Regional Environmental Factors Affecting Bomb-Derived Radiocarbon Age Validation Studies

by
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The primary responsibility of the Alaska Fisheries Science Center's (AFSC) Age and Growth Program is to provide accurate fish ages for annual stock assessments. Accurate age data are important because the age composition of commercially exploited fish populations is critical in setting harvest limits for the sustainability of the resource. Ages of most commercially important fish caught in the Gulf of Alaska or eastern Bering Sea are estimated by counting (reading) the annual growth rings in the fish's otoliths (ear bones) (Fig. 1). Otoliths from species such as walleye pollock, sablefish, Pacific cod, Atka mackerel, yellowfin sole, Pacific ocean perch, and various other flatfish and rockfish species are collected from National Marine Fisheries Service survey cruises, the North Pacific Groundfish Observer Program, foreign fisheries agencies, and state agencies. More than 20,000 otoliths are read by AFSC scientists each year.

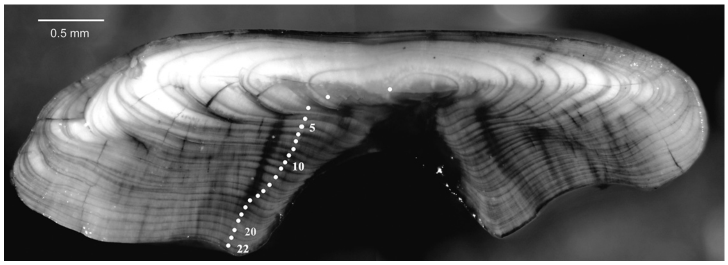

Figure 1. An image of a yellowfin sole otolith that was transversely cut and burnt. The white dots mark the pattern of annual growth rings counted to estimate an age of 22 years old. Photo by Delsa Anderl.

Accurate age estimation is often a difficult task as the interpretation of growth rings is not always clear and can require subjective decisions on what constitutes a year's growth. To confirm the accuracy of age estimates, the Age and Growth Program uses a number of age validation techniques: using known-age fish, radiometric studies, marginal increment analysis, tracking strong fish year classes, mark and recapture, as well as the novel use of radiocarbon (^{14}C) derived from above-ground atomic bomb testing. Serving as a time-stamp in fish otoliths from the Cold War era, bomb-derived ^{14}C is becoming a widely used tool for fish age validation and is considered one of the best methods for this type of research.

During the height of the Cold War, so many nuclear bombs were exploded above ground that it significantly raised the amount of ^{14}C in the atmosphere and in the surface layers of the ocean (Fig. 2). In the surface of the oceans the increase of ^{14}C began in the late 1950s and peaked in about 1970. Because ^{14}C has a half-life of 5,730 years, its presence remains in Earth's air and oceans for millenniums. In a fish spawned during the era of marine ^{14}C increase, the bomb-derived ^{14}C is preserved as a record in its otolith core. An otolith core is material deposited in the first year of life, and in the case of adult fish caught recently but spawned in the era of marine increase, serves as a record of the ^{14}C level during the birth year. When bomb-derived carbon is used to validate the age of the adult fish, the increase in ^{14}C found in otoliths is matched with recognized amounts in biological structures of known age. Thus, if we know the year a fish was collected and have estimated the fish's age by reading the growth rings, then we can estimate when the otolith core was laid down and, accordingly, how much ^{14}C activity there should be in that core.

To apply this validation method, first a ^{14}C "reference chronology" (a time-series of ^{14}C measurements) is developed from the otoliths of fish with known birth years. If juvenile fish collected during the era of marine ^{14}C increase are available, they can supply the known-age otoliths. In this case, the age, or birth year, of juvenile (1-year old) fish can be confirmed by fish length, spawning timing, and catch date, and the ^{14}C in the otoliths of these fish can be measured and used to provide the reference chronology. The ^{14}C reference chronology is then compared to ^{14}C measured in adult otolith cores being validated, the "test specimens." The adult test specimens and known-age reference chronology, however, often are not from the same species (a focal point later in this article). Test specimens are chosen such that the range of estimated birth years spans the era of rapid marine ^{14}C increase (the late 1950s to about 1970). So, for example, if a test specimen was caught in the year 2000 and was estimated to be 40 years old via growth-zone counts (i.e., born in 1960), the specimen would be an appropriate candidate for validation testing.

