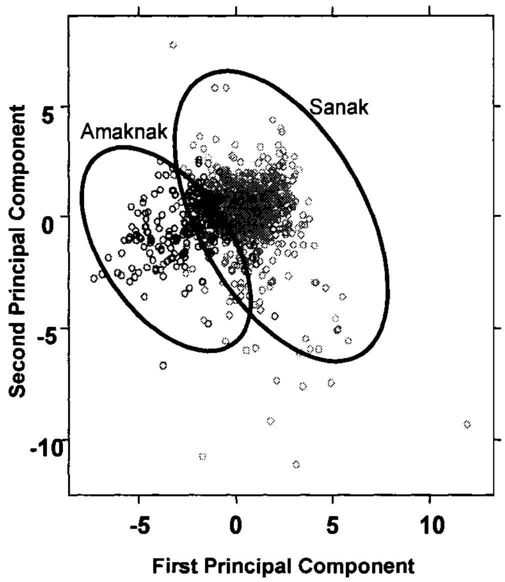

Figure 1.7: First principal component (PC1). PC1 represents differences in archaeological site soils between islands.

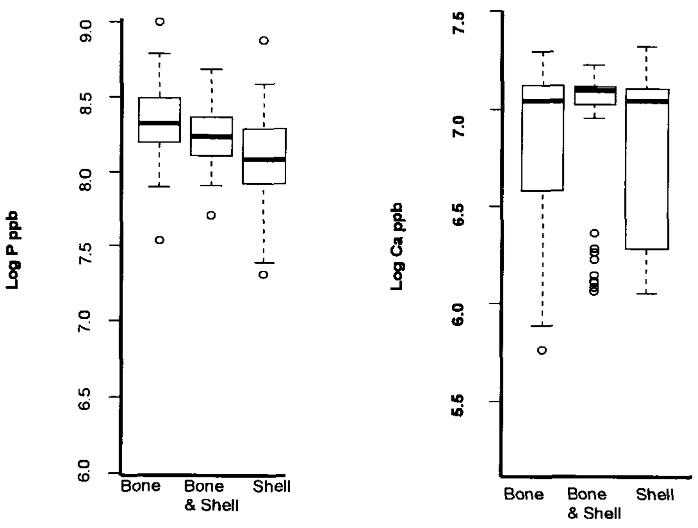

Figure 1.8: Concentrations of P and Ca in different midden types.

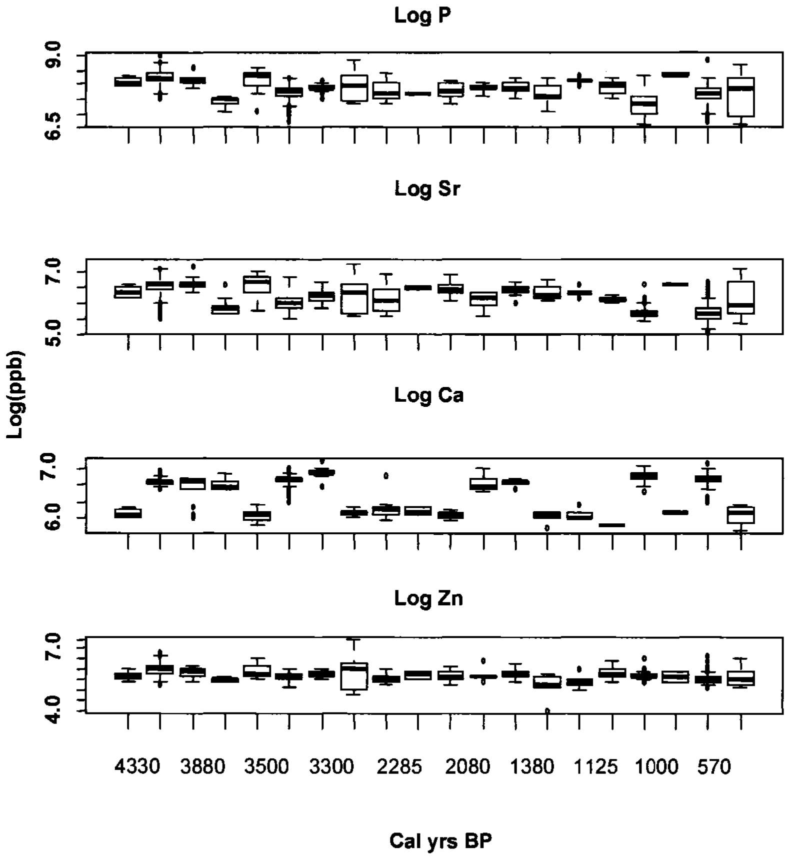

Figure 1.9: Concentrations of select elements in anthropogenic soils from the past 4,500 years.

Tables

Table 1.1: Chemical elements and related human activities

ELEMENT FOUND IN SOIL	HUMAN ACTIVITY CORRELATES
High levels of P and N	Bone, waste (includes organic matter), manure
High levels of N and Ca	Bone
High levels of Mg	Fish and bird bone, wood ash, heat treatment of rocks
High levels of K	Waste, wood ash
High levels of Ca and Sr	Prehistoric soil house floors
High levels of P and K	Hearths
High levels of Ca and P	Marine shell
High levels of P, Ca, K, and Mg	Fish processing areas, Kiln areas
Low levels of Fe, Al, and K	Burial soils
High levels of Mn, P, and Sr	Fish processing areas
High levels of Fe, Ti, and Al	Lithic production areas, natural soils

(compiled from 9,10,17,18,20,21,27,28,29,36,42)

Table 1.2: Locations and radiocarbon dates of sites discussed in text

Site	Location (UTM)		Material	Laboratory #	Date (BP)	Cal Date (BP)
	Easting	Northing				
XFP-31	653215.05	6036643.41	charcoal	CAMS 110652	2225±35	2200-2300
XFP-34	652883.69	6036267.33	charcoal	CAMS 127641	345±35	320-400
XFP-50	653947.23	6035579.29	charcoal	CAMS 110654	415±45	450-520
XFP-50			charcoal	CAMS 90203	1640±40	1515-1570
XFP-51	655559.15	6036034.46	charcoal	CAMS 110655	2475±35	2500-2750
XFP-53	655306.98	6035690.48	charcoal	CAMS 90204	1215±40	1070-1170
XFP-54	655279.29	6035339.58	charcoal	BETA 194363	3410±50	3630-3760
XFP-54			charcoal	CAMS 110656	3470±40	3790-3890
XFP-54			charcoal	BETA 194362	3750±40	4130-4400
XFP-56	655412.09	6035298.58	charcoal	CAMS 90213	920±40	950-1000
XFP-56			charcoal	CAMS 110659	1005±50	900-970
XFP-56			charcoal	CAMS 90206	1355±40	1260-1310
XFP-56			charcoal	CAMS 110657	1435±35	1300-1350
XFP-56			charcoal	CAMS 110658	1540±45	1460-1520
XFP-56			charcoal	CAMS 90208	1725±40	1645-1695
XFP-57	650967.37	6036650.59	charcoal	CAMS 90217	1030±40	920-980
XFP-57			charcoal	CAMS 90205	1120±40	970-1060
XFP-58	648472.75	6030438.15	charcoal	CAMS 110660	2070±35	2130-2160
XFP-63	649681.58	6029367.57	charcoal	CAMS 110664	2090±35	2040-2200
XFP-63			charcoal	CAMS 110665	3360±40	3600-3695
XFP-67	658317.25	6032675.34	charcoal	CAMS 110666	2480±35	2540-2600
XFP-67			charcoal	CAMS 110667	3050±30	3330-3385
XFP-78	644890.33	6031432.44	charcoal	CAMS 110669	535±35	520-560
XFP-96	647771.03	6030533.12	charcoal	CAMS 110675	1265±35	2090-2195
XFP-96			charcoal	CAMS 110676	2115±35	2360-2400
XFP-96			charcoal	CAMS 110677	2275±45	2200-2300
XFP-103	649468.69	6029522.27	charcoal	CAMS 110679	3550±35	3880-3950
XFP-103			charcoal	CAMS 110680	3590±35	3890-4000
XFP-110	649797.96	6029236.30	charcoal	CAMS 110686	385±40	440-500
XFP-111	649728.98	6036037.79	charcoal	CAMS 110688	265±35	285-320

Table 1.2 (cont)

Site	Location (UTM)		Material	Laboratory #	Date (BP)	Cal Date (BP)
XFP-111			charcoal	CAMS 110687	3870±35	4290-4350
XFP-113	644455.59	6031709.56	charcoal	CAMS 110689	2095±35	2090-2167
XFP-115	643824.81	6039815.21	charcoal	CAMS 110690	2115±35	2090-2200
XFP-121	642574.53	6040197.55	charcoal	CAMS 110693	315±35	356-430
XFP-121	642511.58	6040129.35	charcoal	CAMS 110692	355±35	320-380
XFP-124			charcoal	CAMS 110695	950±50	800-875
XFP-141	642449.89	6039882.26	charcoal	CAMS 127708	1620±35	1510-1555
XFP-141			charcoal	CAMS 127709	980±35	900-930
XFP-143	641471.65	6038718.16	charcoal	CAMS 110699	2115±30	2100-2190
XFP-143			charcoal	CAMS 110698	3505±40	3770-3855
XFP-146	641087.63	6038862.97	charcoal	CAMS 110702	365±35	430-490
XFP-147	641290.18	6038877.93	charcoal	CAMS 110703	1145±40	980-1085

Table 1.3: Sample categories and their descriptions.

Category	Description
Off	Samples from natural soils outside of site boundaries
On	All samples taken within site boundaries-includes non-cultural samples
Non-cultural	Samples that are on-site but contain sterile layers between and at base of site occupation layers
Midden	All midden samples-includes house midden samples
Bone Midden	Midden samples containing only bone remains
Bone and Shell Midden	Midden samples containing bone and shellfish remains
Shell Midden	Midden samples containing only shellfish remains
House	All samples within visible house pits-includes house berm, house floor and house midden samples
House Berm	Samples from visible house berms at edge of prehistoric house pits
House Floor	Samples from known house occupation layers within house pit boundaries
House Midden	Samples from thin midden layers within visible house pits
Burial Soils	Samples from under and around human burials

Table 1.4: Comparison of DFA outcomes from select soil samples from open excavations and test pits to samples taken from coring across archeological sites.

Group	**Subset**[a]	**Complete Data Base**	**Group**	**Subset**[a]	**Complete Data Base**
On	98.8%	97%	Off	100%	97%
House	60%	83%	Midden	90%	80%
House Berm		90%	House Floors		68%
House Midden		88%	Sites without Midden		94%
Bone and Shell Midden	87%	85%	Bone Midden	65%	64%
Shell Midden	46%	53%			
Sanak Bone Middens		82%	Amaknak Bone Middens		82%
Sanak Bone and Shell Middens		94%	Amaknak Bone and Shell Middens		85%
Sanak Shell Middens		66%	Amaknak Shell Middens		62%

[a] Subset is defined as samples collected from known archaeological contexts.

Table 1.5: Means of elements from all sites sampled [ln(ppb)].

Group	**Log Al**	**Log Ba**	**Log Ca**	**Log Fe**	**Log K**	**Log Mg**	**Log Mn**	**Log P**	**Log Sr**	**Log Ti**	**Log Zn**
UNL 50	8.21	5.94	7.10	7.59	6.28	7.22	6.93	8.18	6.45	6.93	5.96
XFP-031	8.31	5.50	6.24	8.41	6.48	7.38	5.79	7.67	6.04	7.29	5.53
XFP-034	8.35	5.45	6.33	8.47	6.49	7.38	5.78	7.61	5.99	7.34	5.31
XFP-053	8.35	5.40	6.13	8.58	6.41	7.31	5.43	8.12	6.32	7.23	5.43
XFP-057	8.36	5.74	7.26	8.37	6.42	7.34	6.78	7.26	5.64	7.27	5.71
XFP-063	8.23	5.79	7.14	8.24	6.44	7.33	6.65	7.69	5.99	7.11	5.67
XFP-067	8.27	5.74	7.39	8.43	6.50	7.41	6.62	7.65	6.07	7.10	5.76
XFP-078	8.26	5.69	7.19	8.39	6.30	7.18	6.53	7.57	5.67	7.17	5.58
XFP-096	8.21	4.89	6.07	8.45	6.38	7.43	5.59	7.67	6.36	7.12	5.16
XFP-101	8.33	5.65	6.15	8.57	6.73	7.46	5.64	7.81	6.26	7.26	5.53
XFP-103	8.21	5.92	6.88	8.31	6.44	7.40	6.30	8.11	6.61	7.05	5.80
XFP-110	7.97	5.59	6.08	8.24	6.67	7.39	5.86	8.37	6.86	6.78	5.93
XFP-111	8.18	5.53	6.14	8.47	6.74	7.25	5.79	8.06	6.35	7.18	5.64
XFP-112	7.93	5.14	5.86	8.14	6.53	7.33	5.28	7.37	5.99	6.81	5.15
XFP-113	8.16	4.94	6.33	8.44	6.49	7.29	5.67	7.72	6.51	7.28	5.55
XFP-115	8.31	5.49	6.06	8.61	6.57	7.51	5.60	7.70	6.37	7.30	5.90
XFP-116	8.19	5.24	6.27	8.47	6.63	7.43	5.79	8.04	6.61	7.28	5.76
XFP-121	8.27	6.00	6.17	8.58	6.84	7.43	5.86	8.35	6.79	7.25	6.07
XFP-124	8.37	5.98	6.15	8.65	6.46	7.27	5.46	8.35	6.56	7.36	5.67
XFP-141	8.32	5.71	6.21	8.50	6.88	7.35	5.85	8.39	6.76	7.37	5.95
XFP-142	8.38	5.56	6.16	8.52	6.78	7.38	5.81	7.70	6.05	7.29	5.82
XFP-143	8.10	5.38	5.93	8.37	6.83	7.45	5.57	8.36	6.77	6.81	5.83
XFP-146	8.18	5.19	6.10	8.39	6.87	7.24	5.30	7.32	5.71	7.22	5.38
XFP-147	8.11	5.18	5.77	8.47	7.12	7.37	5.37	7.88	6.09	6.91	5.85
XFP-050	8.22	5.82	7.04	8.21	6.81	7.25	6.64	7.87	6.07	7.05	5.72
XFP-051	8.29	6.07	6.17	8.12	6.69	7.79	5.83	7.94	6.21	7.22	5.82
XFP-054	8.09	5.65	6.93	8.05	6.25	7.19	6.51	7.01	5.71	6.93	5.46
XFP-056	8.12	5.77	7.06	8.12	6.32	7.20	6.52	7.90	6.41	7.02	5.76
XFP-058	8.04	5.68	6.11	8.06	6.49	7.46	5.43	7.80	6.44	7.01	5.67

Table 1.6: Group means of all elements [ln(ppb)].

Group	Log Al	Log Ba	Log Ca	Log Fe	Log K	Log Mg	Log Mn	Log P	Log Sr	Log Ti	Log Zn
On	8.25	5.64	6.95	8.19	6.40	7.29	6.48	7.73	6.02	7.13	5.66
Off	8.28	5.50	6.82	8.34	6.38	7.28	6.27	6.67	5.49	7.20	5.47
House	8.31	5.57	6.92	8.37	6.49	7.35	6.41	7.67	5.90	7.21	5.57
House Berm	8.30	5.68	6.72	8.35	6.42	7.39	6.23	7.61	5.98	7.23	5.59
House Floor	8.23	5.91	7.04	7.84	6.38	7.26	6.80	8.07	6.33	7.02	5.86
House Midden	8.18	5.86	7.08	7.60	6.31	7.24	6.81	8.05	6.34	6.92	5.84
Midden	8.27	5.85	6.95	7.84	6.37	7.29	6.65	8.10	6.48	6.96	5.84
Bone Midden	8.20	5.92	6.89	7.93	6.39	7.28	6.67	8.19	6.44	6.98	5.99
Bone and Shell Midden	8.14	5.82	7.00	7.73	6.32	7.26	6.70	8.13	6.56	6.93	5.87
Shell Midden	8.17	5.79	6.96	7.88	6.29	7.33	6.59	7.98	6.45	6.98	5.81
Non-cultural	8.31	5.63	7.01	8.35	6.40	7.29	6.44	7.46	5.75	7.22	5.56
Burial	8.17	6.05	7.10	8.21	6.38	7.17	6.91	8.19	6.53	6.97	6.01
Sanak Midden	8.16	5.73	6.80	8.24	6.49	7.38	6.30	7.91	6.42	7.05	5.77
Amaknak Midden	8.18	5.94	7.09	7.52	6.28	7.21	6.95	8.26	6.55	6.90	5.99

References

[1] O. Arrhenius, Die Phosphoatfräge, Zeitschrift für Pflanzenenernährung 10 (1929) 185-194.

[2] L.T. Black, The History and Ethnohistory of the Aleutians East Borough, 1st ed., The Limestone Press, Fairbanks, 1999.

[3] C.A. Burk, Geology of the Alaska Peninsula Island Arc and Continental Margin Part I, Geological Society of America, Princeton, NJ, 1965.

[4] J.H. Burton, A.W. Simon, Acid extraction as a simple and inexpensive method for compositional characterization of archaeological ceramics, American Antiquity 58 (1993) 45-59.

[5] W.G. Cavanagh, S. Hirst, C.D. Litton, Soil phosphate, site boundaries, and change point analysis, Journal of Field Archaeology 15 (1988) 67-83.

[6] D.A. Croll, J.L. Maron, J.A. Estes, E.M. Danner, G.V. Byrd, Introduced predators transform subarctic islands from grassland to tundra, Science 307 (2005) 1959-1961.

[7] L.P. Gough, R.C. Severson, H.T. Shacklette, Element concentrations in soils and other surficial materials of Alaska: An account of the concentrations of 43 chemical elements, ash, and pH in soil and other unconsolidated regolith samples, US Geological Survey, 1988.

[8] M.A. Griffith, A pedological investigation of an archaeological site in Ontario, Canada, I. An examination of the soils in and adjacent to a former village, Geoderma 24 (1980) 327-336.

[9] M.A. Griffith, A pedological investigation of an archaeological site in Ontario, Canada, II. Use of chemical data to discriminate features of the Benson Site, Geoderma 25 (1981) 27-34.

[10] B.W. Hoffman, The Organization of Complexity: A Study of Late Prehistoric Village Organization in the Eastern Aleutian Region, Department of Anthropology, University of Wisconsin, Madison, 2002, p. 437.

[11] G.L. Hunt, P.J. Stabeno, Oceanography and ecology of the Aleutian Archipelago: spatial and temporal variation, Fisheries Oceanography 14 (2005) 292-306.

[12] B.R. Jicha, D.W. Scholl, B.S. Singer, G.M. Yogodzinski, S.M. Kay, Revised age of Aleutian Island Arc formation implies high rate of magma production, Geology 34 (2006) 661-664.

[13] L.L. Johnson, E.G. Wilmerding, Bringing the house down: Modeling construction and deconstruction of Aleut semisubterranean houses, Archaeology in the Aleut Zone of Alaska: Some recent research 58 (2001) 127-150.

[14] J.W. Jordan, H. Maschner, Coastal paleogeography and human occupation of the western Alaska Peninsula, Geoarchaeology: An International Journal 15 (2000) 385-414.

[15] K.T. Khlebnikov, Notes on Russian America: Parts II-V: Kad'iak, Unalashka, Atkha, The Pribylovs, The Limestone Press, Fairbanks, 1994.

[16] K.J. Knudson, L. Frink, B.W. Hoffman, T.D. Price, Chemical characterization of Arctic soils: activity area analysis in contemporary Yup'ik fish camps using ICP-AES, Journal of Archaeological Science 31 (2004) 443-456.

[17] V.A. Konrad, R. Bonnichsen, V. Clay, Soil chemical identification of ten thousand years of prehistoric human activity areas at the Munsungun Lake Thoroughfare, Maine, Journal of Archaeological Science 10 (1983) 13-28.

[18] I. Kurz, C.D. O'Reilly, H. Tunney, Impact of cattle on soils properties and nutrient concentrations in overland flow from pasture in Ireland, Agriculture Ecosystems and Environment 113 (2006) 378-390.

[19] J.B. Lambert, S.V. Simpson, J.E. Buikstra, D.K. Charles, Analysis of soil associated with Woodland burials, in: J.B. Lambert (Ed.), Archaeological Chemistry III, American Chemical Society, Washington DC, 1984, pp. 97-113.

[20] J. Linderholm, E. Lundberg, Chemical characterization of various archaeological soil samples using main and trace elements determined by inductively coupled plasma-atomic emission spectrometry, Journal of Archaeological Science 21 (1994) 303-314.

[21] R.I. Macphail, J. Cruise, The soil micromorphologist as team player; a multianalytical approach to the study of European microstratigraphy, in: P. Goldberg, V.T. Holliday, C.R. Ferring (Eds.), Earth Sciences in Archaeology, Kluwer Academic/Plenum Publishers, New York, 2001, pp. 241-265.

[22] J.L. Maron, J.A. Estes, D.A. Croll, E.M. Danner, S.C. Elmendorf, S.L. Buckelew, An introduced predator alters Aleutian Island plant communities by thwarting nutrient subsidies, Ecological Monographs 76 (2006) 3-24.

[23] W. Matthews, Micromorphological characterization and interpretation of occupation deposits and microstratigraphic sequences at Abu Salabikh, Southern Iraq, in: T. Bahram, M. Bates, R.I. Macphail (Eds.), Archaeological Sediments and Soils, Archetype Books, London, 1995.

[24] W. Matthews, C.A.I. French, T. Lawrence, D.F. Cutler, M.K. Jones, Microstratigraphic traces of site formation processes and human activities, World Archaeology 29 (1997) 281-308.

[25] R.W. McDowell, J.J. Drewry, R.W. Muirhead, R.J. Paton, Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland, Australian Journal of Soil Research 41 (2003) 1521-1532.

[26] W.D. Middleton, T.D. Price, Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using inductively coupled plasma-atomic emission spectroscopy, Journal of Archaeological Science 23 (1996) 673-687.

[27] W.D. Middleton, Craft Specialization at Ejutla, Oaxaca, Mexico: An Archaeometric Study of the Organization of Household Craft Production, Department of Anthropology, University of Wisconsin-Madison, Madison, 1998.

[28] W.D. Middleton, Identifying chemical activity residues on prehistoric house floors: a methodology and rationale for multi-elemental characterization of a mild acid extract of anthropogenic sediments, Archaeometry 46 (2004) 47-65.

[29] P.J. Reimer, M.G.L. Baillie, E. Bard, A. Bayliss, J.W. Beck, C.J.H. Bertrand, P.G. Blackwell, C.E. Buck, G.S. Burr, K.B. Cutler, P.E. Damon, R.L. Edwards, R.G. Fairbanks, M. Friedrich, T.P. Guilderson, A.G. Hogg, K.A. Hughen, B. Kromer, G. McCormac, S. Manning, C.B. Ramsey, R.W. Reimer, S. Remmele, J.R. Southon, M. Stuiver, S. Talamo, F.W. Taylor, J. van der Plicht, C.E. Weyhenmeyer, IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP, Radiocarbon 46 (2004) 1029-1058.

[30] S.N. Rodionov, J.E. Overland, N.A. Bond, Spatial and temporal variability of the Aleutian climate, Fisheries Oceanography 14 (2005) 3-21.

[31] M.B. Schiffer, Archaeological context and systemic context, American Antiquity 37 (1972) 156-165.

[32] M.B. Schiffer, Toward the identification of formation processes, American Antiquity 48 (1983) 675-706.

[33] M.B. Schiffer, Formation Processes of the Archaeological Record, University of New Mexico Press, Albuquerque, NM, 1987.

[34] D.W. Scholl, T.L. Vallier, A.J. Stevenson, H.F. Ryan, Contrasting processes controlling basin formation in Cenozoic island arcs, Tonga and Aleutian Ridges, American Association of Petroleum Geologists Bulletin 70 (1986) 646-646.

[35] J. Schuldenrain, Geochemistry, phosphate fractionation, and the detection of activity areas at prehistoric North American sites, Pedological Perspectives in Archaeological Research, Soil Science Society of America, Madison, WI, 1995.

[36] Soil Conservation Service, Exploratory Soil Survey of Alaska, United States Department of Agriculture, 1979.

[37] D.J. Shillington, H.J.A. Van Avendonk, W.S. Holbrook, P.B. Kelemen, M.J. Hornbach, Composition and structure of the central Aleutian Island Arc from arc-parallel wide-angle seismic data, Geochemistry Geophysics Geosystems 5 (2004).

[38] G.C. Sigua, M.J. Williams, S.W. Coleman, R. Starks, Nitrogen and phosphorus status of soils and trophic state of lakes associated with forage-based beef cattle operations in Florida, Journal of Environmental Quality 35 (2006) 240-252.

[39] I. Veniaminov, Notes on the Islands of the Unalashka District, The Limestone Press, Ontario Canada, 1984.

[40] T.W. Walker, J.K. Syers, The fate of phosphorus during pedogenesis, Geoderma 15 (1979) 1-19.

[41] E.C. Wells, Investigating activity patterns in Pre-Hispanic plazas: weak acid extraction ICP-AES analysis of anthrosols at Classic Period El Coyote, northwestern Honduras, Archaeometry 46 (2004) 67-84.

[42] W.I. Woods, Soil chemical investigation in Illinois archaeology: two example studies in archaeological chemistry, in: J.B. Lambert (Ed.), Archaeological Chemistry III, American Chemical Society, Washington DC, 1984, pp. 67-78.

Chapter 2 Inferring past changes in salmon abundance over the Holocene from stable isotope records ($\delta^{15}N$ and $\delta^{13}C$) of coastal Alaskan lakes, western Gulf of Alaska.[1]

Abstract

Sediment cores were collected in 2004 from two lakes on Sanak Island, Alaska to determine long-term changes in numbers of returning salmon and paleoclimate information from nitrogen and carbon stable isotope analysis, carbon to nitrogen ratios and other proxies. One lake is within a sockeye salmon system, and the other is without salmon. These cores span the entire post-glacial period, from ~16,000 cal yr BP. Volcanic activity in the area, as well as climate change affected both $\delta^{15}N$ and $\delta^{13}C$ in both lakes. Data suggest that after ~ 4,000 cal yrs BP the sedimentary $\delta^{15}N$ in anadromous Deep Lake becomes significantly enriched relative to the control, suggesting input of marine-derived nutrients (MDN) from spawning salmon. MDN and inferred salmon abundance is reduced around 1,000 cal yrs BP, and at highest levels during the Little Ice Age (700–100 cal yrs BP). The MDN fluctuations within Deep Lake sediments generally follow MDN from other lakes throughout Alaska. Despite high flushing rates and small salmon escapement numbers this research suggests the use of changes in $\delta^{15}N$

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[1] Misarti N, Finney B, Maschner H. 2007. Inferring past changes in salmon abundance over the Holocene from stable isotope records ($\delta^{15}N$ and $\delta^{13}C$) of coastal Alaskan lakes, western Gulf of Alaska. Prepared for Limnology and Oceanography.

is a valid method to track salmon productivity through time if there is a viable control lake with which to compare.

Introduction

Fisheries research in the northeastern Pacific has become extremely important, specifically research on salmon due to their economic, socio-cultural and ecological importance to the northern Pacific-rim region. Salmon stocks respond to anthropogenic stresses such as commercial fishing as well as to climate change. For example, fluctuations in salmon stocks coinciding with climate regimes such as the Pacific Decadal Oscillation (PDO) have been well documented by researchers over the past 15 years (Ware and Thompson 1991, 2005; Beamish and Bouillon 1993; Hare and Francis 1995; Mantua et al. 1997; Beamish et al. 1999; Hare et al. 1999; Hare and Mantua 2000; Mantua and Hare 2002; Mueter and Norcross 2002; Bond et al. 2003). Although these data have helped understand natural influences on salmon, they are of relatively short duration or incomplete for many stocks. Paleolimnologic studies of sockeye salmon (*Oncorhynchus nerka*) nursery lakes can trace past sockeye abundances and add to our comprehension of how climatic change impacts salmon.

Sediment cores were collected in 2004 from two lakes on Sanak Island, Alaska (Figure 2.1) as part of a larger biocomplexity project aimed at understanding the climatic, environmental, and human history of the island. Deep Lake (54° 25.005' North; 162° 40.725' East, informal name) is within a watershed with one of the larger historical sockeye salmon runs on the island (ADF&G 2006), and was cored with the goal of reconstructing past salmon abundances within its catchment area. Swan Lake (54° 26.996' North; 162° 43.619 East, informal name) was cored for comparison, as it is similar to Deep Lake in size and depth but not part of a salmon spawning system. The objectives of this research were 1) to reconstruct salmon/marine derived nutrient (MDN) fluctuations, 2) to attempt to develop data on climate change for the island from proxies in the cores, and 3) to correlate any such changes with paleoclimatic records and large scale environmental disruptions such as large inputs of volcanic ash. Stable carbon and nitrogen isotope ($\delta^{15}N$ and $\delta^{13}C$) data and carbon to nitrogen ratios (C:N), loss on ignition (LOI), and magnetic susceptibility were used as environmental proxies and radiocarbon dating was used to provide chronological control.

Sources of $\delta^{15}N$ and $\delta^{13}C$ variability in lakes

The $\delta^{15}N$ signature in lake sediments is a function of nutrient source and subsequent fractionations associated with diagenetic alteration and nitrogen processing. Much of the nitrogen in lake watersheds that is ultimately delivered to lakes is derived from atmospheric N ($\delta^{15}N$ of 0.0‰) (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005). This nitrogen is recycled in soils and supplied by rivers, runoff and groundwater as dissolved inorganic nitrogen (DIN; mainly nitrate and ammonium), and dissolved organic nitrogen (DON) from plants and soils. Watershed nitrogen may also be supplied to sediments in particulate form from plant and/or soil material. Ammonia has a $\delta^{15}N$ range of -10 to 0‰, while nitrates range from -4 to 4‰ (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005). Terrestrial plants range from -5 to 0.5-1.0‰ and aquatic plants and algae range up to 8.0‰ (Meyers and

Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005). Interpretations of $\delta^{15}N$ sedimentary records can be difficult due to the complicated nature of the nitrogen cycle, but $\delta^{15}N$ may be useful in identifying changes over time of nitrogen sources and availability within a lake.

In sockeye nursery lakes, $\delta^{15}N$ in sediment cores can also be utilized as a technique to determine long-term sockeye abundances (Finney 1998; Finney et al. 2000, 2002). Adult sockeye obtain ~99% of their body weight in the ocean and then transport those marine-derived nutrients (MDN) into freshwater when they return to their spawning grounds. Their carcasses can increase the $\delta^{15}N$ of the lake nutrient pool, which is reflected in phytoplankton and can subsequently be used to trace changes in the numbers of returning sockeye over time (Finney 1998). For the most part, paleolimnology has had success in tracing salmon fluctuations in lakes with large escapements and low flushing rates (Finney et al. 2000, 2002; Gregory-Eaves et al. 2003). In areas with shallower coastal lakes and high precipitation, such as on Sanak Island, AK, nutrient retention from MDN has been found to be much lower than in lakes with higher escapements and low flushing rates (Holtham et al. 2004). This low nutrient retention may affect the magnitude of $\delta^{15}N$ signatures, thus making it more difficult to interpret $\delta^{15}N$ trends in terms of salmon abundance.

$\delta^{13}C$ in sediments can be used as a tracer for past changes in terrestrial and aquatic carbon cycles as the proportions of different terrestrial and lacustrine organic matter, in conjunction with the $\delta^{13}C$ of DIC (dissolved inorganic carbon), largely determine the sediment $\delta^{13}C$ (Meyers and Teranes 2001). For example, phytoplankton range from -47 to -26‰ (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005). C_3 plants and macrophytes can, however, overlap with the ranges for phytoplankton (from -32 to -22‰ and -50 to -11‰, respectively) (Meyers and Ishiwatari 1993; Meyers and Teranes 2001). C:N can also be used to distinguish terrestrial from aquatic plant input into sediment organic matter (Leng et al. 2005). Organic material from phytoplankton generally has C:N below 10, while organic material from terrestrial plants has higher C:N (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005). If the organic material is predominantly from terrestrial vegetation, then $\delta^{13}C$ in sediments can be used to provide information on changing vegetation over time (Meyers and Teranes 2001). The $\delta^{13}C$ in sediments can be used to reconstruct past productivity rates if the organic matter in sediments is predominantly of aquatic origin, as higher $\delta^{13}C$ in phytoplankton corresponds to increased rates of primary productivity (Meyers and Teranes 2001). The positive relationship between productivity and $\delta^{13}C$ is due to the fact that organisms discriminate against heavier isotopes, but this occurs to a lesser extent when carbon and nitrogen are limiting. Larger phytoplankton blooms and faster cell growth rates (e.g. a highly productive system) can result in less fractionation during uptake and a draw-down of DIC concentrations, both factors leading to the $\delta^{13}C$ of phytoplankton increasing in comparison to times when there are fewer and slower growing phytoplankton (Laws et al. 1995).

Site Description

The Aleutian Islands are located on the edge of the North American tectonic plate and formed in response to the subduction of the Pacific plate where it converges with the North American plate. Cool summers and mild winters with high winds and rain are characteristic of the climate in the Aleutians (Hunt and Stabeno 2005; Rodionov et al. 2005). The area is dominated in the winter by the Aleutian Low, a weather system of extremely low average pressure that affects the eastern North Pacific, the Bering Sea and Sea of Okhotsk (Rodionov et al. 2005). Summertime atmospheric temperatures in the Aleutians are between 5° C and 10° C while average winter temperatures are around 0° C. Annual precipitation varies from 530 mm to 2080 mm (Rodionov et al. 2005). The U.S. Weather Bureau stations nearest to Sanak Island are located in Cold Bay on the Alaska Peninsula and Unimak Island and record averages of 960 mm and 1290 mm in annual precipitation, respectively (Black 1977).

Sanak Island, the location of both lakes in this study, is located at the eastern most part of the Aleutian chain, 55 km south of False Pass in the North Pacific (Figure 2.1). The cool summers, mild winters, and heavy year-round precipitation sustains mostly grassy tundra with some crowberry tundra on exposed hills and grass-sedge marsh in low-lying wet areas. The island is largely at low elevation, with the exception of Sanak Peak, and consists of small hills and low-lying areas with many small, shallow ponds and streams.

There is a century-long, though incomplete, record of salmon counts by species and bay/stream on Sanak Island (ADF&G 2006). The data suggest that in the early

1900's numbers of salmon returning to Sanak Island to spawn were higher than in recent times (Table 2.1). However, the numbers reflect total salmon counts for the entire island prior to 1927, and are specific for the catchment associated with Deep Lake from 1963 to the present. Prior to the 1900's there are only anecdotal accounts of the numbers of fish returning to the Sanak area and archaeological evidence of salmon remains from many sites around the island. In 1771 Solov'ev, a Russian fur merchant, explored Sanak Island by foot and boat, and noted that there were numerous lake-fed salmon streams but fish counts were fairly low. Similarly a report from the Russian-American Company from 1824 suggests that salmon numbers were much lower than nearby on the Alaska Peninsula (Black 1999). However, Veniaminov, a Russian cleric who lived in the Aleutians for 10 years from 1824-1834, described the southern portion of Sanak as having "relatively plentiful" numbers of returning salmon (Veniaminov 1984).

Deep Lake is small and shallow with a surface area of ~0.33 km^2, and a maximum depth of ~0.7 m. The lake most likely has a high flushing rate based on rainfall, watershed area and discharge observations. A stream runs from Salmon Bay through a chain of lakes including Deep Lake. Deep Lake was selected as the most likely to hold a record of past changes in MDN as it is the deepest lake in the chain and has an ancient fish weir at the head of its outlet stream. The lake and stream system support pink (*Oncorhynchus gorbuscha*), sockeye and in recent years an occasional run of coho salmon (*Oncorhynchus kisutch*), but abundance of all species is fairly low (Table 2.1). Swan Lake is located at the base of Sanak Peak and has a surface area of ~ 0.25 km^2. It is also a shallow lake (1.2 m deep) with no apparent connection to a salmon stream system.

It is entirely possible that both lakes have been affected by the introduction of ungulates, the subsequent introduction of two new plant species, Kentucky blue-grass (*Poa pratensis*) and dandelion (*Taraxacum officinale*) (Huntly pers. comm.), and the possible change in soil chemistry noted between islands in the Sanak archipelago with cattle and those without (Misarti unpub.). In the mid 1900's the first commercial beef production started on Sanak and in the 1960's a cattle ranch had a large herd of nearly 500 cattle (Black 1999). A number of horses were brought to the island at this time. Many cattle and a small herd of horses now roam wild on Sanak Island and grasses are cropped short, even during the summer months, by these free ranging ungulates.

Methods

Sediment cores were collected in the summer of 2004 using a Livingston piston corer from an inflatable catamaran raft. The cores were extruded in the field into rigid plastic tubes and wrapped in plastic wrap in order to preserve stratigraphic integrity. The cores span the entire post-glacial period, and were collected from a sockeye nursery lake (Deep Lake = 426 cm long) and a control lake (Swan Lake = 610 cm long). Both lakes had firm core tops allowing undisturbed recovery of the sediment water interface and upper sediments using the Livingston corer. Cores were kept cool in the field and quickly shipped to the University of Alaska Fairbanks where they were stored at ~4° C. The cores were split in two with one half reserved for archival purposes. Sediments were described in terms of general lithology, and sampled continuously at 1 cm intervals along the length of each core. Each sediment sample was measured for wet and dry bulk density, water content, LOI at 500° C and 850° C and magnetic susceptibility. Analysis of samples for %C, %N, $\delta^{15}N$ and $\delta^{13}C$ was completed in the Alaska Stable Isotope Facility, University of Alaska Fairbanks. Stable isotope ratios are expressed in the standard notation:

$$\delta X (‰) = [(R_{sample}/R_{standard}) - 1] \times 1000$$

where X is ^{13}C or ^{15}N and R_{sample} is $^{13}C/^{12}C$ or $^{15}N/^{14}N$, respectively. $\delta^{13}C$ and $\delta^{15}N$ are expressed relative to Vienna Pee Dee Belemnite (VPDB) and atmospheric N_2 (air), respectively. Samples were analyzed on a Finnigan Delta^{plus}XP IRMS and analytical precision, established by analysis of multiple (n = 8 per each 50 samples run) peptone standards throughout the run, was approximately ± 0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$. Organic N and C concentrations were calculated as a percentage by weight while C to N molar ratios (C:N) were calculated by: C:N concentration x $C_{atomic\ weight}$ / $N_{atomic\ weight}$ (or 14/12).

Flushing rates were calculated by estimating the volume of the lake (mean depth*lake size) and the volume of water passing through each year (annual precipitation*watershed size). Total volume of water passing through the system was calculated as: [(volume/year)/volume of the lake].

