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Carbon and nitrogen isotope ratios in bowhead whales (*Balaena mysticetus*) and their zooplankton prey as indicators of feeding strategy and environmental change

Vinette, Kimberly Ann, M.S.

University of Alaska Fairbanks, 1993

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CARBON AND NITROGEN ISOTOPE RATIOS IN BOWHEAD WHALES

***(Balaena mysticetus)* AND THEIR ZOOPLANKTON PREY**

AS INDICATORS OF FEEDING STRATEGY

AND ENVIRONMENTAL CHANGE

A

THESIS

Presented to the Faculty of the University of Alaska

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

Kimberly A. Vinette, B. A.

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Fairbanks, Alaska

December 1992

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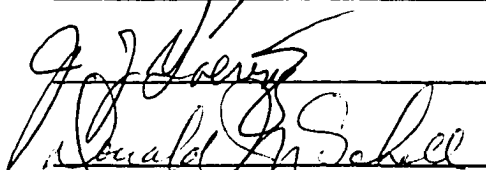
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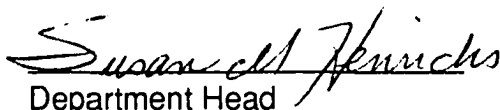
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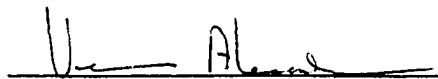


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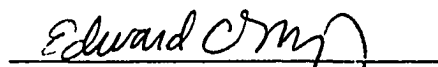
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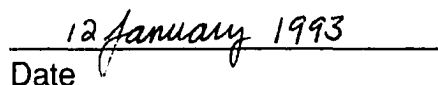


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12 January 1993
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ABSTRACT

This study details regional, seasonal and inter-annual differences in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of zooplankton in the Bering and Chukchi Seas. These isotopic variations were correlated with inter-annual and long-term variations in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of bowhead whale baleen.

Statistical analyses indicate significant ^{13}C -enrichment in Bering/Chukchi seas zooplankton relative to Beaufort Sea zooplankton, supporting the observed trends of ^{13}C -depletion at higher latitudes and enrichment at lower latitudes. Bering/Chukchi seas zooplankton show a weak trend in ^{13}C -depletion between 1987-1990, possibly due to inter-annual environmental changes affecting phytoplankton $\delta^{13}\text{C}$. The $\delta^{13}\text{C}$ of baleen produced in fall/winter months is inversely correlated to sea surface temperature trends in the Bering Sea. Long-term changes in baleen $\delta^{13}\text{C}$ may be helpful in assessing past climatic change.

The observed $\delta^{15}\text{N}$ oscillations in baleen may be due to changes in trophic level of prey between seasonal feeding grounds or from physiological cycles in the bowhead whale.

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CHAPTER 1. INTRODUCTION

Statement of Problem

The Bering and Chukchi seas are two of the most productive areas of the world oceans, supporting vast commercial fisheries and large populations of marine mammals. The food chains supporting these important resource species are based on correspondingly rich primary productivity. Past studies have used measurements of stable carbon and nitrogen isotopes to investigate the dynamics of energy and nutrient movements within this ecosystem (Dunton 1985; McConnaughey and McRoy 1979; Saupe et al. 1989; Schell et al. 1989; Wada and Hattori 1976). Saupe et al. (1989) showed the geographic trends in carbon isotope ratios in zooplankton in general terms and the variations in carbon isotope ratios between taxa. The present study was conducted to detail the regional differences in zooplankton carbon and nitrogen isotope ratios and to attempt to test rigorously for statistical differences between regions,

between years and between cruises to relate these differences to oceanographic variables. The interannual and longer-term variations in carbon and nitrogen isotope ratios in the baleen of bowhead whales (*Balaena mysticetus*) and their zooplankton prey were investigated also. The variations in zooplankton isotope ratios may reflect changes in phytoplankton primary productivity supporting them. In addition, this study attempts to explain that oscillations of nitrogen isotope ratios present along the baleen plates of bowhead whales are due to the trophic level of prey and not to geographical gradients of $\delta^{15}\text{N}$ within prey taxa. This is based on assumptions concerning the whale's seasonal feeding habits in summering versus wintering grounds.

Oceanographic Overview

The northern Bering Sea shelf (Figure 1) is generally 50 meters in depth or less (Aagaard et al. 1985). The map shows the bathymetric contours and major circulation patterns of the Chukchi/Bering shelf (Coachman et al. 1975; Springer 1988). The Anadyr Water (AW), Bering Shelf Water (BSW) and Alaskan

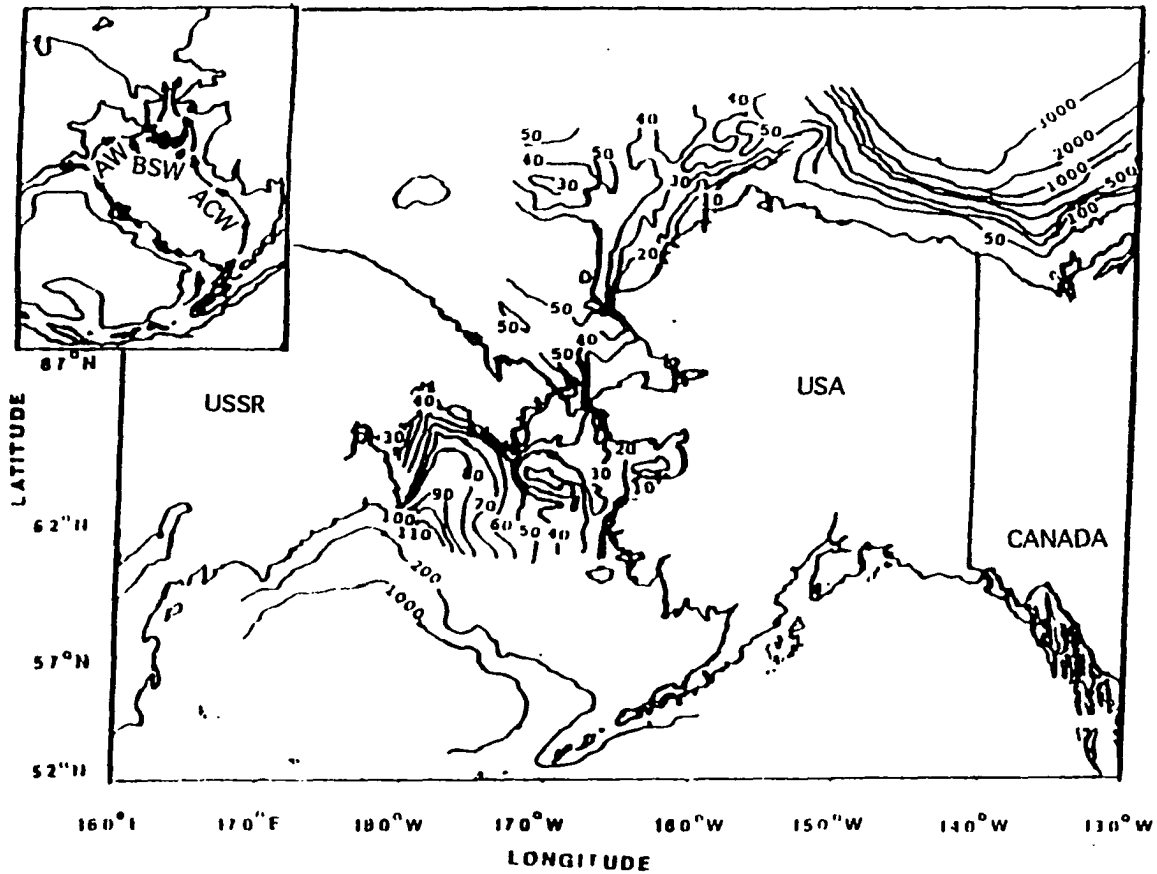


Figure 1. Map of the Beaufort Sea, Bering/Chukchi Shelf showing bathymetric contours in meters and major circulation patterns. AW=Anadyr Water, BSW=Bering Shelf Water, ACW=Alaskan Coastal Water (from Coachman et al. 1975; Springer 1988, Fissel et al. 1987).

Coastal Water (ACW) are the principal water masses flowing northward through Bering Strait. Alaskan Coastal Water originates in the southeastern Bering Sea and characteristically has lower salinity due to fresh water input from rivers. The Bering Shelf and Anadyr waters originate south of St. Lawrence Island. Anadyr Water is an extension of the Bering Slope Current and acquires a high nutrient content due to winter mixing, similar to that found in offshore waters of the Bering Sea Basin (Coachman et al. 1975; Kinder et al. 1975). Bering Shelf Water is mixed with Anadyr Water at the frontal systems at the shelf break (Coachman 1986). Nutrients are conserved below the euphotic zone until they reach the shallow shelf where they support intense phytoplankton growth in the summer months.

During summer, warmer water masses composed of the Alaskan Coastal Water and the higher salinity Bering Shelf water pass through Bering Strait and move northeastward past Point Barrow and enter the Beaufort Sea (Mountain 1974; Aagaard 1984; Fissel et al. 1987). In transit, Alaskan Coastal Water mixes with the surface water (runoff) and can be traced to

147-148 degrees West, while the Bering Sea water, which has a temperature maximum at a deeper layer, can be traced to 143 degrees West (Aagaard 1984). The Beaufort Sea also receives considerable fresh water input. Seven major rivers drain into the Beaufort Sea: The Colville, Kuparuk, Sagavanirktok, Canning, Kongakut, Firth and Mackenzie. Approximately 80% of the total fresh water input from these rivers is discharged by the Mackenzie River (Fissel et al. 1987).

Productivity and Seasonality

The Beaufort Sea is ice-covered 9-10 months per year, with landfast ice forming in the fall and extending up to 50 km seaward by the end of winter. The seasonal and permanent pack ice is moved westward by the clockwise Beaufort Gyre and prevailing easterly winds and forms a pressure-ridge system at its contact with the landfast ice. Along the shelf margin, currents move westward within the Beaufort Gyre and the deeper Bering Sea water flows eastward on the outer continental shelf (Norton and Weller 1984). Ice cover may persist into July and

significant open water is present only between July and September.

Beaufort Sea phytoplankton assemblages include the diatoms *Chaetoceros* spp., other diatoms, dinoflagellates and flagellates (Horner 1984). *Chaetoceros* spp. are generally most numerous followed by dinoflagellates. Estimated annual primary production in the Beaufort Sea is 16-36 g C m⁻² yr⁻¹ (Schell et al. 1984), including both ice algae and phytoplankton.