The microscopic cores from adult test specimens are removed from the otoliths of the adult fish and are analyzed by accelerator mass spectrometry. The ^{14}C values in both the test specimens and reference chronology are plotted with respect to the birth year. If the ^{14}C increase in both the reference chronology and the test specimens' otolith cores displays the same timing, then the test specimen age estimates are typically considered accurate or validated. Conversely, if the timing differs, the growth-zone test age estimates may be in error.

There is one main assumption made when using the bomb radiocarbon age validation method: the reference chronology must be biologically and environmentally representative of the test specimens under evaluation. This means that in the absence of ageing error, the magnitude and timing of the ^{14}C increase should be similar in both the reference and test chronologies. Ideally, the reference chronology and test chronology should be conspecific and from the same geographic area, but unfortunately this is rarely the case. Potential failures in meeting this assump-

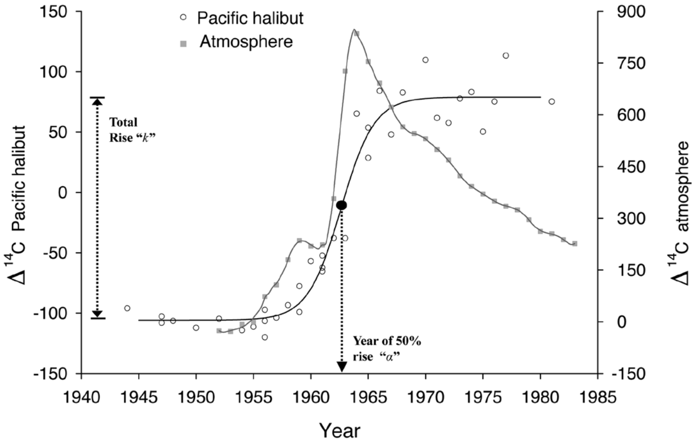

Figure 2. Atmospheric and Pacific halibut Δ14C chronologies showing an increase in 14C coinciding with the era of above-ground atomic bomb testing. Logistic function fit to Pacific halibut Δ14C is labeled with two parameters of interest

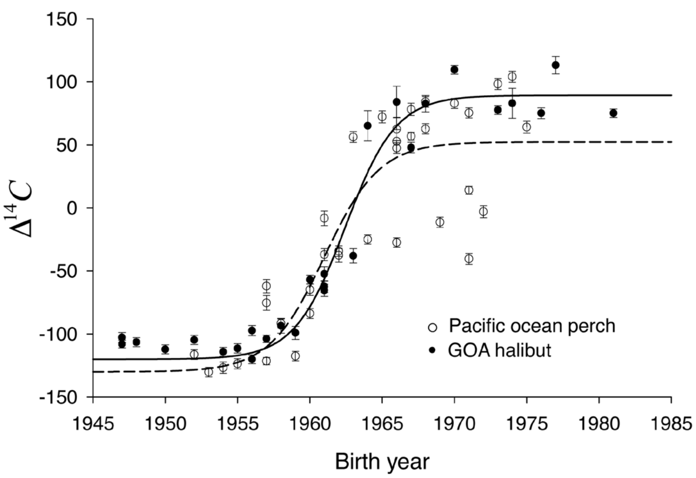

Figure 3. Predicted Δ14C curves fit to Pacific ocean perch test samples and a Gulf of Alaska Pacific halibut reference dataset.

tion have become the focus of increasing scrutiny as the Age and Growth Program expands the use of this age validation method through investigation into the timing and strength of the bomb-derived ^{14}C marine signal and its relationship to oceanographic gradients in the North Pacific Ocean. Oceanographic processes such as currents, wind mixing, or upwelling may change the level of bomb-derived ^{14}C in fish otoliths, requiring further exploration to understand such relationships.

Recent AFSC Age Validation Studies

The Age and Growth Program has successfully completed two bomb-derived ^{14}C age validations and has several others in process. Age estimates of Pacific ocean perch (*Sebastes alutus*) and Dover sole (*Microstomus pacificus*) are confirmed as accurate. These studies relied on a Pacific halibut (*Hippoglossus stenolepis*) reference chronology developed at the International Pacific Halibut Commission from juvenile specimens. Figure 3 illustrates the coherence between predicted response curves fit to the Pacific ocean perch test sample and the Pacific halibut reference $\Delta^{14}C$ data sets, both from the Gulf of Alaska. Additional studies using bomb-derived radiocarbon to validate age estimates of Greenland halibut (*Reinhardtius hippoglossoides*), northern rockfish (*Sebastes polyspinis*), yellowfin sole (*Limanda aspera*), and Pacific geoduck (*Panopea generosa*) also are in progress.