An age model was constructed using 17 calibrated atomic mass spectrometry (AMS) radiocarbon dates from terrestrial macrofossils found in cores from three lakes on Sanak. Cores were correlated by matching 13 tephras based on their visual characteristics and stratigraphic placement (Figure 2.2). Tephra layers were initially identified both visually and by magnetic susceptibility (Figure 2.3). Radiocarbon dates for all samples were derived from terrestrial macrofossils found in the lake cores and were analyzed at the Center for Atomic Mass Spectroscopy (CAMS), Lawrence Livermore National Laboratory. The dates were calibrated using Calib 5.02 from Queen's University Belfast's ^{14}Chrono Centre (Reimer et al. 2004). Age-depth relationships and sediment accumulation rates were determined using third-order polynomial fits ($r^2 = 0.96$) with AMS and interpolated tephra dates. Tephra dates were interpolated using the closest top and bottom bracketing AMS dates among three different cores (Figure 2.3). I adjusted depths in my age models by removing the thickness of four large, single-deposit ash accumulations in order to better estimate accumulation rates of non-tephra events, assuming the deposition of these relatively thick deposits was relatively instantaneous.

Results

Despite their relatively small sizes and shallow depths, these two lakes yielded a sediment record that appears to be continuous, and extends back to the deglaciation of Sanak Island. According to the age/depth model developed using the 17 calibrated radiocarbon ages from three lakes on Sanak Island, sediment in both Deep and Swan Lakes has been accumulating since ~16,000 calibrated years before present (cal yrs BP) (Figure 2.3). Flushing rates in Deep and Swan appear to be close to 2 times the volume of the lakes per year.

The basal sediments in both Swan and Deep Lakes are glacial in origin, and consist of light brownish/gray laminated glacial mud and sand with several tephras. The average sedimentation rate for Swan Lake is 0.034 cm/yr, with a range 0.016 -0.1 cm/yr.

There is a fairly steady rate of sedimentation of ~0.028 cm/yr until about 6,000 cal yrs BP, then a much faster rate of 0.05-0.1 cm/yr until about 3,500 cal yrs BP. The younger sediments from 3,500 cal yrs BP to present accumulate much slower (0.016-0.025 cm/yr). Average sedimentation rates for Deep Lake are ~0.019 cm/yr with a range of 0.013-0.066 cm/yr. Sedimentation rates are steadily ~0.04 cm/yr from deglaciation until about 10,650 cal yrs BP when they decrease to ~0.02 cm/yr. There is an increase in sedimentation rates at ~6,500 cal yrs BP to ~0.025 cm/yr and then a large decrease from ~4,000 cal yrs BP to the present with sedimentation rates of ~0.016 cm/yr.

The relatively slow rate of sedimentation of both Deep and Swan Lakes are punctuated with large accumulations of tephras from volcanic activity (Figures 2.2 and 2.3). Throughout this time period there are several large volcanic events recorded in both lakes including one at ~3620 cal yrs BP and one at ~4730 cal yrs BP, with average ash falls of 10 cm in thickness in each lake core (Figure 2.2). Two larger volcanic events occurred earlier in the record, one at ~7230 cal yrs BP, with an average of 40 cm of ash in each core and one at ~10,765 cal yrs BP, approximately 35 cm thick in each core (Figure 2.2). There are numerous other smaller volcanic events recorded by thin bands of tephras across the lake cores (≤ 1.0 cm). None of the tephras have yet been thoroughly studied and therefore cannot be correlated to previously investigated volcanic events in the area.

Sediments in both lakes are light to dark olive brown organic mud, with occasional terrestrial and aquatic micro- and macrofossils (Munsell colors 2.5Y, 10YR, and 5YR family). Both lakes are heavily laminated, with numerous light gray to black fine to very coarse volcanic tephras. The organic matter content in both Deep and Swan lakes (Figure 2.3) as estimated by LOI ranges from 1-22%. In general, organic matter content is moderately high above the organic-poor glacial lacustrine muds at the bottom of each record, except for intervals dominated by volcanic tephras. Deep Lake magnetic susceptibility normalized to sample mass (SI units/g) ranges from 2-124 while Swan's is from 3-189. The higher SI units/g reflect the volcanic ashes. Figure 2.3 shows an inverse relationship between LOI and SI units/g and these measurements together help identify the many tephras in each core.

Carbon and nitrogen in Deep Lake sediments (Table 2.3) range from 0.38% to 7.48% and 0.01% to 0.79%, respectively. C:N ratios vary between 7.77 and 18.65 with a mean of 12.29 ±1.9 (Table 2.3, Figure 2.4). There are periods of notably lower C:N between 3,000 to 4,000 cal yrs BP, 7,500 and 8,000 cal yrs BP, as well as ~11,000 cal yrs BP and ~12,000 cal yrs BP. $\delta^{13}C$ values range between -25.5‰ to -18.7‰ (mean = -20.8‰ ±1.2) with a notable decrease ~10,500 to 11,000 cal yrs BP and one between ~13,000 to 14,000 cal yrs BP (Figure 2.4). $\delta^{15}N$ varies between -1.2‰ and 4.4‰ (mean 1.0‰ ±1.0) with decreases ~11,000 cal yrs BP, between 7500 cal yrs BP and 8000 cal yrs BP, ~5,000 cal yrs BP, and ~3,500 cal yrs BP (Figure 2.4).

Swan Lake sediment carbon and nitrogen (Table 2.3) ranges from 0.03% and 5.98% and 0.0% and 0.47%, respectively. C:N ranges between 9.5 and 18.64 with a mean of 15.29 ±5.6 (Table 2.3, Figure 2.4). This is slightly higher than Deep Lake's mean C:N. There is only one large drop in Swan Lake C:N ~11,000 cal yrs BP (Figure 2.4). $\delta^{13}C$ values in Swan Lake sediments are fairly high, between -28.2‰ to -16.9‰ (mean =

-21.24‰ ±2.3) with notable decreases ~11,000 cal yrs BP and ~7,000 cal yrs BP (Table 2.3, Figure 2.4). $\delta^{15}N$ varies between -5.0‰ and 3.7‰ (mean -0.2‰ ±1.4) with decreases ~11,000 cal yrs BP, ~7500 cal yrs BP and ~3,500 cal yrs BP (Figure 2.4).

Despite Swan and Deep lakes being of a similar age, size and depth, the sediments of the two lakes have fairly different isotopic compositions. $\delta^{15}N$ is significantly higher in Deep Lake than in Swan Lake (single-factor ANOVA, $p < 0.0001$). There is a difference in $\delta^{13}C$ between the two lakes as well (single factor ANOVA, $p = 0.025$), though it is of lesser significance than that of $\delta^{15}N$. C:N is significantly different between the two lakes as well (single factor ANOVA, $p < 0.0001$), even if the single high point near the top of Swan Lake is excluded (Figure 2.4). By ~4,000 - 3,500 cal yrs BP this deviation in $\delta^{15}N$ and C:N is statistically noticeable. During this period in time Deep Lake's sediment average $\delta^{15}N$ is higher overall than the preceding 10,000 years (mean 1.3 ±0.5‰) while Swan Lake's average sediment $\delta^{15}N$ remains the same as the preceding 10,000 years (-0.2 ±0.5‰) (Figure 2.3). In addition, $\delta^{15}N$ in sediments from Deep Lake from 3,500 cal yrs BP to the present has a weak significant difference when compared to older sediments (single-factor ANOVA, $p = 0.08$) while there is no statistical difference in the Swan Lake values when sediment $\delta^{15}N$ from 3,500 cal yrs BP to the present are compared to earlier sediments. The statistical difference between Deep Lake $\delta^{15}N$ becomes more pronounced when the last 4,000 years are compared to 4,000-8,000 cal yrs BP (single-factor ANOVA, $p = 0.002$; Table 2.3). Variability in $\delta^{13}C$ in Deep Lake sediments is reduced beginning ~6,000 cal yrs BP, while Swan Lake $\delta^{13}C$ is three times as variable (Deep Lake variance = 0.5, Swan Lake variance = 1.7). Deep Lake trends begin to deviate from Swan Lake starting ~6,000 cal yrs BP (Figure 2.4).

Discussion

Prior studies of lake core sediments have shown that any changes in elemental composition of sedimentary organic material during early diageneses are usually not large enough to erase the large differences in allochthonous and autochthonous matter (Meyers and Ishiwatari 1993; Meyers and Teranes 2001). There is no systematic downcore decrease in %N and %C of either lake, which suggests little diagenetic change in either element. In fact, %C and %N show a small overall decline over the Holocene. The mean %N and %C in Deep and Swan lakes, though similar, are different enough to result in significant differences in C:N between the lakes. The lower C:N in Deep Lake might suggest relatively higher lake productivity, or lower terrestrial input. The organic carbon content in both lakes is more than 1%, which indicates that C:N values should be a reliable indicator of the organic matter source for both lakes; i.e. that most of the nitrogen is in particulate organic matter (Meyers and Teranes 2001).

Both lakes have fairly low $\delta^{15}N$, though as discussed Deep Lake has higher overall mean $\delta^{15}N$ than Swan Lake. The overall low values of $\delta^{15}N$ are most likely due to high flushing rates. Though no limnological studies have been conducted on these small island lakes, they are relatively shallow and annual precipitation is high, hencr the relatively high flushing rates. Stockner (1987) found that coastal lakes, specifically those along the Northeast Pacific, tended to be fast-flushing and they experienced maximum water input (and therefore nutrient loads from fluvial input) in the winter when water temperatures, column stability, and light availability are low. Therefore lakes such as those on Sanak Island experience their greatest input of nutrients at a time when algae, phytoplankton, and zooplankton are less able to take advantage of that availability. Since flushing rates are so high and water column stability low during winter months the nutrients are simply not retained in the system (Cederholm et al. 1989; Kline et al. 1993; Bilby et al. 1998; Scharf 1999; Holtham et al. 2004). Coastal lakes can therefore be phosphorous (P) limited, which limits primary productivity. If P is limiting primary productivity, then the nitrogen pool may be large relative to biological uptake and nitrogen isotope fractionation would be high, lowering $\delta^{15}N$ values in organisms within coastal lake systems. In previous paleolimnology studies of MDN, lakes with low flushing rates and very high escapement densities have $\delta^{15}N$ values from 4.0‰ - 9.0‰ depending on their location, while control lakes averaged between 1.0‰ - 4.0‰ (Finney et al. 2000, 2002). In comparison to these lakes, Deep Lake has a very low escapement density (Table 2.1) and very high flushing rates. This suggests that Deep Lake is similar to the oligotrophic lakes with low nitrogen levels in coastal British Columbia discussed by Holtham et al. (2004). In fact, based on the historical escapement reported by ADF&G (2006) and the relationship between sedimentary $\delta^{15}N$ and escapement/lake area shown by Finney et al. (2000; Figure 2.2C) the $\delta^{15}N$ level of Deep Lake is not unexpected for a sockeye nursery lake of its characteristics. Further, the relative high $\delta^{15}N$ in Deep Lake compared to Swan Lake (>1.0‰), is consistent with input of MDN.

There is a smaller statistical difference in $\delta^{13}C$ between the lakes. Since $\delta^{13}C$ is associated with the terrestrial input of lakes as well as the productivity (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Leng et al. 2005), this difference is consistent with the C:N and $\delta^{15}N$ data.

C:N in both Deep and Swan lakes is relatively low (with the exception of two peaks in Swan Lake). Lacustrine algae generally have C:N values between 4 -10, while C_3 terrestrial (or vascular) plants, such as those growing on Sanak Island, can range anywhere from 20 and higher (Meyers and Teranes 2001). The means of both lakes (Deep Lake = 12 and Swan Lake = 15) suggest a mix of algal and terrestrial inputs, which is common for many lakes (Meyers and Teranes 2001; Talbot 2001). In general, times of low $\delta^{15}N$ correspond with peaks of C:N in Deep Lake while this occurs to a lesser degree in Swan Lake (Figure 2.4). This could correspond to periods of high terrestrial input (Leng et al. 2005; Talbot 2001). However, there is no corresponding decrease or increase in $\delta^{13}C$ when C:N increases in either lake. It is possible that C:N changes in Deep Lake after ~6,000 cal yrs BP correspond to an increase or decrease in MDN.

Changes in proxy data through time

In utilizing the proxy data to reconstruct salmon abundance over time, I consider only the Holocene, since comparisons are best between entities in a similar environmental state. Earlier portions of the record are complicated by a landscape adjusting to deglaciation, fairly different vegetation regimes (Misarti et al. 2007) and sediment infilling of the lake basins. The ontogeny of lakes is governed by many mechanisms and past productivity of a lake can be higher or lower than present day as they respond to changing climates, landscape developments and nutrient inputs. For example, during early post-glacial periods, accumulation rates of N and P are commonly high (Wetzel, 1983) as is reflected in the earlier portion of Deep and Swan Lakes records. Furthermore, in shallow lake basins where sedimentation has reduced water depths such as those of Swan and Deep Lakes, rates of lake ontogeny can greatly accelerate. Over time the origin of organic matter itself changes (i.e. between terrestrial and aquatic). As the depth of the lake decreases, the input from terrestrial/littoral plants increases, changing the organic chemistry of the lake. For all of the above reasons I will discuss only the last 6,000 years in detail.

The two lakes have corresponding changes over time in trends in sedimentation rates. Both Swan and Deep lake sedimentation rates accelerate at ~6,500 cal yrs BP but slow again ~4,000 - 3,500 cal yrs BP, shortly after the start of Neoglacial. These rates are independent of volcanic activity, which causes short peaks in sedimentation as larger ash layers are laid down over short periods of time.

Evidence suggests that volcanism can affect both Deep and Swan Lakes in terms of productivity. For instance, there is a drop in $\delta^{15}N$ immediately following each large ash layer in both lakes. Most volcanic layers are relatively thin (<1.0 cm) and do not appear to affect $\delta^{15}N$ to a large degree, but the four large tephra layers discussed in the results (each > 10.0 cm) do impact $\delta^{15}N$ signatures (Figure 2.4). This suggests that one of the primary reasons for steep decreases in productivity of both lakes is due to volcanic activity. There is a large reduction in δ^{13}C and %C following large layers of ash in the lake cores as well (Figure 2.4), which may be the result of a destabilization of the landscape and a greater input of terrestrial organic matter or possibly a decrease in photosynthesis resulting from a decrease in light intensity associated with volcanic events.

There are historic accounts of a two year period from 1824-1826 AD which saw fairly high volcanic activity along the Alaska Peninsula and eastern Aleutians, with many eruptions that disrupted daily life (Black 1977; Veniaminov 1984; Khlebnikov 1994; Black 1999). One specific volcanic eruption in October of 1826 obscured the sun for 8 days (Black 1999) and left ash coating Sanak and its surrounding islands almost two feet thick (Khlebnikov 1994). According to Russian-American accounts, people had irritated eyes and throats for weeks afterward and introduced domestic animals, such as pigs, which had previously flourished on nearby islands were found dead supposedly from the ash (Veniaminov 1984; Khlebnikov 1994; Black 1999). Caribou herds decreased on the lower Alaska Peninsula as well and it was believed they moved farther up the peninsula in order to avoid the ash from the 1826 eruption (Veniaminov 1984). Streams ran with ash/mud for months after this event (Khlebnikov 1994; Black 1999), yet neither lake core studied showed a thick layer of ash from this time period. This suggests that the four, much larger, pyroclastic events recorded in the lake cores must have had a devastating impact on both terrestrial and aquatic local environments that is reflected in the decreased productivity of both lakes.

Climate change also appears to influence Deep and Swan Lakes. There is an increase of $\delta^{15}N$ in Deep and Swan Lake at the onset of the Neoglacial (~4,000 cal yrs BP) which was discussed above. There is a further $\delta^{15}N$ increase in Deep Lake as climate changes towards the cooler temperatures of the Little Ice Age (LIA). Interestingly, there is a decrease in $\delta^{15}N$ during the Medieval Warm Period (MWP) in the sediments of Deep Lake while $\delta^{15}N$ in Swan Lake increases at this time (Figures 2.5 and 2.6). More than likely this difference is due to a decrease in MDN in Deep Lake as is seen in other lakes in Alaska during the MWP (Finney et al. 2000, 2002).

Although much of the history of both $\delta^{15}N$ and $\delta^{13}C$ in the lake cores have similar trends for about 10,000 years (Figure 2.4), the traits begin to diverge ~6,000 cal yrs BP (Figures 2.5 and 2.6). Starting a little before 6,000 cal yrs BP, there was a change in climate towards moister conditions indicated by advancing Alaskan glaciers (Calkin et al. 2001) and changes in pollen analyzed from cores in Cold Bay Alaska, less than 50 km from Sanak Island (Jordan and Krumhardt 2003). Coastal erosion data in northern Alaska also show, an increase in storminess around this time as well (Mason and Jordan 1993; Jordan and Mason 1999). At this time $\delta^{15}N$ first started to be systematically higher in Deep Lake. By 3,500 cal yrs BP average $\delta^{15}N$ in Deep Lake sediments was higher overall and significantly different than the preceding 10,000 years, while Swan Lake's was not altered. This suggests a further increase in MDN in Deep Lake after the start of the Neoglacial, a trend that is also seen in Iliamna Lake, on the Alaska Peninsula and Karluk Lake on Kodiak Island (Finney, pers. comm.). After 3,500 cal yrs BP Deep Lake has trends in the $\delta^{15}N$ of its sediments (Figure 2.5) that are recorded in the sediments of other

Alaskan lakes with MDN. There is an overall increase in MDN in lakes around Alaska after the start of the Neoglacial, a period of cooler air temperatures, increased storminess and advancing glacial ice (Bradley 1999; Calkin et al. 2001; Finney et al. 2000, 2002) that is mirrored in Deep Lake sediments (Figure 2.5).

Around 1,000-1,200 cal yrs BP, within the MWP when climate was warmer and drier than now in many parts of the Northern Hemisphere (Stine 1994; Bradley 1999; Calkin et al. 2001; Jones et al. 2001; Esper et al. 2002; MacDonald and Case 2005), there was a decrease in $\delta^{15}N$ in sediments from lakes with salmon runs deriving from both the Bering Sea and the northeastern Pacific (Finney et al. 2000, 2002; Finney pers. comm.). Deep Lake also had a slight decrease in $\delta^{15}N$ of its sediments at this time (Figures 2.5 and 2.6). These same Alaskan lakes with MDN had an increase in $\delta^{15}N$ in sediments around the time of the LIA, a period of cooler, wetter climate ~700-150 cal yrs BP (Bradley 1999; Finney et al. 2000, 2002; Roberts 2004) as did Deep Lake (Figure 2.3). It appears that sockeye began to spawn in the Deep Lake watershed in sizeable numbers relative to the N mass balance by ~6,000 cal yrs BP, but numbers of returning salmon must have further increased ~3,500 - 4,000 cal yrs BP as seen in the statistical increase in $\delta^{15}N$ and (Figures 2.5 and 2.6, Table 2.4).

Swan Lake, without the influence of MDN, had little significant change over the last 6,000 years (Table 2.4). It is possible that changing amounts of precipitation, wind and water temperatures affected Swan Lake $\delta^{15}N$ and $\delta^{13}C$, and such trends were obscured in Deep Lake due to additional input from MDN. For example, while Deep Lake $\delta^{15}N$ slowly decreased toward the height of the MWP, Swan Lake's $\delta^{15}N$ slowly increased (Figures 2.5 and 2.6). Perhaps warmer water temperatures and less precipitation increased phytoplankton productivity in Swan Lake, thereby increasing its $\delta^{15}N$. As productivity increased in Swan Lake, DIN would have been drawn down and phytoplankton would have taken up more $\delta^{15}N$, thereby raising the $\delta^{15}N$ value within the food web and eventually the sediments. In such a shallow lake it is unlikely that light would be a limiting factor unless wind action increased to the point that suspended particulate matter decreased light availability. This could explain the negative relationship in $\delta^{15}N$ seen in Swan Lake versus Deep Lake after 6,000 cal yrs BP. This is speculative as the changes are less than 1‰.

The C:N of Deep Lake supports this hypothesis as well. Starting at ~6,000 cal yrs BP the C:N ratio began to decrease, reflecting greater nitrogen input from aquatic sources (Figure 2.5). There was a noticeable increase ~1,500 cal yrs BP in Deep Lake's C:N, possibly reflecting smaller numbers of returning sockeye (Figure 2.4) leading up to the MWP. Another decrease in C:N occurred as the colder and wetter conditions that culminated in the LIA began. Swan Lake C:N, on the other hand, did not have a similar trend (Figure 2.4).

Conclusion

My results show relatively early deglaciation in this region, and thus paleolimnologic records of past environmental change cover the period from about ~16,000 BP to present. Deglaciation on Sanak Island began earlier than on the nearby

Alaska Peninsula (Jordan et al. 2005). Although small and shallow, sediments from Deep and Swan Lakes provide complete post-glacial records of regional volcanic activity and lake productivity. Changes in sedimentation rates were often associated with large, well-documented climate changes, as were stable isotope values of both carbon and nitrogen. For example, primary production in Swan Lake appears to have increased during periods of warmer atmospheric temperatures and decreased during colder climatic periods.

Despite high flushing rates and small historic salmon escapement numbers, this research suggests that fluctuations in $\delta^{15}N$ can infer salmon productivity through time if corresponding data from a viable control lake are available for comparison. In the case of anadromous Deep Lake, enrichment in $\delta^{15}N$ relative to Swan Lake after ~6,000 cal yrs BP may suggest the development of a sockeye salmon return sufficient to impact nitrogen isotopic mass balance. The data suggest that ~3,500 cal yrs BP, the salmon returns significantly increased and that there was a decline in salmon returns ~1,000 cal yrs BP, a period associated with regional climate anomalies during the MWP. Salmon returns appeared to reach maximum levels during the LIA. These changes in salmon returns inferred by MDN generally correlate with well-known periods of climate change, and other salmon reconstructions for the North Pacific.

Figures

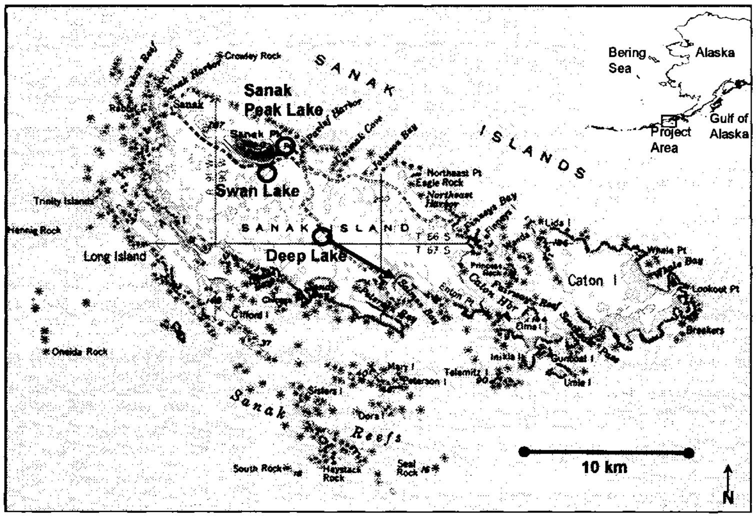

Figure 2.1: Location of Sanak Island and the study lakes.

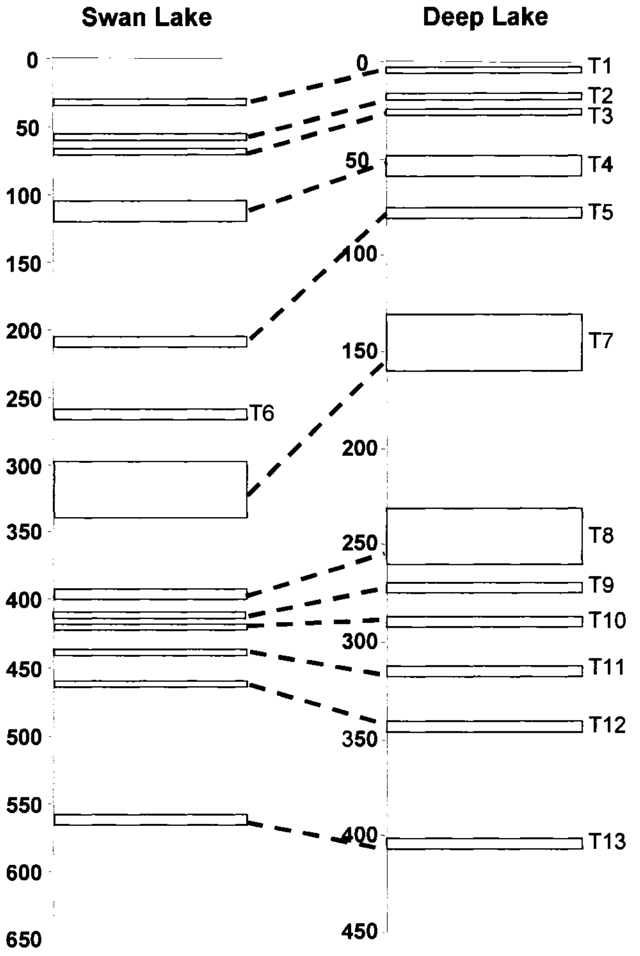

Figure 2.2: Depth, thickness and correlations of tephras between Deep and Swan Lakes.

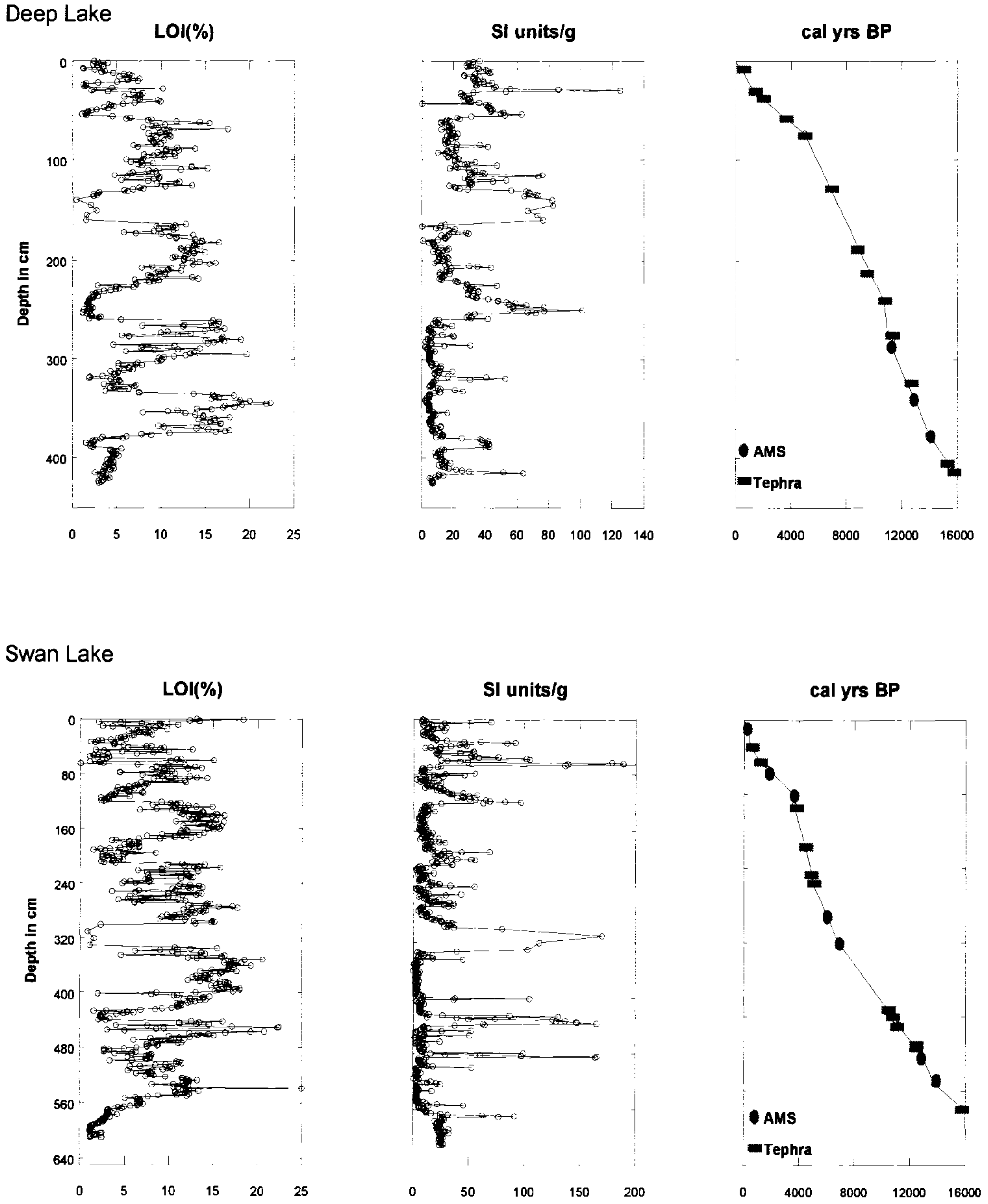

Figure 2.3: Downcore plots of loss on ignition, magnetic susceptibility and calibrated ages based on radiocarbon dates and estimated tephra dates (Tables 2.2 and 2.3).

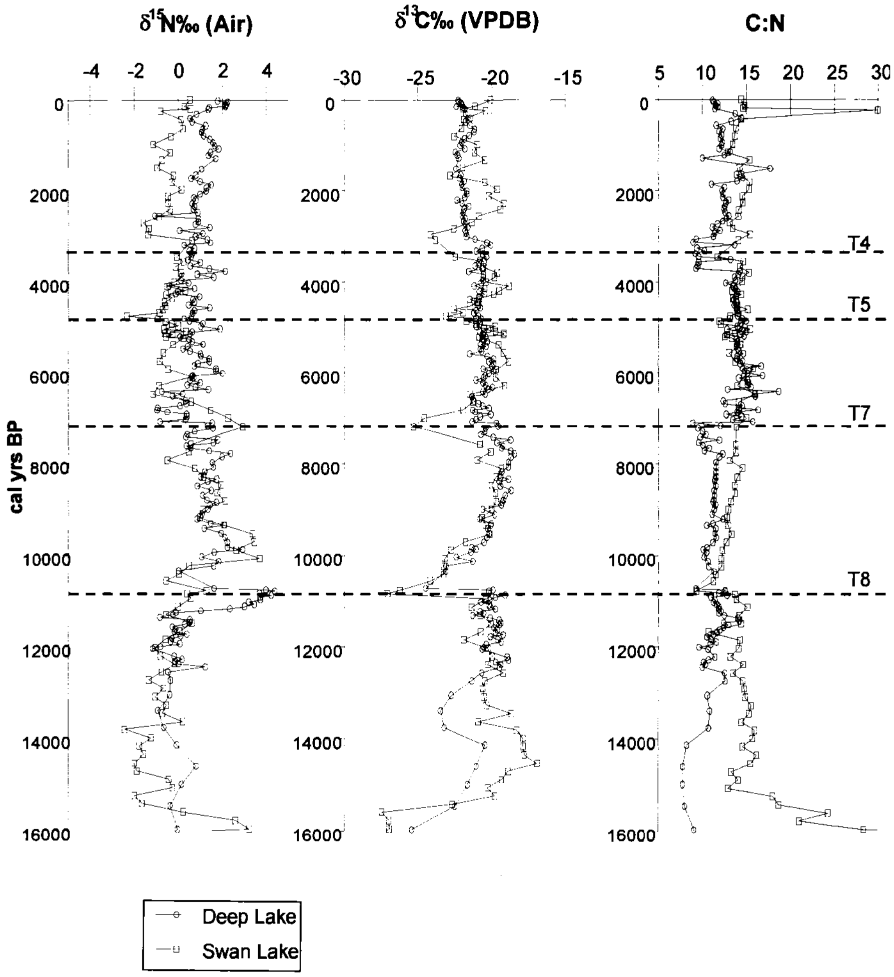

Figure 2.4: Temporal trends in δ^{15}N, δ^{13}C and C:N in Deep and Swan Lakes.

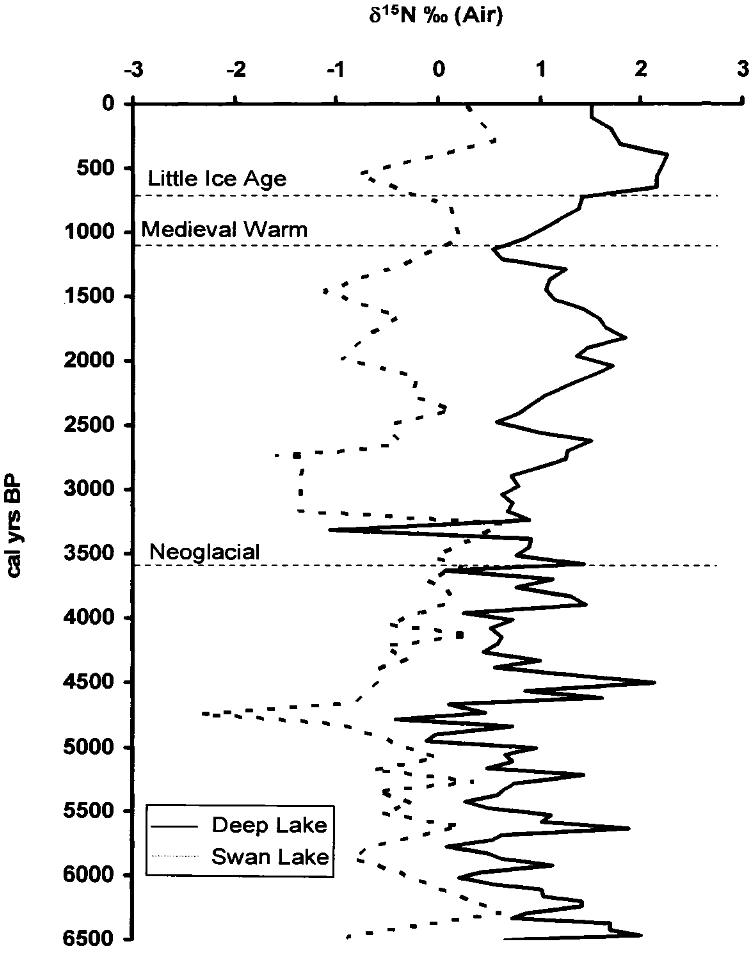

Figure 2.5: Detail of δ^{15}N records of the last 6,500 years in Deep and Swan Lakes. Horizontal dashed lines represent periods of major climate transitions in this region.

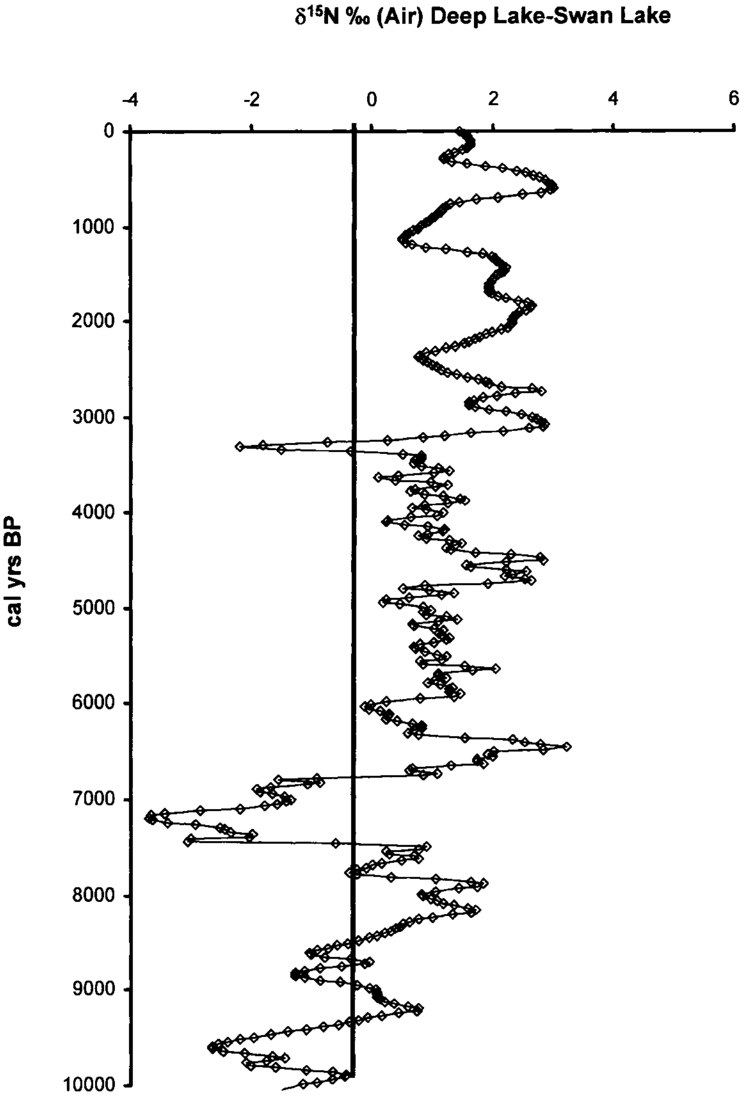

Figure 2.6: Differences in $\delta^{15}N$ in Deep versus Swan Lakes over the past 10,000 years. $\delta^{15}N$ data in both lakes were interpolated to every 25 years in the calculations of $\delta^{15}N$ differences.

Tables

Table 2.1: Escapement data from Salmon Bay, Sanak Island, AK. Numbers from 1911 to 1930 are an island total while those from 1963 represent only Salmon Bay, its tributaries and Deep Lake (Rich and Ball 1930; ADF&G 2006).

Location	Year	Survey Type	Coho	Chum	Pink	King	Red
All Bays	1911	Catch-beach seine			25232		46067
All Bays	1912	Catch-beach seine		1854	10700		23592
All Bays	1914	Catch-beach seine					46004
All Bays	1915	Catch-beach seine					30677
All Bays	1917	Catch-beach seine		3147	319		22626
All Bays	1920	Catch-beach seine			132		8283
All Bays	1922	Catch-beach seine			99		19857
All Bays	1923	Catch-beach seine			2209		10012
All Bays	1924	Catch-beach seine			1854		5427
All Bays	1927	Catch-beach seine		44	18		736
Salmon Bay	1963	Aerial survey					6000
Salmon Bay	1985	Aerial survey			2000		6200
Salmon Bay	1986	Aerial survey			1000		2700
Salmon Bay	1990	Aerial survey					4000
Salmon Bay	1995	Aerial survey			3200		600
Salmon Bay	1996	Aerial survey					200
Salmon Bay	2001	Aerial survey	1000		2800		2600
Salmon Bay	2002	Aerial survey			3000		2500
Salmon Bay	2003	Aerial survey	2500		5000		2900
Salmon Bay	2004	Aerial survey	1700		1500		6000
Salmon Bay	2005	Aerial survey			4700		1800
Salmon Bay	2006	Aerial survey					700

Table 2.2: Radiocarbon dates of terrestrial plant macrofossils in lake cores from Sanak Island.