Primary productivity in the Bering Sea has been estimated to range between 120-400 g C m⁻² yr⁻¹ (Iverson et al. 1979, Sambrotto et al. 1984, Walsh et al. 1989). The Bering Sea shelf is approximately 45 percent covered by sea ice between November and May (Goering and Iverson 1981). From March to May, ice algae and other micro-organisms on the undersurface of the ice are the major primary producers in the Bering Sea (2.2-4.8 mg C m⁻² day⁻¹). At this time primary productivity in the water column below the ice is low.

Ice edge phytoplankton are typically chain-forming

diatoms, such as neritic centric diatoms and pennate ice-plankton (Alexander and Cooney 1979). When the seasonal ice melts creating a low-salinity surface layer, high primary productivity accompanies the lower salinity waters left by the retreating ice. The ice edge bloom is followed by an intense spring bloom in the open water (McRoy and Goering 1974). In early spring (April-May), the high nutrient supply supports fast-growing, small, centric diatoms, which are characteristically *Chaetoceros* spp. and *Thalassiosira* spp. Later in the spring (May-June), diatoms are typically medium to long chain-forming species of *Chaetoceros* and some *Rhizosolenia alata*.

Zooplankton Distribution

Figures 2-4 show summer distributions of copepods, euphausiids, and amphipods in nearshore communities, middle-shelf/coastal communities and oceanic/outer-shelf communities. Zooplankton biomass in the oceanic community averaged 35.5 g m^{-2} with the zooplankton biomass over the

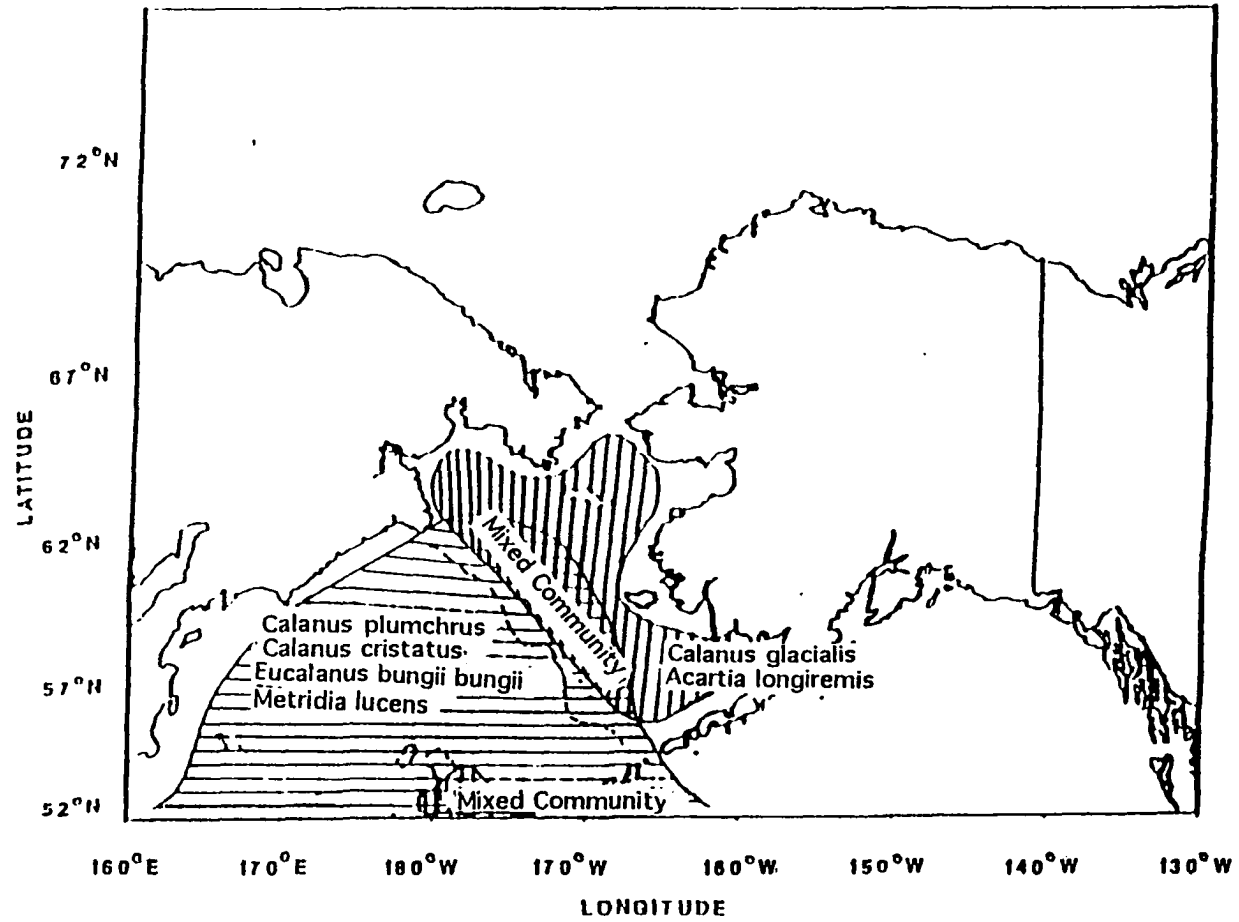


Figure 2. Copepod distribution in the Bering Sea upper water layers from early to mid-summer (from Motoda and Minoda, 1974).