In ongoing yellowfin sole age validation research, the comparison of its ^{14}C chronology to the Pacific halibut reference has lead to realizations that the North Pacific may not be adequately represented by a single reference chronology. Yellowfin sole from the eastern Bering Sea show an increase in ^{14}C which is 3 to 4 years sooner than that from the Gulf of Alaska Pacific halibut reference chronology (Fig. 4). In this example, it is not possible to determine whether a potential over-ageing error (3 to 4 years) has occurred or if a possible environmental difference between ^{14}C in the eastern Bering Sea and Gulf of Alaska is present. These two interpretations are confounded. The yellowfin sole example illustrates the importance of comparing test chronologies to representative reference

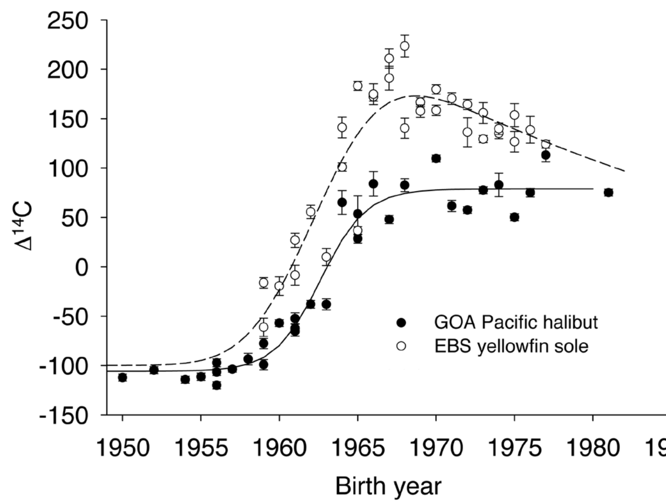

Figure 4. Predicted Δ14C curves fit to eastern Bering Sea yellowfin sole test samples and a Gulf of Alaska Pacific halibut reference dataset.

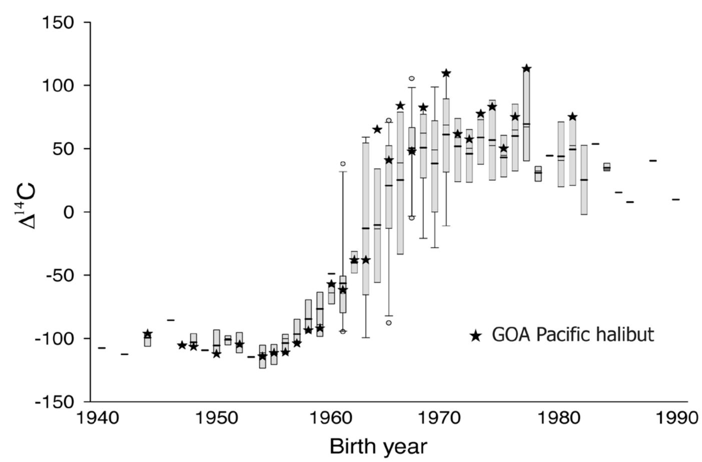

Figure 5. Box-whisker plots of Δ14C data measured in fish otoliths and bivalve shells from 12 data sets in the North Pacific Ocean. Boxes are interquartiles, whiskers show 95th percentiles, solid dark horizontal bar is the mean, light horizontal bar is the median and points are outliers. Gulf of Alaska Pacific halibut Δ14C values are shown as stars.

chronologies. This issue has led us to consider broader regional differences in oceanic processes of the North Pacific that could cause bomb-derived ^{14}C to be area-specific.