Lake	Depth (cm below surface)	CAMS Lab ID	Age (BP)	Age (cal yrs BP)
Swan Lake	9	124453	265±35	280-330
Swan Lake	48.5	124452	2295±35	2360-2400
Swan Lake	81	124454	3045±35	3275
Swan Lake	115	127196	3385±40	3630-3700
Swan Lake	173.5	N75223	3995±35	4460-4590
Swan Lake	219	124455	4420±35	3000-3100
Swan Lake	495	127197	10760±40	12750-12920
Swan Lake	533	111108	11900±60	13680-13970
Sanak Peak Lake	188	111103	1755±45	1700-1720
Sanak Peak Lake	292	111104	2400±40	2400-2520
Sanak Peak Lake	332	111105	3025±50	3130-3410
Sanak Peak Lake	504	111106	5840±60	6650-6790
Sanak Peak Lake	777	111107	9690±110	11120-11275
Sanak Peak Lake	803	115524	11810±70	13820-13650
Deep Lake	280	115525	9850±60	11200-11320
Deep Lake	376	115582	12070±55	13850-13990
Deep Lake	408	115526	13080±80	15190-15740

Table 2.3: Estimated ages of volcanic events correlated between lake cores.

Volcanic Event	**Tephra Number**	**Age (cal yrs BP)**
Brown	T1	442
Flesh	T2	1237
Unknown 2	T3	1712
Green	T4	3586
Purple 1	T5	4960
Flesh 2	T6	6032
White (orange sandy)	T7	6825
Lapilli	T8	10716
Green 2	T9	11005
Orange	T10	11201
Grey	T11	12404
Black	T12	13010
Yellow	T13	15773

Table 2.4: Means and SD of nitrogen and carbon of Deep and Swan Lakes over the entire record, and selected time periods (cal yrs BP).

Proxy	**Deep Lake Average**	**Deep Lake 0-4,000**	**Deep Lake 4,000-8,000**	**Deep Lake 8,000-12,000**	**Swan Lake Average**	**Swan Lake 0-4,000**	**Swan Lake 4,000-8,000**	**Swan Lake 8,000-12,000**
δ^{15}N (‰)	1.0±1.0	1.1±0.6	0.7±0.7	1.4±1.3	-0.2±1.4	-0.3±0.6	-0.2±1.0	1.1±1.3
δ^{13}C (‰)	-20.8±1.2	-21.6±0.6	-20.4±0.7	-20.2±1.1	-21.2±2.3	-21.2±1.3	-20.8±1.5	-21.5±2.1
C:N	12.3±1.9	12.1±1.6	13.6±1.9	11.5±0.9	15.3±5.6	14.8±3.1	13.9±0.9	13.0±1.4
%N	0.3±0.2	0.2±0.1	0.3±0.1	0.4±0.2	0.3±0.2	0.2±0.1	0.3±0.1	0.3±0.1
%C	2.9±1.6	1.7±1.0	2.9±0.9	4.3±1.8	3.1±1.8	2.7±1.7	3.9±1.6	4.0±1.5

References

ADF&G. 2006. Westward Region salmon escapement survey database. Alaska Department of Fish & Game Division of Commercial Fisheries.

BEAMISH, R. J., and D. R. BOUILLON. 1993. Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences **50:** 1002-1016.

BEAMISH, R. J., D. J. NOAKES, G. A. MCFARLANE, L. KLYASHTORIN, V. V. IVANOV, and V. KURASHOV. 1999. The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences **56:** 516-526.

BILBY, R. E., B. R. FRANSEN, and P. A. BISSON. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: Evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences **53:** 164-173.

BILBY, R. E., B. R. FRANSEN, P. A. BISSON, and J. K. WALTER. 1998. Response of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) to the addition of salmon carcasses to two streams in southwestern Washington, USA. Canadian Journal of Fisheries and Aquatic Sciences **55:** 1909-1918.

BLACK, R. F. 1977. Influence of Holocene climatic changes on Aleut expansion into the Aleutian Islands, Alaska. Anthropological Papers of the University of Alaska **18:** 31-42.

BLACK, L. T. 1999. The history and ethnohistory of the Aleutians East Burough, 1st ed. The Limestone Press.

BOND, N. A., J. E. OVERLAND, M. SPILLANE, and P. STABENO. 2003. Recent shifts in the state of the North Pacific. Geophysical Research Letters **30**.

BRADLEY, R. S. 1999. Paleoclimatology: reconstructing climates of the Quaternary, Second ed. Academic Press.

CALKIN, P. E., G. C. WILES, and D. J. BARCLAY. 2001. Holocene coastal glaciation of Alaska. Quaternary Science Reviews **20:** 449-461.

CEDERHOLM, C. J., D. B. HOUSTON, D. L. COLE, and W. J. SCARLETT. 1989. Fate of coho salmon (*Oncorhynchus kisutch*) carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences **46:** 1347-1355.

ESPER, J., E. R. COOK, and F. H. SCHWEINGRUBER. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science **295:** 2250-2253.

FINNEY, B. P. 1998. Long-term variability of Alaska sockeye salmon abundance determined by analysis of sediment cores. North Pacific Anadromous Fisheries Community Bulletin **1:** 388-395.

FINNEY, B. P., I. GREGORY-EAVES, J. SWEETMAN, M. S. V. DOUGAS, and J. P. SMOL. 2000. Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. Science **290:** 795-799.

FINNEY, B. P., I. GREGORY-EAVES, M. S. V. DOUGLAS, and J. P. SMOL. 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature **416:** 729-733.

GREGORY-EAVES, I., J. P. SMOL, M. S. V. DOUGLAS, and B. P. FINNEY. 2003. Diatoms and sockeye salmon (*Oncorhynchus nerka*) population dynamics: reconstructions of salmon-derived nutrients over the past 2,200 years in two lakes from Kodiak Island, Alaska. Journal of Paleolimnology **30:** 35-53.

HARE, S. R., and R. C. FRANCIS. 1995. Climate change and salmon production in the Northeast Pacific Ocean, p. 357-372. *In* R. J. Beamish [ed.], Climate change and northern fish populations. Canada Special Publication of Fisheries and Aquatic Sciences.

HARE, S. R., N. J. MANTUA, and R. C. FRANCIS. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries **24:** 6-14.

HARE, S. R., and N. J. MANTUA. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography **47:** 103-145.

HOLTHAM, A. J. and others 2004. The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (*Oncorhynchus nerka*) nutrient dynamics in Alaska and British Columbia. Journal of Paleolimnology **32:** 255-271.

HUNT, G. L., and P. J. STABENO. 2005. Oceanography and ecology of the Aleutian Archipelago: spatial and temporal variation. Fisheries Oceanography **14:** 292-306.

JONES, P. D., T. J. OSBORN, and K. R. BRIFFA. 2001. The evolution of climate over the last millennium. Science **292:** 662-667.

JORDAN, J. W., and O. K. MASON. 1999. A 5000 year record of intertidal peat stratigraphy and sea level change from northwest Alaska. Quaternary International **60:** 37-47.

JORDAN, J. W., and A. KRUMHARDT. 2003. Postglacial climate and vegetation of the Western Alaska Peninsula. Alaska Journal of Anthropology **1:** 16-33.

JORDAN, J. W., B. P. FINNEY, D. ODORCZUK, N. MISARTI, and H. MASCHNER. 2005. Paleoecology of the Sanak Archipelago, 70th Annual Society for American Archaeology Meetings.

KHLEBNIKOV, K. T. 1994. Notes on Russian America: Parts II-V: Kad'iak, Unalashka, Atkha, The Pribylovs. The Limestone Press.

KLINE, T. C., J. J. GOERING, O. A. MATHISEN, P. H. POE, P. L. PARKER, and R. S. SCALAN. 1993. Recycling of elements transported upstream by runs of Pacific salmon 2. $\delta^{15}N$ and $\delta^{13}C$ evidence in the Kvichak River Watershed, Bristol Bay, Southwestern Alaska. Canadian Journal of Fisheries and Aquatic Sciences **50:** 2350-2365.

LAWS, E. A., B. N. POPP, R. R. BIDIGARE, M. C. KENNICUTT, and S. A. MACKO. 1995. Dependence of Phytoplankton Carbon Isotopic Composition on Growth-Rate and CO_2 (Aq) - Theoretical Considerations and Experimental Results. Geochimica et Cosmochimica Acta **59:** 1131-1138.

LENG, M. J. and others 2005. Isotopes in lake sediments, p. 147-184. *In* M. L. Lenf [ed.], Isotopes in paleoenvironmental research. Springer.

MACDONALD, G. M., and R. A. CASE. 2005. Variations in the Pacific Decadal Oscillation over the past millenium. Geophysical Research Letters **32:** 1-4.

MANTUA, N., S. R. HARE, Y. ZHANG, J. M. WALLACE, and R. C. FRANCIS. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society **78:** 1069-1079.

MANTUA, N. J., and S. R. HARE. 2002. The Pacific decadal oscillation. Journal of Oceanography **58:** 35-44.

MASON, O. K., and J. W. JORDAN. 1993. Heightened North Pacific storminess during synchronous Late Holocene erosion of Northwest Alaska beach ridges. Quaternary Research **40:** 55-69.

MASON, O. K., D. K. SALMON, and S. L. LUDWIG. 1996. The periodicity of storm surges in the Bering Sea from 1898 to 1993, based on newspaper accounts. Climatic Change **34:** 109-123.

MEYERS, P. A., and R. ISHIWATARI. 1993. Lacustrine organic geochemistry: an overview of indicators of organic matter sources and diagenesis in lake sediments. Organic Geochemistry **20:** 867-900.

MEYERS, P. A., and J. L. TERANES. 2001. Sediment organic matter, p. 239-269. *In* W. M. Last and J. P. Smol [eds.], Tracking environmental change using lake sediments: physical and geochemical methods. Kluwer Academic Publishers.

MISARTI, N., B. P. FINNEY, and H. D. G. MASCHNER. 2007. Paleoenvironmental records of Sanak Island, AK, 72nd Annual Society for American Archaeology Meetings.

MUETER, F. J., and B. L. NORCROSS. 2002. Spatial and temporal patterns in the demersal fish community on the shelf and upper slope regions of the Gulf of Alaska. Fishery Bulletin **100:** 559-581.

REIMER, P. J. and others 2004. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon **46:** 1029-1058.

RICH, W. H., and E. M. BALL. 1930. Statistical review of the Alaska salmon fisheries. Part 1: Bristol Bay and the Alaska Peninsula. Bulletin of the United States Bureau of Fisheries.

ROBERTS, N. 2004. The Holocene; An environmental history, Second ed. Blackwell Publishing.

RODIONOV, S. N., J. E. OVERLAND, and N. A. BOND. 2005. Spatial and temporal variability of the Aleutian climate. Fisheries Oceanography **14:** 3-21.

SCHARF, W. 1999. Restoration of the highly eutrophic Lingese Reservoir. Hydrobiologia **416:** 85-96.

STINE, S. 1994. Extreme and persistent drought in California and Patagonia during Medieval time. Nature **369:** 546-549.

STOCKNER, J. G. 1987. Lake fertilization: The enrichment cycle and lake sockeye salmon (*Oncorhynchus nerka*) production, p. 198-215. *In* H. D. Smith, L. Margollis and C. C. Wood [eds.], Sockeye salmon (*Oncorhynchus nerka*) population biology and future management, Vol. 96. Canadian Special Publications of Fisheries and Aquatic Sciences.

TALBOT, M. R. 2001. Nitrogen isotopes in paleolimnology, p. 401-440. *In* W. M. Last and J. P. Smol [eds.], Tracking environmental change using lake sediments: physical and geochemical methods. Kluwer Academic Publishers.

VENIAMINOV, I. 1984. Notes on the islands of the Unalashka District. The Limestone Press.

WARE, D. M., and R. E. THOMSON. 1991. Link between long-term variability in upwelling and fish production in the Northeast Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences **48:** 2296-2306.

---. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. Science **308:** 1280-1284.

WETZEL, R. G. 1983. Limnology. Saunders College Publishing.

Chapter 3 Changes in Northeast Pacific marine ecosystems over 4,500 years: Evidence from stable isotope analysis of bone collagen from archaeological middens.[1]

Abstract

Stable isotope analysis of nitrogen and carbon ($\delta^{15}N$ and $\delta^{13}C$) of bone collagen from coastal archaeological middens has the potential to yield information on food web dynamics and ocean productivity through time. I investigated changes in the stable nitrogen and carbon isotope composition of six marine species over the past 4,500 years. These species include Steller sea lions (*Eumetopias jubata*), Harbor seals (*Phoca vitulina*), Northern fur seals (*Callorhinus ursinus*), sea otter (*Enhydra lutris*), Pacific cod (*Gadus macrocephalus*) and sockeye salmon (*Oncorhynchus nerka*). Samples were collected from archaeological middens on Sanak Island located on the eastern edge of the Aleutian archipelago in the eastern North Pacific Gulf, Alaska. Of the marine mammals sampled for this study the sea otter had the highest mean $\delta^{13}C$ (-11.9 ± 0.7‰) and lowest $\delta^{15}N$ (14.5 ± 1.4‰), while Northern fur seals had the lowest $\delta^{13}C$ (-13.6 ± 1.4‰) and Steller sea lions had the highest $\delta^{15}N$ (18.4 ± 1.4‰). Cod isotope ratios demonstrate the demersal, near shore habitat (-12.5 ± 0.9‰ $\delta^{13}C$, 16.1 ± 1.4‰ $\delta^{15}N$) while salmon isotope ratios are consistent with an open ocean habitat and lower trophic level signature

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[1] Misarti N, Finney B, Maschner H, and M Wooller. 2007. Changes in Northeast Pacific marine ecosystems over 4,500 years: Evidence from stable isotope analysis of bone collagen from archaeological middens. Prepared for Oecologia.

(-15.2 ± 1.4‰ $\delta^{13}C$, 11.5 ± 1.7‰ $\delta^{15}N$). Salmon had a significant difference in $\delta^{13}C$ over six prehistoric time periods while otters had a difference in $\delta^{15}N$ for the same six time periods. Mean $\delta^{13}C$ of modern animals is significantly lower than prehistoric animals, possibly due to a decrease in productivity in the Gulf of Alaska, and suggests that our current understanding of twentieth century North Pacific climate regimes may not be useful analogs of marine ecosystems beyond the last 200 years. Correlations of $\delta^{15}N$ and $\delta^{13}C$ were negative for all species with the exceptions of salmon before ~1,000 calendar years before present (cal yrs BP). These patterns changed after ~1,000 cal yrs BP. Although it appears that $\delta^{15}N$ and $\delta^{13}C$ of species that inhabit different water bodies have reacted to climate change in different ways, the overall structure of the food web in this portion of the Northeast Pacific has remained relatively unchanged for the last 4,500 years.

Introduction

Historical increases and decreases in both pelagic and anadromous fish have been linked to changes in North Pacific climate (Ware and Thomson 1991; Hollowed and Wooster 1992; Beamish and Bouillon 1993; Francis and Hare 1994; Hare and Francis 1995; Roemmich and McGowan 1995; Welch et al. 1998; Mantua 2004). These changes in climate can also affect other aspects of marine ecosystems, such as species composition, abundance and geographic distribution of shellfish, fish and sea mammals (Venrick et al. 1987; Baumgartner et al. 1992; Francis and Hare 1994; Ware 1995; Anderson and Piatt 1999; Hare and Mantua 2000; Hirons et al. 2001; Benson and Trites 2002). These well-studied patterns can be used as analogs to explain past changes. For instance, the Pacific Decadal Oscillation (PDO) has characterized the climatic states of the North Pacific for most of the last century and has alternated between two ocean climate modes, often referred to as regimes, every ~20 - 30 years (Mantua and Hare 2002). Alternate states (positive or negative) of the PDO affect sea surface temperature (SST), sea level pressure (SLP), the strength of the Aleutian Low (AL), wind strength, storm intensity, mixed layer depth and ocean current patterns (Overland et al. 1999). A warm PDO phase appears to favor production of salmon in the Gulf of Alaska (GOA), the Aleutian Islands and Bering Sea but is detrimental to salmon production in the California Currents system on the Northwest Coast (Beamish and Bouillon 1993; Francis and Hare 1994; Beamish et al. 1999; Hare et al. 1999; Mueter et al. 2002). Moreover, gadids and other flatfish increased in numbers in the GOA and Bering Sea during these years while shrimp and capelin decreased (Beamish 1993; Botsford et al. 1997; Anderson and Piatt 1999). Zooplankton increased in the GOA but decreased in the Bering Sea, along British Columbia and the West Coast (Brodeur and Ware 1992; Francis and Hare 1994, Roemmich and McGowan 1995; Sugimoto and Tadokoro 1998; Hare and Mantua 2000; Overland and Stabeno 2004). Pinnipeds, including Steller sea lions (*Eumetopias jubata*, SSL), Harbor seals (*Phoca vitulina,* HS), and Northern fur seals (*Callorhinus ursinus*, NFS), have declined in the western GOA and the Bering Sea since the 1980's (Francis et al. 1998; Gentry 1998; Hirons et al. 2001; Wynne and Foy 2002; Stabeno et al. 2005). Many possible hypotheses have been proposed to explain these changes including food or nutrient limitations related to climatic change that occurred when gadid fish became the dominant fishes in these areas (Trites 1992; Anderson and Piatt 1999; Francis et al. 1998). Alternatively, these declines may have resulted from increased predation by killer whales (Jackson et al. 2001; Springer et al. 2003).

An example of the impact of climate on the marine ecosystems of the North Pacific took place during the winter of 1998/99. During this time a different atmospheric pattern (sometimes referred to as the Victoria Pattern) altered storm and SST trends in the eastern North Pacific (Benson and Trites 2002). The central Pacific Ocean SST north and west of Hawaii increased while there were cooler conditions from Vancouver Island to the Baja Peninsula. The GOA and Bering Sea continued to have warmer SST than during a negative PDO (Bond et al. 2003). In response to these changes California Current zooplankton doubled in biomass from previous years and were dominated by cold-water species as opposed to the warm water species seen previously, and anchovy, chinook and coho stocks increased along the west coast of the continental US (Bond et al. 2003). Some groundfish stocks in this region also increased, while in the GOA herring stayed low in numbers and groundfish increased (Mueter 2004).

The different climate-ecosystem patterns, such as those seen in the PDO versus the Victoria Pattern, can be used to asses paleoecological data and characterize the occurrence and persistence of these patterns over longer time scales. Studies of past marine ecosystems and their responses to environmental changes in the North Pacific have primarily been based on historical data, which generally cover fewer than 100 years, and have focused primarily on decadal regime shifts. Only a few researchers have investigated past, long-term changes in these ecosystems employing various sets of proxy data, including stable isotopes (Burton et al. 2002; Causey et al. 2005; Maschner 2000; Finney et al. 2000, 2002).

Stable isotope analysis can often enhance more conventional studies of diet in marine ecosystems, as stable isotopic information can integrate diet over longer time periods compared to stomach content or observational data. More importantly for this study, dietary information on past ecosystems is recorded in the stable isotope ratios of carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$ respectively) in bone (Schoeninger and DeNiro 1984), and can illuminate past trophic dynamics. In general, stable isotopic variations between organisms reflect different feeding ecologies, trophic positions and the isotopic composition of a food web's base (Fry and Sherr 1984). Therefore an organism's tissue has a stable isotopic composition that can be used to trace dietary inputs (DeNiro and Epstein 1981; Schoeninger and DeNiro 1984; Doucett et al. 1996; Hobson et al. 1996, 1997; Hirons et al. 2001). $\delta^{15}N$ increases in marine food webs by approximately 3‰ per trophic level while $\delta^{13}C$ increases by an average of 2‰ from primary to secondary producers and from 0.5‰ to 1‰ in higher trophic levels (Michener and Schell 1994; Post 2002). This has allowed researchers to place an organism relative to others in a trophic system (Wada et al. 1991). If an organism switches trophic level it can be detected by a change in $\delta^{15}N$. In addition to trophic position, variations in $\delta^{13}C$ in food webs can be related to geography (Schell 2000), possible fluctuations in primary productivity (Hirons et al. 2001) that are linked to climate shifts (Francis and Hare 1994), and to changing carbon inputs linked to events unrelated to productivity (McRoy et al. 2004).

Phytoplankton discriminate against heavier isotopes, but this changes when carbon and nitrogen are less available in a system. Since nitrogen is one of the limiting factors of productivity in many of the world's oceans, there will be less nitrate (or dissolved inorganic nitrogen) in a less productive system. Therefore, $\delta^{15}N$ should theoretically increase within organisms of a less productive marine system as more isotopically heavy nitrogen is taken up into the food web and the number of trophic levels increases as nitrogen gets recycled within the system. For carbon isotopes, the opposite is theoretically true. Larger phytoplankton blooms and faster cell growth rates (e.g. a highly productive system such as upwelling nearshore systems) draw down DIC concentrations and phytoplankton $\delta^{13}C$ becomes relatively higher (Laws et al. 1995). Therefore, $\delta^{15}N$ and $\delta^{13}C$ should be inversely related as productivity increases or decreases over time.

However, both climate and local oceanographic conditions can also influence $\delta^{15}N$ and $\delta^{13}C$ changes over time in an ecosystem. For example, during times when the AL is particularly strong it affects the GOA gyre (a HNLC body of water, limited by iron) with increased upwelling and Ekman transport and decreased SST (Overland et al. 1999; Hare and Mantua 2000). The water column is less stable and nutrients and phytoplankton, which are mixed throughout the upper layers, are carried out of the gyre to the shelf so primary productivity in the gyre could be very low due. Therefore, both ^{15}N and ^{13}C would be depleted in phytoplankton. In times of less intense ALs (reduced upwelling and Ekman transport) blooms, though still limited, would increase in the gyre due to warmer waters and some availability of nutrients (e.g. iron). If plant cell growth was fast enough, $\delta^{13}C$ in phytoplankton may increase (per Laws et al. 1995) while $\delta^{15}N$ may remain depleted.

During times when the AL is strong, GOA shelf waters experience increased vertical mixing in the winter (thought to determine spring nutrient levels) and increased SSTs. Increased precipitation increases streamflow and decreases surface salinity (Gargett 1997; Stabeno et al. 2005). Increased SST and decreased surface salinity increase stability of stratification. These factors combined tend to favor larger phytoplankton blooms on the shelf (Ware and Thompson 1991; Gargett 1997), which may cause carbon to be drawn down by quick plant cell growth but not nitrogen (which is not limiting for coastal GOA waters). However, if the water stability increased enough to limit nitrogen, or if a bloom was large enough to draw nutrients down, then both $\delta^{15}N$ and $\delta^{13}C$ would be expected to increase in phytoplankton. Depending on local conditions (oceanographic, climate and seasonal) $\delta^{15}N$ and $\delta^{13}C$ in the food web may not necessarily have an inverse relationship.

Stable isotopic signatures can be preserved in a range of animal tissues and compounds. Bone is often well preserved in archaeological middens permitting researchers to compare isotopic signatures over hundreds to thousands of years. Bone collagen is well suited for this type of study as it has a slower turnover rate relative to muscle tissue, organs and blood, reflecting a longer period in an organism's lifetime (Ambrose and Norr 1993; Lambert and Grupe 1993), and allowing researchers to compare organisms' overall trophic status (Schoeninger and DeNiro 1984). This point is important when dealing with archaeological remains of sea mammals for several reasons. First, with the exception of HS, it is often difficult to age an animal beyond broad categories such as "juvenile" or "adult". Second, most sea mammal species' skeletal remains have not been sufficiently studied to be able to determine sex from different elements (although with some sexually dimorphic species adult males can be identified by the sheer size of elements). Third, despite knowing the exact location of an archaeological midden one cannot control for the vast areas over which many sea mammals forage throughout their life times (see below). Bone collagen integrates many years as well as geographic foraging areas and so allows a comparison of average isotope values over many hundreds of years. This study uses $\delta^{15}N$ and $\delta^{13}C$ of bone collagen from several marine species recovered from archaeological middens to discuss the persistence of 20th century climate regimes, effects of climate on different marine ecosystems, and individual species' reactions to these changes over the past 4,500 years.

Study site and faunal overview

The site of the research presented here, Sanak Island, is located at the eastern most part of the Aleutian chain, 40 km south of the Alaska Peninsula in the North Pacific and is situated on the outer continental shelf, which is fairly broad in this region (Figure 3.1). Cool summers and mild winters with high winds and rain are characteristic of the climate in this region (Hunt and Stabeno 2005; Rodionov et al. 2005). The area is dominated in the winter by the AL, a weather cell of extremely low pressure, which affects the eastern North Pacific, the Bering Sea and Sea of Okhotsk (Rodionov et al. 2005). The primary ocean currents in the area are the Alaska Coastal Current (ACC) and the Alaska Stream (AS). The ACC carries fresher, warmer water from the coastal areas of the GOA down the coast of the Peninsula and along the eastern most islands of the chain, as opposed to the AS, which flows along the shelf break and carries colder, more saline and nutrient rich waters from the subarctic gyre in the Gulf (Hunt and Stabeno 2005; Ladd et al. 2005; Logerwell et al. 2005).

Sanak Island was deglaciated by circa 16,000 calendar years before present (cal yrs BP) (Misarti unpub.). Since this time, with the exception of the Younger Dryas (Mann and Hamilton 1995), a general trend of warmer and drier periods has oscillated with cooler periods of increased precipitation. Tree-ring chronologies from various areas have been used to reconstruct climate states and search for PDO-like variations in the North Pacific Ocean and Bering Sea (D'Arrigo et al. 2005; MacDonald and Case 2005) and show that the PDO is typical for the past ~200 years. Beyond the past 200 years however, the PDO appears to be only an intermittently strong mode of variation in time periods between 500 and 700 cal yrs BP with a strongly negative period from 1,000 to 700 cal yrs BP (roughly the same time as the Medieval Warm Period (MWP) (MacDonald and Case 2005).

Animals analyzed for this study include SSL, HS, NFS, sea otters (*Enhydra lutris*, SO), Pacific cod (*Gadus macrocephalus*) and sockeye salmon (*Oncorhynchus nerka*). For the purposes of this study it is important to know the modern prey species and trophic position of these animals.

SO have been known to forage on sea urchin, abalone, crab, mussels and clams, octopus, tunicates, shrimp species and kelp-forest fish throughout their habitat (Kenyon 1969; Kvitek and Oliver 1992; Watt et al. 2000; Estes et al. 2003; Bodkin et al. 2004). SO were selected for this study because they are considered keystone species in kelp forest communities in the Aleutians, influencing many other nearshore species, which in turn can effect local physical oceanographic processes such as light, temperature and water motion (Simenstad et al. 1978; Dayton 1985; Duggins et al. 1989; Simenstad et al. 1993; Estes and Duggins 1995; Watt et al. 2000; Steneck et al. 2002; Reisewitz et al. 2006). In the eastern portion of the GOA, SO are also known to forage heavily on bivalves and urchins in soft-bottom communities (Kvitek et al. 1992). SO numbers in the Aleutians have declined rapidly since the 1990s, a fact that has been attributed by some researchers to predation by killer whales (Estes et al. 1998; Doroff et al. 2003; Springer et al. 2003). SO to the east of Kodiak Island however, do not appear to be declining in numbers, nor do they appear to be declining west of Attu Island in the Aleutians (Doroff et al. 2003).

In today's ecosystem, Pacific cod along the lower Alaska Peninsula that are smaller than 60 cm prey mostly on invertebrates such as Tanner crabs, polychaetes, and crangonid shrimp while fish species such as walleye pollock are important parts of diets only of cod larger than 60 cm (Yang 2004). Just after the 1976/77 regime shift however, pandalid shrimp and capelin were the main food species of Pacific cod in Pavlof Bay on the Alaska Peninsula (Albers and Anderson 1985). Studies in the Bering Sea have shown that when warmer water temperatures allow cod and capelin habitat to overlap, cod will feed heavily on capelin (Ciannelli and Bailey 2005). Shrimp and capelin in the GOA have declined substantially since the 1976/77 regime shift (Botsford et al. 1997) and this decline may have been the impetus for diet changes in cod.

Pacific salmon are opportunistic feeders and their diets include everything from copepods, euphausiids, squid, ctenophores and jellies to small fish (Burgner 1991; Welch and Parsons 1993). However, it appears from both stomach content and stable isotope analyses, that chinook (*Oncorhynchus tshawytshaw*) are more likely to feed on fish species than pink (*Oncorhynchus gorbuscha*), chum (*Oncorhynchus keta*), and sockeye salmon, and that the latter three species feed in more open ocean habitats than do chinook and coho (*Oncorhynchus kisutch*) (Satterfield and Finney 2002). Both cod and salmon stocks have fluctuated (though not in conjunction with one another) with changing regime shifts in the past 40 years (Hollowed and Wooster 1992; Francis and Hare 1994; Hare and Mantua 2000).

SSL are wide-ranging animals that return to rookeries to pup and breed (Call and Loughlin 2005; Fadley et al. 2005). Their habitat extends along the Pacific Rim from the Kurile Islands across the North Pacific and south through California. Today, SSL diet includes species such as walleye pollock, Atka mackerel, salmon, Pacific cod, arrowtooth flounder, herring, sandlance, Irish lord, squid and octopus (Sinclair and Zeppelin 2002). Common components of SSL diets in the eastern Aleutian Islands include walleye Pollock, Pacific herring, salmon spp and Atka mackerel while SSL in the western Aleutians feed off the continental shelf on Atka mackerel and cephalopods (Call and Loughlin 2005). Around Kodiak Island major components of the SSL diet include sandlance, arrowtooth flounder, Pacific cod and walleye pollock (Wynne and Foy 2002). The rapid decline of SSL in some areas in the past few decades has prompted many explanations such as nutritional stress, a shift in diet and predation by killer whales (Francis et al. 1998; Hirons et al. 2001; Springer et al. 2003; deHart et al. submitted).

NFS spend much of the year at sea, traveling from breeding grounds in the Bering Sea south to foraging grounds on the western coasts of the US and Canada (Gentry 1998). Much of the populations' current breeding grounds are located in the Pribilof Islands, however, archaeological evidence suggests that NFS bred in the Aleutians and along the Alaska Peninsula and coast of Washington prior to the late 1700's (Etnier 2002). NFS are opportunistic feeders and as such have a wide variety of prey including small schooling fish (10-20 cm in size) and squid (Gentry 1998; York 1995). While at rookeries in the Pribilofs, male NFS forage in offshore waters west of the islands and later move around and through the passes in the Eastern Aleutians. Females and juveniles forage in offshore waters from the coast of California to the Pribilof Islands. Numbers of NFS in the Pribilof Islands have declined since the 1950's but no clear cause for this has been defined (York 1995).

HS range from the southeastern Bering Sea through the GOA to California. Unlike NFS, HS are believed to stay closer (within 50 km) to their coastal haulouts (Iverson et al. 1997; Frost et al.1999), although satellite tracking studies have shown that juveniles can range more widely than previously thought (Lowry et al. 2001). Typical prey items include large and small herring and pollock, octopus, cephalopds, sandlance, capelin, flatfish, cod, salmon, and shrimp (Pitcher 1980a, b; Iverson et al. 1997). HS have had a marked decline in numbers in the GOA since the 1950's (Pitcher 1990) but no one particular assessment as to why these declines have occurred has been agreed upon.

In the past ~50 years, changes from the lowest trophic levels (phytoplankton blooms and copepod biomass) to the highest (SSL and other pinnipeds) have been documented and examined in the North Pacific Ocean and Bering Sea. While this study cannot elucidate ecosystem change on a decadal scale, it can offer insight to broad-scale changes over long periods of time.

Materials and methods

Sample collection and chronology

Bulk midden samples were collected from 24 archaeological middens on Sanak Island, Alaska in 2004 and span approximately the past 4,500 cal yrs (Table 3.1). All bone was identified to species, element, right/left side, and age category when possible based upon initial identifications at Idaho State University (Tews 2005) and corroborated using comparison collections provided by University of Alaska's Anthropology Department and the Museum of the North. All identifiable elements of marine mammals from each site were separated into left and right and the element with the largest number of lefts/rights with the additional information of age indicators was used to assign individuals of each species. Five age categories were used; infant, juvenile, subadult, adult and adult +. Infant is defined as 100% coverage of the juvenile cortex, lack of epiphyses, and very small in size. The term juvenile was defined as missing some epiphyses while those that were attached would have pronounced epiphyseal lines. Juveniles may also have a large proportion of juvenile cortex. Subadults would have all epiphyses fused but would still have pronounced epiphyseal lines. Some juvenile cortex may still be present, but only at distal and proximal ends. Adults have fully ramified cortex and no epiphyseal lines while adult + have signs of degenerative pathologies.

Prehistoric samples included bones of SSL (minimum number of individuals (MNI)=15), HS (MNI=27), NFS (MNI=21), SO (MNI=88), pacific cod (number of identifiablel specimens (NISP)=101) and salmon (NISP=91) vertebrae. A total of 131 NISP SO bones were sampled but only 60 could be counted as individuals using Grayson's (1984) definition of MNI. However, stable isotope ratios of carbon and nitrogen in bone collagen have proven to be consistent over skeletal elements in an individual (DeNiro and Schoeninger 1983). Based on a difference of at least 1‰ in either

$\delta^{13}C$ or $\delta^{15}N$ from any of the possibly associated individuals described above, an additional 28 samples were added to the data set for a total of 88 MNI. Integrated samples of fish (five separate samples from each midden) were chosen due to the fact that fish vertebrae were used for analysis and there is no assurance that each vertebra represents a different individual. Each sample therefore represents an average isotope ratio for cod or salmon during a specific time period. Number of samples (NS) used for salmon and cod were reduced (NS=34 and NS=35 respectively).

Pink and sockeye salmon currently spawn in Sanak streams and lakes (Willis and Ball 1930; ADF&G 2006) although a small number of chum salmon were collected in beach seines from 1912 to 1927 (Willis and Ball 1930). Satterfield and Finney (2002) found similar $\delta^{13}C$ and $\delta^{15}N$ values for all three salmon species in the GOA, which can be attributed to similar feeding locations and prey items. Therefore despite difficulty associated with identifying vertebrae to a single species it is likely that my data are relevant to this group of lower trophic level salmon.

Radiocarbon dates of charcoal in archaeological middens produced by Beta Analytic (BETA) and the Center for Atomic Mass Spectroscopy (CAMS) were calibrated using Calib 5.02 (Reimer et al. 2004). Samples were collected from 16 midden deposits (Table 3.1).

Three species (SO, cod and salmon) were found in numbers sufficient to study changes over time in the archeological record. Time periods for SO, cod and salmon analyses were chosen by dividing the sites into six different time periods based on radiocarbon dates (Figure 3.2). The six time periods were chosen based on discontinuity in the recovered archaeological record (i.e. years the Sanak Island archipelago was either uninhabited or no archaeological sites with middens are known as yet) or oldest and youngest calibrated site dates did not overlap. When possible, large, known climatological periods such as the Neoglacial, MWP and the Little Ice Age (LIA) were associated with time period descriptions (Table 3.2). The modern period was defined as the last 50 years.

Sample preparation and stable isotope analysis

All collagen samples were prepared using bone collagen extraction procedures described by Matheus (1997). Slices of compact, cortical bone weighing between 0.1 and 1.0 grams were cleaned in a sonicator. Lipids were removed from the bone using a methanol/chloroform procedure (Bligh and Dyer 1959). The bones were then demineralized in 6N HCl and ultra-pure water. The length of time to demineralize bone varied on a sample-by-sample basis. The remaining material was rinsed to neutral pH in ultra-pure water, soaked in 5% KOH for 8 hours to eliminate contamination from surrounding humic soils, and rinsed to neutral again. Samples were gelatinized by adding 0.05 ml of 3N HCl to 5 ml of ultra-pure water and heated to 65 °C. The samples were filtered and then placed in a freeze drier for 48 hours. Analysis of these samples was completed in the Alaska Stable Isotope Facility, University of Alaska-Fairbanks. Stable isotope ratios are expressed using the standard delta notation:

$$\delta X\ (‰) = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$$

where X is ^{13}C or ^{15}N and R $_{sample}$ is $^{13}C/^{12}C$ or $^{15}N/^{14}N$, respectively. $\delta^{13}C$ and $\delta^{15}N$ are expressed relative to Vienna Pee Dee Belemnite (VPDB) and atmospheric N_2 (air), respectively. Samples were analyzed on a Finnigan Delta^{plus}XP IRMS and analytical precision, established by analysis of multiple peptone standards throughout each run, was ~ ± 0.2‰ for both carbon and nitrogen.

Data analysis and display

All comparative modern salmon and cod muscle tissue (some samples analyzed by Satterfield 2000 and Hirons 2001) have been corrected to reflect the isotopic fractionations for C and N between muscle tissue and bone collagen in fish. $\delta^{13}C$ in bone collagen of large fish that inhabit cold ocean waters is ~2.5‰ greater than muscle tissue while $\delta^{15}N$ in bone collagen is ~1.0‰ less (Appendix A). Therefore, all modern isotope values for cod and salmon are based on muscle tissue converted to collagen values.

Depletion in the $\delta^{13}C$ isotopic composition of dissolved inorganic carbon (DIC) in the worlds' oceans due to the increase in anthropogenic CO_2 released into the atmosphere (often referred to as the Oceanic Suess Effect) since the Industrial Revolution in the eastern North Pacific is estimated to be -0.62 ± 0.17‰ as of 1991 (Ortiz et al. 2000). Although this is a smaller estimate of change than published values for some oceanic regions, Schell (2001) notes that in the areas where upwelling and winter deep mixing occur at higher latitudes such as the study region, the effects of anthropogenic decrease of $\delta^{13}C$ are diminished. In the GOA and other areas of the North Pacific north of 50°, there has been a reduced accumulation of anthropogenic traces such as $\delta^{13}C$ (Gruber et al. 1999; Schell 2001; Quay et al. 2003; Guilderson et al. 2006). All $\delta^{13}C$ of the modern (i.e. 1952 – 2000) samples used in this study have been adjusted according to year of sample using a modified equation from Hilton et al. (2006) in order to be directly compared to pre-historic values:

$$\text{Suess Effect Correction Factor} = a^{*}\exp(b^{*}0.027)$$

where a = the maximum annual rate of $\delta^{13}C$ decrease in the North Pacific (in this case -0.012 derived from Tanaka et al. (2003) and -0.014 derived from Quay et al. (1992) which closely matches Gruber et al. (1999) estimate of global oceanic change and those of Williams et al. (2007) estimate based on corals in the Northeastern Pacific), b = the year represented by the death of the animal (Hirons 2001) minus 1850 (the start of the Industrial Revolution), and 0.027 describes the curve presented by Gruber et al. (1999) for change in the $\delta^{13}C$ of the worlds' oceans from 1945-1997. This equation yields a maximum decrease from 1850 to 2007 of 0.97‰, a number that is compatible with Ortiz et al.'s (2000) estimated decrease of 0.62‰ in the North Pacific by 1991.

Results

The mean C:N calculated for the midden bone samples is 3.2 ± 0.2 and falls within the range of values (2.9-3.6) considered to be indicative of collagen that has not undergone diagenesis (Tuross et al. 1988; Koch et al. 1994; Hedges et al. 2005). A summary of the isotopic results of archaeological specimens from Sanak Island (Table

3.3, Appendix B) shows that of the marine mammals sampled for this study the SO had the lowest mean δ^{15}N and the highest mean δ^{13}C while NFS had the lowest δ^{13}C, and SSL had the highest δ^{15}N. Cod have higher δ^{13}C and δ^{15}N values compared with salmon (Table 3.3).