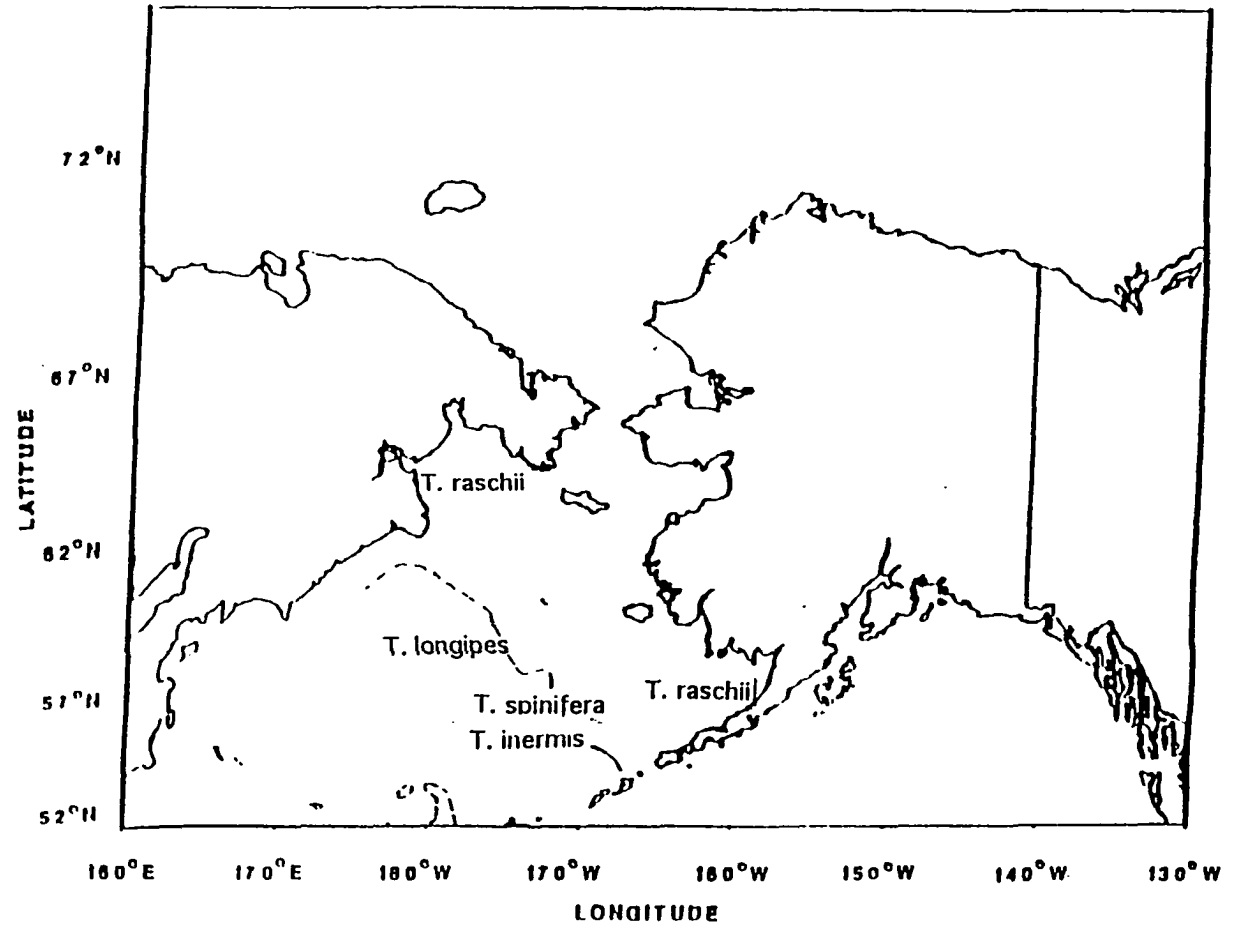


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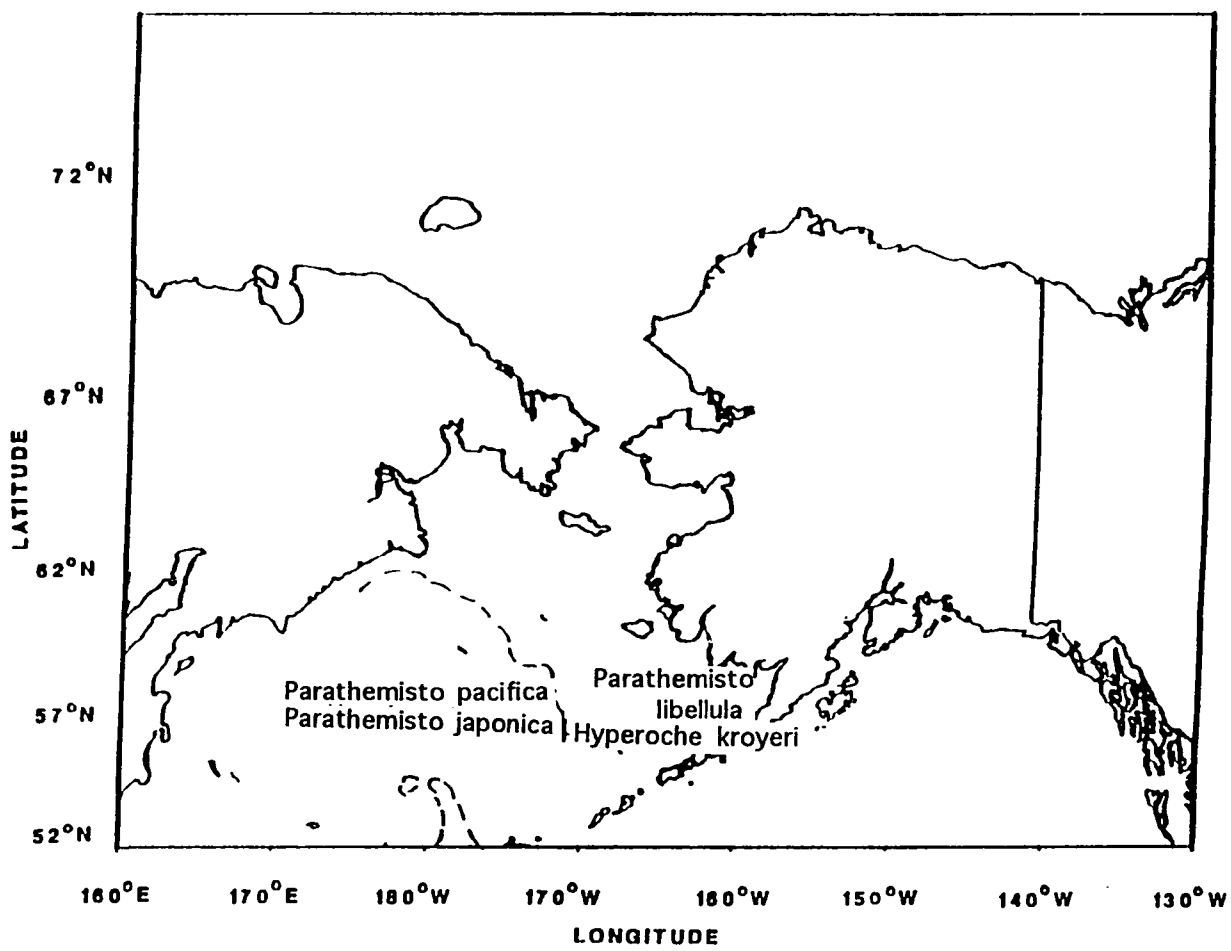


Figure 4. Amphipod distribution in the Bering Sea from early to mid-summer (from Motoda and Minoda 1974).

southern shelf of the Bering Sea equal to 52.2 g m^{-2} and that of the northern shelf equal to 21.8 g m^{-2} . Zooplankton stocks in oceanic waters are highest in May-June and lowest in November while shelf zooplankton stocks are lowest in spring and highest in late summer (Cooney 1981).

A majority of the oceanic population overwinters at depth and the large calanoid copepods *Calanus cristatus* and *C. plumchrus* reproduce without feeding in late winter (Cooney 1981). The young rise to the surface prior to the spring bloom. Shelf species *Pseudocalanus* spp. and *Acartia longiremis* produce several generations of young while one generation of *C. marshallae* young are produced in the summer. Cooney (1981) found that *Pseudocalanus* spp. and *Acartia longiremis* were ineffective grazers of spring bloom phytoplankton over the middle shelf. Stage II phytoplankton in the middle shelf domain do not appear to be grazed by the small copepods. Stage II and III diatoms appear to be grazed by the large calanoid copepods of the outer shelf, perhaps leading to the flagellate and dinoflagellate dominance in numbers. Over the outer shelf, about

50% of the phytoplankton biomass was grazed by *C. cristatus*, *C. plumchrus*, and *Eucalanus bungii bungii* (Cooney 1981; Cooney and Coyle 1982). These copepods graze on chain-forming and spiny diatoms. Oceanic grazers, including euphausiids and large calanoid copepods, winter in deep water beyond the shelf break (Cooney 1981; Cooney and Coyle 1982). They surface in the outer shelf domain to feed on spring bloom phytoplankton, including large, chain-forming diatoms. Euphausiids may graze on *Phaeocystis* spp.

Stable Isotope Ratios as Biological Tracers

Stable isotope analyses involve comparisons of changes in the ratios of $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ resulting from biological processes such as carbon fixation, respiration, excretion and metabolism. Fractionation, or the natural isotope variation between product and reactant, is dependent on both thermodynamic equilibria and kinetic processes (Ehleringer and Rundel 1989). An "isotope effect" is the physical property resulting from fractionation. Isotope effects depend on the

relative rates of reaction of substrates containing ^{12}C or ^{13}C (Berry 1989; Hayes 1983). Since these isotope ratio changes are small (beyond the third significant figure), δ notation is the convention used for reporting values:

$$\delta X_{\text{sample}} = \frac{\left[\left(R_{\text{sample}} - R_{\text{standard}} \right) - 1 \right]}{R_{\text{standard}}} \times 1000$$

where δX_{sample} is the sample isotope ratio difference in delta units, and R_{sample} and R_{standard} are the absolute isotope ratios of the sample and standard, respectively.

Stable isotopes can be used as tracers of biological energy flow if the carbon sources are limited to two and have contrasting isotope ratios. Transfer of $\delta^{13}\text{C}$ between trophic levels is conservative, so the $\delta^{13}\text{C}$ of an organism closely reflects the $\delta^{13}\text{C}$ of its food (DeNiro and Epstein 1978; Fry and Sherr 1984). The animal's whole body is typically enriched by 0.7-1.0‰ (on the average) relative to diet (DeNiro and Epstein 1978). If isotopic ratios differ among regions, isotopic

analysis can be used to estimate food intake from the different regions by a migratory organism (Fry and Sherr 1984). In contrast to $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ increases approximately 3-3.4‰ with each trophic level (Fry and Sherr 1984, Minagawa and Wada 1984). Figure 5 shows the relatively conservative $\delta^{13}\text{C}$ over increasing trophic level for a variety of organisms from the Chukchi and Bering seas (Feder et al. 1990). Figure 6 shows the enrichment of $\delta^{15}\text{N}$ with trophic level for the same organisms.

Fractionation within the organism varies with tissue type due to differing metabolic processes. The $\delta^{13}\text{C}$ of muscle closely reflects dietary $\delta^{13}\text{C}$, whereas lipids are generally depleted by 2-8‰ relative to the diet. Keratinous proteins are typically 2-6‰ enriched relative to diet (Tieszen et al. 1983; DeNiro and Epstein 1978; Jones et al. 1981; Mizutani and Wada 1988). Isotopic fractionation of nitrogen is affected by both food source and internal fractionation (Minagawa and Wada 1984). The $\delta^{15}\text{N}$ of phytoplankton from marine and freshwater systems studied ranged between 5 and 7‰ in the Bering Sea

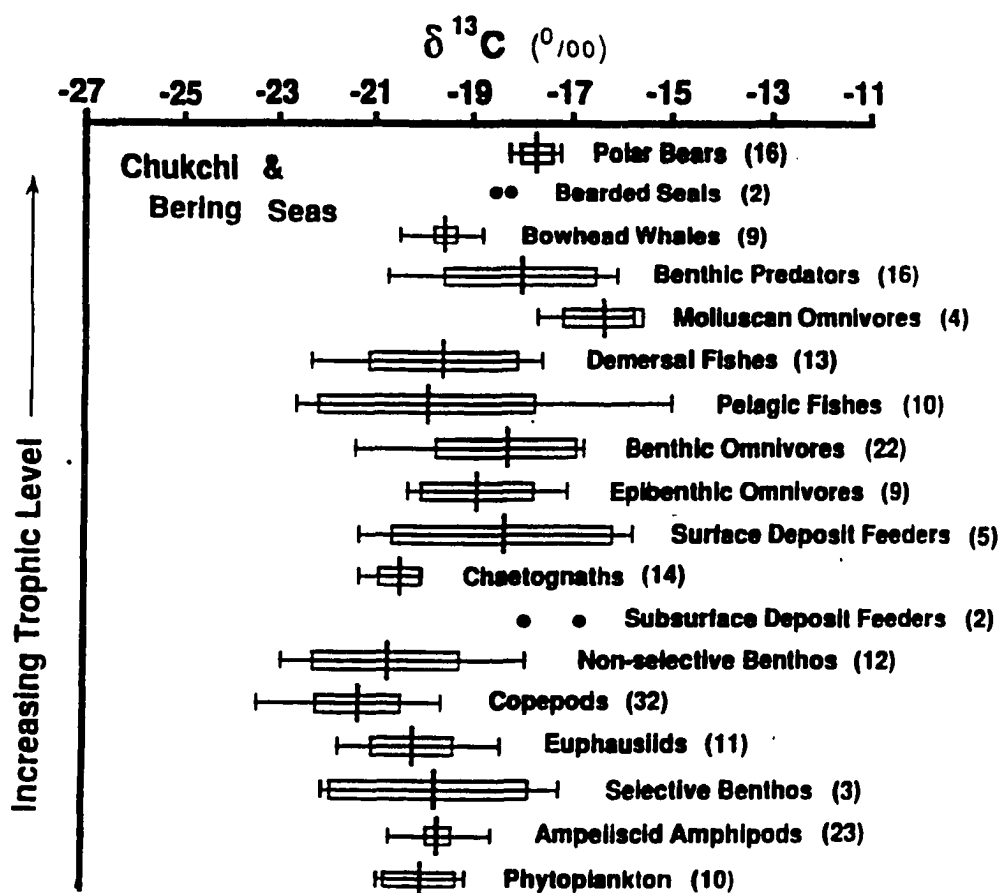


Figure 5. Carbon isotope ratio values for organisms from the northern Bering and Chukchi seas in order of increasing trophic level. Average (vertical bars), range (horizontal lines), standard deviation (box) and single samples (dots) (from Feder et al. 1990).