New Investigations

To investigate potential different levels of ^{14}C among regions of the North Pacific, we used a diverse pool of data from published literature in addition to datasets from completed and ongoing ^{14}C age validation studies at the AFSC (Table 1). In all, we used 12 sets of data that ranged in location from southern California to the Gulf of Alaska and represented 10 different species (Fig. 5). Each dataset comprised about 30 specimens with estimated birth years based on growth-zone counts coinciding with the era of increasing ^{14}C, measured $\Delta^{14}C$ values with standard errors, and approximate collection locations (latitude). (Note that $\Delta^{14}C$ is a standardized notation of presenting ^{14}C results in relation to an internationally used standard.) During the radiocarbon pulse from atomic bomb testing, the rate of ^{14}C incorporation into marine calcium carbonate structures, such as otoliths, increased to a maximum and then began to decrease very slowly when testing abated. The rate of incorporation from the atmosphere to marine organisms is most likely affected by oceanic processes such as upwelling. The carbon brought to the mixed surface layer of the ocean by upwelling does not contain bomb-derived ^{14}C, so this process dilutes the bomb-derived ^{14}C in surface waters. In the eastern North Pacific upwelling decreases with increasing latitude. The surface waters (< 100 m depth) are where most of the species considered reside as juveniles. Therefore, we hypothesized that upwelling and therefore latitude would have an important impact on the functional response of the $\Delta^{14}C$ signatures from each species. The process of ^{14}C incorporation can in general be described mathematically as a logistic response function with three parameters, two of which are important in age validation and understanding ocean processes (Fig. 2). The first model parameter, α, is defined as the year in which 50% of the total increase in $\Delta^{14}C$ occurs and describes the timing of the increase. The second parameter k describes the maximum total rise in $\Delta^{14}C$. In this article we do not consider the third parameter, the slope or rate of rise in $\Delta^{14}C$ during the year of 50% increase. However, we will describe the results in terms of the two key parameters α and k.

Main Findings

Latitude and upwelling were important factors in predicting the timing and total rise of the increase in $\Delta^{14}C$ for each species. We found that the total rise in $\Delta^{14}C$ concentration was greater farther north. The total rise described by the model parameter k increased lin-

Table 1. Species used in analysis with abbreviation used in Figure 7, general latitude of capture, and associated upwelling index (positive values indicate upwelling, and negative indicate downwelling).

Species	Abbreviation	Latitude (°N)	Upwelling Index
Bocaccio rockfish	BRCK	37	209
Petrale sole	P SOLE	39	167
Canary rockfish - south	CNRY S	45	35
Canary rockfish - north	CNRY N	49	35
Geoduck	GEOD	54	-16
Quillback rockfish	QRCK	56	-15
Pacific halibut, SE Alaska	SE HAL	57	-15
Yelloweye rockfish	YRCK	57	-8
Northern rockfish	NRCK	60	-2
Dover sole	D SOLE	60	1
Pacific ocean perch	POP	60	0
Pacific halibut north GOA	NW HAL	60	0

Bomb-Derived Radiocarbon: Related Facts

- The United States conducted 215 known atmospheric nuclear tests between 1945 and 1963; the Soviet Union conducted 219 during the same time period.
- An additional 94 known atmospheric nuclear tests were conducted between 1945 and 1996 by the United Kingdom (21), France (50), and China (23).
- The Partial Test Ban Treaty, signed in 1963 by the governments of the United States, Soviet Union, and United Kingdom, prohibits test detonations of nuclear weapons except underground.
- The largest nuclear bombs ever deployed had an explosive yield of over 10 megatons. A megaton is an explosive force equivalent to that of 1.0 million tons of TNT.
- For each megaton, an estimated 7.4 kg of ^{14}C were released into the atmosphere.
- Naturally occurring ^{12}C constitutes 99% of all carbon, ^{13}C comprises about 1%, and ^{14}C is found in trace amounts of about 1 part per trillion.
- The atmospheric increase in ^{14}C between 1952 and 1963 was nearly 100%.
- The increase of ^{14}C in the marine environment became apparent in about 1958 and peaked in about 1970.
- ^{14}C is introduced into the oceans through gas exchange between air and sea surface and mixes at different regional rates, dependent on the prevalent oceanic process acting in a specific area.
- Calcium carbonate is the main component of fish otoliths. Bomb-derived ^{14}C has been measured in many marine carbonate structures: fish otoliths, coral, and shells of bivalves.
- The use of bomb-derived ^{14}C in otoliths is considered one of the best methods for fish age validation research.