All prehistoric species have higher mean δ^{13}C compared to their modern counterparts even after correcting for the Oceanic Suess Effect (Figure 3.3). When compared to modern (1950's to present day) collagen counterparts as analyzed by Hirons (2001), prehistoric SSL and HS had statistically higher δ^{13}C (single-factor ANOVA, $P< 0.005$ and $P\ll 0.001$ respectively) while prehistoric NFS yielded no significant differences from modern samples for δ^{13}C (single-factor ANOVA, $P = 0.35$). Prehistoric SO and salmon had significantly higher δ^{13}C (single-factor ANOVA, $P\ll0.001$). Prehistoric cod had significantly higher δ^{13}C (single-factor ANOVA, $P=0.001$) than modern cod. Salmon and SO had significant differences in δ^{15}N between prehistoric and modern samples (single-factor ANOVA $p\ll 0.001$). Comparisons of modern and prehistoric δ^{15}N for cod, SSL, NFS, and HS yielded no differences.

SO, the only mammalian species with high enough sample numbers to compare to each other over the six prehistoric time periods, had a significant difference in δ^{13}C (single-factor ANOVA, $P= 0.07$) and in δ^{15}N (single-factor ANOVA, $P= 0.003$) over the six prehistoric time periods when using all 88 individuals (Figure 3.4). Variation in δ^{15}N and δ^{13}C for cod over the six time periods was not statistically significant (Figure 3.4).

Changes in $\delta^{13}C$ of salmon were statistically significant (single-factor ANOVA, P= 0.028) but no statistically significant changes were found for $\delta^{15}N$ (Figure 3.4).

Changing trends in the correlation of $\delta^{13}C$ and $\delta^{15}N$ were noted in graphical representations of the data ~1,000 cal yrs BP and so this trend was tested statistically. Correlations of means of $\delta^{13}C$ and $\delta^{15}N$ of all individuals for each species at times before 1,000 cal yrs BP were compared to correlations at times after 1,000 cal yrs BP. For most species, correlations between $\delta^{13}C$ and $\delta^{15}N$ varied between periods over the last 4,500 years (Table 3.4). SSL, SO and NFS $\delta^{13}C$ and $\delta^{15}N$ were negatively correlated before 1,000 cal yrs BP, while $\delta^{13}C$ and $\delta^{15}N$ were positively correlated after 1,000 cal yrs BP (Table 3.4). HS $\delta^{13}C$ and $\delta^{15}N$ were not correlated before 1,000 cal yrs BP and then positively correlated after 1,000 cal yrs BP. Salmon $\delta^{13}C$ and $\delta^{15}N$ were positively correlated throughout the entire 4,500 years (Table 3.4). Cod $\delta^{13}C$ and $\delta^{15}N$ were positively correlated before 1,000 cal yrs BP but negatively correlated after (Table 3.4).

Discussion

General

Based on the mean $\delta^{15}N$ and $\delta^{13}C$ for each species, some trophic level and foraging habitat trends are evident. For example, the elevated $\delta^{13}C$ signature for SO reflects a benthic/near shore diet of invertebrates that consume intertidal plants and macro-algae with elevated $\delta^{13}C$ in comparison to offshore phytoplankton (Fry and Sherr 1984) and prey items that include deposit-feeding bivalves (Hobson and Welch 1992). Salmon, on the other hand, have isotopic signatures relatively depleted in ^{15}N and ^{13}C, indicating both lower trophic level foraging and an open-ocean habitat (Figure 3.5). Satterfield (2000) distinguished between $\delta^{15}N$ and $\delta^{13}C$ in oceanic versus coastal areas in the GOA for copepods and salmon. Both $\delta^{15}N$ and $\delta^{13}C$ were lower in the open ocean than in coastal areas. The coastal/shelf isotopic enrichment is likely due to higher primary production and a longer food chain. In comparison, cod collagen reflects the enrichment of both isotopes for coastal waters and for benthic prey species. Different prey items for cod and salmon obviously play a role in the isotopic diversity of salmon and cod.

SSL, HS, and NFS data show high, and generally similar, trophic positions. NFS have the most depleted $\delta^{15}N$ and $\delta^{13}C$ of all three pinnipeds species, which more than likely reflects the species' mixed continental shelf and open water foraging patterns than absolute relative trophic position. SSL have the highest $\delta^{15}N$, which may simply reflect their ability to forage on larger fish than HS and NFS, while HS have the highest $\delta^{13}C$ of all the pinnipeds species. This may be due to the use of more near shore foraging grounds.

The changing correlations of $\delta^{15}N$ and $\delta^{13}C$ I present (Table 3.4) are not consistent with simple shifts in the organisms' trophic level. An increase in trophic level should show a positive linear relationship between $\delta^{15}N$ and $\delta^{13}C$ with a slope of ~ 3:1 ($\delta^{15}N$: $\delta^{13}C$), while a decrease should be a negative relationship along a similar slope.

However, this is complicated by mixed diets, and physical and biological oceanographic processes.

When compared to modern trophic levels and food web positions of all species, it appears that the basic structure of the food web is the same over the past 4,500 years (Figures 3.3 and 3.6), but changes in isotope values occurred throughout this time within this basic food web structure (see details below). For example, the data reveal decreases in mean $\delta^{13}C$ of modern versus archaeological specimens (Figure 3.3, Table 3.3). Overall, pelagic species have a larger decrease in $\delta^{13}C$ from prehistoric to modern times. I hypothesize that environmental change led to different relationships between $\delta^{13}C$ and $\delta^{15}N$ in deep ocean/gyre versus shelf waters.

The pelagic realm (coastal and open water)

Mean $\delta^{13}C$ for SSL, NFS, HS, and salmon are enriched by 0.5 - 1.6‰ compared to their modern counterparts, even after modern values were corrected for the Oceanic Suess Effect (see Materials and Methods). Thus, the lower $\delta^{13}C$ of these specimens relative to their modern counterparts cannot be attributed solely to the Suess Effect, unless this effect has been greatly underestimated. There are several possible explanations/hypotheses for the observed changes.

One possible reason for a change in $\delta^{13}C$ of pelagic species is the recent reduction of ice in the Bering Sea (Niebauer 1998; Parkinson and Cavalieri 2002). Ice algae can have higher $\delta^{13}C$ than phytoplankton, and would have played a reduced role in the food web as winter ice area in the Bering Sea decreased (McRoy et al. 2004). NFS feed part of the year in the Bering Sea and many individuals cross through Unimak and False Pass. Sanak Island is close to both passes and it is possible that along with NFS, the SSL and HS captured near Sanak Island may also have fed in Bering Sea waters. Young SSL on the Pacific side of the eastern Aleutians move through the passes and into the Bering Sea in late spring (Call and Loughlin 2005). Clusters of SSL rookeries near Sanak Island are associated with both diet and population growth with rookeries on the Bering Sea side of the Alaska Peninsula and eastern Aleutians (Sinclair et al. 2005). Both of these studies suggest that SSL from the North Pacific have forage locations in the Bering Sea. There are no studies that suggest HS move between the Pacific and Bering but the pattern of reduced $\delta^{13}C$ with no change in $\delta^{15}N$ for HS is similar to SSL and NFS.

Burton et al. (2001, 2002) proposed that differences in mean $\delta^{15}N$ and $\delta^{13}C$ between archaeological and modern samples of NFS are due to a difference in location of foraging from middle latitudes to higher latitudes, suggesting that the NFS harvested prehistorically in California were year-round residents in that area. NFS are the only marine mammal in this study whose mean archaeological $\delta^{15}N$ appears different (~1.1‰ lower) than the modern $\delta^{15}N$ mean, though they are not statistically different (single-factor ANOVA, p=0.146) due to the high variance in the prehistoric data. Most of the prehistoric NFS in my study were juveniles while modern specimens were of varying ages. Newsome et al. (2006) showed that $\delta^{15}N$ in NFS between 6 and 20 months of age (after weaning) decreased dramatically and was lower than both pre-weaned and adult $\delta^{15}N$, while $\delta^{13}C$ did not change. The disproportionate number of juveniles in this study makes it difficult to draw any conclusions about possible changes in $\delta^{15}N$ in comparison to the modern data.

The possibility of a change in SSL, NFS and HS foraging location is also a viable hypothesis. Theoretically, a decrease in $\delta^{15}N$ would also be expected if a change from shelf to deep water forage location occurred over the past few millennia. However, Burton and Koch (1999) found that pinnipeds foraging in various locations, but at similar trophic levels, had similar $\delta^{15}N$ composition of bone collagen but widely ranging $\delta^{13}C$. $\delta^{13}C$ values are generally lower in deep water than on the continental shelf. This is due to several factors, including differences in DIC from shelf waters to deep waters, growth rate and species composition of phytoplankton, and the input of carbon-enriched $\delta^{13}C$ from kelp and other macroalgae in coastal areas (Goericke et al. 1994; Michener and Schell 1994; Laws et al. 1995). It is possible that the pinnipeds found in archaeological middens on Sanak Island spent a greater percentage of time foraging in nearshore waters while modern pinnipeds utilize more offshore waters, though this explanation does not explain the lack of change in $\delta^{15}N$. Clark (1986) discusses the possibility of changes in storm patterns forcing NFS closer to shore, as well as fluctuations in herring distribution and numbers as a rationale for the sudden increase in numbers of NFS foraging around Kodiak Island in the 1700's.

A final hypothesis for the depletion of $\delta^{13}C$ in modern times across all pinnipeds is an overall decrease in the primary production of the pelagic zone in the northeast Pacific/southern Bering for recent times compared to the past 4,500 years. Some researchers have suggested that the recent depletion in $\delta^{13}C$ is due to a decrease in ocean primary productivity over time in the GOA and the Bering Sea (Schell 2000, 2001; Hirons et al. 2001; Hobson et al. 2004; Newsome et al. 2007). According to Kim et al. (2004) there has been an overall warming trend in SST in the Northeast Pacific over the last 7,000 years. Warming ocean waters could have caused a change in mixed layer depth and increased stratification in summer months, thereby reducing available nutrients that, in turn, reduced primary productivity. Gargett (1997) stated that there is an "optimal stability" window in which mixing and stratification are balanced enough to create geographic areas of high primary productivity. Conditions on either side of this window (i.e. too warm or too much mixing of the water column) are not conducive to large phytoplankton blooms. Freeland et al. (1997) used historical nutrient and weather data and suggested it indicates that over time there has been a decrease in mixed layer depth, decreasing the nitrate supply to the euphotic zone that is entrained yearly in the North Pacific by winter deep-mixing. Williams et al. (2007) used a similar argument to explain the reduction in both $\delta^{13}C$ and $\delta^{15}N$ in corals in the eastern Aleutian Islands over the last century. As discussed above, lower primary productivity can result in increased ^{13}C discrimination in primary producers, lowering the overall $\delta^{13}C$ in a food web.

All pelagic species in this study had a decrease in mean $\delta^{13}C$ (-0.5 to -2.7‰) from prehistoric to modern times, with the largest decrease in salmon, the one species that spends the majority of their lifetime in offshore, deep ocean waters in the gyre. The modern data in this study includes marine mammals from pre- and post- 1977/78 regime shift, spanning the well-known changes in the North Pacific and Bering ecosystems and climate, and thereby excluding a trend based solely upon a single "regime". The decrease in mean $\delta^{13}C$ in modern pelagic organisms suggests that perhaps the Northeast Pacific pelagic ecosystem has been, on average, in a different state than in the preceding 4,500 years. Perhaps the recent warming has resulted in stratification that exceeds the "optimal" productivity window when compared to the past 4,500 years. This hypothesis assumes that foraging locations for pinnipeds did not change from coastal to deep ocean realms.

NFS and SSL $\delta^{13}C$ and $\delta^{15}N$ are negatively correlated but only until ~1,000 cal yrs BP (Table 3.4). After 1,000 cal yrs BP the two isotope ratios are positively correlated. HS $\delta^{13}C$ and $\delta^{15}N$ are positively correlated after 1,000 cal yrs BP but are not correlated before. Hobson and Welch (1992) found that $\delta^{13}C$ and $\delta^{15}N$ for animals at the higher trophic levels of arctic food chains were not correlated, just as HS in this study were not correlated before 1,000 cal yrs BP. It is not surprising that all pinnipeds in this study have similar trends in $\delta^{13}C$ and $\delta^{15}N$, as their modern prey items are similar and in similar trophic positions. It is difficult, however, to explain the changing relationships for pinnipeds, as they do not have the same trends as two of their modern potential prey items, cod and salmon. It is possible that neither of these fish played a large role in their diets prior to 1,000 cal yrs BP but open-water pelagic fish such as salmon play a larger role today.

Deep water/open ocean realm

The only species that spends the majority of its life in the open ocean in this study is salmon. Although median $\delta^{15}N$ changes over the six pre-historic time periods (Table

3.2; Figure 3.4), suggesting changes in trophic level or prey over time, there is no statistically significant change in salmon, most likely due to high variance within each time period. This high variance within each time period, which could average many decades to century long regime shifts, makes it difficult to discuss any prolonged period of change in prey items and trophic level for sockeye salmon over the last 4,500 years. There is, however, a significant change in $\delta^{13}C$ over the six time periods (Figure 3.4). The largest changes took place between Periods 1-2 and 2-3, with the median from each time period changing slightly over 2‰. Periods 3 and 4 have individual samples with the highest $\delta^{13}C$ after which the median drops slowly until Period 6. When salmon numbers are high during Period 2 (Table 3.2) (Finney et al. 2000, 2002), bottom-up theories suggest that $\delta^{13}C$ would be relatively higher (Brodeur and Ware 1992; Beamish and Bouillon 1993; Laws et al. 1995). In fact, my data show that $\delta^{13}C$ is actually the same or lower relative to other periods over the last 4,500 years (Figure 3.4). During Periods 1 (when salmon numbers are low but just starting to rise), 3 (a period when salmon numbers had been high but were dropping) and 4 (when salmon numbers are low) according to lake core data (Finney et al. 2000, 2002, pers. comm.), the $\delta^{13}C$ of sockeye collagen is relatively high (Figure 3.4). In Period 6, salmon abundance is high (Table 3.2) and $\delta^{13}C$ of salmon are low (Figure 3.4). Perhaps instead of coupling to primary productivity, the fluctuations in $\delta^{13}C$ for salmon are based on changes in geographic areas salmon inhabited (per Schell 2000). Differences in areas of upwelling may shift over time in response to AL position. Similarly, changes in upwelling rates may affect $\delta^{13}C$ as well, with higher rates bringing more carbon to surface waters and therefore lowering $\delta^{13}C$ in the food web. Iron in the North Pacific is thought to be mainly from the atmosphere, so increased upwelling rates may mean reduced iron concentrations and therefore slower growth of primary producers (Freeland et al. 1997), which may also lower $\delta^{13}C$ in the food web (Laws et al. 1995).

Sockeye are the only species with a consistently positive correlation between $\delta^{13}C$ and $\delta^{15}N$ throughout the last 4,500 years (Table 3.4). They are also the only species that spend most of their lives in the open waters of the gyre. As discussed previously, it is possible that salmon move forage locations as wind patterns, SST, and upwelling areas change. Perhaps salmon are moving onto the shelf margins or farther from shelf margins depending on climatic conditions. Satterfield and Finney (2002) noted increasing $\delta^{13}C$ and $\delta^{15}N$ in copepods on a transect from open waters in the gyre to on-shelf waters (Figure 3.5). If salmon moved from one water body to another due to climate change, or if the conditions of the body of water they inhabited changed enough to simulate current differences between on-shelf and off-shelf, salmon $\delta^{13}C$ and $\delta^{15}N$ would fluctuate in a positively correlated manner. This may also explain the counter-intuitive data of low sockeye numbers in spawning lakes but high $\delta^{13}C$ discussed previously. Perhaps it is not as advantageous for salmon to feed in on-shelf waters (where $\delta^{13}C$ is higher) as it is in the gyre.

The benthic/nearshore realm

Cod $\delta^{15}N$ and $\delta^{13}C$ do not appear to have fluctuated much over the last 4,500 years. There are small changes over the six time periods that are not statistically significant (Figure 3.4, single-factor ANOVA, $p=0.23$ and 0.13, respectively, for $\delta^{15}N$ and $\delta^{13}C$). Comparison of prehistoric to modern cod data does not reveal any significant difference in $\delta^{15}N$ (single-factor ANOVA, $p=0.1$) between the two groups, but does show a difference in $\delta^{13}C$ (single-factor ANOVA, $p=0.001$). However, the change in mean $\delta^{13}C$ between modern and prehistoric cod is less than 1‰, and not of biological significance. This remarkable lack of change in $\delta^{15}N$ and $\delta^{13}C$ over the past 4,500 years may be due to cod's broad semi-demersal feeding habits. Despite changing climate and prey availability, it may be that the basic food web structure of the coastal/nearshore/benthic habitats did not alter to the extent of forcing cod to change their already diverse feeding habits, or to change foraging locations. Although some changes may have occurred, they may not have been large enough to be visible in the $\delta^{15}N$ and $\delta^{13}C$ data. For example, cod switched some prey items due to the changes after the 1976/77 regime shift (Albers and Anderson 1985; Yang 2004), but not their foraging location. If the prey items before and after the regime shift held similar trophic positions, the $\delta^{15}N$ and $\delta^{13}C$ of cod before and after the shift may not have a discernable difference in these isotope values if the base of the food web did not change.

Cod are the only species whose $\delta^{13}C$ and $\delta^{15}N$ are positively correlated before 1,000 cal yrs BP but negatively correlated after 1,000 cal yrs BP, and the only semi-demersal species in the study that spend their time in the waters of the ACC. As all cod samples are from locations along the Alaska Peninsula, we can look to local explanations for these two trends. There may be differences in levels of nutrients transported within the ACC and down the Alaska Peninsula, which could cause changes in relationships between $\delta^{13}C$ and $\delta^{15}N$. For example, iron could become a limiting factor to growth if less was carried in the ACC in times of less runoff from rivers.

SO $\delta^{15}N$ and $\delta^{13}C$ over the last 4,500 years has allowed the development of hypotheses about environmental change over time based on changing sea level as well as top-down effects of population size on foraging conditions. SO had a significant difference in $\delta^{15}N$ over the six prehistoric time periods. My SO $\delta^{15}N$ data suggest a change over time from a more mixed diet (including a greater emphasis on fish) in the earliest record for this study around 4,500 cal yrs BP, to one based more on benthic invertebrates (while still including fish), by ~400 cal yrs BP. The earlier portion of the record could be partially explained by changing sea levels on Sanak Island and a less stable intertidal community prior to this time. During periods of falling sea level there is a dominance of rocky shores, while during times of high sea levels, coastal areas are filled in with sediment (Graham et al. 2003). Coastal habitat would alter along with these shoreline changes.

Sea level on Sanak was ~5 m above modern sea level ~4,000 cal yrs BP (Jordan et al. 2005), which could cause exposure of kelp to high wave action and sandy deposits along shorelines, making it difficult for kelp beds to be established in many areas around the Sanak Island archipelago. At this time, mean SO $\delta^{15}N$ is high and individual $\delta^{15}N$ is more variable, while $\delta^{13}C$ is at its lowest. In a less productive community, SO may have been more opportunistic feeders with pelagic fish and other prey playing a larger part in the diet than they do in well-established kelp forest communities. Sea level dropped slowly to 2-3 meters above modern sea level by 2,000 cal yrs BP (Jordan et al. 2005), probably accompanied by a decrease in wave action due to emergence of barrier bars and increased kelp growth. Mean $\delta^{15}N$ of SO dropped almost 2‰ between 3,800 and 2,700 cal yrs BP, and then remained fairly constant until the LIA (Figure 3.5), suggesting a less mixed diet for the otter population as a whole after 2,700 cal yrs BP.

Top-down processes could affect isotopic signatures of SO, as they were an important subsistence resource for the Aleut. This would, of course, be a local phenomenon. During Period 1, SO remains are frequent when compared to other sea mammals (Betts and Tews 2007). Watt et al. (2000) compared diet studies from the 1950's and 1960's in the Aleutians when SO were at equilibrium density, to the 1990's when SO population had declined. They observed that kelp forest and other fish were a much more important dietary item in the 1950's and 1960's than they were in the 1990's, when sea urchin were a greater percentage of the diet. If SO were at equilibrium density ~4,500 cal yrs BP but were subsequently heavily exploited by the Aleut causing a population decline then a shift in diet similar to that recorded between the 1950's and the 1990's may have occurred. In fact, by ~3,750 cal yrs BP SO frequency had declined drastically (Betts and Tews 2007), and perhaps reflects not only a change in subsistence to larger sea mammals but also a smaller SO population. By 2,750 cal yrs BP, after almost 2,000 years of exploitation, SO $\delta^{15}N$ had declined.

The lower $\delta^{15}N$ and $\delta^{13}C$ in modern as compared to prehistoric SO suggests that top-down mechanisms through over-hunting may be the best explanation for changes in SO isotopes. Although otters may have switched towards a more benthic foraging strategy 2,000-3,000 cal yrs BP, it is possible that SO diet changed further sometime in the past 250 years. This may be due partly to the near extinction of otters through hunting that began in the 1750's with Russian fur trading. As otter numbers declined, urchin numbers increased, and overgrazing of kelp may have created urchin barrens (Simenstad et al. 1978; Dayton 1985; Duggins et al. 1989; Estes and Duggins 1995; Steneck et al. 2002). Urchin barrens have fewer fish (although they can be more species diverse) and invertebrates, so as otters returned in numbers they may have preyed on more pelagic fish species as well as the overly abundant urchins. All 13 modern SO samples came from the Aleutian Islands and the Alaska Peninsula, and were collected between 1960 and 2000. It is very possible that they were collected from areas with urchin barrens or newly recovering kelp forests, and therefore reflect a very different ecosystem than the prehistoric SO, whose isotopic values reflect healthier kelp forest systems during the prior few thousand years.

$\delta^{13}C$ and $\delta^{15}N$ correlations for SO are difficult to explain. SO $\delta^{13}C$ and $\delta^{15}N$ are negatively correlated until ~1,000 cal yrs BP but weakly positively correlated after 1,000 cal yrs BP. SO may have been forced to make pelagic fish a larger portion of their diet at specific points in time and so may reflect correlations much like those of pinnipeds rather than cod. Increased sample sizes over all time periods will perhaps make these patterns more clear.

Conclusions

My research illustrates that species from different water bodies in the Northeast Pacific reacted in different ways to climate change. When comparing shifts in mean $\delta^{13}C$ and $\delta^{15}N$ in salmon, cod and SO over the past 4,500 years, it became clear that the organisms in different habitats reacted in different ways to either top-down or bottom-up forcing mechanisms. The changes in isotopic signatures of the species studied did not correspond to changes expected if species distribution and numbers changed in ways recently documented during PDO-like regime shifts and its effects on the GOA/NE Pacific waters.

SO were the only species that had a significant change in $\delta^{15}N$ over the six prehistoric time periods. It is possible that bottom-up processes such as changes in sea level might have affected kelp bed communities more than climate change and thus changed relative proportions of kelp-based versus pelagic fish diets. Top-down processes such as hunting pressures by humans may also have affected SO $\delta^{15}N$ by altering the kelp-forest community in which they foraged.

All modern animals, regardless of habitat size, location, and prey items, showed a significant decrease in $\delta^{13}C$ when compared to prehistoric ones. These changes are greater than those attributed to the Suess Effect, and at this time are best explained by the hypothesis that there has been an overall reduction in primary productivity in the Northeast Pacific in the late 20th century. The changes in $\delta^{13}C$ of salmon over the six time periods used in this study have yet another implication. It is possible that intensified AL may affect not only the primary productivity in deep ocean waters in the GOA, but perhaps the geographic locations where sockeye forage as well.

There appears to be some change in the marine environment ~1,200-800 cal yrs BP, which may have changed how $\delta^{13}C$ and $\delta^{15}N$ relate to one another in different species and/or different water bodies. $\delta^{13}C$ and $\delta^{15}N$ correlations in species foraging in different habitats (with the exception of salmon), changed during this time period, and suggests an adjustment across all ecosystems. These shifts may be localized for species such as cod or SO that are believed to have smaller foraging territories.

My research reveals advantages in analysis of $\delta^{13}C$ and $\delta^{15}N$ of bone collagen from archaeological middens as an effective tool for better understanding broad scale paleoenvironmental change.

Figures

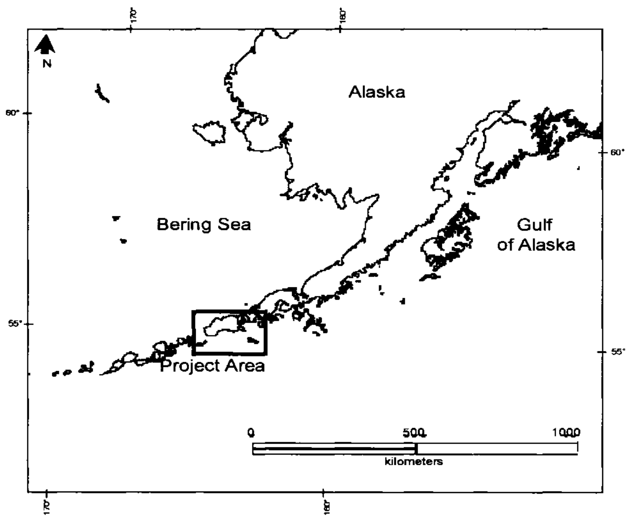

Figure 3.1: Location of study area in the Gulf of Alaska.

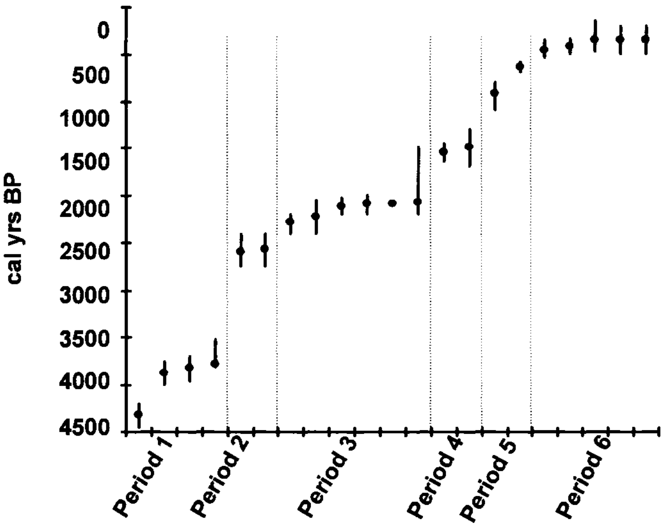

Figure 3.2: Calibrated radiocarbon ages of sites used for this study. Time periods were subdivided (vertical dashed lines) based on breaks in the radiocarbon age distribution.

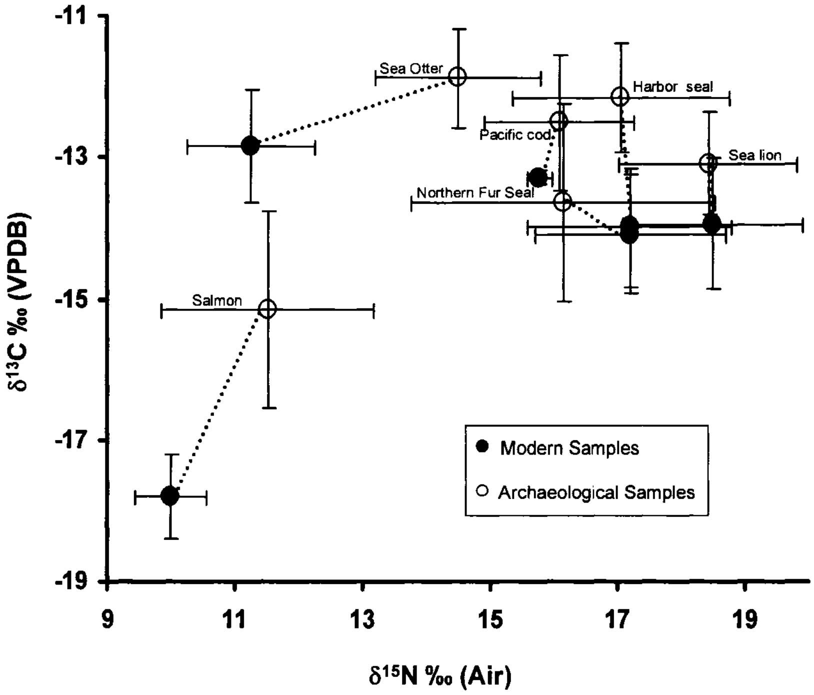

Figure 3.3: Means and standard deviations of bone collagen $\delta^{13}C$ and $\delta^{15}N$ from both modern and archaeological specimens. Modern data (~1950-2000 AD) from Satterfield (2000), Hirons (2001) and Appendix A have been corrected for the Suess Effect (see methods). Modern samples of cod and salmon are based on analysis of muscle and have been adjusted to collagen values based on the fractionation of $\delta^{13}C$ and $\delta^{15}N$ between muscle and collagen.

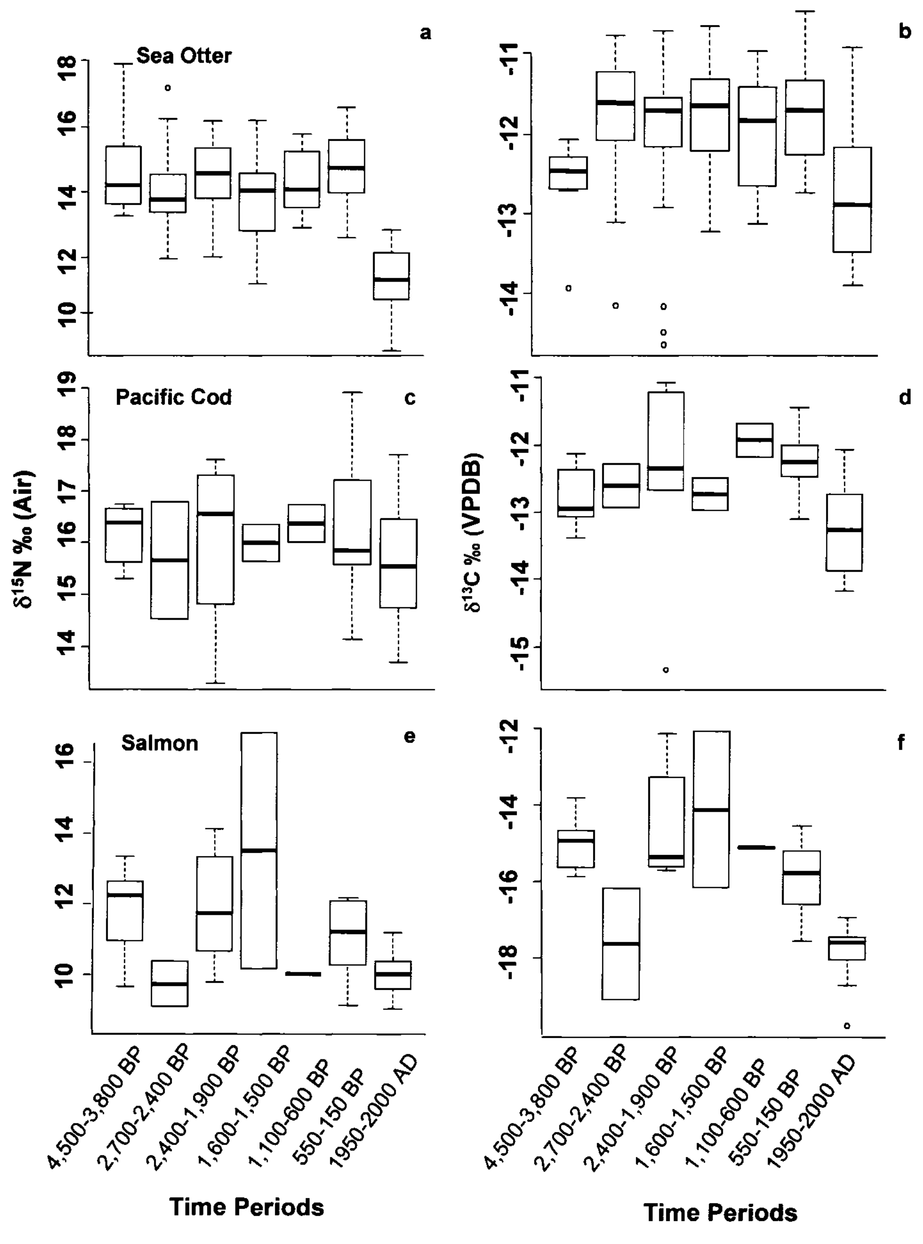

Figure 3.4: $\delta^{13}C$ and $\delta^{15}N$ medians and spread of SO, cod and salmon showing change over the six time periods discussed in the text. BP refers to calendar years before present. Modern data (~1950-2000 AD) from Satterfield (2000), Hirons (2001) and Appendix A have been corrected for the Suess Effect (see methods). Modern samples of cod and salmon are based on analysis of muscle and have been adjusted to collagen values based on the fractionation of $\delta^{13}C$ and $\delta^{15}N$ between muscle and collagen.

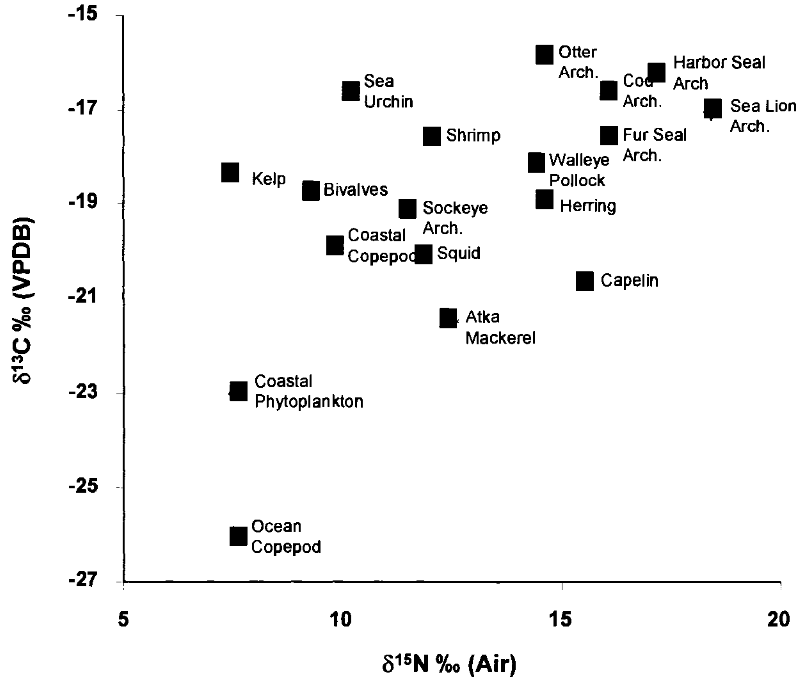

Figure 3.5: Trophic position of archaeological mammals and fish with some selected modern prey species. All samples corrected for fractionation between muscle tissue and bone collagen. Prey data compiled from: Schoeninger and DeNiro 1984; Duggins et al. 1989; Boutton 1991; Hobson and Welch 1992; Hobson et al. 1997; Satterfield 2000; Hirons 2001; Kline and Willette 2002.

Tables

Table 3.1. Radiocarbon dates of charcoal samples from sites referred to in this study. Calibrations were calculated using Calib 5.02 (Reimer et al. 2004).

Site	Laboratory #	Date (BP)	Cal Date (cal yrs BP)
XFP-31	CAMS 110652	2225±35	2200-2300
XFP-50	CAMS 110654	415±45	450-520
XFP-50	CAMS 90203	1640±40	1515-1570
XFP-52	CAMS 90212	190±40	145-215
XFP-52	CAMS 90207	420±40	460-515
XFP-56	CAMS 90213	920±40	950-1000
XFP-56	CAMS 110659	1005±50	900-970
XFP-56	CAMS 90206	1355±40	1260-1310
XFP-58	CAMS 110660	2070±35	2130-2160
XFP-61	CAMS 110662	2475±35	2760-2850
XFP-61	CAMS 110661	4515±40	5100-5360
XFP-63	CAMS 110664	2090±35	2040-2200
XFP-63	CAMS 110665	3360±40	3600-3695
XFP-67	CAMS 110666	2480±35	2540-2600
XFP-67	CAMS 110667	3050±30	3330-3385
XFP-96	CAMS 110675	1265±35	2090-2195
XFP-96	CAMS 110676	2115±35	2360-2400
XFP-96	CAMS 110677	2275±45	2350-2400
XFP-103	CAMS 110679	3550±35	3880-3950
XFP-103	CAMS 110680	3590±35	3890-4000
XFP-110	CAMS 110686	385±40	440-500
XFP-111	CAMS 127641	4040±35	4490-4540
XFP-111	CAMS 127700	4025±35	4480-4530
XFP-111	CAMS 110687	3870±35	4290-4350
XFP-115	CAMS 110690	2115±35	2090-2200
XFP-119	CAMS 110691	620±35	550-660
XFP-121	CAMS 110693	315±35	356-430
XFP-121	CAMS 110692	355±35	320-380
XFP-133	CAMS 127705	335±35	350-400
XFP-133	CAMS 127706	365±35	430-495
XFP-143	CAMS 110699	2115±30	2100-2190
XFP-143	CAMS 110698	3505±40	3770-3855

Table 3.2. Regional climate and ecological changes corresponding to the time periods of midden samples used in this study.

Time Period (cal yrs BP)	**Description***
Period 1 **(4,000-3,800)**	Onset of neoglaciation, lower temperatures, precipitation systematically higher than the past few thousand years in central coastal GOA, abrupt drop in SST, drop in numbers of returning salmon in lakes on Kodiak Island, sea level on Sanak Island ~4-5 meters above today's levels
(3,800-2,750)	No known archaeological sites with middens on Sanak Island
Period 2 **(2,750-2,400)**	Ice advance from 3,300-2,100 cal yrs BP in southern AK and GOA glaciers, temperatures still low, increase in numbers of salmon returning to Kodiak Island lakes, sea level on Sanak Island slowly dropping
Period 3 **(2,400-1,900)**	Drop in SST starting at 2,000 cal yrs BP with a low at 1,800 cal yrs BP, drop in numbers of returning sockeye, sea level on Sanak 2-3 meters above today's levels
(1,900-1,600)	No known archaeological sites with middens on Sanak Island
Period 4 **(1,600-1,500)**	Rise in SST until ~1,500 cal yrs BP then a slow drop, atmospheric temperature drop starting ~1,600 cal yrs BP, drop in numbers of returning sockeye in GOA lakes, sea level on Sanak slowly dropping towards today's levels
(1,500-1,100)	No known archaeological sites with middens on Sanak Island
Period 5 **(1,100-600)**	Onset of MWP, periods of higher temperatures between 900-850 cal yrs BP, 800-750 cal yrs BP and 600 cal yrs BP, decrease in SST at 1,000 cal yrs BP, decrease in sockeye returns around Alaska at 1,000 cal yrs BP then an increase from 900-850 BP a small decrease ~700 cal yrs BP, increase ~600 cal yrs BP, unlike the Bering and western Aleutians there is moderate atmospheric cooling in the GOA, eastern Aleutians from 1,100-750 cal yrs BP
(600-550)	No known archaeological sites with middens on Sanak Island
Period 6 **(550-150)**	LIA, drop in atmospheric temperatures, drop in SST ~500 cal yrs BP and advance of land-based glaciers, some fluctuation in sockeye salmon returns from 400 cal yrs BP on but overall increase during the LIA with a decreasing trend in all lakes in GOA at the end of the LIA

***Data from Huesser et al. 1985; Mann and Hamilton 1995; Finney et al. 2000, 2002; Gedalof and Mantua 2002; Calkin et al. 2001; Mann 2001; Kim et al. 2004; Savinetsky et al. 2004; Anderson et al. 2005; Causey et al. 2005; D'Arrigo et al. 2005; Jordan et al. 2005.**

Table 3.3. Location, number, sample type and mean isotopic value of archaeological and modern specimens.