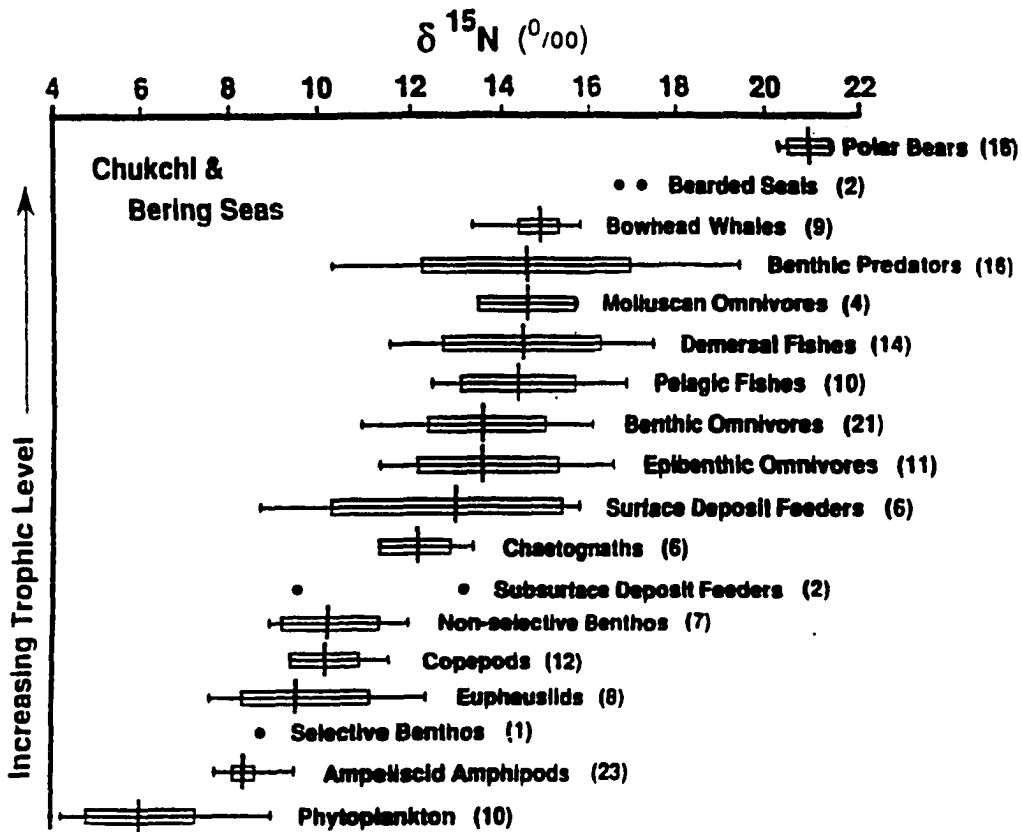


Figure 6. Nitrogen isotope ratio values for organisms from the northern Bering and Chukchi seas in order of increasing trophic level. Average (vertical bars), range (horizontal lines), standard deviation (box) and single samples (dots) (from Feder et al. 1990).

and Lake Ashinoko (Wada and Hattori 1976). Analysis of zooplankton, fish and birds within an ecosystem showed enrichments of near 3‰ in $\delta^{15}\text{N}$ with each increase of trophic level.

Latitudinal Isotopic Gradients

Rau et al. (1982) described a $\delta^{13}\text{C}$ gradient over latitude in zooplankton collected by several workers over the world oceans (Figure 7). Zooplankton in the southern hemisphere had a steeper carbon isotope gradient than those from similar latitudes in the northern hemisphere. Rau et al. (1982) initially suggested that a temperature-plankton $^{13}\text{C}/^{12}\text{C}$ relationship does not exist as a common factor in all oceans, and postulated that latitudinal variations in plankton carbon isotope values are due to geographic differences in plankton biosynthesis and metabolism. Recently, Rau et al. (1989) suggested that changes in the partial pressure of carbon dioxide (pCO_2) are responsible for the geographical gradient. The concentration of

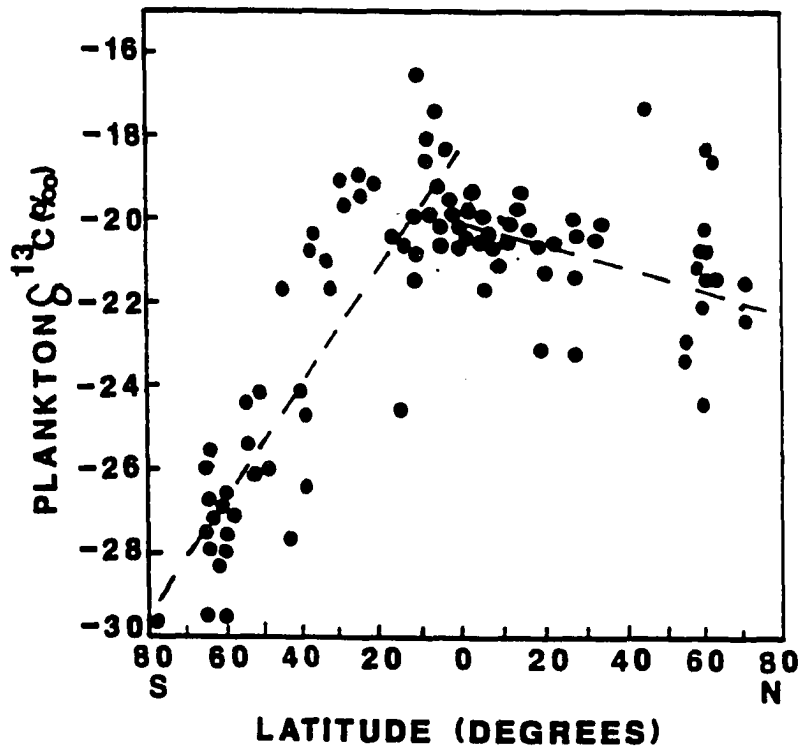


Figure 7. Carbon isotope ratios of plankton versus latitude.
(from Rau et al. 1982).

dissolved free carbon dioxide [$\text{CO}_{2(\text{aq})}$] increases with decreasing surface water temperatures associated with increases in latitude.

Lower temperatures favor formation of [$\text{CO}_{2(\text{aq})}$] relative to bicarbonate. The [$\text{CO}_{2(\text{aq})}$] is up to 2.5 times greater at high latitudes (near 60 degrees South) than at low latitudes (near 10 degrees South). Rau et al. (1989) argue that the much larger free CO_2 pool in cold waters may cause phytoplankton $\delta^{13}\text{C}$ depletions by allowing increased discrimination for the lighter isotope.

In contrast, temperature and nutrient regimes seem to determine the $\delta^{13}\text{C}$ value of the phytoplankton populations off Georges Bank, Maine (40-43 degrees North, 66-70 degrees West). Fry and Wainright (pers. comm.) have found that fast growing, ^{13}C -enriched phytoplankton predominated in environments that were enriched with nutrients. The slow growing phytoplankton species, which were comparatively ^{13}C -depleted, predominated under nutrient limited conditions. They found that in

experiments enriched with nutrients (nitrogen + phosphorus + silicate), algal cells had increased $\delta^{13}\text{C}$ values relative to cells that were enriched with only nitrogen and phosphorus. In experiments that included silicate, the dominant species were fast growing pennate and centric diatoms. Slower growing dinoflagellates predominated in nutrient-limited seawater, and the overall phytoplankton particulate organic matter was more ^{13}C -depleted.

Zooplankton Isotope Ratios

Saupe et al. (1989) described the isotopic trend in $\delta^{13}\text{C}$ of zooplankton found across the Beaufort, Chukchi and Bering seas (Figure 8). Zooplankton from the Bering and Chukchi seas are enriched in ^{13}C relative to zooplankton in the western Beaufort Sea, which in turn, are enriched relative to zooplankton in the eastern Alaskan and Canadian Beaufort Sea (Table 1). In all regions studied, euphausiids were enriched relative to copepods by a minimum of 1‰. Relative biomasses of major taxa varied across the Beaufort Sea, with copepods as the

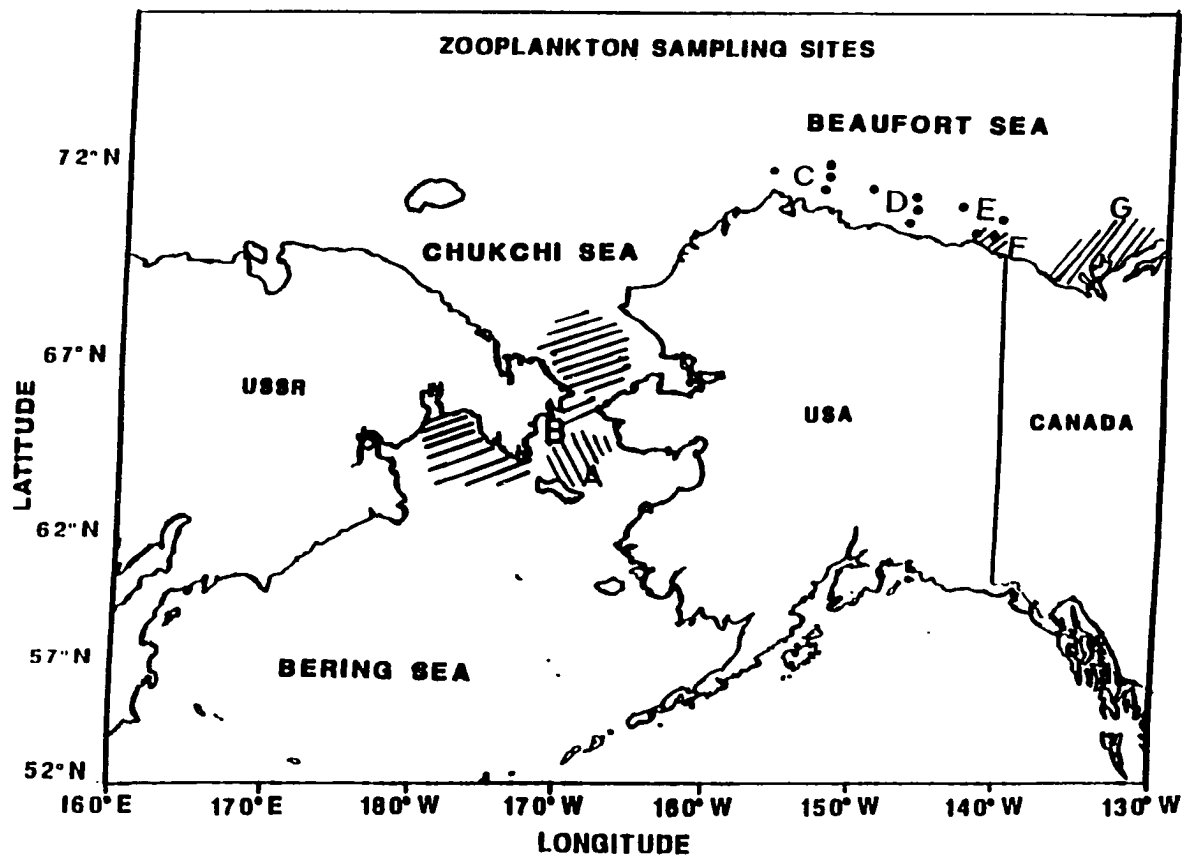


Figure 8. Collection sites for zooplankton samples reported in Saupé et al. (1989). A: TH87, HX87, B: SU87, TH87, C-E: PS86, F: AM86, ZOOP85, G: TA86, CA85.