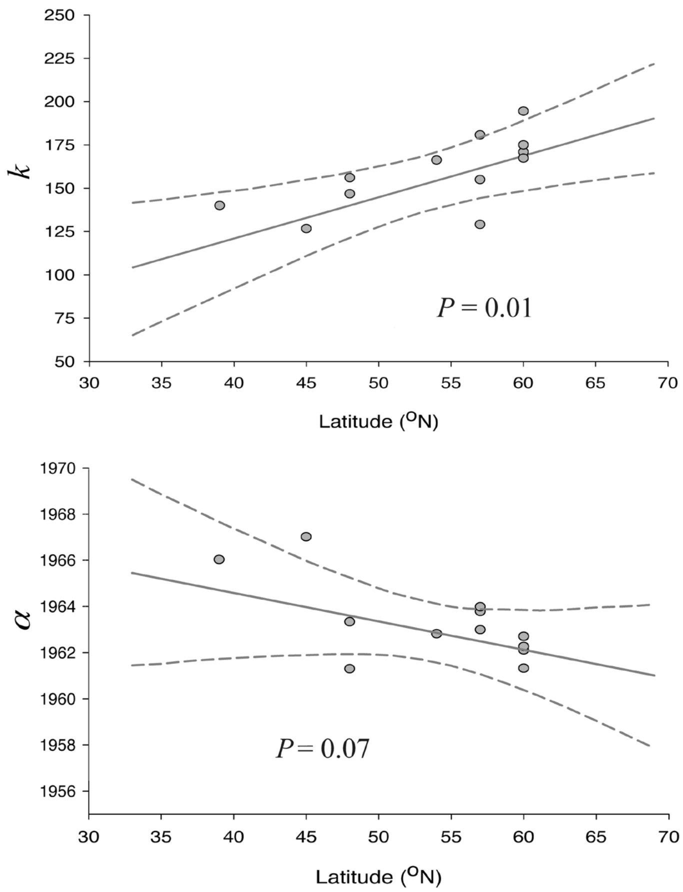

Figure 6. Observed magnitude $\Delta^{14}C$ rise and year of 50% rise (dots) and predicted (solid line) relationship with latitude. Dashed lines show 95% credibility intervals. Significance of the relationship with latitude is calculated as the tail probability that the value of the slope is greater than or less than zero.

early and significantly with latitude ($P = 0.01$). Also, we found that the timing of the $\Delta^{14}C$ concentration increase (α) occurred earlier with increasing latitude ($P = 0.07$) (Fig. 6). Model parameters were also related to the upwelling index, but in this case had nonlinear responses. The parameter k increased significantly ($P = 0.05$) with a declining upwelling index south of about lat. 48°-50°N, but north of this latitude it stabilized at a constant value (Fig. 7). Additionally, the parameter α showed evidence of shifting to an earlier year with declining upwelling south of about lat. 48°-50°N, but this relationship was not significant ($P = 0.34$). North of about lat. 48°-50°N, the parameter α also stabilized (Fig. 7).

A Better Understanding

The species we considered from the eastern North Pacific Ocean reside in different ocean systems. South of approximately lat. 48°N, the California Current promotes a strong upwelling system. North of lat. 48°N, the predominant currents are the Alaska Current, the Alaska Coastal Current, and the Alaskan Stream, which are influenced by freshwater input from many small coastal streams and glacial ablation. Freshwater input in the form of rainfall or seasonal snow melt provides a comparatively quick link between the ^{14}C in the nearshore marine environment and that in the atmosphere. Also, the Alaska Coastal Current is predominately a downwelling system. Therefore, as a result of oceanic processes, the bomb-derived ^{14}C values in the ocean surface water south of 48°N may be lower and may occur later in time due to dilution with upwelled water, a source of carbon devoid of bomb-derived ^{14}C. The ^{14}C in surface waters north of 48°N could be higher and occur earlier due to a closer link to the atmosphere through continental freshwater input and other process like wind mixing.

The general trend in $\Delta^{14}C$ in the 12 datasets examined may be explained further by additional consideration of oceanic processes and currents in the eastern North Pacific. Figure 8 shows that upwelling increases south of about 48°N but changes very little to the north of this latitude. However, wind stress increases north of 48° N (Fig. 8) and theoretically could account for better mixing (i.e., increased strength and earlier timing) of atmospheric bomb-derived ^{14}C into northern surface waters.