Species	Location	# of Samples	Sample Type	Mean δ^{13}C ± S.D.[f]	Mean δ^{15}N ± S.D.
Archaeological					
E. lutris	Sanak	88	bone	-11.9 ± 0.8	14.5 ± 1.4
C. ursinus	Sanak	27	bone	-13.6 ± 1.4	16.1 ± 2.4
P. vitulina	Sanak	37	bone	-12.2 ± 0.8	17.1 ± 1.7
E. jubata	Sanak	15	bone	-13.1 ± 0.7	18.4 ± 1.4
G. macrocephalus	Sanak	101	bone	-12.5 ± 1.0	16.1 ± 1.2
O. nerka	Sanak	91	bone	-15.2 ± 1.4	11.5 ± 1.7
Modern					
E. lutris	GOA[d]	13	bone	-12.8 ± 0.9	11.3 ± 1.0
C. ursinus[a]	GOA[d]	10	bone	-14.1 ± 0.8	17.2 ± 1.5
P. vitulina[a]	GOA[d]	48	bone	-14.0 ± 0.8	17.2 ± 1.6
E. jubata[a]	GOA[d]	13	bone	-13.9 ± 0.9	18.5 ± 1.4
G. macrocephalus[a]	Alaska Pen.	29	bone/muscle[c]	-13.3 ± 0.0	15.8 ± 1.1
O. nerka[b]	GOA[d]	23	bone/muscle[c]	-17.8 ± 0.6	10.0 ± 0.5

Modern data from Hirons (2001)[a] and Satterfield (2000)[b].

[c] All modern fish muscle tissue has been corrected for fractionation difference between bone and muscle (see methods).

[d] GOA=Gulf of Alaska. All samples collected from Unimak Island to Kodiak Island and the western tip of the Kenai Peninsula.

[e] All modern carbon isotope values have been corrected to account for Suess Effect changes in the Eastern North Pacific (see methods).

Table 3.4. Summary of changes in Spearman's correlations of carbon and nitrogen isotopes by site dates before and after 1,000 cal yrs BP.

Species	**Before 1000 BP (r=)**	**After 1000 BP (r=)**
E. lutris	-0.52	0.26
C. ursinus	-0.66	0.90
P. vitulina	Not correlated	0.90
E. jubata	-0.40	0.50
G. macrocephalus	0.75	-0.37
Oncorhyncus ssp.	0.73	0.50

References

Alaska Department of Fish and Game (2006) Westward Region salmon escapement survey database. In. Alaska Department of Fish and Game, Division of Commercial Fisheries, Kodiak., p 10

Albers WD, Anderson PJ (1985) Diet of Pacific Cod, *Gadus macrocephalus*, and Predation on the Northern Pink Shrimp, *Pandalus borealis*, in Pavlof Bay, Alaska. Fishery Bulletin 83:601-610

Ambrose SH, Norr L (1993) Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: Lambert JB, Grupe G (eds) Prehistoric human bone-archaeology at the molecular level. Springer-Verlag, New York, pp 1-38

Anderson L, Abbott MB, Finney BP, Burns SJ (2005) Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 64:21-35

Anderson PJ, Piatt JF (1999) Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series 189:117-123

Baumgartner TR, Soutar A, Ferreirabartrina V (1992) Reconstruction of the history of Pacific sardine and northern anchovy populations over the past 2 millennia from sediments of the Santa-Barbara Basin, California. California Cooperative Oceanic Fisheries Investigations Reports 33:24-40

Beamish RJ (1993) Climate and exceptional fish production off the West Coast of North America. Canadian Journal of Fisheries and Aquatic Sciences 50:2270-2291

Beamish RJ, Bouillon DR (1993) Pacific salmon production trends in relation to climate. Canadian Journal of Fisheries and Aquatic Sciences 50:1002-1016

Beamish RJ, Noakes DJ, McFarlane GA, Klyashtorin L, Ivanov VV, Kurashov V (1999) The regime concept and natural trends in the production of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 56:516-526

Benson AJ, Trites AW (2002) Ecological effects of regime shifts in the Bering Sea and Eastern North Pacific Ocean. Fish and Fisheries 3:95-113

Betts MW, Tews AM (2007) 4,500 years of Aleut economic and ecosystem change on Sanak Island, Alaska. In: 72nd Annual Society for American Archaeology Conference Proceedings, Austin TX

Bligh EG, Dyer WJ (1959) A rapid method of total lipid extraction and purification. Canadian Journal of Biochemistry and Physiology 37:911-917

Bodkin JL, Esslinger GG, Monson DH (2004) Foraging depths of sea otters and implications to coastal marine communities. Marine Mammal Science 20:305-321

Bond NA, Overland JE, Spillane M, Stabeno P (2003) Recent shifts in the state of the North Pacific. Geophysical Research Letters 30

Botsford LW, Castilla JC, Peterson CH (1997) The management of fisheries and marine ecosystems. Science 277:509-515

Boutton TW (1991) Stable carbon isotope ratios of natural materials: II. Atmospheric, terrestrial, marine, and freshwater environments. In: Coleman DC, Fry B (eds) Carbon isotope techniques. Academic Press, San Diego, pp 173-185

Brodeur RD, Ware DM (1992) Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fisheries Oceanography 1:32-38

Burgner R (1991) Life history of sockeye salmon (*Oncorhynchus nerka*). In: Groot C, Margolis L (eds) Pacific salmon life histories. UBC Press, Vancouver, pp 1-118

Burton RK, Gifford-Gonzalez D, Snodgrass JJ, Koch PL (2002) Isotopic tracking of prehistoric pinniped foraging and distribution along the central California Coast: preliminary results. International Journal of Osteoarchaeology 12:4-11

Burton RK, Koch PL (1999) Isotopic tracking of foraging and long-distance migration in Northeastern Pacific pinnipeds. Oecologia 119:578-585

Burton RK, Snodgrass JJ, Gifford-Gonzalez D, Guilderson T, Brown T, Koch PL (2001) Holocene changes in the ecology of northern fur seals: insights from stable isotopes and archaeofauna. Oecologia 128:107-115

Calkin PE, Wiles G, Barclay DJ (2001) Holocene coastal glaciation of Alaska. Quaternary Science Reviews 20:449-461

Call KA, Loughlin TR (2005) An ecological classification of Alaskan Steller sea lion (*Eumetopias jubatus*) rookeries: a tool for conservation/management. Fisheries Oceanography 14:212-222

Causey D et al. (2005) The palaeoenvironment of humans and marine birds of the Aleutian Islands: three millennia of change. Fisheries Oceanography 14:259-276

Ciannelli L, Bailey KM (2005) Landscape dynamics and resulting species interactions: the cod-capelin system in the Southeastern Bering Sea. Marine Ecology Progress Series 291:227-236

Clark DW (1986) Archaeological and historical evidence for an 18th-century "blip" in the distribution of the northern fur seal at Kodiak Island, Alaska. Arctic 39:39-42

D'Arrigo R, Mashig E, Frank D, Wilson R, Jacoby G (2005) Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. Climate Dynamics 24:227-236

Dayton PK (1985) Ecology of kelp communities. Annual Review of Ecology and Systematics 16:215-245

deHart PAP, Stegall VK, Finney BP, Koch PL, Wooller MJ (submitted) An investigation of the historical ecology of Steller sea lions using stable isotopes. Marine Mammal Science

DeNiro M, Epstein S (1981) Influence of diet on the distribution of nitrogen isotopes in animals. Geochimica et Cosmochimica Acta 45:341-351

DeNiro M, Schoeninger MJ (1983) Stable carbon and nitrogen isotope ratios of bone collagen: variations within individuals, between sexes, and within populations raised on monotonous diets. Journal of Archaeological Science 10:199-203

Doroff AM, Estes JA, Tinker MT, Burn DM, Evans TJ (2003) Sea otter population declines in the Aleutian archipelago. Journal of Mammalogy 84:55-64

Doucett RR, Power G, Barton DR, Drimmie RJ, Cunjak RA (1996) Stable isotope analysis of nutrient pathways leading to Atlantic salmon. Canadian Journal of Fisheries and Aquatic Sciences 53:2058-2066

Duggins DO, Simenstad CA, Estes JA (1989) Magnification of secondary production by kelp detritus in coastal marine ecosystems. Science 245:170-173

Estes JA, Duggins DO (1995) Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. Ecological Monographs 65:75-100

Estes JA, Tinker MT, Williams TM, Doak DF (1998) Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282:473-476

Estes JA, Riedman ML, Staedler MM, Tinker MT, Lyon BE (2003) Individual variation in prey selection by sea otters: patterns, causes and implications. Journal of Animal Ecology 72:144-155

Etnier MA (2002) The effects of human hunting on northern fur seal (*Callorhinus ursinus*) migration and breeding distributions in the late Holocene. In: Department of Anthropology. University of Washingotn, Seattle Washington

Fadely BS, Robson BW, Sterling JT, Greig A, Call KA (2005) Immature Steller sea lion (*Eumetopias jubatus*) dive activity in relation to habitat features of the eastern Aleutian Islands. Fisheries Oceanography 14:243-258

Finney BP, Gregory-Eaves I, Douglas MSV, Smol JP (2002) Fisheries productivity in the Northeastern Pacific Ocean over the past 2,200 years. Nature 416:729-733

Finney BP, Gregory-Eaves I, Sweetman J, Dougas MSV, Smol JP (2000) Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. Science 290:795-799

Francis RC, Hare SR (1994) Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science. Fisheries Oceanography 3:279-291

Francis RC, Hare SR, Hollowed AB, Wooster WS (1998) Effects of interdecadal climate variability on the oceanic ecosystems of the Northeast Pacific. Fisheries Oceanography 7:1-21

Freeland H, Denman K, Wong CS, Whitney F, Jacques R (1997) Evidence of change in the winter mixed layer in the Northeast Pacific Ocean. Deep-Sea Research Part I-Oceanographic Research Papers 44:2117-2129

Frost KJ, Lowry LF, VerHoef JM (1999) Monitoring the trend of harbor seals in Prince William Sound, Alaska, after the Exxon Valdez oil spill. Marine Mammal Science 15:494-506

Fry B, Sherr EB (1984) δ^{13}C Measurements as Indicators of Carbon Flow in Marine and Freshwater Ecosystems. Contributions to Marine Science 27:13-47

Gargett AE (1997) The optimal stability 'window': a mechanism underlying decadal fluctuations in North Pacific salmon stocks? Fisheries Oceanography 6:109-117

Gedalof Z, Mantua NJ (2002) A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophysical Research Letters 29:2204-2208

Gentry RL (1998) Behavior and ecology of the northern fur seal. Princeton University Press, Princeton, NJ

Goericke R, Montoya JP, Fry B (1994) Physiology of isotopic fractionation in algae and cyanobacteria. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publication, London, pp 187-221

Graham MH, Dayton PK, Erlandson JM (2003) Ice ages and ecological transitions on temperate coasts. Trends in Ecology & Evolution 18:33-40

Grayson DK (1984) Quantitative zooarchaeology: topics in the analysis of archaeological faunas. Academic Press, Inc., New York

Gruber N et al. (1999) Spatiotemporal patterns of carbon-13 in the global surface oceans and the Oceanic Suess Effect. Global Biogeochemical Cycles 13:307-335

Guilderson TP, Roark EB, Quay PD, Page SRF, Moy C (2006) Seawater radiocarbon evolution in the Gulf of Alaska: 2002 observations. Radiocarbon 48:1-15

Hare SR, Francis RC (1995) Climate change and salmon production in the Northeast Pacific Ocean. In: Beamish RJ (ed) Climate change and northern fish populations, vol 121. Canada Special Publication of Fisheries and Aquatic Sciences, pp 357-372

Hare SR, Mantua NJ (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145

Hare SR, Mantua NJ, Francis RC (1999) Inverse production regimes: Alaska and West Coast Pacific salmon. Fisheries 24:6-14

Hedges RE, Stevens RE, Koch PL (2005) Isotopes in bones and teeth. In: Leng MJ (ed) Isotopes in palaeoenvironmental research. Springer, The Netherlands, pp 117-145

Hilton GM, Thompson DR, Sagar PM, Cuthbert RJ, Cherel Y, Bury SJ (2006) A stable isotopic investigation into the causes of decline in a sub-Antarctic predator, the rockhopper penguin (*Eudyptes chrysocome*). Global Change Biology 12:611-625

Hirons AC, Schell DM, Finney BP (2001) Temporal records of delta C-13 and delta N-15 in North Pacific pinnipeds: inferences regarding environmental change and diet. Oecologia 129:591-601

Hirons AC (2001) Trophic dynamics of pinniped populations in Alaska using stable carbon and nitrogen isotope ratios. Institute of Marine Science. University of Alaska, Fairbanks

Hobson KA, Schell DM, Renouf D, Noseworthy E (1996) Stable carbon and nitrogen isotopic fractionation between diet and tissues of captive seals: implications for dietary reconstructions involving marine mammals. Canadian Journal of Fisheries and Aquatic Sciences 53:528-533

Hobson KA, Sease JL, Merrick RL, Piatt JF (1997) Investigating trophic relationships of pinnipeds in Alaska and Washington using stable isotope ratios of nitrogen and carbon. Marine Mammal Science 13:114-132

Hobson KA, Sinclair EH, York AE, Thomason JR, Merrick RE (2004) Retrospective isotopic analyses of Steller sea lion tooth annuli and seabird feathers: a cross-taxa approach to investigating regime and dietary shifts in the Gulf of Alaska. Marine Mammal Science 20:621-638

Hobson KA, Welch HE (1992) Determination of trophic relationships within a high arctic marine food web using delta-C-13 and delta-N-15 analysis. Marine Ecology-Progress Series 84:9-18

Hollowed AB, Wooster WS (1992) Variability of winter ocean conditions and strong year classes of Northeast Pacific groundfish. ICES Marine Science Symposia 195:433-444

Huesser CJ, Huesser LE, Peteet DM (1985) Late-Quaternary climate change on the American North Pacific Coast. Nature 315:485-487

Hunt GL, Stabeno PJ (2005) Oceanography and ecology of the Aleutian Archipelago: spatial and temporal variation. Fisheries Oceanography 14:292-306

Iverson SJ, Frost KJ, Lowry LF (1997) Fatty acid signatures reveal fine scale structure of foraging distribution of harbor seals and their prey in Prince William Sound, Alaska. Marine Ecology-Progress Series 151:255-271

Jackson JBC et al. (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638

Jordan JW, Finney BP, Odorczuk D, Misarti N, Maschner H (2005) Paleoecology of the Sanak Archipelago. In: 70th Annual Society for American Archaeology Meeting, Salt Lake City, Utah

Kenyon KW (1969) The sea otter in the Eastern Pacific Ocean. Dover Publishers

Kim JH et al. (2004) North Pacific and North Atlantic sea-surface temperature variability during the Holocene. Quaternary Science Reviews 23:2141-2154

Kline TC, Willette TM (2002) Pacific salmon (*Oncorhynchus* spp.) early marine feeding patterns based on N-15/N-14 and C-13/C-12 in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 59:1626-1638

Koch PL, Fogel ML, Tuross N (1994) Tracing the diets of fossil animals using stable isotopes. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publications, London, pp 63-92

Kvitek RG, Oliver JS (1992) Influence of sea otters on soft-bottom prey communities in Southeast Alaska. Marine Ecology-Progress Series 82:103-113

Ladd C, Hunt GL, Mordy CW, Salo SA, Stabeno PJ (2005) Marine environments of the eastern and central Aleutian Islands. Fisheries Oceanography 14:22-38

Lambert JB, Grupe G (1993) Prehistoric human bone: archaeology at the molecular level. Springer-Verlag, New York

Laws EA, Popp BN, Bidigare RR, Kennicutt MC, Macko SA (1995) Dependence of phytoplankton carbon isotopic composition on growth rate and CO_2 (Aq) - theoretical considerations and experimental results. Geochimica et Cosmochimica Acta 59:1131-1138

Logerwell EA et al. (2005) Geographic patterns in the demersal ichthyofauna of the Aleutian Islands. Fisheries Oceanography 14:93-112

Lowry LF, Frost KJ, VerHoef JM, DeLong RA (2001) Movements of satellite-tagged subadult and adult harbor seals in Prince William Sound, Alaska. Marine Mammal Science 17:835-861

MacDonald GM, Case RA (2005) Variations in the Pacific Decadal Oscillation over the past millennium. Geophysical Research Letters 32

Mann DH (2001) Climate during the past millennium. Weather 56:91-102

Mann DH, Hamilton TD (1995) Late Pleistocene and Holocene paleoenvironments of the North Pacific coast. Quaternary Science Reviews 14:449-471

Mantua N (2004) Methods for detecting regime shifts in large marine ecosystems: a review with approaches applied to North Pacific data. Progress in Oceanography 60:165-182

Mantua NJ, Hare SR (2002) The Pacific decadal oscillation. Journal of Oceanography 58:35-44

Maschner H (2000) Catastrophic change and regional interaction: the southern Bering Sea in a dynamic world system. In: Appelt M, Berglund J, Gullov HC (eds) Identities and cultural contacts in the Arctic: proceedings from a conference at the Danish National Museum, November 30-December 2, 1999, Vol 8. Danish National Museum, Copenhagen, pp 252-265

Matheus P (1997) Laboratory procedures for extracting and purifying collagen from fossil and modern bone. Institute of Marine Science, University of Alaska-Fairbanks

McRoy CP, Gradinger R, Springer AM, Bluhm B, Iverson SJ, Budge S (2004) Stable isotopes reveal food web shifts due to arctic sea ice decline. In: AGU 2004 Joint Assembly, vol. EOS Transactions B34A-05, Montreal, Canada

Michener RH, Schell DM (1994) Stable isotope ratios as tracers in marine aquatic food webs. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publication, London, pp 136-156

Mueter FJ (2004) Gulf of Alaska. In: PICES Report on marine ecosystems of the North Pacific, North Saanich, BC, pp 129-150

Mueter FJ, Ware DM, Peterman RM (2002) Spatial correlation patterns in coastal environmental variables and survival rates of salmon in the north-east Pacific Ocean. Fisheries Oceanography 11:205-218

Newsome SD, Etnier MA, Kurle CM, Waldbauer JR, Chamberlain CP, Koch PL (2007) Historic decline in primary productivity in the western Gulf of Alaska and eastern Bering Sea: isotopic analysis of northern fur seal teeth. Marine Ecology-Progress Series 332:211-224

Newsome SD, Koch PL, Etnier MA, Aurioles-Gambao D (2006) Using carbon and nitrogen isotope values to investigate maternal strategies in northeast Pacific otariids. Marine Mammal Science 22:556-572

Niebauer HJ (1998) Variability in Bering Sea ice cover as affected by a regime shift in the North Pacific in the period 1947-1996. Journal of Geophysical Research-Oceans 103:27717-27737

Ortiz JD, Mix AC, Wheeler PA, Key RM (2000) Anthropogenic CO_2 invasion into the northeast Pacific based on concurrent delta C-13(DIC) and nutrient profiles from the California Current. Global Biogeochemical Cycles 14:917-929

Overland JE, Adams JM, Bond NA (1999) Decadal variability of the Aleutian Low and its relation to high-latitude circulation. Journal of Climate 12:1542-1548

Overland JE, Stabeno PJ (2004) Is the climate of the Bering Sea warming and affecting the ecosystem? EOS 85:309-316

Parkinson CL, Cavalieri DJ (2002) A 21 year record of Arctic sea-ice extents and their regional, seasonal and monthly variability and trends. In: Annals of Glaciology, Vol 34, 2002, pp 441-446

Pitcher KWa (1980) Food of the Harbor Seal, *Phoca vitulina* in the Gulf of Alaska. Fishery Bulletin 78:544-549

Pitcher KWb (1980) Stomach contents and feces as indicators of Harbor Seal, *Phoca vitulina*, foods in the Gulf of Alaska. Fishery Bulletin 78:797-798

Pitcher KW (1990) Major decline in number of harbor seals, *Phoca vitulina richardsi*, on Tugidak Island, Gulf of Alaska. Marine Mammal Science 6:121-134

Post DM (2002) Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83:703-718

Quay P, Sonnerup R, Westby T, Stutsman J, McNichol A (2003) Changes in the C-13/C-12 of dissolved inorganic carbon in the ocean as a tracer of anthropogenic CO_2 uptake. Global Biogeochemical Cycles 17

Quay PD, Tilbrook B, Wong CS (1992) Oceanic uptake of fossil-fuel CO_2 C-13 evidence. Science 256:74-79

Reimer PJ et al. (2004) IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon 46:1029-1058

Reisewitz SE, Estes JA, Simenstad CA (2006) Indirect food web interactions: sea otters and kelp forest fishes in the Aleutian archipelago. Oecologia 146:623-631

Rodionov SN, Overland JE, Bond NA (2005) Spatial and temporal variability of the Aleutian climate. Fisheries Oceanography 14:3-21

Roemmich D, McGowan J (1995) Climatic warming and the decline of zooplankton in the California Current (Vol 267, Pg 1324, 1995). Science 268:352-353

Satterfield FR (2000) A comparison of sockeye salmon (*Oncorhynchus nerka*) in two climate regimes in the North Pacific Ocean using stable carbon and nitrogen isotope ratios. In: Institute of Marine Science. University of Alaska, Fairbanks, AK

Satterfield FR, Finney BP (2002) Stable isotope analysis of Pacific salmon: insight into trophic status and oceanographic conditions over the last 30 years. Progress in Oceanography 53:231-246

Savinetsky AB, Kiseleva NK, Khassanov BF (2004) Dynamics of sea mammal and bird populations of the Bering Sea region over the last several millennia. Palaeogeography Palaeoclimatology Palaeoecology 209:335-352

Schell DM (2000) Declining carrying capacity in the Bering Sea: isotopic evidence from whale baleen. Limnology and Oceanography 45:459-462

Schell DM (2001) Carbon isotope ratio variations in Bering Sea biota: the role of anthropogenic carbon dioxide. Limnology and Oceanography 46:999-1000

Schoeninger MJ, DeNiro M (1984) Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochimica et Cosmochimica Acta 48:625-639

Simenstad CA, Duggins DO, Quay PD (1993) High turnover of inorganic carbon in kelp habitats as a cause of delta-C-13 variability in marine food webs. Marine Biology 116:147-160

Simenstad CA, Estes JA, Kenyon KW (1978) Aleuts, sea otters and alternative stable-state communities. Science 200:403-411

Sinclair EH, Moore SE, Friday NA, Zeppelin TK, Waite JM (2005) Do patterns of Steller sea lion (*Eumetopias jubatus*) diet, population trend and cetacean occurrence reflect oceanographic domains from the Alaska Peninsula to the central Aleutian Islands? Fisheries Oceanography 14:223-242

Sinclair EH, Zeppelin TK (2002) Seasonal and spatial differences in diet in the western stock of Steller sea lions (*Eumetopias jubatus*). Journal of Mammalogy 83:973-990

Springer AM et al. (2003) Sequential megafaunal collapse in the North Pacific Ocean: an ongoing legacy of industrial whaling? Proceedings of the National Academy of Sciences of the United States of America 100:12223-12228

Stabeno PJ, Hunt GL, Macklin SA (2005) Introduction to processes controlling variability in productivity and ecosystem structure of the Aleutian Archipelago. Fisheries Oceanography 14:1-2

Steneck RS et al. (2002) Kelp forest ecosystems: biodiversity, stability, resilience and future. Environmental Conservation 29:436-459

Sugimoto T, Tadokoro K (1998) Interdecadal variations of plankton biomass and physical environment in the North Pacific. Fisheries Oceanography 7:289-299

Tanaka T, Watanabe YW, Watanabe S, Noriki S, Tsurushima N, Nojiri Y (2003) Oceanic Suess Effect of delta C-13 in subpolar region: the North Pacific. Geophysical Research Letters 30

Tews AM (2005) Prehistoric Eastern Aleut subsistence; 5,000 years of faunal variations. In: Department of Anthropology. Idaho State University, Pocatello, ID, pp 1-243

Trites AW (1992) Northern fur seals: why have they declined? Aquatic Mammals 18:3-18

Tuross N, Fogel ML, Hare PE (1988) Variability in the preservation of the isotopic composition of collagen from fossil bone. Geochimica et Cosmochimica Acta 52:929-935

Venrick EL, McGowan JA, Cayan DR, Hayward TL (1987) Climate and chlorophyll-a: long-term trends in the Central North Pacific Ocean. Science 238:70-72

Wada E, Mizutani H, Minagawa M (1991) The use of stable isotopes for food web analysis. Critical Reviews in Food Science and Nutrition 30:361-371

Ware DM (1995) A century and a half of change in the climate of the Northeast Pacific. Fisheries Oceanography 4:267-277

Ware DM, Thomson RE (1991) Link between long-term variability in upwelling and fish production in the Northeast Pacific Ocean. Canadian Journal of Fisheries and Aquatic Sciences 48:2296-2306

Watt J, Siniff DB, Estes JA (2000) Inter-decadal patterns of population and dietary change in sea otters at Amchitka Island, Alaska. Oecologia 124:289-298

Welch DW, Ishida Y, Nagasawa K (1998) Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Canadian Journal of Fisheries and Aquatic Sciences 55:937-948

Welch DW, Parsons TR (1993) $\delta^{13}C$ - $\delta^{15}N$ values as indicators of trophic position and competitive overlap for Pacific salmon (*Oncorhynchus* spp.). Fisheries Oceanography 2:11-23

Williams B, Risk M, Stone R, Sinclair D, Ghaleb B (2007) Oceanographic changes in the North Pacific Ocean over the past century recorded in deep-water gorgonian corals. Marine Ecology-Progress Series 335:85-94

Willis RH, Ball EM (1930) Statistical review of the Alaska salmon fisheries Part I: Bristol Bay and the Alaska Peninsula. In: Bulletin of the United States Bureau of Fisheries Vol. XLIV. Department of Commerce, Washington DC, p 673

Wynne K, Foy R (2002) Is it food now? Gulf Apex Predator-Prey study. In: DeMaster D, Atkinson S (eds) Steller sea lion decline: is it food II?, vol. AK-SG-02-02. University of Alaska Sea Grant Program, Fairbanks, p 80

Yang MS (2004) Diet changes of Pacific cod (*Gadus macrocephalus*) in Pavlof Bay associated with climate changes in the Gulf of Alaska between 1980 and 1995. Fishery Bulletin 102:400-405

York AE (1995) The relationship of several environmental indices to the survival of juvenile male northern fur seals (*Callorhinus ursinus*) from the Pribilof Islands. In: Beamish RJ (ed) Climate change and northern fish populations, vol 121. Canadian Special Publication of Fisheries and Aquatic Sciences, pp 317-327

Appendix A

Fractionation of muscle tissue to collagen of $\delta^{15}N$ and $\delta^{13}C$ in large Northeast Pacific fish

Introduction

Isotope analyses in archaeological studies have been utilized for many years and in many forms. Most of the studies have been conducted on human remains in order to pinpoint transitions to agriculture (the transition from C_3 to C_4 plants using carbon isotopes), geographical areas people inhabited (using strontium and barium isotopes or carbon and nitrogen isotopes), or simply how much of a particular food type was being consumed (such as marine versus terrestrial using carbon and nitrogen isotopes) (DeNiro 1987; Sealy et al. 1991; Lambert and Grupe 1993; Pate 1994; Ezzo et al. 1997; Lambert 1997; Price et al. 1998, 2000, 2002; Lee-Thorpe and Sponheimer 2003; Schweissing and Grupe 2003; Knudson et al. 2004; Newsome et al. 2004). Recently, paleoecologists have utilized remains from archaeological middens in order to reconstruct past environmental and/or ecosystem changes (Burton and Koch 1999; Burton et al. 2001, 2002; Hirons et al. 2001; Newsome et al. 2006, 2007; DeHart et al. submitted). All of these studies based on archaeological midden remains utilize analysis of bone collagen and/or tooth dentin. These are interesting and exciting data sets, but in order to compare past and present environments it is often necessary to compare bone collagen data sets to modern day ecological data sets that rarely use bone collagen.

Ecologists have determined fractionation between different types of tissue for many species through comparative studies of muscle to hair, vibrissae, internal organs, scales of fish, blubber of sea mammals, feathers of birds etc., but rarely are collagen data included in these studies (Tiezsen et al. 1983; Farquhar et al. 1989; Hobson and Clark 1992; Hobson et al. 1996, 1997; Satterfield 2000; Hirons 2001; Vander-Zanden and Rasmussen 2001; Satterfield and Finney 2002; Greave et al. 2004; Newsome et al. 2006). There are a few studies on the fractionation between muscle tissue and collagen for mammals (Schoeninger and DeNiro 1984; Koch et al. 1994; Hedges et al. 2005), however, there are no such studies for large fish (although see Sholto-Douglas et al. 1991), a major contributor to archaeological midden remains in many coastal and some inland sites. This research paper aims to determine the fractionation between muscle and bone collagen of large fish that inhabit colder ocean waters. In this case three salmon species and Pacific cod [*Oncorhyncus nerka* (sockeye), *Oncorhyncus kisutch* (coho), *Oncorhyncus tshawytshaw* (chinook) and *Gadus macrocephalus* (Pacific cod)] were analyzed for carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$ respectively) of bone collagen, muscle tissue and lipid extracted muscle tissue.

Methods

Sample preparation and stable isotope analysis

Collagen samples were prepared using bone collagen extraction procedures described by Matheus (1997). Slices of compact, cortical bone weighing between 0.1 and 1.0 grams were cleaned in a sonicator. Lipids were removed using a methanol/chloroform procedure (Bligh and Dyer 1959) and bones were then demineralized in 6N HCl and ultra-pure water. The samples were next rinsed to neutral pH with ultra-pure water. Samples were gelatinized by adding 0.05 ml of 3N HCl to 5 ml of ultra-pure water and heated to 65 °C. The samples were filtered and lyophilized at -75 °C for 48 hours.

Muscle tissue was collected from areas that visually appeared to be predominantly muscle with no skin or fatty tissues attached. The muscle was rinsed thoroughly with ultra-pure water and samples from each fish were divided in two. One half was treated to remove lipids using a methanol/chloroform procedure (Bligh and Dyer 1959) and then rinsed several times. All muscle samples were lyophilized at -75 °C for 48 hours.

Analysis of all samples was completed in the Alaska Stable Isotope Facility, University of Alaska Fairbanks. Stable isotope ratios are expressed in the standard notation:

$$\delta X\ (‰) = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$$

where X is ^{13}C or ^{15}N and R_{sample} is $^{13}C/^{12}C$ or $^{15}N/^{14}N$ respectively. $\delta^{13}C$ and $\delta^{15}N$ are expressed relative to Vienna Pee Dee Belemnite (VPDB) and atmospheric N_2 (air), respectively. Samples were analyzed on a Finnigan Delta^{plus}XP IRMS and analytical precision, established by analysis of multiple analyses of a peptone standard throughout each run, was ~ ±0.2‰ for both carbon and nitrogen.

Results and Discussion

The mean C:N calculated for the bone samples was 3.4 ±0.1 and falls within the range of values (2.9-3.6) considered to be indicative of collagen that has not undergone any diagenesis (Tuross et al. 1988; Koch et al. 1994; Hedges et al. 2005). Sockeye (n=7) do not appear to differ greatly from one another regardless of geographical location or marine versus freshwater locations (Table A.1). Coho salmon (n=3) were recovered only from marine waters but geographic location does not appear to influence δ^{13}C and δ^{15}N either (Table A.1). Only one chinook salmon and one Pacific cod were analyzed and so no comparisons were possible (Table A.1).

The differences in δ^{13}C and δ^{15}N between lipid extracted muscle tissue and un-treated muscle tissue were minimal (mean 0.2 ± 0.7‰ and 0.1 ± 0.0‰ respectively). This is probably due to the fact that the muscle tissue was trimmed of any fatty portions before processing. δ^{13}C in bone collagen of large fish that inhabit cold ocean waters is ~2.5‰ greater than muscle tissue while δ^{15}N in bone collagen is ~0.8 to 1.0‰ less (Table A.1; Figure A.1). These results are very different from those published for fractionation of mammal tissue to collagen. δ^{13}C in bone collagen is generally 5‰ greater than in an animals' diet (Schoeninger and DeNiro 1984; Koch et al. 1994; Hedges et al. 2005) while muscle tissue is 0.5 to 1.0‰ greater. Therefore, in order to compare them with bone collagen, one would increase muscle tissue sample $\delta^{13}C$ by ~4‰. No $\delta^{15}N$ fractionation between muscle tissue and bone collagen of mammals has been determined in these studies (Schoeninger and DeNiro 1984).

Conclusion

Sockeye and silver salmon, as well as Pacific cod, fell within the mean fractionation for all samples. The one chinook sample did not fall within the mean, although it is unclear as to why this may have occurred. There is very little difference in either $\delta^{13}C$ or $\delta^{15}N$ between lipid extracted muscle tissue and non-lipid extracted tissues. These results show that even in fish with known high lipid content such as salmon species, relatively pure muscle tissue samples were obtained. I have also shown that the fractionation of muscle tissue to collagen in large fish from cold ocean waters is very different than that of sea mammals. $\Delta^{13}C$ between muscle tissue and collagen is ~2.5 ± 1.8‰ and $\Delta^{15}N$ is ~ -1.0 ± 0.3‰. Species of fish, prey items and foraging habitat do not appear to affect fractionation of muscle tissue to collagen or lipid content of muscle tissue.

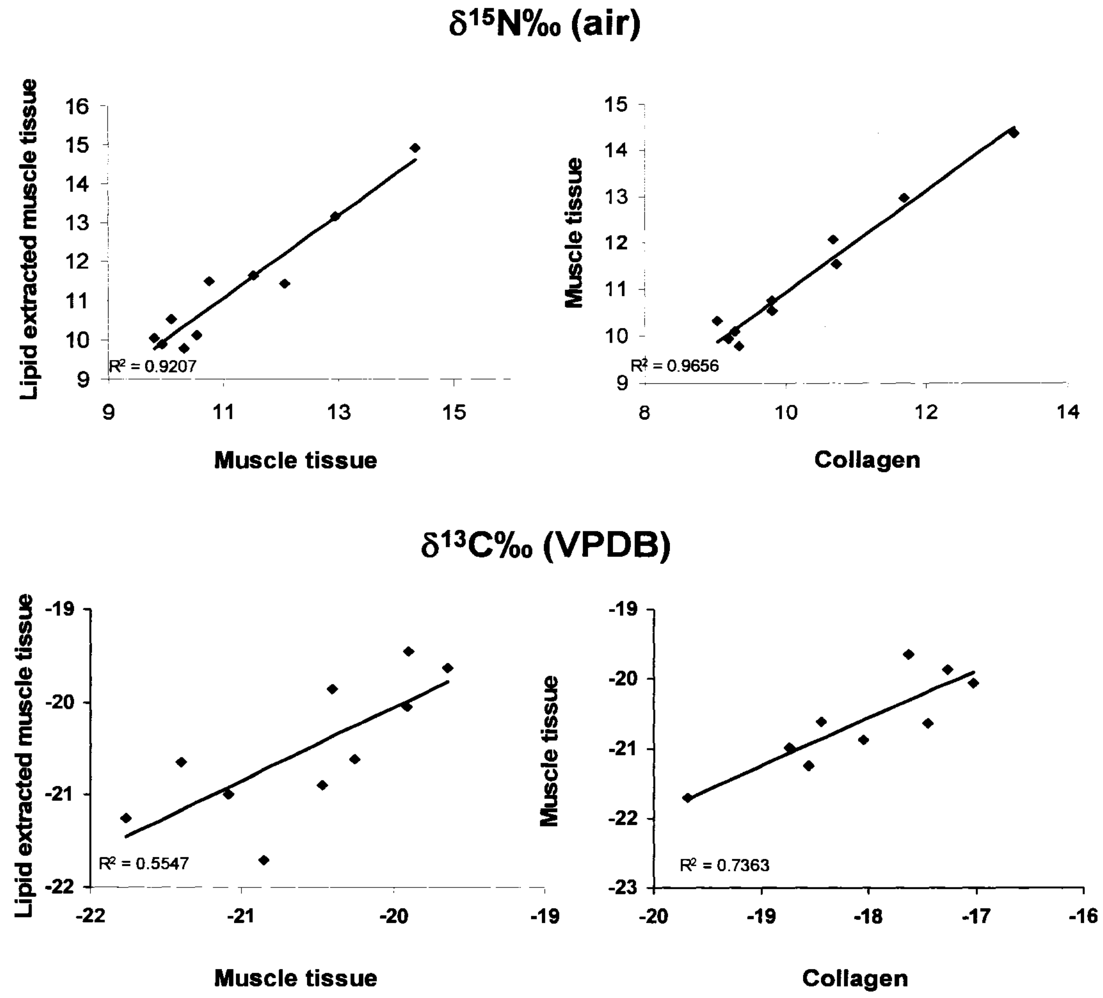

Figure A.1. Linear regressions and r^2 values of lipid extracted muscle tissue, non-lipid extracted muscle tissue and muscle tissue and collagen of both $\delta^{15}N$ and $\delta^{13}C$.

Table A.1: Results of isotopic analysis. Differences and means of differences between lipid and non-lipid extracted muscle tissue and collagen and lipid and non-lipid extracted tissue.