TABLE 1. $\delta^{13}\text{C}$ values of major taxonomic groups in Alaskan and Canadian waters. Letters in parentheses represent sampling areas in Figure 8. When n=2, measurements only are listed (from Saupe et al. 1989).

| <u>AREA</u> | | <u>COPEPODS</u> | <u>EUPHAUSIIDS</u> | <u>CHAETOGNATHS</u> | <u>AMPHIPODS</u> |
|---|----|-----------------|--------------------|---------------------|------------------|
| NORTHERN BERING SEA JUNE 1987 (A) | x | -20.9 | -19.4 | -20.9 | -19.6 |
| | SD | 0.8 | 0.6 | 0.3 | 0.8 |
| | n | 22 | 7 | 7 | 11 |
| NORTHERN BERING/ SOUTHERN CHUKCHI SEAS AUG.-OCT. 1987 (B) | x | -21.1 | -19.7 | -20.4 | -19.8 |
| | SD | 0.8 | 0.9 | 0.5 | 0.6 |
| | n | 39 | 19 | 16 | 4 |
| WESTERN ALASKAN BEAUFORT SEA OCT. 1986 (C) | x | -22.8 | -21.7 | -20.2 | -21.3 |
| | SD | 0.9 | 0.8 | 0.3 | 0.8 |
| | n | 5 | 15 | 6 | 4 |
| CENTRAL ALASKAN BEAUFORT SEA OCT. 1986 (D) | x | -24.6 | -23.5 | ---- | -22.8 |
| | SD | 0.6 | 0.4 | ---- | 1.5 |
| | n | 4 | 8 | ---- | 4 |
| EASTERN ALASKAN BEAUFORT SEA SEPT. 1985 (F) | x | -25.8 | -19.7,-23.6 | ---- | -26.6 |
| | SD | 0.8 | | ---- | 0.3 |
| | n | 7 | 2 | ---- | 3 |
| SEPT.-OCT. 1986 (E & F) | x | -25.9 | -24.5 | -22.5,-21.9 | -24.6 |
| | SD | 1.5 | 1.4 | | 1.4 |
| | n | 39 | 10 | 2 | 7 |
| SOUTHERN CANADIAN BEAUFORT SEA SEPT. 1985 (G) | x | -26.7 | -24.0 | ---- | ---- |
| | SD | 0.7 | 0.2 | ---- | ---- |
| | n | 6 | 3 | ---- | ---- |
| AUG.-SEPT. 1986 (G) | x | -25.1 | -23.2,-23.4 | -23.0,-22.6 | -24.1,-26.0 |
| | SD | 1.0 | | | |
| | n | 6 | 2 | 2 | 2 |

dominant taxa in the east and euphausiids in the west. Weighted carbon isotope values across the Beaufort Sea (Figure 9) show a 4‰ carbon isotope gradient. Schell et al. (1989) suggest this taxonomic and geographic gradient may account for the oscillations in carbon isotope ratios along the baleen plates of bowhead whales.

Isotopic Studies on Bowhead Whales

The National Environmental Protection Act requires the Minerals Management Service to conduct environmental impact studies in frontier regions subject to oil and gas leasing. The effects of offshore drilling led to studies on the migration of bowhead whales and their life history including habitat usage, feeding ecology and population recruitment rates. The whales are also protected by the Endangered Species Act and the Marine Mammal Protection Act. Other concerns were raised over harvest rates of bowhead whales by Alaskan Inupiat subsistence whalers.

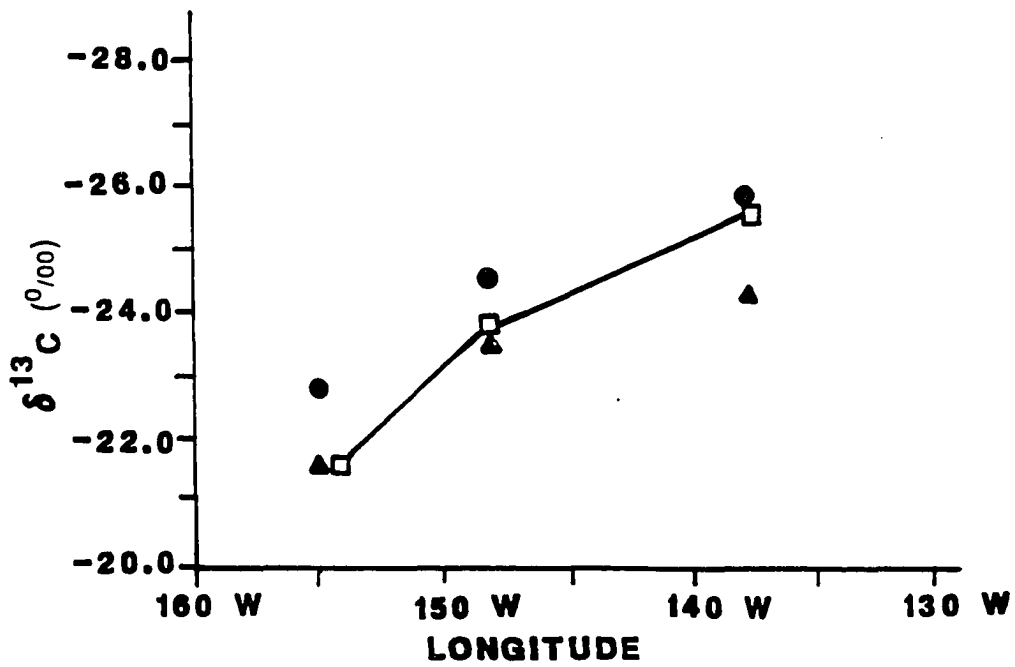


Figure 9. $\delta^{13}\text{C}$ means for copepods (●) and euphausiids (▲) and average $\delta^{13}\text{C}$ weighted for biomass fractions (□) (from Saupe et al. 1989).

Natural History of Bowhead Whales

Bowhead whales (*Balaena mysticetus*) once inhabited much of the arctic/sub-arctic oceanic region. The western arctic stock, the largest remaining population, winters in the western Bering Sea from late November to early April (Figure 10). In early April, the whales enter the ice and follow open leads northeastward to gain access to the eastern Beaufort Sea, where they arrive in late June and early July. The summer range of the whales is in the Canadian Beaufort Sea as far west as Kaktovik (Fraker, 1984). In late summer and early fall (August-September), the whales begin their westward migration back to the Bering Sea. Most of the whales migrate out of the Beaufort Sea by mid-October, with a few remaining until early November. Once past Point Barrow, the whales migrate westward through the Chukchi Sea toward Wrangel Island and southward along the Chukotka peninsula, Siberia. During this time, they feed heavily on zooplankton that have matured over the summer. Between November and December, they arrive at their wintering grounds in the northwestern Bering Sea.

The feeding apparatus of the bowhead whale consists of

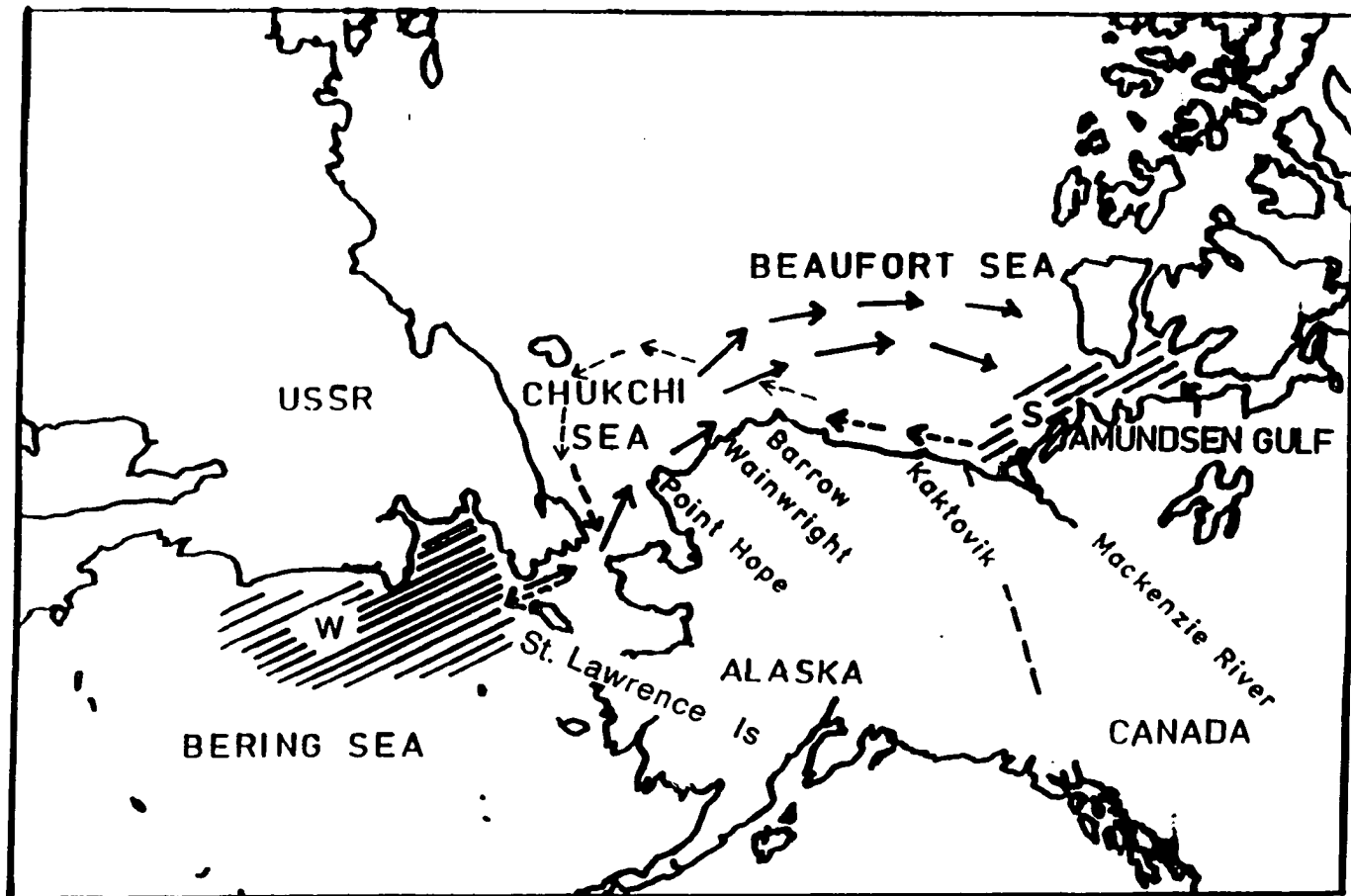


Figure 10. Migratory route of the western arctic population of bowhead whales (*Balaena mysticetus*) (from Schell et al. 1989).

approximately 250 to 350 baleen plates of up to 4 m in length suspended from each side of the maxilla bone (upper jaw) (Marquette 1977). Baleen plates consist of nonliving keratinaceous substance derived from the germinal epithelium of the maxilla (Lambertsen et al. 1989). The entire baleen apparatus is made up of the gums, connective tissue, main baleen plates and minor plates and baleen hairs. Baleen hairs are frayed strands of baleen on the inner length of the plate and are the filtering mechanism for collecting zooplankton. As the plates grow, the distal end wears down with age as keratin strands continue to fray. Plates vary in length, with the longest plates being in the middle of the baleen rack.