It appears that our hypothesis is likely correct; upwelling and other oceanic processes related to latitude do impact the functional response of the $\Delta^{14}C$ signatures. This analysis is ongoing research and future investigations will consider several additional indices that may provide more understanding of the relation between the increase of bomb-derived ^{14}C and environmental parameters such as wind sheer, sea surface temperature, and river discharge.

What is Next?

Our study highlights the importance of using the correct reference chronology for bomb-derived ^{14}C age validation studies. With an incorrect reference, yellowfin sole, for example, could be interpreted as being over-aged. We do not think this is the case based

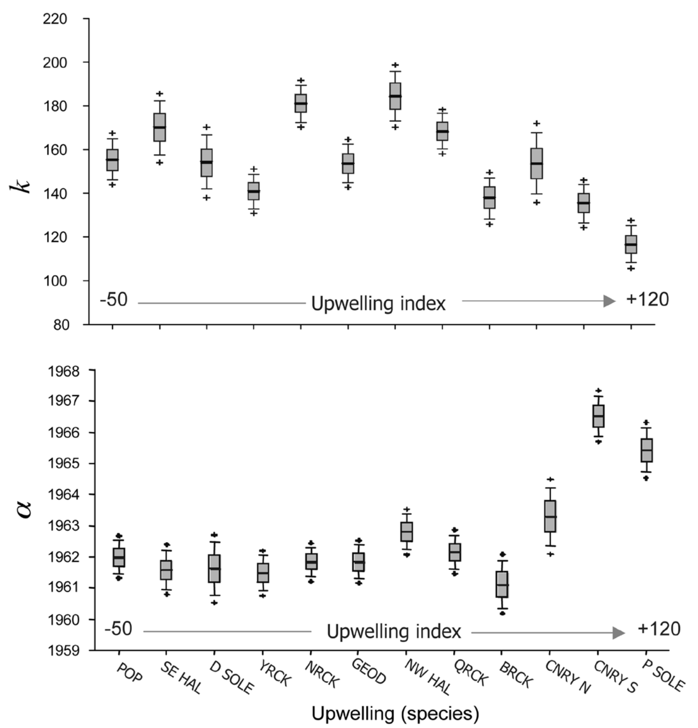

Figure 7. Box-whisker plots of model predicted $\Delta^{14}C$ values by species and arranged by strength of upwelling index. Boxes are interquartiles, whiskers show 90th percentiles, pluses are 95th percentiles, solid dark horizontal bar is the mean. See Table 1 for abbreviated species names.

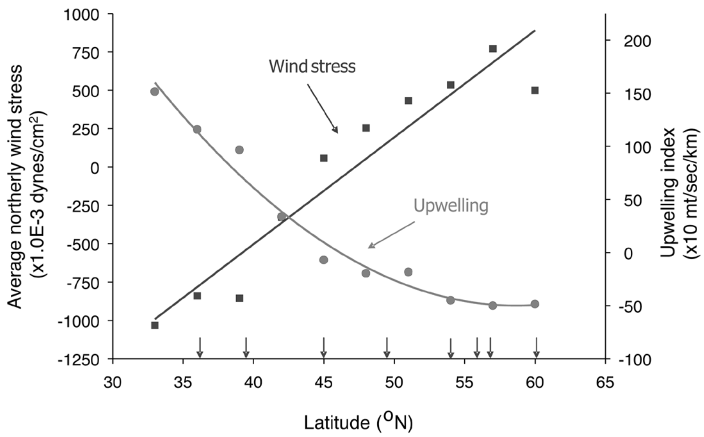

Figure 8. Average northerly wind stress and upwelling index versus latitude. Arrows indicate general latitude of species capture.

on previous research at the AFSC (see Further Reading, Kimura et al. 2007). As bomb-derived ^{14}C age validation studies go forward at the AFSC we need to be careful about the choice of appropriate reference chronologies. Also, new reference chronologies are needed for other regions of the North Pacific Ocean. To this end, we are currently assisting the Northwest Fisheries Science Center in developing a new reference chronology based on petrale sole (*Eopsetta jordani*) from the California Current system. We also are collaborating with the International Pacific Halibut Commission to develop a new reference chronology based on Pacific halibut from the eastern Bering Sea.

Further Reading

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