δ^{15}N (Air) ‰

	Fish sample	Collagen (C)	Tissue (T)	Lipid extracted tissue (LT)		T-C Δ^{15}N	LT-C Δ^{15}N	LT-T Δ^{15}N
Chitna River-sockeye	R1	9.34	9.79	10.03		0.45	0.69	0.24
Chitna River-sockeye	R2	9.28	10.09	10.52		0.81	1.24	0.43
Yukon River-sockeye	R3	9.19	9.93	9.88		0.74	0.69	-0.05
Chitna River-sockeye	R4	9.81	10.75	11.5		0.94	1.69	0.75
Kodiak-sockeye	R5	9.03	10.32	9.78		1.29	0.75	-0.54
Unalaska-sockeye	R6	11.18	10.87	9.73		-0.31	-1.45	-1.14
Unalaska-sockeye	R7	9.8	10.53	10.11		0.73	0.31	-0.42
Valdez-coho	S1	11.67	12.96	13.14		1.29	1.47	0.18
Unalaska-coho	S2	10.67	12.07	11.42		1.4	0.75	-0.65
Unalaska-coho	S3	10.73	11.52	11.62		0.79	0.89	0.10
Yukon River-chinook	K1	13.24	14.35	14.9		1.11	1.66	0.55
Pavlof -cod	C1	16.55	17.1	17.56		0.55	1.01	0.46
					Mean (no R6)*:	**0.92**	**1.00**	**0.10**
					Mean:	**0.80**	**0.81**	**0.01**
					St. Dev:	**0.32**	**0.45**	**0.46**

δ^{13}C (VPDB) ‰

	Fish sample	Collagen (C)	Tissue (T)	Lipid extracted tissue (LT)	T-C Δ^{13}C	LT-C Δ^{13}C	LT-T Δ^{13}C
Chitna River-sockeye	R1	-18.06	-22.97	-21.04	-4.91	-2.98	1.93
Chitna River-sockeye	R2	-19.69	-21.71	-20.85	-2.02	-1.16	0.86
Yukon River-sockeye	R3	-18.73	-20.99	-21.09	-2.26	-2.36	-0.10
Chitna River-sockeye	R4	-18.05	-20.89	-20.47	-2.84	-2.42	0.42
Kodiak-sockeye	R5	-18.56	-21.25	-21.76	-2.69	-3.2	-0.51
Unalaska-sockeye	R6	-17.03	-20.06	-19.91	-3.03	-2.88	0.15
Unalaska-sockeye	R7	-17.45	-20.65	-21.4	-3.2	-3.95	-0.75
Valdez-coho	S1	-18.44	-20.62	-20.25	-2.18	-1.81	0.37
Unalaska-coho	S2	-17.26	-19.86	-20.4	-2.6	-3.14	-0.54
Unalaska-coho	S3	-17.62	-19.64	-19.64	-2.02	-2.02	0.00
Yukon River-chinook	K1	-22.54	-19.45	-19.9	3.09	2.64	-0.45
Pavlof Bay -cod	C1	-13.33	-16.61	-15.81	-3.28	-2.48	0.80

Table A.1 (cont.)

Mean (no K1)*:	**-2.82**	**-2.58**	**0.24**
Mean:	**-2.33**	**-2.15**	**0.18**
St. Dev:	**1.88**	**1.67**	**0.76**

* R6 and K1 were removed from calculations due to possible laboratory or instrument error.

References

Bligh EG, Dyer WJ (1959) A rapid method of total lipid extraction and purification. Canadian Journal of Biochemistry and Physiology 37:911-917

Burton RK, Koch PL (1999) Isotopic tracking of foraging and long-distance migration in Northeastern Pacific pinnipeds. Oecologia 119:578-585

Burton RK, Snodgrass JJ, Gifford-Gonzalez D, Guilderson T, Brown T, Koch PL (2001) Holocene changes in the ecology of northern fur seals: insights from stable isotopes and archaeofauna. Oecologia 128:107-115

Burton RK, Gifford-Gonzalez D, Snodgrass JJ, Koch PL (2002) Isotopic tracking of prehistoric pinniped foraging and distribution along the central California coast: preliminary results. International Journal of Osteoarchaeology 12:4-11

deHart PAP, Stegall VK, Finney BP, Koch PL, Wooller MJ (submitted) An investigation of the historical ecology of Steller sea lions using stable isotopes. Marine Mammal Science

DeNiro M (1987) Stable isotopy and archaeology. American Scientist 75:182-191

Ezzo JA, Johnson CM, Price TD (1997) Analytical perspectives on prehistoric migration: a case study from East-Central Arizona. Journal of Archaeological Science 24:447-466

Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology 40:503-537

Greave DK, Hammill MO, Eddington JD, Pettipas D, Schreer JF (2004) Growth rate and shedding of vibrissae in the Grey seal, *Halichoerus grypus:* A cautionary note for stable isotope diet analysis. Marine Mammal Science 20:296-304

Hedges RE, Stevens RE, Koch PL (2005) Isotopes in bones and teeth. In: Leng MJ (ed) Isotopes in palaeoenvironmental research. Springer, The Netherlands, pp 117-145

Hirons AC (2001) Trophic dynamics of pinniped populations in Alaska using stable carbon and nitrogen isotope rat. Institute of Marine Science. University of Alaska, Fairbanks

Hirons AC, Schell DM, Finney BP (2001) Temporal records of delta C-13 and delta N-15 in North Pacific pinnipeds: inferences regarding environmental change and diet. Oecologia 129:591-601

Hobson KA, Clark GR (1992) Assessing avian diets using stable isotopes II: factors influencing diet-tissue fractionation. Condor 94:189-197

Hobson KA, Schell DM, Renouf D, Noseworthy E (1996) Stable carbon and nitrogen isotopic fractionation between diet and tissues of captive seals: implications for dietary reconstructions involving marine mammals. Canadian Journal of Fisheries and Aquatic Sciences 53:528-533

Hobson KA, Sease JL, Merrick RL, Piatt JF (1997) Investigating trophic relationships of pinnipeds in Alaska and Washington using stable isotope ratios of nitrogen and carbon. Marine Mammal Science 13:114-132

Knudson KJ, Price TD, Buikstra JE, Blom DE (2004) The use of strontium isotope analysis to investigate Tiwanaku migration and mortuary ritual in Bolivia and Peru. Archaeometry 46:5-18

Koch PL, Fogel ML, Tuross N (1994) Tracing the diets of fossil animals using stable isotopes. In: Lajtha K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell Scientific Publications, London, pp 63-92

Lambert JB (1997) Traces of the past: unraveling the secrets of archaeology through chemistry. Helix Books, Reading, MA

Lambert JB, Grupe G (1993) Prehistoric human bone: archaeology at the molecular level. Springer-Verlag, New York

Lee-Thorpe J, Sponheimer M (2003) Three case studies used to reassess the reliability of fossil bone and enamel isotope signals for paleodietary studies. Journal of Anthropological Archaeology 22:208-216

Matheus P (1997) Laboratory procedures for extracting and purifying collagen from fossil and modern bone. Institute of Marine Science, University of Alaska-Fairbanks

Newsome SD, Phillips DL, Culleton BJ, Guilderson TP, Koch PL (2004) Dietary reconstruction of an early to middle Holocene human population from the central California coast: insights from advanced stable isotope mixing models. Journal of Archaeological Science 31:1101-1115

Newsome SD, Koch PL, Etnier MA, Aurioles-Gambao D (2006) Using carbon and nitrogen isotope values to investigate maternal strategies in Northeast Pacific otariids. Marine Mammal Science 22:556-572

Newsome SD, Etnier MA, Kurle CM, Waldbauer JR, Chamberlain CP, Koch PL (2007) Historic decline in primary productivity in the western Gulf of Alaska and eastern Bering Sea: isotopic analysis of northern fur seal teeth. Marine Ecology-Progress Series 332:211-224

Pate FD (1994) Bone chemistry and paleodiet. Journal of Archaeological Method and Theory 1:161-209

Price TD, Grupe G, Schroter P (1998) Migrations in the Bell Beaker period of Central Europe. Antiquity 72:405-411

Price TD, Middleton WD, Manzanilla L (2000) Immigrations and the ancient city of Teotihuacan in Mexico: a study using strontium isotope ratios in human bone and teeth. Journal of Archaeological Science 27:903-913

Price TD, Burton JH, Bentley RA (2002) The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44:117-136

Satterfield FR (2000) A comparison of sockeye salmon (*Oncorhynchus nerka*) in two climate regimes in the North Pacific Ocean using stable carbon and nitrogen isotope ratios. Institute of Marine Science. University of Alaska, Fairbanks, AK

Satterfield FR, Finney BP (2002) Stable isotope analysis of Pacific salmon: insight into trophic status and oceanographic conditions over the last 30 years. Progress in Oceanography 53:231-246

Schoeninger MJ, DeNiro M (1984) Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochimica et Cosmochimica Acta 48:625-639

Schweissing MM, Grupe G (2003) Stable strontium isotopes in human teeth and bone: a key to migration events of the late Roman period in Bavaria. Journal of Archaeological Science 30:1373-1383

Sealy JC, van der Merwe NJ, Sillen A, Kruger FJ, Krueger HW (1991) 87Sr/86Sr as a dietary indicator in modern and archaeological bone. Journal of Archaeological Science 18:211-228

Sholto-Douglas AD, Field JG, James AG, van der Merwe NJ (1991) C-13/C-12 and N-15/N-14 isotope ratios in the southern Benguela ecosystem: indicators of food web relationships among different size-classes of plankton and pelagic fish. Differences between fish muscle and bone collagen tissues. Marine Ecology-Progress Series 78:23-31

Tiezsen LL, Boutton TW, Tesdahl KG, Slade NA (1983) Fractionation and turnover of stable carbon isotopes in animal tissues: implications for $\delta^{13}C$ analysis of diet. Oecologia 57:32-37

Tuross N, Fogel ML, Hare PE (1988) Variability in the preservation of the isotopic composition of collagen from fossil bone. Geochimica et Cosmochimica Acta 52:929-935

Vander-Zanden MJ, Rasmussen JB (2001) Variation in $\delta^{15}N$ and $\delta^{13}C$ trophic fractionation: implications for aquatic food web studies. Limnology and Oceanography 46:2061-2066

Appendix B

Table of raw data of all mammals studied

Table B.1: Description of age and element for each individual mammal studied with corresponding isotope values.

Sample #	Species	Element	Side	Age	$\delta^{15}N$	$\delta^{13}C$
1	*E. lutris*	Femur	Right	Adult	15.35	-11.56
2	*E. lutris*	Humerus	Right	Adult	14.39	-11.66
3	*E. lutris*	Humerus	Right	Adult	15.10	-11.98
4	*E. lutris*	Femur	Left	Adult	14.05	-11.67
5	*E. lutris*	Femur	Right	Adult	13.15	-11.59
6	*E. lutris*	Femur	Right	Adult	14.81	-11.32
7	*E. lutris*	Femur	Left	Subadult	13.64	-11.07
8	*E. lutris*	Humerus	Left	Subadult	13.45	-11.21
9	*E. lutris*	Humerus	Left	Adult	16.41	-12.47
11	*E. lutris*	Femur	Right	Adult	14.47	-10.85
12	*E. lutris*	Humerus	Right	Juvenile	17.16	-13.11
13	*E. lutris*	Humerus	Left	Adult	15.98	-11.73
14	*E. lutris*	Femur	Left	Adult	13.64	-11.47
15	*E. lutris*	Humerus	Left	Adult	14.39	-11.54
16	*E. lutris*	Femur	Left	Adult	13.78	-11.20
17	*E. lutris*	Humerus	Right	Adult	13.40	-10.80
18	*E. lutris*	Humerus	Left	Adult	13.77	-11.35
19	*E. lutris*	Femur	Left	Adult	12.63	-12.14
20	*E. lutris*	Humerus	Left	Adult	16.26	-11.71
21	*E. lutris*	Humerus	Right	Juvenile	14.59	-11.28
22	*E. lutris*	Humerus	Right	Adult	17.94	-11.93
23	*E. lutris*	Humerus	Left	Juvenile	11.18	-10.68
24	*E. lutris*	Humerus	Left	Subadult	14.30	-11.57
25	*E. lutris*	Humerus	Unknown	Adult	15.38	-12.77
26	*E. lutris*	Humerus	Left	Adult	14.36	-11.14
27	*E. lutris*	Humerus	Left	Adult	14.48	-11.38
28	*E. lutris*	Humerus	Unknown	Subadult	15.10	-11.94
29	*E. lutris*	Femur	Unknown	Adult	18.72	-13.14
30	*E. lutris*	Humerus	Left	Adult	13.70	-11.08
31	*E. lutris*	Femur	Left	Adult	14.69	-11.78
32	*E. lutris*	Humerus	Right	Adult	15.54	-11.16
33	*E. lutris*	Humerus	Right	Unknown	16.22	-11.10
34	*E. lutris*	Humerus	Right	Adult	13.16	-12.56
35	*E. lutris*	Humerus	Right	Juvenile	15.52	-11.38
36	*E. lutris*	Humerus	Right	Adult	16.56	-10.49
37	*E. lutris*	Humerus	Left	Adult	14.36	-11.55
38	*E. lutris*	Femur	Left	Adult	14.97	-11.75
39	*E. lutris*	Humerus	Right	Juvenile	14.70	-11.04

Table B.1 (cont.)

Sample #	Species	Element	Side	Age	$\delta^{15}N$	$\delta^{13}C$
40	*E. lutris*	Humerus	Right	Unknown	14.78	-11.71
41	*E. lutris*	Femur	Right	Adult	14.99	-11.40
42	*E. lutris*	Humerus	Right	Adult	13.18	-12.06
43	*E. lutris*	Femur	Left	Adult	14.12	-11.23
44	*E. lutris*	Humerus	Left	Adult	15.16	-11.56
45	*E. lutris*	Humerus	Left	Subadult	14.70	-11.68
46	*E. lutris*	Humerus	Left	Juvenile	15.52	-11.02
48	*C. ursinus*	Humerus	Left	Juvenile	13.86	-15.20
49	*E. lutris*	Rib	Left	Subadult	14.91	-11.57
50	*E. lutris*	Rib	Right	Adult	15.32	-11.03
51	*E. lutris*	Humerus	Right	Adult	13.99	-11.98
52	*E. lutris*	Vert.-Thoracic	NA	Subadult	15.44	-11.78
53	*E. lutris*	Mandible	Right	Adult	13.75	-11.69
54	*Pinniped*	Vert.-Lumbar	NA	Subadult	17.95	-12.90
55	*C. ursinus*	Innominate	Right	Juvenile	13.22	-11.95
56	*E. lutris*	Metapodial	Unknown	Adult	13.74	-12.54
57	*Otarriid*	Rib	Left	Adult	16.17	-13.37
58	*E. jubata*	Radius	Left	Subadult	17.01	-13.05
60	*Otarriid*	Fibula	Right	Subadult	22.49	-13.34
61	*P. vitulina*	Mandible	Right	Subadult	17.45	-11.45
62	*P. vitulina*	Humerus	Left	Infant	20.46	-10.62
63	*C.ursinus*	Innominate	Right	Juvenile	13.06	-10.85
64	*E. jubata*	Femur	Right	Juvenile	19.73	-12.78
65	*E. lutris*	Femur	Left	Juvenile	14.68	-11.55
66	*E. jubata*	Humerus	Left	Subadult	17.69	-12.81
67	*E. jubata*	Humerus	Right	Adult	18.20	-11.32
68	*E. jubata*	Humerus	Right	Subadult	18.63	-12.78
69	*E. jubata*	Humerus	Left	Subadult	19.42	-12.84
70	*E. lutris*	Ulna	Right	Adult	13.99	-11.87
71	*E. lutris*	Ulna	Left	Juvenile	16.18	-11.72
72	*E. lutris*	Rib	Left	Subadult	13.99	-11.32
73	*E. jubata*	Innominate	Left	Subadult	18.91	-13.10
76	*Otarriid*	Radius	Right	Subadult	11.32	-13.90
77	*Otarriid*	Scaphoid	Right	Adult	18.96	-13.02
78	*Phoca*	Phalanx-Medial	Unknown	Subadult	19.41	-12.55
79	*Otarriid*	Phalanx-Medial	Unknown	Subadult	14.16	-12.40
80	*Otarriid*	Phalanx-Medial	Unknown	Adult	18.52	-12.74
81	*E. lutris*	Humerus	Right	Adult	13.17	-12.50
82	*E. lutris*	Femur	Right	Juvenile	12.88	-10.99
83	*E. lutris*	Femur	Right	Adult	17.84	-13.20
84	*E. lutris*	Tibia	Right	Subadult	13.32	-11.51
85	*E. lutris*	Femur	Left	Adult	18.04	-13.79
86	*Phoca*	Vert.-Lumbar	NA	Adult	17.43	-11.62

Table B.1 (cont.)

Sample #	**Species**	**Element**	**Side**	**Age**	$\delta^{15}N$	$\delta^{13}C$
88	*Phoca*	Radius	Left	Subadult	14.84	-13.06
89	*E. lutris*	Innominate	Right	Juvenile	15.76	-11.74
90	*P. vitulina*	Tibia	Right	Adult	16.97	-11.99
91	*P. vitulina*	Humerus	Left	Juvenile	14.27	-12.36
92	*C.ursinus*	Scapula	Right	Subadult	20.34	-14.40
93	*E. lutris*	Ulna	Right	Adult	13.37	-12.05
94	*E. lutris*	Femur	Left	Adult	13.75	-12.40
95	*Phoca*	Humerus	Left	Adult	15.71	-12.14
96	*E. lutris*	Tibia	Right	Subadult	12.58	-11.30
97	*E. lutris*	Humerus	Left	Adult	14.97	-12.73
98	*E. lutris*	Ulna	Right	Adult	16.20	-13.23
99	*E. lutris*	Tibia	Right	Unknown	12.40	-11.63
100	*E. lutris*	Femur	Left	Adult	14.86	-11.31
101	*E. lutris*	Femur	Right	Juvenile	13.04	-11.80
102	*E. lutris*	Ulna	Left	Adult	13.10	-11.59
103	*E. lutris*	Ulna	Right	Adult	14.37	-11.94
104	*E. lutris*	Scapula	Right	Adult	12.50	-11.37
105	*E. lutris*	Tibia	Right	Juvenile	14.44	-10.94
106	*Phoca*	Phalanx-Medial	Unknown	Adult	14.00	-12.35
108	*Otarriid*	Ulna	Right	Subadult	18.98	-13.91
109	*E. lutris*	Femur	Left	Juvenile	14.37	-12.57
110	*Otarriid*	Metapodial	Unknown	Adult	16.70	-13.53
111	*Otarriid*	Rib	Right	Adult	17.48	-11.80
112	*P. vitulina*	Radius	Right	Subadult	17.85	-11.52
113	*P. vitulina*	Maxilla	Left	Subadult	18.46	-13.30
114	*E. lutris*	Femur	Right	Juvenile	15.62	-12.01
115	*E. lutris*	Femur	Right	Juvenile	14.37	-11.69
116	*E. lutris*	Femur	Right	Subadult	15.17	-14.65
117	*E. lutris*	Femur	Left	Juvenile	15.39	-11.66
118	*C. ursinus*	Femur	Right	Juvenile	13.52	-15.04
119	*E. jubata*	Humerus	Left	Adult	18.27	-13.51
120	*E. lutris*	Ulna	Left	Subadult	15.29	-11.38
121	*E. lutris*	Tibia	Right	Adult	12.63	-12.20
122	*E. lutris*	Tibia	Right	Subadult	15.43	-12.38
123	*E. lutris*	Fibula	Unknown	Juvenile	14.18	-14.49
124	*E. lutris*	Ulna	Right	Adult	13.79	-10.74
125	*E. lutris*	Ulna	Left	Subadult	16.18	-12.33
126	*E. lutris*	Femur	Right	Infant	13.70	-12.40
127	*C.ursinus*	Tibia	Left	Juvenile	14.33	-11.84
128	*Otarriid*	Astragulus	Left	Adult	18.19	-12.75
130	*Otarriid*	Tibia	Right	Subadult	18.02	-13.14
131	*C. ursinus*	Humerus	Right	Adult	13.74	-15.15
132	*C.ursinus*	Tibia	Right	Subadult	15.39	-14.56

Table B.1 (cont.)

Sample #	Species	Element	Side	Age	$\delta^{15}N$	$\delta^{13}C$
133	*C. ursinus*	Femur	Left	Subadult	15.28	-14.59
134	*P. vitulina*	Tibia	Right	Subadult	17.29	-12.61
135	*E. lutris*	Mandible	Left	Subadult	12.73	-11.69
137	*C.ursinus*	Innominate	Right	Adult	15.00	-11.13
138	*E. jubata*	Humerus	Left	Subadult	18.10	-12.87
139	*E. jubata*	Humerus	Left	Adult	18.20	-13.57
140	*E. lutris*	Mandible	Left	Subadult	13.73	-12.27
141	*E. lutris*	Ulna	Left	Adult	12.24	-14.16
142	*E. lutris*	Vert.-Thoracic	NA	Adult	15.38	-11.29
143	*E. lutris*	Vert.-Thoracic	NA	Adult+	15.50	-12.34
144	*E. lutris*	Ulna	Right	Adult	12.38	-11.41
146	*Phoca*	Phalanx-P1	Right	Adult	17.00	-12.46
147	*C. ursinus*	Tibia	Left	Juvenile	14.62	-11.99
149	*P. vitulina*	Mandible	Left	Subadult	16.22	-13.81
150	*P. vitulina*	Mandible	Left	Subadult	20.50	-10.80
151	*P. vitulina*	Innominate	Right	Adult	16.59	-11.89
152	*Phoca*	Scapula	Left	Adult	16.28	-11.80
154	*C. ursinus*	Humerus	Right	Juvenile	16.90	-14.46
156	*P. vitulina*	Innominate	Left	Adult	17.00	-12.77
157	*E. jubata*	Radius	Left	Subadult	21.10	-14.60
158	*E. lutris*	Astragulus	Unknown	Adult	15.80	-14.17
159	*E. lutris*	Rib	Left	Adult	14.50	-12.15
160	*Otarriid*	Navicular	Unknown	Juvenile	16.73	-14.28
161	*P. vitulina*	Radius	Right	Adult	18.89	-12.81
162	*E. lutris*	Innominate	Left	Infant	13.99	-11.62
163	*E. lutris*	Innominate	Left	Juvenile	11.94	-12.02
164	*E. jubata*	Ulna	Left	Subadult	14.96	-13.54
165	*E. jubata*	Humerus	Right	Adult	17.59	-13.65
166	*E. lutris*	Tibia	Right	Subadult	13.56	-12.27
167	*E. lutris*	Tibia	Right	Subadult	13.31	-11.92
168	*E. lutris*	Tibia	Right	Juvenile	14.97	-12.01
169	*E. lutris*	Innominate	Left	Subadult	13.63	-10.87
170	*E. lutris*	Tibia	Right	Adult	14.06	-11.07
171	*E. lutris*	Ulna	Right	Adult	14.20	-11.10
172	*E. lutris*	Tibia	Left	Adult	11.98	-12.14
173	*E. lutris*	Phalanx-Distal	Unknown	Subadult	15.35	-11.85
175	*Otarriid*	Rib	Right	Adult	18.63	-13.46
176	*Otarriid*	Tibia	Right	Subadult	16.16	-14.23
177	*P. vitulina*	Mandible	Right	Subadult	18.22	-11.90
178	*P. vitulina*	Humerus	Left	Subadult	18.35	-12.10
179	*P. vitulina*	Mandible	Right	Subadult	15.30	-11.36
180	*C. ursinus*	Femur	Right	Adult	16.62	-13.28
181	*C. ursinus*	Femur	Right	Juvenile	14.04	-15.83

Table B.1 (cont.)

Sample #	**Species**	**Element**	**Side**	**Age**	δ^{15}N	δ^{13}C
182	*C. ursinus*	Ulna	Left	Juvenile	18.80	-14.01
183	*C. ursinus*	Ulna	Right	Juvenile	15.59	-14.69
184	*E. lutris*	Femur	Right	Subadult	13.67	-12.06
185	*E. lutris*	Tibia	Right	Juvenile	14.12	-12.93
186	*E. lutris*	Tibia	Left	Adult	14.71	-11.39
187	*E. lutris*	Tibia	Left	Adult	14.39	-11.93
188	*E. lutris*	Femur	Right	Adult	14.62	-12.14
189	*E. lutris*	Femur	Right	Juvenile	12.00	-11.32
190	*E. lutris*	Rib	Right	Subadult	15.45	-11.23
191	*C. ursinus*	Phalanx-Medial	Unknown	Subadult	18.94	-12.71
192	*Otarriid*	Phalanx-Medial	Unknown	Juvenile	17.36	-13.66
193	*Otarriid*	Rib	Right	Adult	16.80	-11.62
194	*Otarriid*	Ulna	Right	Subadult	17.27	-14.90
195	*P. vitulina*	Mandible	Right	Subadult	17.07	-11.96
196	*P. vitulina*	Tibia	Left	Adult	17.85	-11.51
197	*E. lutris*	Humerus	Left	Adult	13.67	-12.36
198	*E. lutris*	Innominate	Left	Subadult	13.89	-12.26
199	*E. lutris*	Metapodial	Unknown	Adult	15.63	-12.43
200	*Otarriid*	Rib	Right	Adult	14.11	-12.64
201	*C. ursinus*	Humerus	Right	Adult	17.95	-13.14
202	*C. ursinus*	Tibia	Right	Subadult	18.09	-14.30
203	*E. lutris*	Tibia	Left	Juvenile	16.23	-11.31
204	*Otarriid*	Radius	Left	Adult	15.43	-13.89
207	*Pinniped*	Vert.-Lumbar	NA	Adult	18.61	-13.68
208	*P. vitulina*	Humerus	Left	Adult	17.54	-11.93
209	*P. vitulina*	Ulna	Right	Subadult	18.54	-12.50
210	*E. jubata*	Humerus	Left	Subadult	19.98	-13.47
212	*P. vitulina*	Innominate	Left	Adult	16.95	-12.05
213	*Otarriid*	Vert.-Lumbar	NA	Adult	17.60	-11.80
214	*E. lutris*	Vert.-Thoracic	NA	Adult	16.57	-12.74
215	*Otarriid*	Phalanx-medial	Unknown	Subadult	19.72	-12.32
216	*E. lutris*	Rib	Right	Juvenile	12.70	-11.67
217	*E. lutris*	Femur	Right	Juvenile	14.00	-12.46
218	*E. lutris*	Radius	Right	Adult	14.86	-11.68
219	*E. lutris*	Phalanx-medial	Unknown	Adult	13.65	-11.24
220	*E. lutris*	Vert.-Thoracic	NA	Adult	14.09	-11.85
221	*Phoca*	Rib	Unknown	Adult	13.48	-11.85
222	*Otarriid*	Tibia-Distal epiphysis	Right	Subadult	18.52	-14.24
223	*E. lutris*	Tibia	Left	Adult	15.32	-11.66
224	*E. lutris*	Rib	Right	Adult	15.64	-12.16
225	*E. lutris*	Vert.-Thoracic	NA	Adult	14.40	-12.31
226	*Otarriid*	Metapodial	Right	Adult	18.24	-14.30
227	*Phoca*	Scapula	Right	Subadult	17.80	-11.84

Table B.1 (cont.)

Sample #	**Species**	**Element**	**Side**	**Age**	**$\delta^{15}N$**	**$\delta^{13}C$**
228	*E. lutris*	Scapula	Left	Adult	13.91	-11.48
229	*E. lutris*	Ulna	Right	Subadult	14.03	-12.82
230	*E. lutris*	Ulna	Left	Juvenile	14.11	-12.55
231	*C. ursinus*	Tibia	Right	Subadult	21.39	-13.76
232	*C. ursinus*	Mandible	Left	Juvenile	17.97	-14.32
233	*E. lutris*	Rib	Right	Adult	13.71	-11.87
236	*C. ursinus*	Tibia	Left	Juvenile	14.64	-12.29
237	*Otarriid*	Tibia	Left	Juvenile	20.46	-13.79
238	*P. vitulina*	Humerus	Right	Adult	14.80	-14.20
239	*C. ursinus*	Scapula	Left	Juvenile	17.97	-14.36
240	*E. lutris*	Rib	Left	Adult	12.58	-12.28
241	*Pinniped*	Sternum	NA	Subadult	16.95	-13.67
242	*E. lutris*	Femur	Left	Juvenile	17.89	-12.14
243	*E. lutris*	Scapula	Left	Adult	13.89	-12.29
244	*E. lutris*	Vert.-Lumbar	NA	Adult	15.39	-13.94
245	*E. lutris*	Scapula	Left	Juvenile	17.06	-12.70
246	*Phoca*	Phalanx-Distal	Unknown	Adult	16.55	-12.08
247	*Otarriid*	Tibia	Right	Subadult	16.26	-14.27
119a	*E. jubata*	Mandible	Left	Adult	18.62	-12.55
248	*E. lutris*	Humerus	Left	Juvenile	13.64	-12.72
249	*E. lutris*	Humerus	Left	Adult	15.20	-12.46
250	*E. lutris*	Humerus	Left	Adult	14.23	-12.67
251	*E. lutris*	Humerus	Left	Adult	13.29	-12.07
252	*E. lutris*	Humerus	Left	Adult	13.25	-12.32
51827	*E. lutris*	Cranial	Fragments	Adult	10.26	-14.38
51830	*E. lutris*	Cranial	Fragments	Adult	10.22	-14.19
21998	*E. lutris*	Cranial	Fragments	Adult	11.32	-14.22
60976	*E. lutris*	Cranial	Fragments	Adult	11.90	-12.07
51828	*E. lutris*	Cranial	Fragments	Adult	10.29	-12.63
61110	*E. lutris*	Cranial	Fragments	Adult	11.30	-13.56
21990	*E. lutris*	Cranial	Fragments	Adult	12.82	-14.03
66868	*E. lutris*	Cranial	Fragments	Adult	11.10	-12.46
21684	*E. lutris*	Cranial	Fragments	Adult	12.68	-13.25
85216	*E. lutris*	Cranial	Fragments	Adult	12.26	-11.87
51829	*E. lutris*	Cranial	Fragments	Adult	11.07	-13.84
48422	*E. lutris*	Cranial	Fragments	Adult	9.13	-13.60
21991	*E. lutris*	Cranial	Fragments	Adult	12.03	-13.64

Chapter 4 Changes in eastern North Pacific ecosystems and their co-occurance with changes in Aleut culture: Preliminary findings from Sanak Island, Alaska.[1]

Abstract

This chapter synthesizes relationships between changes in the North Pacific marine ecosystem and prehistoric Aleut culture through isotopic analyses of lake cores and of bone from prehistoric middens focusing on the region located along the lower Alaska Peninsula (LAP)/eastern Aleutian Islands. Lake core sediments from this project and other studies yielded data concerning Holocene paleoclimate and salmon returns from 6,000 calendar years before present (cal yrs BP). Bone isotope analysis returned information on changing environments and productivity starting ~ 4,500 cal yrs BP. Data from previous zooarchaeological studies from the lower Alaska Peninsula, eastern Aleutian Islands and Sanak Island were also used to track changes in species represented through time. It appears that humans not only adapted to their changing climates/ecosystems in noticeable ways, but may have also changed their local environments.

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[1] Misarti N, Finney B, and Herbert Maschner. Changes in eastern North Pacific ecosystems and their co-occurance with changes in Aleut culture: Preliminary findings from Sanak Island, Alaska. Prepared for Oecologia.

Introduction

The Aleut way of life has been dependant on ocean resources for thousands of years and fluctuations in ocean ecosystems will have impacted this life style (bottom-up processes), even if only at the local level. Conversely, preferential resource consumption may have influenced local ecosystems (top-down processes). Archaeologists have been studying past environments and environmental change in order to determine how they may affect subsistence and cultural change (Jordan and Maschner 2000; Burton et al. 2002; Butler and O'Conner 2004; Reitz 2004; Causey et al. 2005). Furthermore, many archaeologists have cited resource intensification, namely the improved technology for mass harvesting and processing and storage capability and therefore reliance on/use of salmon in the North Pacific, as a harbinger to cultural complexity (Coupland 1985; Matson 1992; Ames 1994; Hayden 1995; Matson and Coupland 1995; Maschner 1998; Fitzhugh 2003; Hoffman 2002) although others point to the use of shellfish as well (Ames and Maschner 1999). Recent research by both archaeologists (Jordan and Maschner 2000; Maschner and Hoffman 2003) and marine scientists (Finney et al. 2002) suggest that changes in the environment of the Northeast Pacific Ocean/ Gulf of Alaska (GOA) may correspond to changes in Aleut and Koniag house form and organization. This study was conceived to further test that hypothesis and gain a clearer understanding on the relationship between cultural change and climate change.

This thesis considers the relationship between change in the North Pacific marine ecosystem and prehistoric Aleut culture through multi-element weak-acid extraction of soils from archaeological sites, isotopic analyses of sediments in lake cores, and isotopic analyses of bone from prehistoric middens focusing on the region located along the lower Alaska Peninsula (LAP)/eastern Aleutian Islands. This interdisciplinary research draws on a range of fields including fisheries, oceanography and archaeology to build on our understanding of long-term climate change and long-term fluctuations in species density and trophic dynamics in the North Pacific, and considers humans as a part of the system. Here we attempt to integrate original data sets and compare and contrast them to published data from the North Pacific in the fields of marine science, paleoclimatology and zooarchaeology, and relate the conclusions to the regional prehistory of the Aleut along the western Alaska Peninsula, and specifically to Sanak Island, AK (Figure 4.1).

Paleoclimates of Alaska and Sanak Island

In order to understand how bottom-up processes could have affected ecosystems and therefore the people who relied on those systems we need to have some understanding of paleoclimates of an area. Sanak Island was deglaciated ~ 16,000 calendar years before present (cal yrs BP) (Jordan et al. 2005; Misarti unpub.). Since this time, with the exception of the Younger Dryas (Mann and Hamilton 1995), a general trend of warmer and drier periods has oscillated with cooler periods of increased precipitation. In the central coastal region of the GOA, by 10,000 BP average summer air temperatures had risen to 14 °C, and by about 8,000 BP up to 16 °C, based on pollen transfer functions (Huesser et al. 1985). During periods of warmer temperatures the subtropical Pacific cyclone mode was predominant and there was much less precipitation. By 5,000 BP summer temperatures in southern Alaska had dropped to 12 °C (Huesser et al. 1985). During colder periods the Aleutian Low predominated over southern Alaska and generated more frequent and intense storms (Huesser et al. 1985). Overall, sea surface temperature (SST) rose in the northeast Pacific over the past 7,000 years (Kim et al. 2004).

By 4,500 BP precipitation was about twice as high as it was ~ 8,000 BP (Huesser et al. 1985; Mann and Hamilton 1995; Savinetsky et al. 2004) and pollen data suggests that temperatures were cooling and conditions were becoming wetter (Jordan and Krumhardt 2003). This is generally considered to be the onset of neoglaciation, and air temperatures were lower than in the previous few thousand years with more frequent and larger storms (Mann and Hamilton 1995). This climate transition corresponds with an increase in salmon/marine-derived nutrients (MDN) from numbers of returning salmon in Deep Lake sediments, Sanak Island (Misarti unpub.). Sea level on Sanak Island was ~4-5 meters above today's levels by 4,000 BP (Jordan et al. 2005). By 3,500 BP there was a large increase in MDN in sockeye nursery lakes on Kodiak (Finney et al. 2002) and a notable increase in Deep Lake MDN on Sanak Island itself (Misarti unpub.). This is also a period of ice advance in alpine and land-terminating glaciers (Huesser et al. 1985; Calkin et al. 2001) and there is evidence of increased storminess along beach ridges along northern Alaska coastlines (Mason and Jordan 1993). Lake core data also suggest that the Aleutian Low shifted eastward and/or intensified between ~4,500 BP and 3,000 BP (Anderson et al. 2005). The ice advances continued until 2,700 BP (Calkin et al. 2001) or

2,100 BP in southern Alaska and Gulf of Alaska glaciers (Huesser et al. 1985). During this period of cooling there was an increase in piscivorous birds in the archaeological record of the western Aleutians (Causey et al. 2005), perhaps due to an increase in pelagic fish. Sea level on Sanak Island dropped to 2-3 meters above today's levels (Jordan et al. 2005). Sometime between 2,500-2,200 cal yrs BP the lower Alaska Peninsula was hit by a major earthquake and the terrestrial landscape subsided by several meters. The accompanying abrupt rise in sea level would have destroyed salmon habitat and disrupted much of the intertidal system (Maschner 2000). Deep Lake does have a brief but very pronounced drop in MDN around this time (Figure 4.2).

Salmon abundance in Kodiak Island and Bristol Bay decreased starting ~2,000 BP (Finney et al. 2002), as did MDN in Deep Lake (Misarti unpub.). According to Calkin et al. (2001) glaciers receded at this time, and $\delta^{18}O$ from sediments in Jellybean Lake, in the southern Yukon showed a weakening and/or westward movement of the Aleutian Low from ~3,000 to 2,000 BP (Anderson et al. 2005). From ~1,700 BP to 1,200 BP beach ridges around Kotzebue Sound prograded, implying less stormy conditions. These records combine to suggest warmer atmospheric temperatures and a decrease in intensity and numbers of storms beginning ~2,000 BP.

A few recent papers suggest some glacial advances between 2,000 and 1,100 BP (Huesser et al. 1985; Calkin et al. 2001), which I will refer to as the pre-Medieval Warm Period (MWP). There was rapid change in $\delta^{18}O$ in Jellybean Lake beginning ~1,200 BP until ~800 BP, which is believed to be tied to a shift in the Aleutian Low (Anderson et al. 2005). There was a coeval increase in sockeye returns on Kodiak Island around 1,200 BP, then a decrease about 1,000 BP (Finney et al. 2002). Becharof and Deep Lakes have a fairly continuous decrease in MDN until ~1,000 BP but levels still remained above pre-neoglacial averages in Deep Lake (Misarti unpub.).

The period from ~1,100 BP to 900 BP coincides with the MWP when mean annual July temperatures reached as high as 14°C on the North Pacific coast (Huesser et al. 1985). Starting ~ 1,100 BP there was a large and rapid decrease in $\delta^{18}O$ in Jellybean Lake and a decrease in MDN in lakes around Alaska (Finney et al. 2000, 2002; Anderson et al. 2005). Deep Lake sediments record a decrease in MDN ~1,100 BP. Glaciers receded from ~1,100 BP to 800 BP (Calkin et al. 2001) and tree ring growth was above average in northern Alaska during the Medieval Warm (D'Arrigo et al. 2005). However, based on a combination of percent decomposition and ash of dated peats and ice-advance data, Causey et al. (2005) found that from 1,100 to 750 BP the GOA and eastern Aleutians may have experienced some moderate cooling, unlike the western Aleutians and the Bering Sea that experienced the warming trends that characterized the MWP.

The period from 750-100 BP coincides with the Little Ice Age, a time of world-wide cooling in the northern hemisphere. During the coldest years of the 1800's, temperatures on the North American continent were on average 1.5 °C colder than today (Mann 2001). The Little Ice Age (LIA) was clearly characterized by variability as witnessed by 4 phases of distinct glacial advances at ~750, 500, 350 and 150 BP (Calkin et al. 2001). Many lakes show a subsequent increase in MDN, and therefore salmon abundance, starting soon after the beginning of the LIA. The $\delta^{18}O$ in Jellybean Lake increases dramatically, suggesting a strengthening of the Aleutian Low (Finney et al.

2000, 2002; Anderson et al. 2005; Chapter 2). There were periods of higher temperatures in northwestern AK between 900-850 BP, 800-750 BP (the highest peaks in the record) and then once again at 600 BP (Mann 2001; D'Arrigo et al. 2005). Sockeye returns increase to the highest levels of the previous 1,000 years on Kodiak Island ~750 but appear to fluctuate with decreases during periods of warmer temperatures not only in lakes on Kodiak but in Bristol Bay as well (Finney et al. 2000, 2002). The Deep Lake MDN record is of lower temporal resolution than these records, but suggests continual increase until ~300 BP. It is interesting to note that throughout the last 300-400 years there is evidence for periods of both Pacific Decadal Oscillation (PDO) and non-PDO influenced climatic regimes, from both tree-ring data on the Seward Peninsula, AK and the Pacific Basin and lakecore data (Gedalof and Mantua 2002; Anderson et al. 2005; D'Arrigo et al. 2005; MacDonald and Case 2005).