Predominant prey species identified in stomach contents of bowhead whales harvested in western and northern Alaska are copepods and euphausiids. Lesser quantities of amphipods and mysids were also found, as well as various invertebrates, fishes and occasional pebbles (Lowry and Frost 1984; Carrol et al. 1987; Lowry et al. 1987). One whale, harvested at Gambell, St. Lawrence Island, May, 1982, had non-planktonic stomach

contents consisting mainly of gammarid amphipods (91.7%), indicating this individual was feeding on the bottom. It also had traces of clam, sculpin, tanner crab, shrimp, cumaceans and several pebbles (Hazard and Lowry 1984).

Isotope Ratios in Baleen

Schell et al (1989) reported the presence of oscillations in keratin carbon isotope ratios along the lengths of baleen plates taken from bowhead whales (Figure 11). These oscillations are presumed to be the result of feeding along the whale's annual migratory route (Figure 10), and are due to the contrasting geographic isotope values in zooplankton prey found in the Beaufort, Chukchi and Bering seas. Newly-formed baleen from whales taken in the spring (April-May) is ^{13}C -enriched, whereas that from whales harvested in the fall (September-October) is ^{13}C -depleted (Figure 11). The isotopic oscillations in the baleen also provide a means of determining growth rates and the ages of subadult bowhead whales (Saupe et al. 1989; Schell et al. 1989).

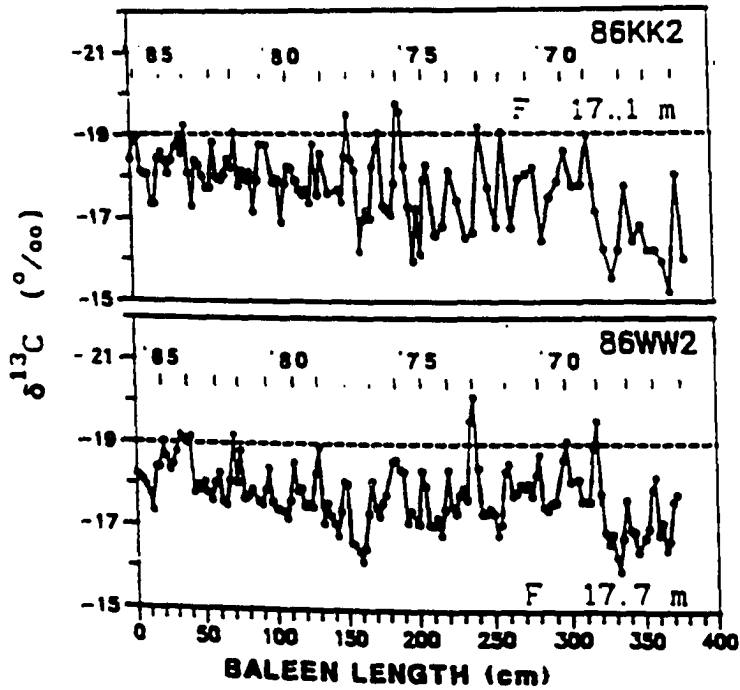


Figure 11. The $\delta^{13}\text{C}$ values along the length of baleen plates from whales 86KK2 (killed in fall) and 86WW2 (killed in spring). Base (newest baleen) is at left in both traces (from Schell et al. 1989).

Schell et al. (1989) analyzed the relative importance of habitats for bowhead whale feeding. Changes in muscle and visceral fat $\delta^{13}\text{C}$ values normalized for internal fractionation, were compared for spring-killed versus fall-killed whales (Figure 12). Schell et al (1989) found changes in $\delta^{13}\text{C}$ of bowhead tissues in subadults that indicated feeding in both summer and fall/winter, whereas adults appeared to derive almost all food during fall and winter feeding.

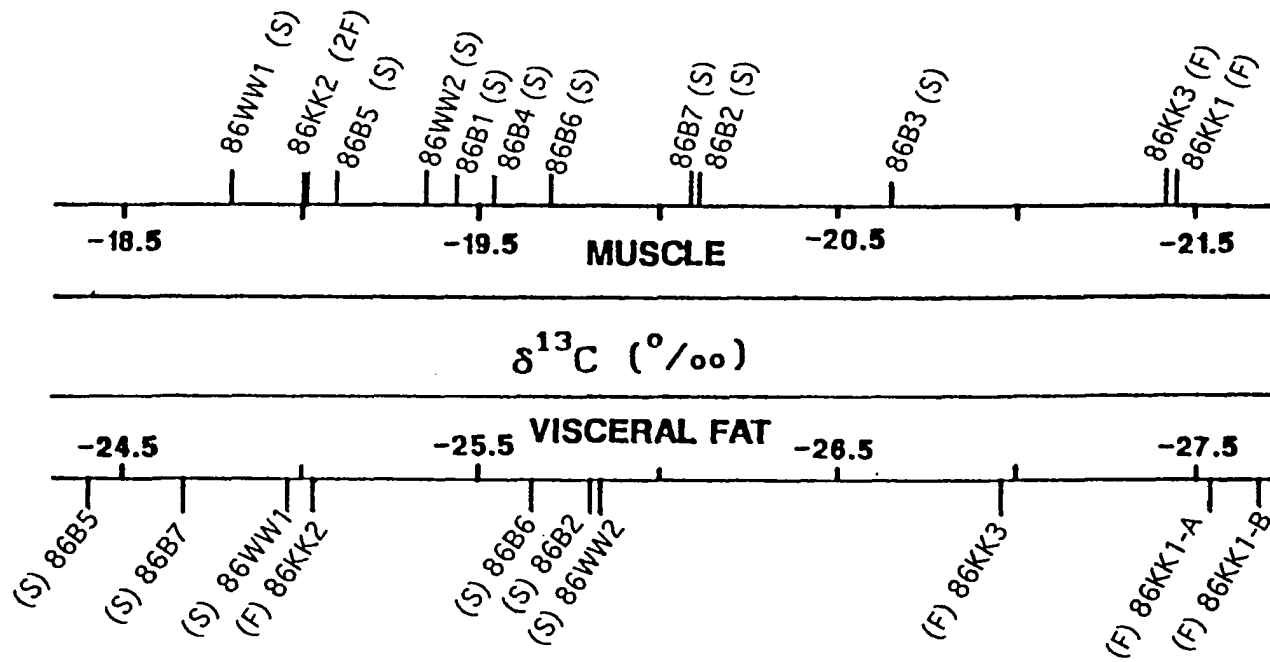


Figure 12. Bowhead whale muscle and visceral fat $\delta^{13}\text{C}$ values are shown for whales harvested in the fall (F) and spring (S), (from Schell et al. 1989).

CHAPTER 2. SCOPE AND OBJECTIVES

The objective of this study was to determine regional variation in stable isotope values in zooplankton over the migratory range of the bowhead whale. Both seasonal and long-term variations were studied and related to changes in the physical environment where possible. Where no environmental controls were evident, hypotheses were posed that would account for the observed isotopic changes.

The specific hypotheses tested were:

1. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of zooplankton taxonomic groups are significantly different between regions of the Beaufort Sea and the Chukchi/Bering seas.
2. Adult bowhead whale (*Balaena mysticetus*) baleen formed in fall-winter months has interannual variations in average $\delta^{13}\text{C}$.
3. Zooplankton have interannual and seasonal variations in average $\delta^{13}\text{C}$ that match those changes observed in the baleen.

Zooplankton isotope ratio variations are indicators of changes in primary production, which, in turn, may indicate changes in the in primary production which in turn may indicate changes in the physical-chemical environment.

4. $\delta^{15}\text{N}$ oscillations in bowhead whale baleen are due to changes in diet between summer and fall-winter feeding areas.

The limitations of this study include the following:

1. Zooplankton were not collected during winter months.

Therefore, there is no insight as to whether the $\delta^{13}\text{C}$ of zooplankton change much over the fall and winter seasons.

2. No data were collected on interannual variability in Beaufort Sea zooplankton, so there is no information on long or short term cycles there.

3. Little information exists on the area or production of the summer range of the bowhead whales. Thus, relative food intake from each seasonal habitat and consequent average $\delta^{13}\text{C}$ of the whale tissues is not specifically known.

4. No information on winter and early spring feeding of bowhead whales exists. Thus, trophic changes with season

leading to isotope ratio changes in whale tissues is speculative.

5. No attempts have been made to relate $\delta^{15}\text{N}$ data to physiological cycles or reproduction in bowhead whales. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of the whale tissues may change independently of food sources.

CHAPTER 3. METHODS

Zooplankton Sampling

Zooplankton samples were collected from several ships of opportunity in the Chukchi and Bering seas during different seasons between 1987 and 1990 (Table 2). Station locations for each cruise are shown in Figures 13-18. The zooplankton data reported by Saupe et al. (1989) also are included in this study and listed in Table 2. Cruises from Saupe et al. (1989) span a regional range from the southern Canadian Beaufort Sea west to the northern Bering Sea (Figure 5).