Prehistory of the western Alaska Peninsula and Sanak Island

In recent years the western portion of the Alaska Peninsula has seen extensive archaeological research (Maschner and Reedy-Maschner 1998, 2005; Hoffman 1999, 2002; Maschner 1999, 2000, 2004; Jordan and Maschner 2000; Jordan 2001; Maschner and Jordan 2001, 2005; Jordan and Krumhardt 2003; Maschner and Bentley 2003; Maschner and Hoffman 2003; Tews 2005) and a clearer understanding of cultural features and change has emerged. Jordan and Maschner (2000) published the first phase chronology for the lower Alaska Peninsula and adjacent islands and have since modified and refined their understanding (Maschner and Jordan 2005). Nine phases were defined that span the end of the Incipient Aleutian Tradition and the Aleutian Tradition as originally defined by McCartney (1984). Unless otherwise cited, all of the information synthesized below is derived from Jordan and Maschner (2000), Maschner and Jordan (2005) and Maschner (pers. comm.).

The Moffet Phase begins ~5,000-3,600 cal yrs BP, and settlements during this time period were small, perhaps 30-60 people per village, as were individual dwellings (4-7 people per household). These few, small villages were located in areas with efficient access to marine, intertidal, riverine and terrestrial resources. In sites along the lower Alaska Peninsula, artifacts consisted of a bifacial technology of basalt projectiles, knives and scrapers, oil lamps, grinding stones, stone bowls, notched netsinkers and some rare polished slate items. Houses were semi-subterranean with surrounding exterior storage pits and red-ochre floors. Salmon, cod, seal and marine birds were located within middens. The oldest sites found on Sanak Island date from 6,000 cal yrs BP but did not have shell middens and therefore there is no preservation of faunal remains. These houses had box hearth and prepared floors. Shell middens appeared in sites on the southeast side of Sanak Island beginning ~4,500 cal yrs BP and were composed of salmon, cod, halibut, pollock, ducks and alcids, geese, cormorants, and some sea mammals, including phocids, otariids, sea otter and some whale (Betts and Tews 2007). Shellfish abounded and species included whelks, clams, limpets, mussels, urchin, barnacles, chitons, periwinkles, dogwinkles etc. (Betts and Tews 2007). Shell middens have not been found on Sanak Island between ~3,800 and 2,750 cal yrs BP.

The Russell Creek Phase began ~3,600-3,300 cal yrs BP and is distinguished from the Moffet Phase by several features. Village and house/household size is still small but houses now contain stone-lined box hearths, though villages are still located in areas with access to marine, intertidal, riverine and terrestrial resources. Artifacts consist of triangular end-blades, bone harpoons without line holes, oil lamps and a few rare microblades and cores. Faunal remains and lithics recovered from these sites suggest subsistence was focused on large marine mammals with riverine and smaller marine resources. There are no sites on Sanak Island from 3,600 to 3,350 cal yrs BP. By ~3,310 cal yrs BP, three sites are found on and around the Sanak archipelago, but only one has a clear, but small, midden associated with it (Betts and Tews 2007; Misarti unpub.).

By 3,300 cal yrs BP house and village size was increasing. The Kinzarof Phase (3,300-2,700 cal yrs BP) is defined by contracting stem end-blades, line-hole harpoons and a few rare toggling harpoons. Large, bifacially-flaked basalt tools were still common and primary subsistence species were salmon, cod, seal and marine birds.

Around 2,700 cal yrs BP there was an increase in expedient tools, especially net sinkers and some houses on the Alaska Peninsula have stone formations. Until ~2,800 cal yrs BP there were still no shell middens in sites on Sanak (Misarti unpub.), at which point in time there was only a single midden site. When shell middens did re-appear (~2,600-2,500 cal yrs BP) they contained very small numbers of previously harvested shellfish, small numbers of salmon, cod, geese, cormorants, smaller numbers of phocids and a few sea otters (Betts and Tews 2007).

The Adamagan Phase began ~2,400 cal yrs BP and ended ~1,900 cal yrs BP. Villages and houses became very large, with 300 to 1,000 people per village and 10-25 people per household and there are more villages, all indicating an increase in population density. Decorated artifacts and labrets were common. Hafted scrapers and knives, once rare, became common as did toggling harpoons. There were fishtail points and some rare polished slate. There was some use of salmon as a subsistence food but sites were located for better access to marine and intertidal resources. Overall it appears that larger sea mammals, including whales, were a greater focus of subsistence. This increase in sites and site size can be found on Sanak Island as well. Sanak Island middens contained remains of sea otters, phocids, very small numbers of otariids, cormorants, geese in small numbers, cod, halibut and very little salmon (Betts and Tews 2007).

During the Ram's Creek Phase (~1,900-1,400 cal yrs BP) there were only a few large villages but many smaller ones. On average, villages ranged from 50-300 people and households contained 10-25 people. Sites continued to be located in areas with easy marine and intertidal access, with only small emphasis placed on the location of salmon streams. Fishtail points became rare and slate more numerous (though not common). Net weights and ground stone persisted. Most of the information for this time period is derived from the Hot Springs site where there is evidence for a ceremonial complex that included anthropomorphic figurines. From ~1,900 to 1,600 cal yrs BP there are no known shell middens on Sanak Island (Misarti unpub.). There are two sites on Sanak Island that date to ~1,550 cal yrs BP that contain shell middens, in which fewer sea otter remains are present but larger numbers of otariids and phocids. Cormorants, geese, a few ducks, salmon, cod, and cottidae are all present.

By 1,400 cal yrs BP houses and villages once again became smaller. The Frosty Creek Phase (1,400-900 cal yrs BP) had numerous villages with a population of 30-60 people and 4-7 people per household. The most notable change from the previous settlement pattern was a move to what are historically pink and chum salmon streams, and sockeye nursery systems, many of these villages had poor access to the open coast. There is very little preservation at these sites as shell middens do not exist. On Sanak Island there was another 400-500 year period with no shell middens. There was more polished slate and some pottery (evidence of contact with the Bering Sea), ground stone and net weights. Defensive sites and refuges were being utilized so there is some evidence for warfare (Maschner and Reedy-Maschner 1998). More importantly, within this time frame there was an introduction of the recurved bow and armor from Asia as well as small, specialized arrow points (Maschner and Reedy-Maschner 1998; Maschner 2000). Two sites with middens dating ~1,000 cal yrs BP have been found on Sanak Island. These middens were the most species rich with many fish, avian and sea mammal species while barnacles, mussels, chitons and periwinkles dominate the shellfish assemblage (Betts and Tews 2007). There is also a site located on a defensible "refuge rock" along the coast of Sanak Island dated to this time period.

During the Cape Glaznap Phase (900-750 cal yrs BP), the first nucleus-satellite houses appear on the Peninsula. Villages were much larger (300 people to a village with 30-50 per household) and are now located along the coast for access to marine, intertidal and sockeye salmon resources. These villages were also easily defensible (Maschner and Reedy-Maschner 1998). Midden deposits were still small and few in number showing little use of the intertidal zone. From the small amount of recovered faunal remains, it appears that the primary focus of subsistence were salmon, whales and geese. Polished slate was present as well as bifacial points but notched stones for net sinkers are now rare.

By 750 cal yrs BP (Izembek Phase) there was a drastic reduction in population on the western Alaska Peninsula and its neighboring islands, which coincides with a massive decrease in population all over the North Pacific. There were very few villages, with 20-30 people per village, and households were once again small (no nucleaus-satellite houses existed). Villages were once again located along the open coast and less emphasis was placed on salmon. There is evidence that Eskimo-related people began to move into the newly depopulated area (McCartney 1984). Sanak Island had few middens from 900-600 cal yrs BP and very few archaeological sites until after 550 cal yrs BP.

By the Morzhovoi Phase (525-200 cal yrs BP), population had drastically increased with 800-2000 people per village and 25-80 people per household. The villages were numerous and although located along coastlines were most often associated with a nearby sockeye nursery system. Middens were extensive and birds, salmon, cod, sea lion, and whales were abundant. There was no pottery but some polished slate. “Izembek” points continued in the record and there were small harpoons with off-center line holes. Refuge rocks were once again in use, suggesting that warfare was endemic (Maschner and Reedy-Maschner 1998). Sanak Island has numerous sites from this time period with large shell middens containing sea mammal, bird, shellfish and fish remains. These archaeological sites are the remains of the cultural traditions of people that the Russians encountered in the 1700's as they explored the Aleutian Islands and Gulf of Alaska. A well-structured sociopolitical system, including corporate households, a class system, highly developed craft specialization and artwork etc. are the hallmarks of the historic Aleut, Koniag, and other Northwest Coast people that first encountered Europeans a little over 250 years ago (Hayden 1995).

Changes in the archaeofaunal record on Sanak Island

The available faunal record from Sanak Island spans from 4,500 cal yrs BP to 150 cal yrs BP and is compiled from 32 discrete middens. Analysis is ongoing, but preliminary findings from 8 different contexts at different time periods allows for some comparison of change in the archaeofaunal assemblage over time on Sanak. The data presented here is exclusively from Betts and Tews (2007). Throughout the entire 4,500 year period fish (specifically salmon ssp., Pacific cod, and the Cottidae family) dominate the assemblage (Betts and Tews 2007). Diet breadth did not change much, with a typical level of 17-22 taxa represented in most of the 4,500 years, with the exception of a period within the MWP in which 32 taxa are represented.

Evenness (V') can be calculated from the Shannon-Weaver Index (H'), where $V' = H' / \ln S$ (Reitz and Wing 1999; Grayson et al. 2001), where S is the number of non-overlapping taxa in the assemblage, H' is defined as $- \Sigma (pi) (\ln pi)$, where pi is the proportion of the number of taxa in the identified sample (Reitz and Wing 1999). The index ranges between 1 and 0; values close to zero reflect a sample dominated by a single species, while values closer to 1 reflect even abundance across all taxa. H' ≤ 0.4 during all time periods, suggesting that a few taxa tend to dominate in the assemblages (Figure 4.3). The large number of fish bones in the middens, principally Pacific cod, salmon, and Cottidae family fish are most likely what influences the evenness index. A plot of richness (Figure 4.3) suggests little change in subsistence breadth over much of the first 3,000 years of the record. However, the midden context dating to ~1,000 cal yrs BP shows a large increase in the number of exploited taxa during this time.

Abundance indices (AI-a normed ratio of a highly ranked taxon to a lower ranked taxon, measured as AI = A/A+B) shift over time for sea mammal, fish, bird, and shellfish species. AI values closer to zero indicate a complete absence of taxon A while those close to 1 indicate a dominating presence. Otariid indices correlated well over time and suggest a large increase in otariid frequencies in middens from ~4,500 cal yrs BP to 3,750 cal yrs BP (Figure 4.4). Frequencies were lower but stayed fairly constant from ~2,600 cal yrs BP to 1,900 cal yrs BP, and then decreased ~1,500 cal yrs BP and 1,000 cal yrs BP (this time period is associated with the MWP). Frequencies increased once again by ~500 cal yrs BP, the time period associated with the Little Ice Age. Interestingly, sea otter frequencies were inversely correlated with otariid frequencies.

Migratory water fowl AI's (cormorant and alcid AI) generally track otariid AI's (Figure 4.4). There was a substantial increase in frequency from 4,500 cal yrs BP to 3,750 cal yrs BP. By 2,500 cal yrs BP these frequencies are declining and by ~2,000 cal yrs BP were fairly low. Frequencies peaked once again at 1,500 cal yrs BP, then declined by 1,000 cal yrs BP (MWP) and began to rise by 500 cal yrs BP (LIA).

Pacific cod are the most abundant fish in all of Sanak Island middens (Figure 4.4). Fish AI's (Cod-cottidae) suggest that cod were extremely frequent from 4,500 to 2,000 cal yrs BP (neoglacial), at which point cod declined drastically until 1,000 cal yrs BP (MWP). Cod frequency then rebounded by ~500 cal yrs BP (LIA). Compared to cod, salmon species are as frequent, though less numerous, in the archaeological record (Figure 4.2). Frequency of salmon did not decline as significantly as Pacific cod during the MWP when salmon-small flatfish AI were investigated. However, when salmon-cottidae AI were explored there was a significant decrease after ~2,000 cal yrs BP and salmon frequency continued to decline throughout the available record.

Shellfish data were more difficult to interpret, with peaks in frequencies of mussel and chiton at 4,500 cal yrs BP, 2,600 cal yrs BP and at 500 cal yrs BP (Figure 4.4), all during times of glacial advances in and around Alaska (Calkin et al. 2001). However, there was a notable decrease in frequency of both mussel and chiton ~3,750 cal yrs BP, well within the range of the neoglacial. Urchin frequency remained low, with the exception of 2,250 cal yrs BP when there was a small increase and 500 cal yrs BP, which showed drastic increase.

Foraging theory, resource depression and intensification

When top-down processes and their possible effects on ecosystems are considered, we need to contemplate interpretations of the zooarchaeological record beyond changing climate and environment. Foraging theory, resource depression and resource intensification have been widely applied to interpret zooarchaeological data, settlement patterns, and even changes in sociocomplexity. Foraging theory, as it applies to humans, describes a general decline in abundance of higher ranked food sources (generally larger vertebrates) under heavy human hunting pressure and the eventual heavy reliance on smaller vertebrates and other lower ranked food sources that have less energy return for energy expended (Winterhalder and Goland 1993; Grayson and Cannon 1999; Grayson 2001; Butler and Campbell 2004). In the case of marine ecosystems and human coastal adaptations, this has been documented both in historic and prehistoric contexts and is widely known as "fishing down the food web" (Pauly et al. 1998, 2001; Reitz 2004). This decline of higher ranked subsistence resources due to harvesting pressure is termed a "resource depression" (Grayson 2001).

"Resource intensification", on the other hand, is defined as increasing the yield of a resource per unit area, and it often implies a narrowing of the subsistence focus (Ames and Maschner 1999; Butler and Campbell 2004). How resource intensification occurs is widely debated. Some believe that intensification occurs precisely because of resource depression. In other words, resource depression leads humans to spend more energy and time on harvesting their resources but innovations in technology allow them to harvest more from a certain area than previously (e.g. Grayson 2001). Some believe that technological and cultural innovations lead directly to intensification. In some ways historical fisheries have traced foraging theory and resource depression/intensification using "catch per unit effort". As commercial fishing increased, resources declined, until new technologies either increased the catch of a species or allowed for larger numbers of smaller species to be harvested (Pauly et al. 1998, 2001).

Lake core records on Sanak Island

Two lakes were cored and analyzed on Sanak Island; Deep Lake, a sockeye nursery lake, and Swan Lake, a control lake with no apparent connection to a salmon spawning system. Although much of the history of both $\delta^{15}N$ and $\delta^{13}C$ in the lake cores was similar for about 10,000 years after deglaciation, the traits begin to diverge ~6,000 cal yrs BP (Figure 4.2). By 3,500 cal yrs BP average $\delta^{15}N$ in Deep Lake sediments were statistically higher overall than the preceding 10,000 years while Swan Lake's was not altered, and $\delta^{15}N$ of sediments from Deep Lake were significantly different when compared to older sediments (single factor ANOVA, $p = 0.002$). This suggests an increase in MDN in Deep Lake after the start of the Neoglacial, a trend that is also seen in Iliamna Lake on the Alaska Peninsula and Karluk Lake on Kodiak Island. There is a decrease in $\delta^{15}N$ around 1,000-1,200 cal yrs BP (Figure 4.2), within the MWP when climate was warmer and drier than now (Stine 1994; Bradley 1999; Calkin et al. 2001; Jones et al. 2001; Esper et al. 2002; MacDonald and Case 2005), in lake sediments with salmon runs deriving from both the Bering Sea and the northeastern Pacific, including Deep Lake (Finney et al. 2000, 2002; Chapter 2). Alaskan salmon lakes generally show an increase in $\delta^{15}N$ in sediments around the time of the LIA, a period of cooler, wetter climate (Bradley 1999; Finney et al. 2000; 2002; Roberts 2004), as does Deep Lake.

Volcanism affects both Deep and Swan Lakes in terms of productivity with large ashfalls (each > 10.0 cm) ~10,780, 7,230, 4,700 and 3,500 cal yrs BP. There is a drop in $\delta^{15}N$, and smaller ones in $\delta^{13}C$, immediately following each large ash layer in both lakes. Most other volcanic layers are relatively thin (<1.0 cm) and do not appear to affect $\delta^{15}N$. This suggests that one of the primary reasons for steep decreases in productivity of both lakes is due to volcanic activity. Written records of volcanic activity, earthquakes and tsunamis and their effects on Alaskan people, have been kept for the last couple of hundred years. Russian ethnohistories recount mass fish kills in bays after volcanic eruptions and earthquakes and reduced numbers of salmon due to suffocation of adults attempting to spawn in lakes and streams (Veniaminov 1984; Khlebnikov 1994; Black 1999). It is even possible that later hatchlings, which could have been affected by oxygen deprivation from sediment layers (Black 1981), could suffer. Veniaminov (1984) described the 1788 tsunami and its destructive power on Sanak Island. Mammals, both marine and terrestrial, were also impacted by thick layers of volcanic ash. Caribou moved north up the Peninsula after a particularly large ashfall in 1826 (Veniaminov 1984), which was also blamed for a sudden reduction in sea otters in the area (Khlebnikov 1994) (though this may have been due more to over hunting). Kenyon (1969) also noticed a drastic reduction in sea otters shortly after the famous 1964 earthquake. The 1912 Katmai eruption was shown to suffocate salmon already in the lakes on Afognak Island, while those salmon that attempted to enter the stream eventually turned back (Workman 1979).

Isotopic record of organisms recovered in archaeological middens on Sanak Island

Animals analyzed for this study include Steller sea lions (*Eumetopias jubata*, SSL), Harbor seals (*Phoca vitulina*), northern fur seals (*Callorhinus ursinus*), sea otters (*Enhydra lutris*), Pacific cod (*Gadus macrocephalus*) and sockeye salmon (*Oncorhynchus nerka*). Samples are derived from 17 discrete middens and span the last 4,500 years. Based on the mean $\delta^{15}N$ and $\delta^{13}C$ for each species, some trophic level and foraging habitat information is evident (Figure 4.5). All species had a decrease in $\delta^{13}C$ from prehistoric to modern times, even when accounting for the Suess Effect (Figure 4.5). Explanations for this change included hypotheses such as a decrease in sea ice and therefore ice algae that have a higher $\delta^{13}C$ than phytoplankton (but not all species analyzed may have fed in the Bering Sea), changes in foraging location of all species could have affected $\delta^{13}C$ (but that does not explain the fact the $\delta^{15}N$ did not change significantly for most species), or that environmental change led to a reduction in productivity in the modern GOA (Misarti unpub.). The conclusion was that climate/environmental change led to this reduction, which in turn may have had different effects in the different ecozones represented by the taxa.

Three species (sea otter, Pacific cod and sockeye salmon) were found in numbers sufficient to study changes over time in the archeological record. Pacific cod have very little change in $\delta^{13}C$ and $\delta^{15}N$ over the last 4,500 years (Figure 4.6). It is likely that cod feed on such a broad prey spectrum that despite changes in ecosystem that could have changed prey availability, cod did not have to change geographic locations nor did they need to change the trophic level at which they were feeding. This stability is reflected in $\delta^{13}C$ and $\delta^{15}N$ (Misarti unpub.). This interpretation makes the difference in the modern versus archeological change in $\delta^{13}C$ noteworthy.

$\delta^{13}C$ and $\delta^{15}N$ of salmon, on the other hand, changed quite a bit over the past 4,500 years (Figure 4.5). High $\delta^{13}C$ and $\delta^{15}N$ in the earlier part of the record suggests that salmon foraged in shelf waters or that primary productivity was higher for much of the neoglacial period, with the exception of one 350 year period from 2,750-2,400 cal yrs BP (Misarti unpub.). The decrease in both $\delta^{13}C$ and $\delta^{15}N$ during the MWP suggests a drop in primary productivity during this time period, or a change in forage location to areas such as the subarctic gyre. The data from the LIA (a decrease in $\delta^{13}C$ and increase $\delta^{15}N$) suggests, however, that perhaps physical conditions had changed and that this time of high primary productivity caused nitrogen limitations while stronger upwelling currents kept carbon levels from being drawn down (Misarti unpub.).

Sea otters appear to have been affected very differently than cod or otter (Figure 4.6). One hypothesis is that sea level and the health of the intertidal invertebrates and the kelp forest ecosystem affected the $\delta^{13}C$ and $\delta^{15}N$ of sea otters (Misarti unpub.). The health of the system could have been affected by environmental/climate change or anthropogenic top-down forcing. In times when $\delta^{13}C$ was low but $\delta^{15}N$ high (i.e. at the onset of neoglaciation) it is possible sea otters included more open-water fish in their diets but when $\delta^{13}C$ was high and $\delta^{15}N$ lower (such as they did during the height of neoglaciation) otter diets were likely dominated by urchins and other benthic invertebrates and perhaps some fish that thrive in kelp forest ecosystems (Misarti unpub.).

None of the temporal patterns of shifts in mean $\delta^{13}C$ and $\delta^{15}N$ in salmon, cod and sea otter were similar to one another when compared over the six time periods studied (the past 4,500 years). Nor did they correspond to what is understood about PDO-like regime shifts and their effects on the GOA/NE Pacific waters. Alternate states (positive or negative) of the PDO affect sea surface temperature (SST), sea level pressure (SLP), the strength of the Aleutian Low (AL), wind strength, storm intensity, mixed layer depth and ocean current patterns (Overland et al. 1999). A warm PDO phase appears to favor production of salmon in the Gulf of Alaska (GOA) while a cold PDO phase appears to play a role in decreased salmon stocks. Strangely, paleodata from lake cores around Alaska showed a different relationship with cooler time periods coinciding with apparent sockeye salmon stock increases (Misarti unpub.). The isotope data did not appear to fit with hypotheses about organisms' discrimination against heavier isotopes until carbon and nitrogen are less available in a system either (Misarti unpub.). Theoretically, when productivity in the GOA is high, $\delta^{13}C$ and $\delta^{15}N$ should be higher in salmon, but the data did not fit this pattern. In fact, my findings did not correspond to relationships between $\delta^{13}C$ and $\delta^{15}N$ resulting from changes in trophic levels or productivity. For example, none of the changes can be said to correspond to the 3:1 change between N and C as an organism changes trophic levels at which it feeds (Misarti unpub.).

Discussion

The information summarized above is the proxy data that are the basis for interpretations of cultural and environmental change. As noted in the introduction there are two sides to this discussion; the effects of climate change on humans and their lifestyles, and the effects humans had on their local environments. First I will discuss the arguments and evidence for bottom-up processes and then later the evidence of top-down processes. Last, but surely not least, I will discuss the catastrophic events such as volcanic activity, that may have impacted humans in the area.

Bottom-up processes

Our most current knowledge shows Sanak was inhabited by at least 6,000 cal yrs BP. Many of the oldest sites on the Alaska Peninsula also date from ~6,000 cal yrs BP (Maschner 2000) as well. Some archaeologists have argued that the spread of people along the eastern Aleutians and Peninsula may have been due to the warmer, less stormy conditions of the Hypsithermal ameliorating conditions for open water travel (McCartney 1984; Dumond 1998). However, such conditions would have existed for several thousand years (i.e. to the beginning of the Holocene). I do not believe that it is coincidence that the first evidence of substantial salmon abundance found in the Deep Lake record on Sanak coincides with the first evidence (so far) that the island was inhabited (Figure 4.7).

This is not to say that salmon were the driving force behind this, but if one considers increasing numbers of salmon as a proxy for increased productivity in the GOA then perhaps the picture becomes a bit clearer. In general, this is consistent with knowledge of how climate evolved over the Holocene and how this may have affected coastal productivity in the GOA. Increases in precipitation suggest a strengthening of the AL, which drives onshore advection of nutrients and wintertime mixing and spring stratification, all essential in accounting for the high productivity of the coastal downwelling GOA shelf region (Freeland et al. 1997). It is possible that a change occurred at a little more than 6,000 cal yrs BP, as registered by a glacial advance in the GOA (Calkin et al. 2001). Such evidence for a cooler and moisture climate may suggest higher ocean productivity, which may be analogous to changes during the LIA, which has also been argued to be a period of enhanced productivity in the northeast Pacific (Finney et al. 2002).

By ~4,500 cal yrs BP shell middens have been found in association with archaeological sites on the southeast side of Sanak Island. Sea otters are abundant in the middens and the isotope data are consistent with a diet of pelagic fish (Figures 4.6 and 4.8). This may have been partially driven by sea level, which may have been too high for kelp forest communities to have established themselves (Misarti unpub.) or the increased storminess that began about this time was keeping kelp density lower (Dayton et al. 1992). Another possibility is that otters were at equilibrium density, so there were fewer urchins and other benthic invertebrates and otters ate more fish (per Watt et al. 2000). Shell middens contain little urchin remains, but more mussels and chitons, so we know that rocky intertidal ecosystems existed. Perhaps the small numbers of sea urchins found in these deposits are indicative of large sea otter populations.

By the start of the Kinzarof Phase (~3,300 cal yrs BP) there was a large enough increase in salmon on Sanak Island to be statistically different from earlier times (Figures 4.2 and 4.7), and a large increase in salmon was observed on Kodiak Island as well (Finney et al. 2002). There are several sources of evidence for cooler, wetter climate (pollen data, glacial advances and increased storminess). No middens have been found on Sanak dating from 3,100-2,600 cal yrs BP. Perhaps marine productivity overall was high enough, weather was calm enough and numbers of people small enough that harvesting the intertidal was not necessary.

By 1,900 cal yrs BP, the Ram's Creek phase on the Peninsula had only a few large villages but many small ones and these villages were not located in areas that appear to make salmon a high priority. Salmon numbers, which had been very high are now beginning to decline in many places, but are actually still far from diminished (Figure 4.7). One environmental explanation for this is a previous catastrophic event a few hundred years beforehand that hurt salmon stocks. People may have begun to focus on other resources (see below). There are no sites with middens on Sanak from 1,900-1,600 cal yrs BP and sites on either side of this time period also have very little in way of shellfish exploitation (Figure 4.4). It is pure conjecture, but perhaps Sanak Island was a place where fish stocks were still thriving and people occupied the island specifically to exploit this resource. By 1,600 cal yrs BP there is evidence that salmon numbers dropped in Deep Lake and other lakes around the GOA, and once again shellfish were exploited on Sanak. There were still very low numbers of sea otters in middens but sea lion frequency was high (Figure 4.8). We know that glaciers were receding at that time and there was a decrease in storminess. Perhaps, despite the fact that sea lions may have moved offshore, humans were once again able to harvest them in higher numbers because seas were calmer.

The next time period for which I have evidence for bottom-up control starts ~1,250 cal yrs BP. Climate was warming and becoming less stormy, and salmon, previously in very high numbers, were just beginning to decline. However, villages were located almost exclusively along salmon streams. Villages were smaller and there is evidence for warfare (Frosty Creek Phase). Pacific cod and otariid frequency dropped, but sea otter frequency increased in Sanak Island middens while cod played a smaller role all over the lower Alaska Peninsula (Figure 4.4). This reduction in cod and otariids may have been due to warming waters.

The timing of the movement of settlements back out to coastal locations at ~900 cal yrs BP (start the Cape Glaznap Phase) cannot be a coincidence. In fact, all lakes in the GOA, including Deep Lake (Figures 4.2 and 4.7), showed the lowest numbers of salmon since the onset of neoglacial conditions by 900 cal yrs BP. The MWP was a time of warm and possibly dry conditions, receding glaciers, and decreasing storminess, all of which appear to hinder productivity in the northeast Pacific. In Sanak middens, animals (otariids, salmon, cod and waterfowl) that have been previously shown to have difficulties in warmer waters dropped in frequency (Figure 4.4). Sea otter and intertidal species increased in frequency once again. This change in frequencies of larger fish and sea mammals to smaller mammals and shellfish appears related not to hunting pressure, but mainly to environmental change. These are the most diverse (species rich) middens on Sanak (Figure 4.3), and it appears people were exploiting every resource they could. The only middens from this time period on Sanak date to ~1,000 cal yrs BP. From 1,500-1,100 cal yrs BP there are no middens on Sanak and from 1,200-1,000 cal yrs BP there are none on the lower Alaska Peninsula. People grouped into large villages and there is evidence of both warfare and trade with distant people.

By 750 cal yrs BP (Izembek Phase) there was a large population collapse all over the GOA. This was most likely a bottom-up process, a culmination and reflection of the low productivity in the northeast Pacific for the preceding few hundred years. Glacial advances and increased storminess were likely improving productivity in the GOA. The oceans appeared to be recovering with an increase in salmon by this time but people were not settling along salmon streams. This could be a cultural lag from the previous years when salmon were an unreliable resource.

The next period that I can attribute some cultural and population change to bottom-up processes is the LIA. There are large ice advances between 750-200 cal yrs BP and evidence for many large and frequent storms. In the Sanak Island middens, the frequency and numbers of all species increased. Sea otters and sea lions were found in about the same frequency in middens on Sanak, there were high frequencies of migratory waterfowl, cod, chiton, mussels and urchins, which may reflect humans exploitation of intertidal resources under stormy conditions. However, salmon relative abundance in middens was low compared to earlier times. Perhaps for Sanak, like many Aleutian

Islands with salmon runs that are generally smaller than on the main land, there was less of an emphasis on salmon at a time when so many other resources were available.

In contrast, villages on the Peninsula can be directly associated with sockeye nursery lakes with substantial runs, coincident with a large increase in salmon over much of the GOA (Figure 4.7). Human populations were larger than at any time period, villages were extremely large and there is evidence for corporate households. The marine ecosystem, including humans, was once again thriving. Sea otters had high median $\delta^{15}N$ and $\delta^{13}C$ (Figure 4.8), evidence for a diet heavy in fish, so perhaps they were at population equilibrium. This correlates with information from Russian ethnographies in the 1700's. Since kelp forests were healthy and well established along much of the coast line at this time I can postulate that the fish in otter diets were kelp forest fish and not more open water fish with lower $\delta^{13}C$.

Top-down changes

By 3,750 cal yrs BP the frequency of sea otters dropped drastically in the middens as did mussel and chiton (Figure 4.2). Sanak Islanders appear to still have a very heavy reliance on fish species at this time, and the frequency of Steller sea lion increased as well (Figure 4.2). This was a time of enhanced neoglacial conditions around the GOA and the cooler, wetter, stormier climate that began ~ 4,500 cal yrs BP was firmly in place. There were no large cultural changes with the exception of introduction of bone harpoons, which may have improved hunting techniques for Steller sea lions. The changes in the archaeological record from this time period appear to be related to top-down processes. By ~3,700 cal yrs BP sea otters were either no longer as important a resource because Steller sea lions became available through new hunting technology and more waterfowl were being taken as well, or otters were impacted by the thousand or so years of hunting on the island. Isotope analysis showed an increase in both $\delta^{15}N$ and $\delta^{13}C$ for otters at this time (Figure 4.8), suggesting that the otter population was higher (and possibly included more fish in their diet) while otters were not hunted by humans. Shortly after this time period, $\delta^{15}N$ and $\delta^{13}C$ decreased once again, suggesting a predominance of urchin and other benthic invertebrates in otter diets. It is therefore possible that heavy predation of otters by humans could have caused a decrease in numbers of otters around Sanak Island, allowing sea urchin populations to increase. The few otters that were left may have fed heavily on the growing numbers of urchins and other invertebrates. Though speculation, this scenario would certainly imply an ecosystem manipulated in some ways by humans (Figure 4.8).

By 2,400 cal yrs BP, houses and village size increased, and line-hole harpoons became part of hunting technology. Betts and Tews (2007) believe sea lions may have moved offshore in response to heavy hunting by humans. In fact, sea otters were once again very frequent in middens and have slightly lower median $\delta^{15}N$ than at 3,700 cal yrs BP, suggesting otter populations around the island had decreased due to hunting pressures by humans. If sea lions moved offshore in response to hunting pressures, then Aleuts may have had to turn to sea otters once again.

Changes in inclusion rates of smaller, less energy efficient resources over time is informative. During the LIA, there intertidal resources were heavily utilized despite the fact that other resources supposedly abounded. Such a change may be in response to village populations, which had become so large (and ethnographic sources agree that these villages were sedentary/semi-sedentary) that Aleuts needed to exploit any and all resources available to them, especially at times of the year when more energy-efficient resources may not have been available.

Volcanism, tsunamis, earthquakes and other catastrophes

There is strong evidence of volcanic activity and the subsequent drop in productivity in the lakes in the lake cores recovered from Sanak Island. It stands to reason that volcanic activity and other natural/cultural catastrophes would have similar deleterious effects on the humans that inhabited the landscape. The largest Holocene volcanic eruptions (~10,780 and 6,800 cal yrs BP) occurred before evidence of human occupation of Sanak. If there had been humans at these times, any survivors more than likely abandoned the area just as Anangula was abandoned after a large volcanic eruption (Black and Laughlin 1964; Black 1974). There is also evidence that a large volcanic eruption may have been the reason for site abandonment on Hog Island off of Unalaska ~8,000 years ago as well.

Circa 4,700 and 3,600 cal yrs BP, there were two large volcanic eruptions recorded in lake cores on Sanak Island (Misarti unpub.). If these ashfalls are scaled to historic records and ethnographic sources can be believed, the amount of ash that fell would have clogged streams and probably also suffocated many intertidal organisms in Sanak's bays. The time period of the earlier tephra coincides with the beginning of the Moffett Phase (~4,800 cal yrs BP), with villages located on high terraces and bluffs. On Sanak a single village existed with middens but was not located by a salmon stream. This is circumstantial evidence at best and it is entirely possible that this particular volcanic eruption did not affect humans to any great extent. Alternatively, there could have been abandonment and resettlement within 50 or 100 years, movements difficult to distinguish due to the resolution of the dating methods.

The second tephra, dated ~3,600 cal yrs BP, could have had a stronger influence on the humans inhabiting Sanak Island. From 3,600 to 3,350 cal yrs BP no sites exist on Sanak Island. There are, however, sites located on the mainland, so it is not a case of people abandoning an entire area, just the islands of the Sanak archipelago. This gap in the archaeological record on Sanak is notable with the additional evidence of a large volcanic event, independently dated.

Conclusions

Bottom-up processes were affecting environments with times of glacial advances and increased storminess seemingly more productive in the GOA/NE Pacific, and the human population in the area seemed to grow during these times. Warmer periods appear to be times of lesser productivity. For example, the MWP appears to be a time when the

GOA underwent some major change. According to lake core data, sockeye salmon returns decreased in most areas of Alaska (Finney et al. 2002; Anderson et al. 2005). There are no sites with middens on Sanak Island from this time, and on the lower Alaska Peninsula and Kodiak Island, humans that relied on marine mammals for a few thousand years suddenly appeared to rely mostly on salmon, and village numbers and size appear to have decreased (Maschner and Reedy-Maschner 1998; Maschner 2000). Finney et al. (2002) show that fluctuations in numbers of returning salmon in Kodiak lakes can be correlated with this major shift in material culture. By about 700 BP there were no large villages on Kodiak or the western Alaska Peninsula (Maschner and Reedy-Maschner 1998; Maschner 2000). Marine populations obviously recovered and humans returned to harvesting the oceans, but the isotope trends discussed above did not return to earlier Holocene, pre-MWP trends.

The LIA ushered in a new period of high productivity in the area and it seems that most ecosystems responded favorably to the cooler temperatures, increased precipitation and increased storminess. By the Russian contact period the Aleut had reached a level of social complexity not seen in previous archaeological evidence. As evidenced by increases in salmon abundance, it appears the GOA had reached high levels of productivity that no longer exist in the modern GOA system.

All of these major climatic periods are potentially punctuated by natural disasters such as volcanic eruptions, earthquakes and tsunamis that can adversely affect all local communities from intertidal to human. I have noted the potential changes in location and village size in response to some of these disasters.

At the onset of neoglacial conditions, people on Sanak were harvesting many sea otters and may have been the cause for a population reduction. As sea otter frequencies decreased in middens, otariid numbers increased. After over 1,000 years of hunting, it is possible that Aleuts were responsible for a change in otariid haul-out locations from local island areas to farther off shore (as per Betts and Tews 2007). It is also possible that after 1,000 or so years of hunting sea otters, humans were responsible for lower population numbers than had been the previous natural state, as is suggested by the $\delta^{15}N$ and $\delta^{13}C$ data of otters recovered from middens on Sanak Island.

The research presented here indicates that both top-down and bottom-up processes were shaping the North Pacific for the past 6,000 years. The Aleut have been an intricate part of the system, both shaping and being shaped by their environment, for thousands of years. It does appear that some changes in archaeological culture can be linked to climate/ecosystem change, with resource consumption restructuring during times when isotope ratios of organisms demonstrate changes as do reconstructed sockeye abundances. It appears that humans may also have caused some local changes with consumption of particular resources causing resource depressions that can be noted not only in zooarchaeological contexts, but in changes in isotope ratios of organisms as well.

Figures

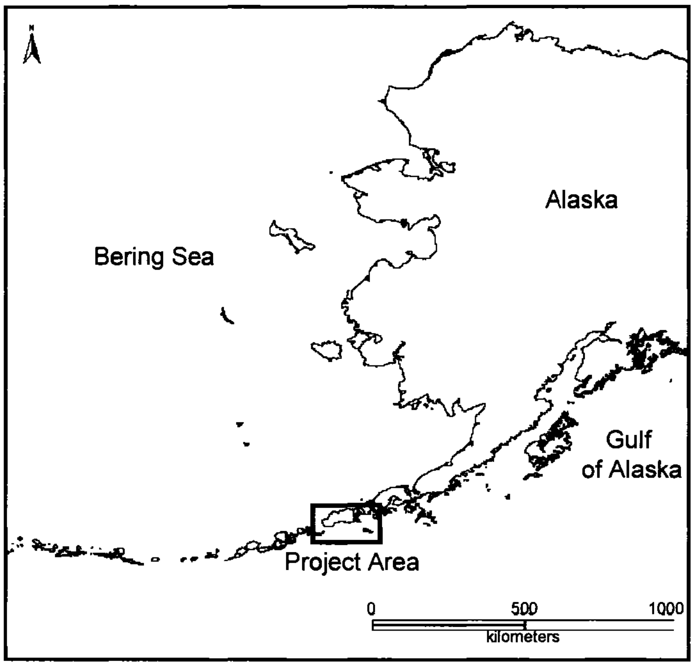

Figure 4.1: Location of study site, Sanak Island, in the Northeast Pacific.