Sample Collection and Treatment

Samples of zooplankton were collected with vertical or oblique net tows at each station. Bongo nets or one meter ring nets of 505 μm mesh were deployed to within five to ten meters of bottom depth and towed through the water column at a rate of 5 meters per minute. Following collection, samples were

TABLE 2. Zooplankton samples collected from cruises in the Beaufort, Chukchi and Bering seas (1985-1990). Cruises through 1987 (*) were Bering and Chukchi zooplankton data reported by Saupe et al. (1989).

M.W. Bradstreet Collections (CA85 & ZOOP85)*

R/V ANNIKA MARIE, September, 1986 (AM86)*

R/V POLAR STAR, October, 1986 (PS86)*

R/V TA, August-September 1986 (TA86)*

R/V ALPHA HELIX, June, 1987 (HX87) *

R/V THOMAS G. THOMPSON, July-August, 1987 (TH87) *

R/V SURVEYOR, September-October, 1987 (SU87) *

R/V ALPHA HELIX, May, 1988 (IE88)

R/V AKADEMIC KOROLEV, July-August, 1988 (AK88)

R/V THOMAS WASHINGTON, September-October, 1988 (TW88)

R/V SURVEYOR, October, 1988 (SU88)

R/V SURVEYOR, October, 1989 (SU89)

R/V SURVEYOR, October, 1990 (SU90)

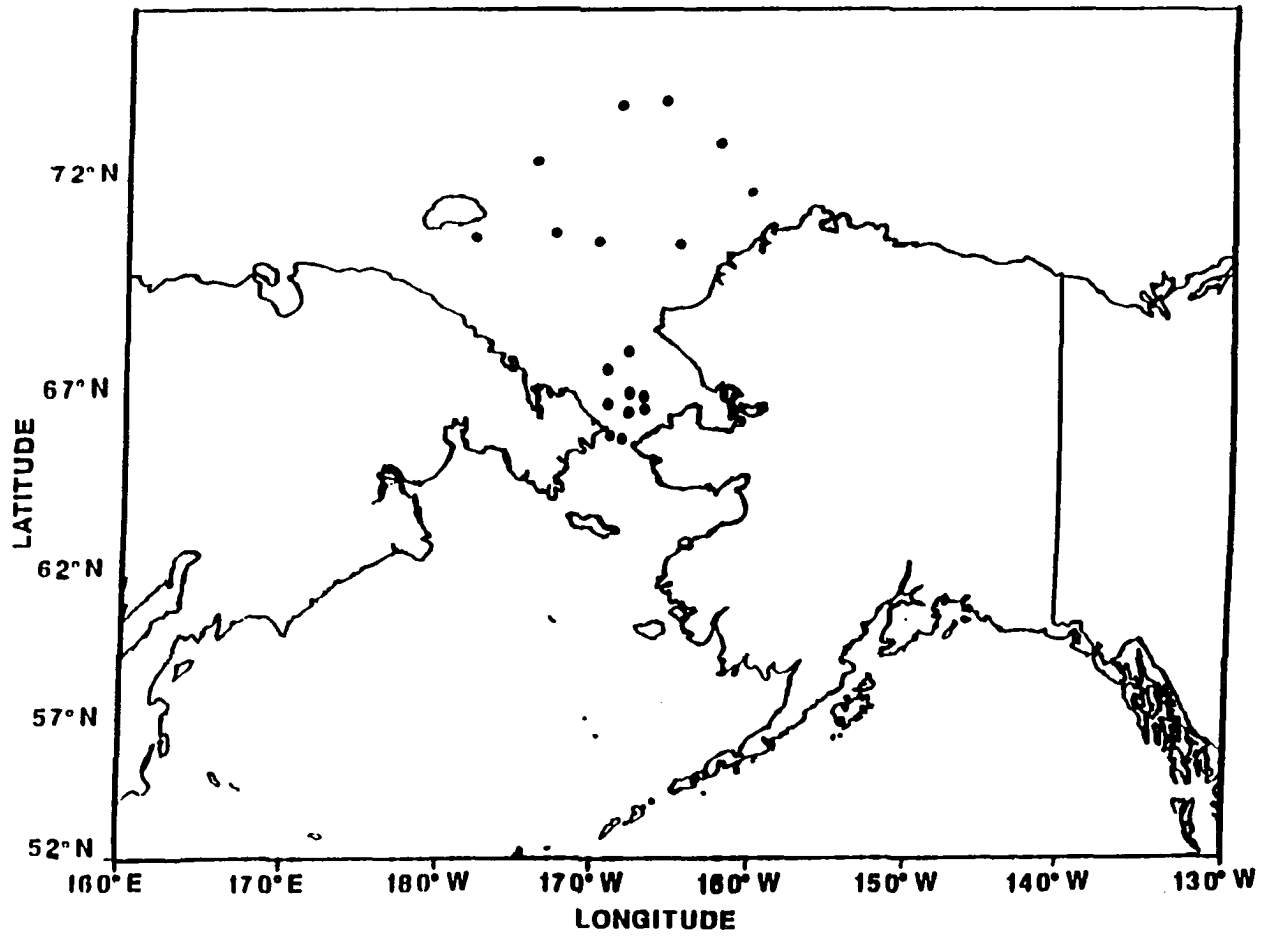


Figure 13. Collection sites for zooplankton samples taken aboard the R/V SURVEYOR, October, 1990 (SU90).

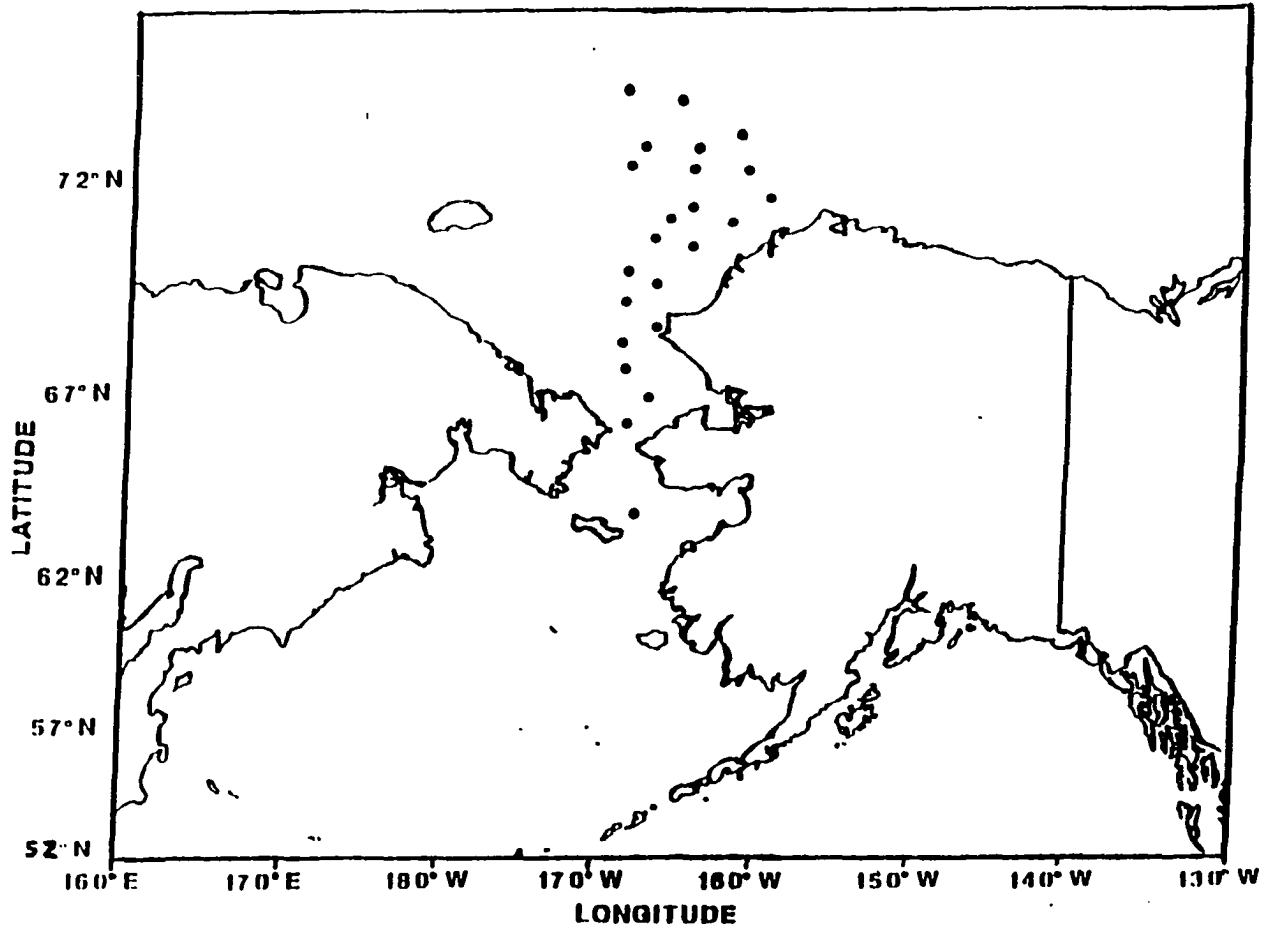


Figure 14. Collection sites for zooplankton samples taken aboard the R/V SURVEYOR, October, 1989 (SU89).