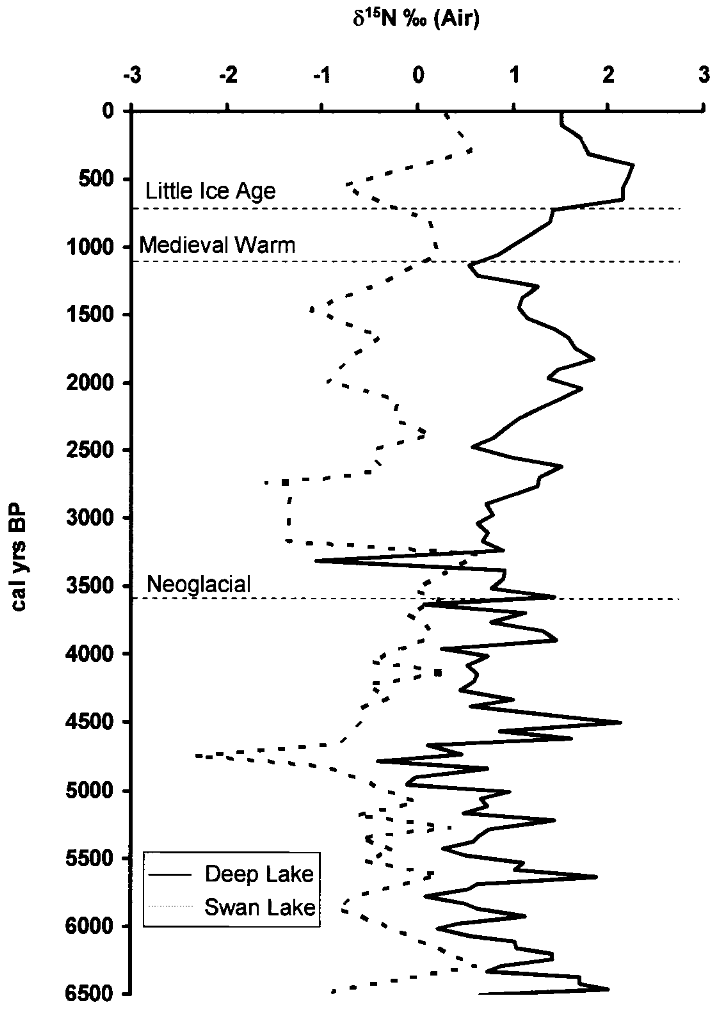

Figure 4.2. A comparison of proxy data between two lakes, Deep Lake-a sockeye salmon nursery, and Swan Lake-a control lake.

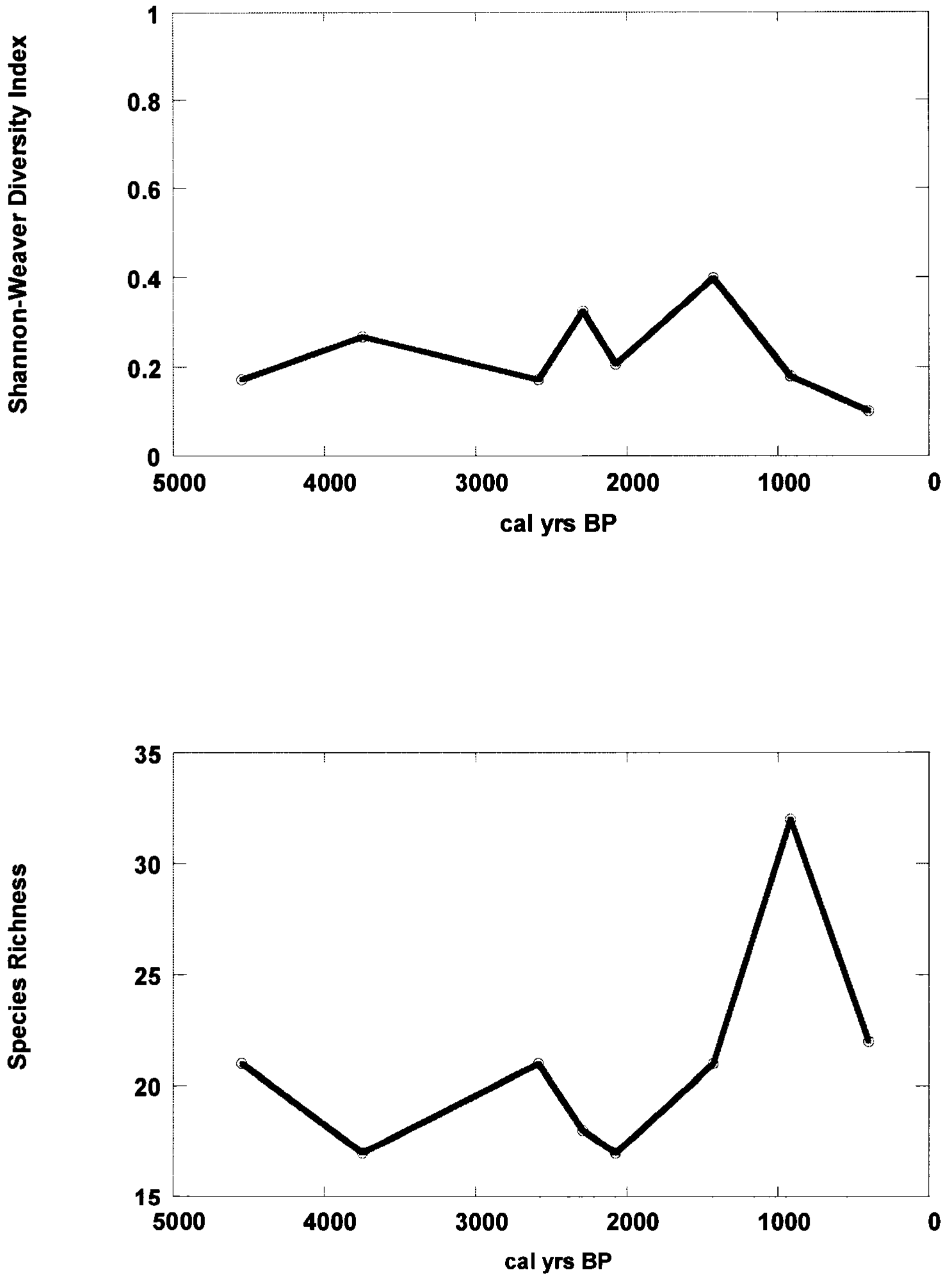

Figure 4.3. Measures of diversity and richness of Sanak Island middens spanning the last 4,500 years.

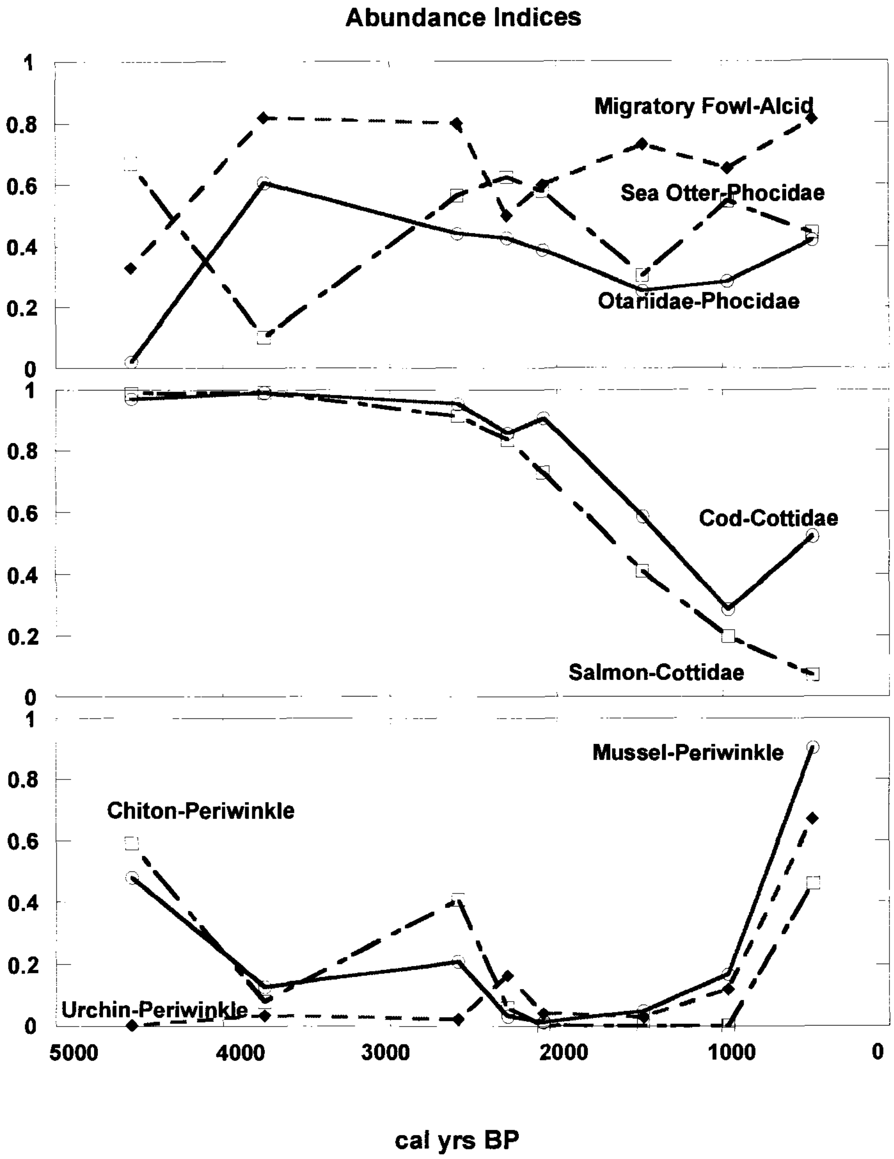

Figure 4.4. Abundance indices of several resources from Sanak Island middens over the last 4,500 years.

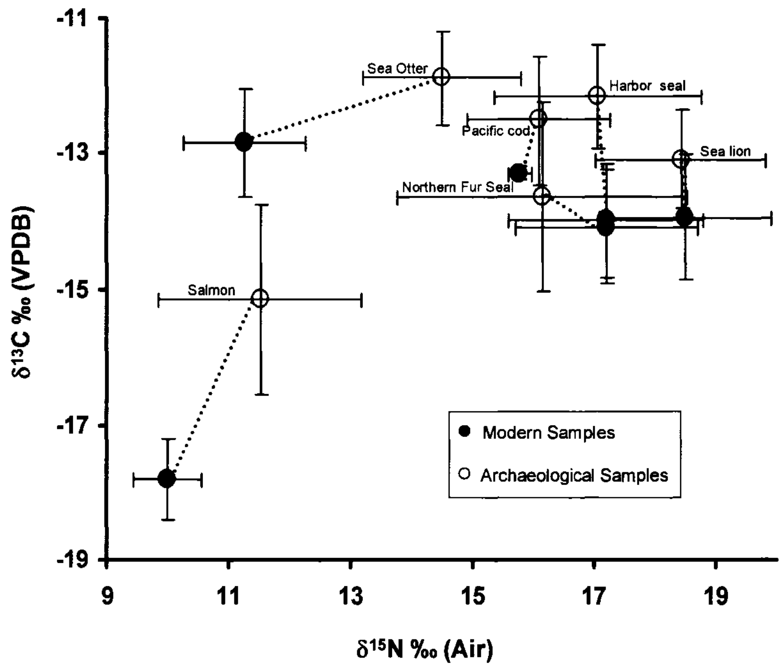

Figure 4.5. Mean values of $\delta^{13}C$ and $\delta^{15}N$ from bone collagen in both modern and archaeological specimens. Modern salmon data from Satterfield (2000) and modern fur seal, sea lion, harbor seal and Pacific cod from Hirons (2001) and Misarti (unpub.). All muscle tissue samples from fish have been corrected to equivalent collagen values based on fractionation of $\delta^{13}C$ and $\delta^{15}N$ between muscle tissue and collagen.

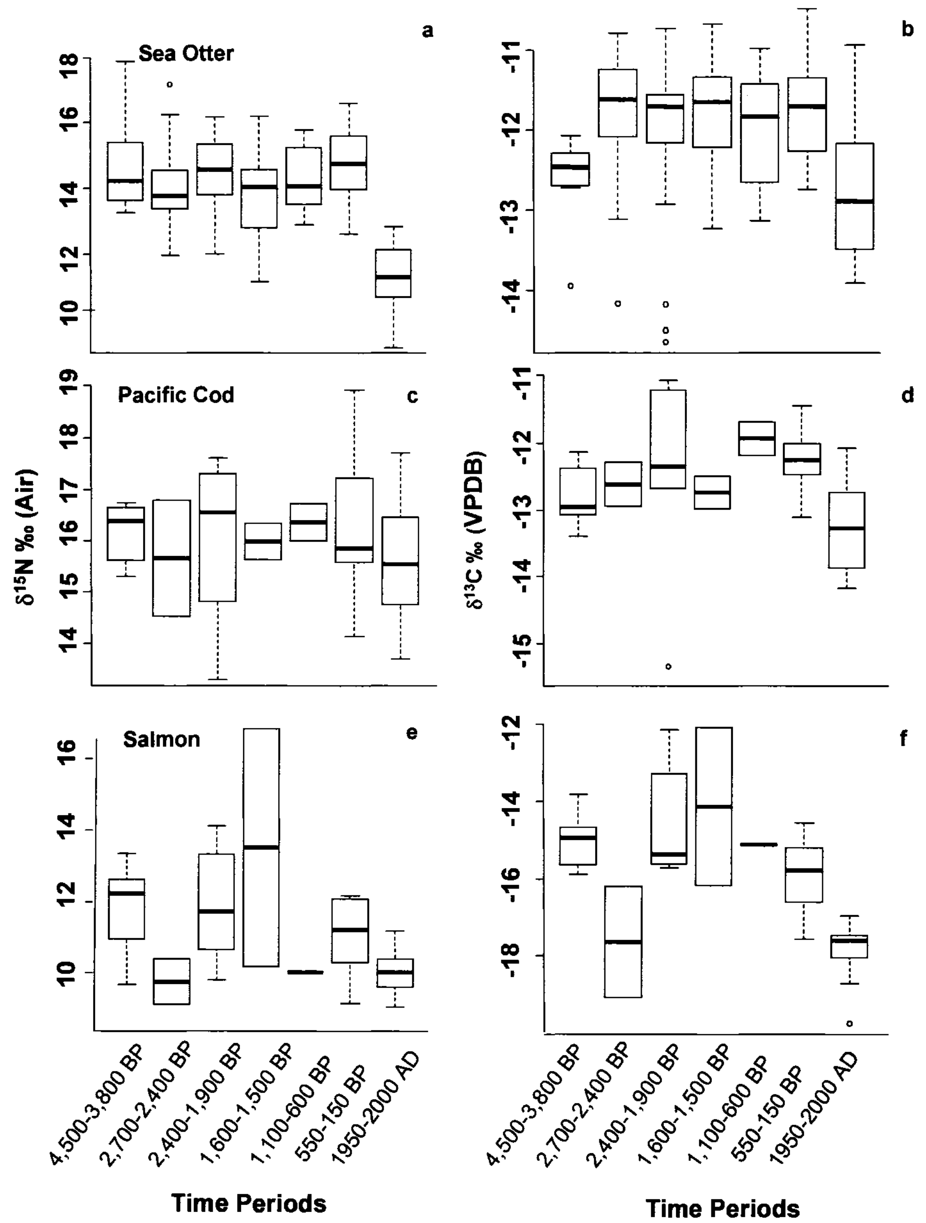

Figure 4.6. $\delta^{13}C$ and $\delta^{15}N$ medians (bars), quartiles (boxes) and spread (whiskers) of sea otter, cod and salmon showing change over the six time periods over the past 4,500 years.

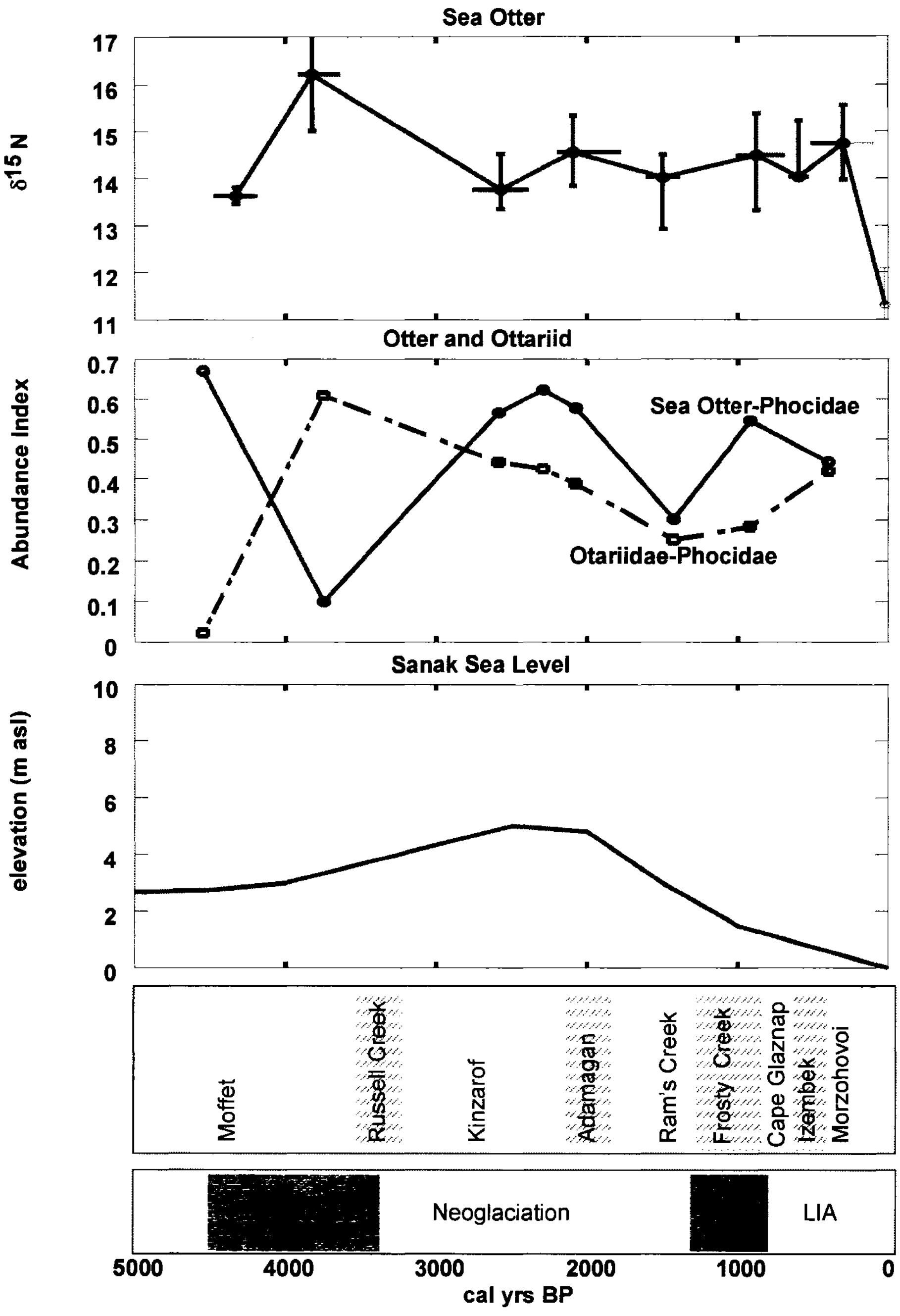

Figure 4.7. Abundance index, $\delta^{15}N$ from salmon and Deep Lake sediments, cultural phases and known climatological periods over the last 5,000 years. Y-error bars of salmon collagen denote the 1st and 2nd quartiles while X-error bars denote the time period each median represents.

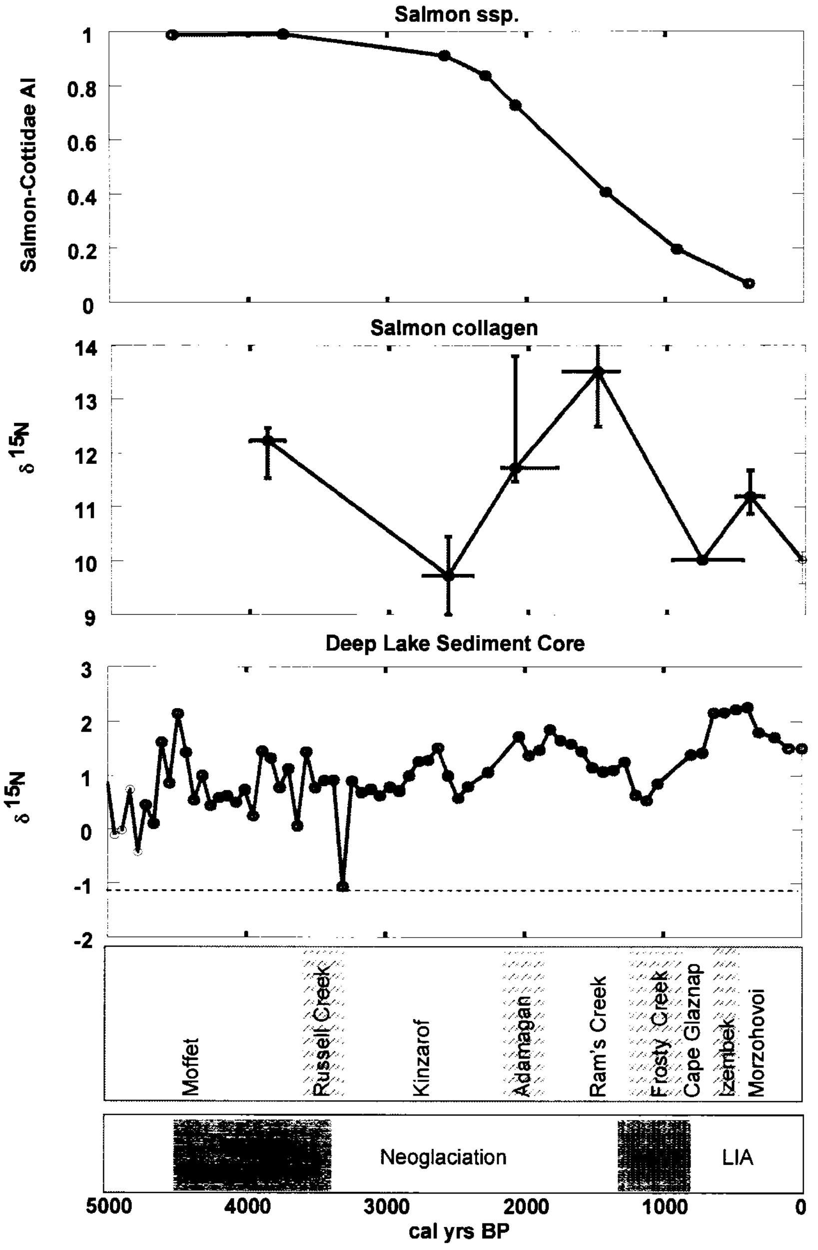

Figure 4.8. Abundance index, $\delta^{15}N$ from sea otters, Sanak Island sea levels, cultural phases and known climatological periods over the last 5,000 years. Y-error bars of sea otter collagen denote the 1st and 2nd quartiles while X-error bars denote the time period each median represents.

References

Ames KM (1994) The Northwest Coast: complex hunter-gatherers, ecology, and social evolution. Annual Review of Anthropology 23:209-229

Ames KM, Maschner HDG (1999) Peoples of the Northwest Coast: their prehistory and archaeology. Thames and Hudson, London

Anderson L, Abbott MB, Finney BP, Burns SJ (2005) Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 64:21-35

Betts MW, Tews AM (2007) 4,500 years of Aleut economic and ecosystem change on Sanak Island, Alaska. In: 72nd Annual Society for American Archaeology Conference Proceedings, Austin TX

Black RF, Laughlin WS (1964) Anangula: A geologic interpretation of the oldest archaeologic sites in the Aleutians. Science 143:1321-1322

Black RF (1974) Late-Quaternary sea level changes, Umnak Island, Aleutians: Their effects on ancient Aleuts and their causes. Quaternary Research 4:264-281

Black LT (1981) Volcanism as a factor in human ecology: the Aleutian case. Ethnohistory 28:313-340

Black LT (1999) The history and ethnohistory of the Aleutians East Borough, 1st edn. The Limestone Press, Ontario, Canada

Bradley RS (1999) Paleoclimatology; reconstructing climates of the Quaternary, Second edn. Academic Press, New York

Burton RK, Gifford-Gonzalez D, Snodgrass JJ, Koch PL (2002) Isotopic tracking of prehistoric pinniped foraging and distribution along the central California coast: Preliminary results. International Journal of Osteoarchaeology 12:4-11

Butler VL, O'Conner JEO (2004) 9000 years of salmon fishing on the Columbia River, North America. Quaternary Research 62:1-8

Butler VL, Campbell S, K, (2004) Resource intensification and resource depression in the Pacific Northwest of North America: a zooarchaeological review. Journal of World Prehistory 18:327-405

Calkin PE, Wiles G, Barclay DJ (2001) Holocene coastal glaciation of Alaska. Quaternary Science Reviews 20:449-461

Causey D et al. (2005) The palaeoenvironment of humans and marine birds of the Aleutian Islands: three millennia of change. Fisheries Oceanography 14:259-276

Coupland G (1985) Restricted access, resource control and the evolution of status inequality among hunter-gatherers. In: Thompson M, Garcia MT, Kense FJ (eds) Status, structure and stratification: current archaeological reconstructions. Archaeological Association of Calgary, Calgary, pp 217-226

D'Arrigo R, Mashig E, Frank D, Wilson R, Jacoby G (2005) Temperature variability over the past millennium inferred from Northwestern Alaska tree rings. Climate Dynamics 24:227-236

Dayton PK, Tegner MJ, Parnell PE, Edwards PB (1992) Temporal and spatial patterns of disturbance and recovery in a kelp forest community. Ecological Monographs 62:421-445

Dumond DE (1998) Maritime adaptation on the northern Alaska Peninsula. Arctic Anthropology 35:187-203

Esper J, Cook ER, Schweingruber FH (2002) Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295:2250-2253

Finney BP, Gregory-Eaves I, Sweetman J, Dougas MSV, Smol JP (2000) Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. Science 290:795-799

Finney BP, Gregory-Eaves I, Douglas MSV, Smol JP (2002) Fisheries productivity in the Northeastern Pacific Ocean over the past 2,200 years. Nature 416:729-733

Fitzhugh B (2003) The evolution of complex hunter-gatherers: archaeological evidence from the North Pacific. Kluwer Academic/Plenum Publishers, New York

Freeland H, Denman K, Wong CS, Whitney F, Jacques R (1997) Evidence of change in the winter mixed layer in the Northeast Pacific Ocean. Deep-Sea Research Part I-Oceanographic Research Papers 44:2117-2129

Gedalof ZE, Mantua NJ (2002) A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophysical Research Letters 29:2204-2208

Grayson DK, Cannon MD (1999) Human paleoecology and foraging theory in the Great Basin. In: Beck C (ed) Models for the millennium: Great Basin anthropology today. University of Utah Press, Salt Lake City, pp 141-151

Grayson DK (2001) The archaeological record of human impacts on animal populations. Journal of World Prehistory 15:1-68

Grayson DK, Delpech F, Rigaud J-P (2001) Explaining the development of dietary dominance by a single taxon at Grotte XVI, Dordogne, France. Journal of Archaeological Science 28:115-125

Hayden B (1995) Pathways to power: principles for creating socioeconomic inequalities. In: Price TD, Feinman G (eds) Foundations of social inequality. Plenum Press, New York, pp 15-85

Hirons AC (2001) Trophic dynamics of pinniped populations in Alaska using stable carbon and nitrogen isotope rat. In: Institute of Marine Science. University of Alaska, Fairbanks

Hoffman BW (1999) Agayadan village: household archaeology on Unimak Island, Alaska. Journal of Field Archaeology 26:147-161

Hoffman BW (2002) The organization of complexity: a study of late prehistoric village organization in the Eastern Aleutian Region. In: Department of Anthropology. University of Wisconsin, Madison, p 437

Huesser CJ, Huesser LE, Peteet DM (1985) Late-Quaternary climate change on the American North Pacific Coast. Nature 315:485-487

Jones PD, Osborn TJ, Briffa KR (2001) The evolution of climate over the last millennium. Science 292:662-667

Jordan JW, Maschner H (2000) Coastal paleogeography and human occupation of the Western Alaska Peninsula. Geoarchaeology: An International Journal 15:385-414

Jordan JW (2001) Late Quaternary sea level change in Southern Beringia: postglacial emergence of the Western Alaska Peninsula. Quaternary Science Reviews 20:509-523

Jordan JW, Krumhardt A (2003) Postglacial climate and vegetation on the Western Alaska Peninsula. Alaska Journal of Anthropology 1:16-33

Jordan JW, Finney BP, Odorczuk D, Misarti N, Maschner H (2005) Paleoecology of the Sanak Archipelago. In: Society for American Archaeology, Salt Lake City, Utah

Kenyon KW (1969) The sea otter in the Eastern Pacific Ocean. Dover Publishers

Khlebnikov KT (1994) Notes on Russian America: Parts II-V: Kad'iak, Unalashka, Atkha, The Pribylovs. The Limestone Press, Fairbanks

Kim JH et al. (2004) North Pacific and North Atlantic sea-surface temperature variability during the Holocene. Quaternary Science Reviews 23:2141-2154

MacDonald GM, Case RA (2005) Variations in the Pacific Decadal Oscillation over the past millennium. Geophysical Research Letters 32

Mann DH, Hamilton TD (1995) Late Pleistocene and Holocene paleoenvironments of the North Pacific Coast. Quaternary Science Reviews 14:449-471

Mann DH (2001) Climate during the past millennium. Weather 56:91-102

Maschner HDG, Reedy-Maschner KL (1998) Raid, retreat, defend (repeat): the archaeology and ethnohistory of warfare on the North Pacific. Journal of Anthropological Archaeology 17:19-51

Maschner HDG (1998) Salmon run volatility, subsistence, and the development of North Pacific societies. In: Hokaido Museum of Northern People (ed) 12th International Abashiri Symposium: Salmon Fishery in the North and its Change through time. Association for the Promotion of Northern Cultures, Abashiri, Hokkaido, Japan

Maschner HDG (1999) Prologue to the prehistory of the lower Alaska Peninsula. Arctic Anthropology 36:84-102

Maschner H (2000) Catastrophic change and regional interaction: The southern Bering Sea in a dynamic world system. In: Appelt M, Berglund J, Gullov HC (eds) Identities and cultural contacts in the Arctic: proceedings from a conference at the Danish National Museum, November 30-December 2, 1999, vol 8. Danish National Museum, Copenhagen, pp 252-265

Maschner HDG, Jordan JW (2001) The Russell Creek manifestation of the Arctic Small Tool tradition on the western Alaska Peninsula. In: Dumond DE (ed) Archaeology of the Aleut zone of Alaska: some recent research. University of Oregon Anthropological Papers No. 58, pp 151-172

Maschner HDG, Hoffman BW (2003) The development of large corporate households along the North Pacific Rim. Alaska Journal of Anthropology 1:44-61

Maschner HDG, Bentley RA (2003) The power law of rank and household on the North Pacific. In: Bentley RA, Maschner HDG (eds) Complex systems and archaeology: empirical and theoretical applications. University of Utah Press, Salt Lake City, pp 47-60

Maschner HDG (2004) Traditions past and present: Allen McCartney and the Izembek Phase of the western Alaska Peninsula. Arctic Anthropology 41:98-111

Maschner HDG, Jordan JW (2005) A new archaeological chronology for the Eastern Aleut. In: Alaska Anthropological Association, Anchorage, AK

Maschner HDG, Reedy-Maschner KL (2005) Aleuts and the sea. Archaeology:63-70

Mason OK, Jordan JW (1993) Heightened North Pacific storminess during synchronous Late Holocene erosion of Northwest Alaska beach ridges. Quaternary Research 40:55-69

Matson RG (1992) The evolution of Northwest Coast subsistence. In: Croes DL, Hawkins RA, Isaac BL (eds) Long-term subsistence change in prehistoric North America. JAI, Greenwich, pp 367-428

Matson RG, Coupland G (1995) The prehistory of the Northwest Coast. Academic Press, New York, New York

McCartney AP (1984) Prehistory of the Aleutian region. In: Damas D (ed) Handbook of North American Indians, vol 5. Smithsonian Institution Press, Washington, D.C., pp 119-135

Overland JE, Adams JM, Bond NA (1999) Decadal variability of the Aleutian Low and its relation to high-latitude circulation. Journal of Climate 12:1542-1548

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing down marine food webs. Science 279:860-863

Pauly D et al. (2001) Fishing down Canadian aquatic food webs. Canadian Journal of Fisheries and Aquatic Sciences 58:51-62

Reitz EJ, Wing E (1999) Zooarchaeology. Cambridge University Press, Cambridge

Reitz EJ (2004) "Fishing down the food web": a case study from St. Augustine, Florida, USA. American Antiquity 69:63-83

Roberts N (2004) The Holocene; an environmental history, Second edn. Blackwell Publishing, Malden, MA

Satterfield FR (2000) A comparison of sockeye salmon (*Oncorhynchus nerka*) in two climate regimes in the North Pacific Ocean using stable carbon and nitrogen isotope ratios. In: Institute of Marine Science. University of Alaska, Fairbanks, AK

Savinetsky AB, Kiseleva NK, Khassanov BF (2004) Dynamics of sea mammal and bird populations of the Bering Sea region over the last several millennia. Palaeogeography Palaeoclimatology Palaeoecology 209:335-352

Stine S (1994) Extreme and persistent drought in California and Patagonia during Medieval time. Nature 369:546-549

Tews AM (2005) Prehistoric Eastern Aleut subsistence; 5,000 years of faunal variations. In: Department of Anthropology. Idaho State University, Pocatello, ID, p 243

Veniaminov I (1984) Notes on the islands of the Unalashka District. The Limestone Press, Ontario Canada

Watt J, Siniff DB, Estes JA (2000) Inter-decadal patterns of population and dietary change in sea otters at Amchitka Island, Alaska. Oecologia 124:289-298

Winterhalder B, Goland C (1993) On population, foraging efficiency, and plant domestication. Current Anthropology 34:710-715

Workman WB (1979) The significance of volcanism in the prehistory of subarctic Northwest North America. In: Sheets PD, Grayson DK (eds) Volcanic activity and human ecology. Academic Press, New York, pp 339-371

General Conclusions

This project resulted in long-term records of the North Pacific ecosystem and explored the relationships between change in the North Pacific marine ecosystem and prehistoric Aleut culture through soil chemistry, isotope analyses of lake cores, and isotope analyses of bone from archaeological middens. This interdisciplinary dissertation involved varied sets of data that complimented one another in many ways.

Chapter 1 proved that weak-acid multi-element extraction of samples collected with augers in combination with analysis of samples obtained from identified features can distinguish house pits, living surfaces within houses, house berms and midden areas without the need for large excavations. This research has also been important in generating data on which chemical elements are related to various features or activity areas in the eastern Aleutians and western Alaska Peninsula. It has been determined that the age of a site does not affect the strength of the anthropogenic chemical signatures for at least the last 4,500 years.

Initially this portion of the dissertation was meant to elucidate changes in resource consumption through time. I found that although it is possible to chemically distinguish sites with shell middens versus those with no middens, it is not possible to distinguish actual resources. It may be that in the future, with more archaeological and experimental studies, specific signatures will eventually be distinguished. Although this portion of the project did not yield results about changing resource consumption over time, it is still of interest to archaeologists who wish to define site boundaries, site features, occupation features and midden matrices without the expense, time, and destruction that come with large excavations.

In Chapter 2, lake core analysis of $\delta^{15}N$ yielded information on a general increase in numbers of salmon during the Holocene, especially during the Neoglacial and Little Ice Age, while showing decreases during warmer periods like the Medieval Warm Period. These changes in salmon returns inferred by marine-derived nutrients generally correlate with well-known periods of climate change and other salmon reconstructions for the North Pacific. Although small and shallow, sediments from Deep and Swan Lakes provide a complete post-glacial record of regional volcanic activity and lake productivity. Despite high flushing rates and small historic salmon escapement numbers, my research suggests that fluctuations in $\delta^{15}N$ can infer salmon productivity through time if corresponding data from a viable control lake is available for comparison. Volcanic activity affected $\delta^{15}N$ and possibly the overall productivity of both lakes. However, large tephras appeared to affect Deep Lake, the salmon nursery lake, to a greater extent than Swan Lake, possibly indicating that volcanic activity had adverse effects on salmon within lake systems.

Bone collagen from sea mammals and fish over the past 4,500 years, as discussed in Chapter 3, generated data from three different ecosystems. Each ecosystem reacted in a unique manner to long-term fluctuations in climate. One change, however, did span all species and all ecosystems. All modern samples, regardless of species, habitat size, location, and prey items, showed a significant decrease in $\delta^{13}C$ when compared to prehistoric samples. These changes are greater than those attributed to the Suess Effect and are not based solely on modern organisms within one climate regime. The best explanation as of now is an overall reduction in primary productivity in the NE Pacific in the late 20th century. The changes in $\delta^{13}C$ of salmon over the six time periods used in this study have yet another implication. It is possible that an intensified Aleutian Low may affect not only the primary productivity in deep ocean waters in the Gulf of Alaska, but perhaps the geographic locations where sockeye forage as well.

In integrating all the sets of data, including archaeological data such as abundance indices of resources and site location and size, a few patterns emerged. It appears that in cooler wetter climates (glacial advances and increased storminess) the Northeast Pacific may have been more productive. Archaeological data reveals that human populations in the area increased during these times. Warmer periods, such as the Medieval Warm Period, seem to have decreased productivity in Northeastern Pacific waters. Overall, sockeye salmon runs increased over the Middle to Late Holocene with decreases during climatically warmer periods which include the modern-day Gulf of Alaska. It appears that ~1000 years ago, during the Medieval Warm Period, the Gulf of Alaska underwent some major change, and humans responded to this decrease in productivity by moving village site location and changing resource strategies.

Sea otter $\delta^{15}N$ and $\delta^{13}C$ spanning 4,500 years suggests that humans may have altered local ecosystems on Sanak Island through sea otter hunting. This may have been in the form of a cascading effect with increases and decreases in sea urchin populations depending on numbers of otters inhabiting local Sanak Island waters.

It appears that volcanic activity (and potentially other types of catastrophic events) had an affect on humans on Sanak Island, with at least one large vocanic event ~ 3,500 years ago coinciding with a break in habitation of the island. More data from well dated contexts will have to be collected in order to discover if other catastrophic events can be correlated to noticeable changes in human subsistence or habitation in the area.

The research presented here indicates that both top-down and bottom-up processes were shaping the North Pacific for the past 6,000 years. Some changes in archaeological culture can be linked to climate/ecosystem change with resource consumption restructuring during times when isotope ratios of organisms and reconstructed sockeye abundance demonstrated change (bottom-up processes). Humans may also have caused some local changes with consumption of particular resources (in this case sea otters) causing resource depressions that can be noted not only in zooarchaeological contexts, but in changes in isotope ratios of organisms as well (top-down processes).

The most important aspect of this research is its long-term temporal records of a portion of the Northeast Pacific. This multi-disciplinary data set can provide guidance for long-term management and conservation of cultural and marine resources, helping to understand the thousands of years that humans have played a role in shaping their environment, and contributing to knowledge of how past changes in climate affected different ecosystems.