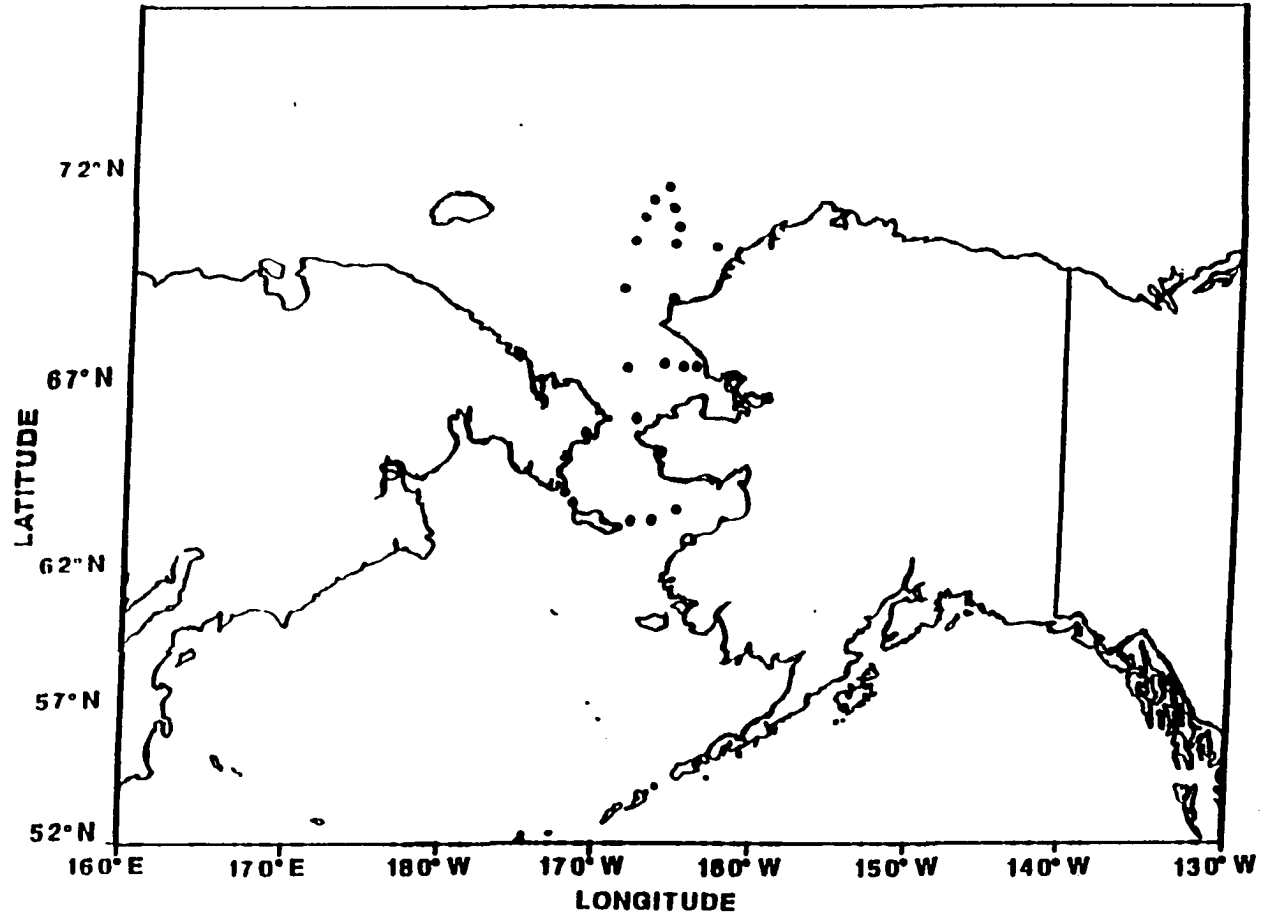


Figure 15. Collection sites for zooplankton samples taken aboard the R/V SURVEYOR, October, 1988 (SU88).

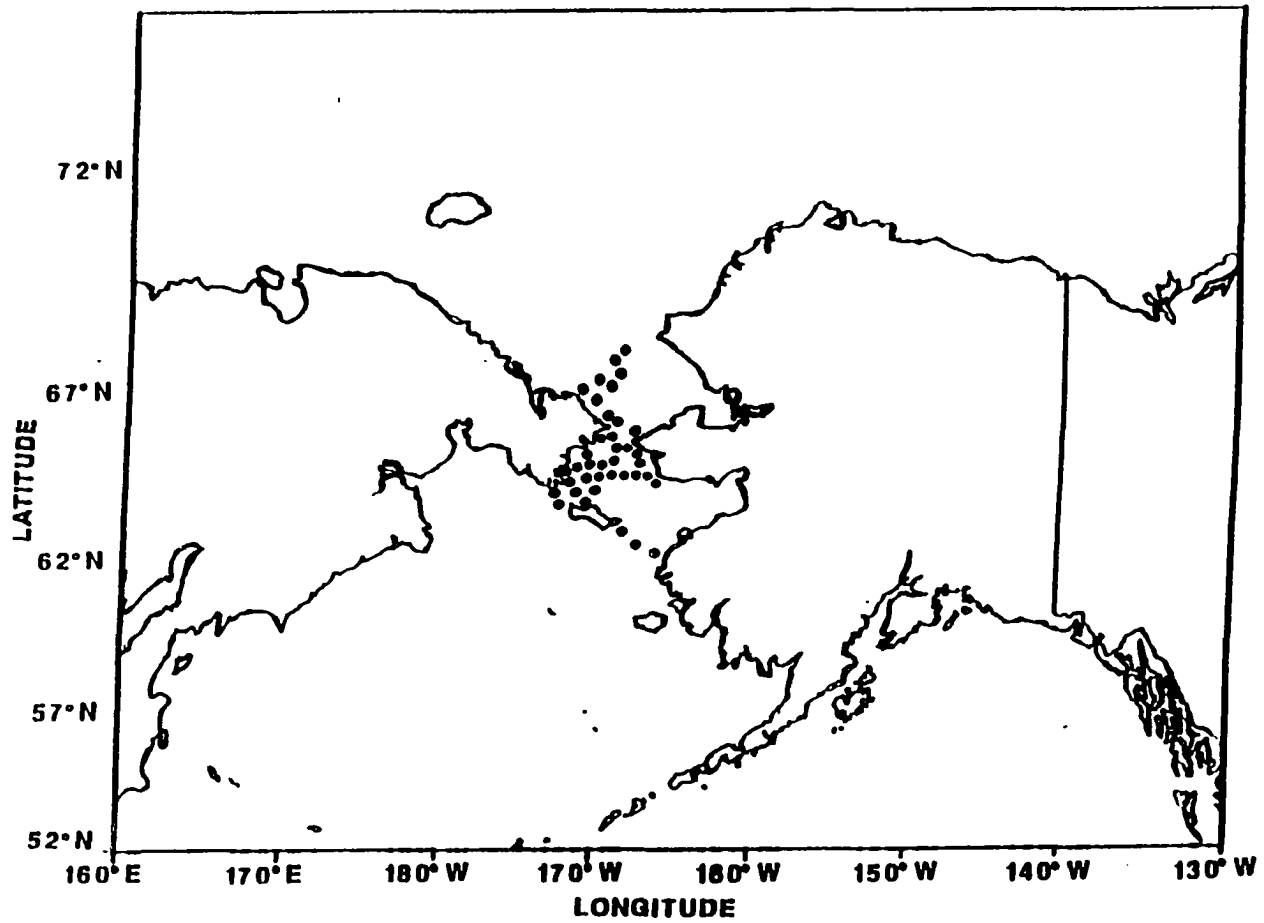


Figure 16. Collection sites for zooplankton samples taken aboard the R/V THOMAS WASHINGTON, September-October, 1988 (TW88).

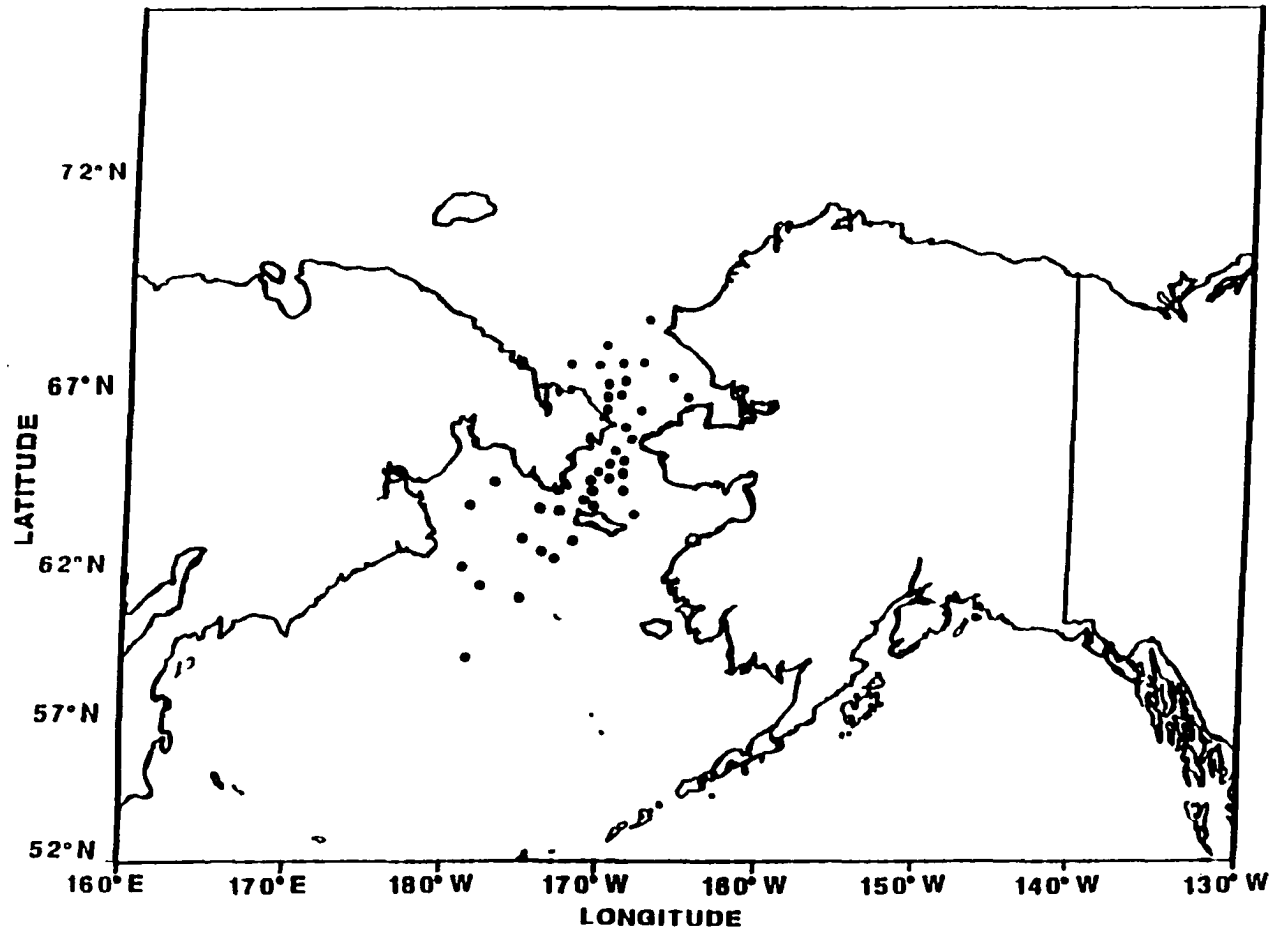


Figure 17. Collection sites for zooplankton samples taken aboard the R/V AKADEMIC KOROLEV, July-August, 1988 (AK88).

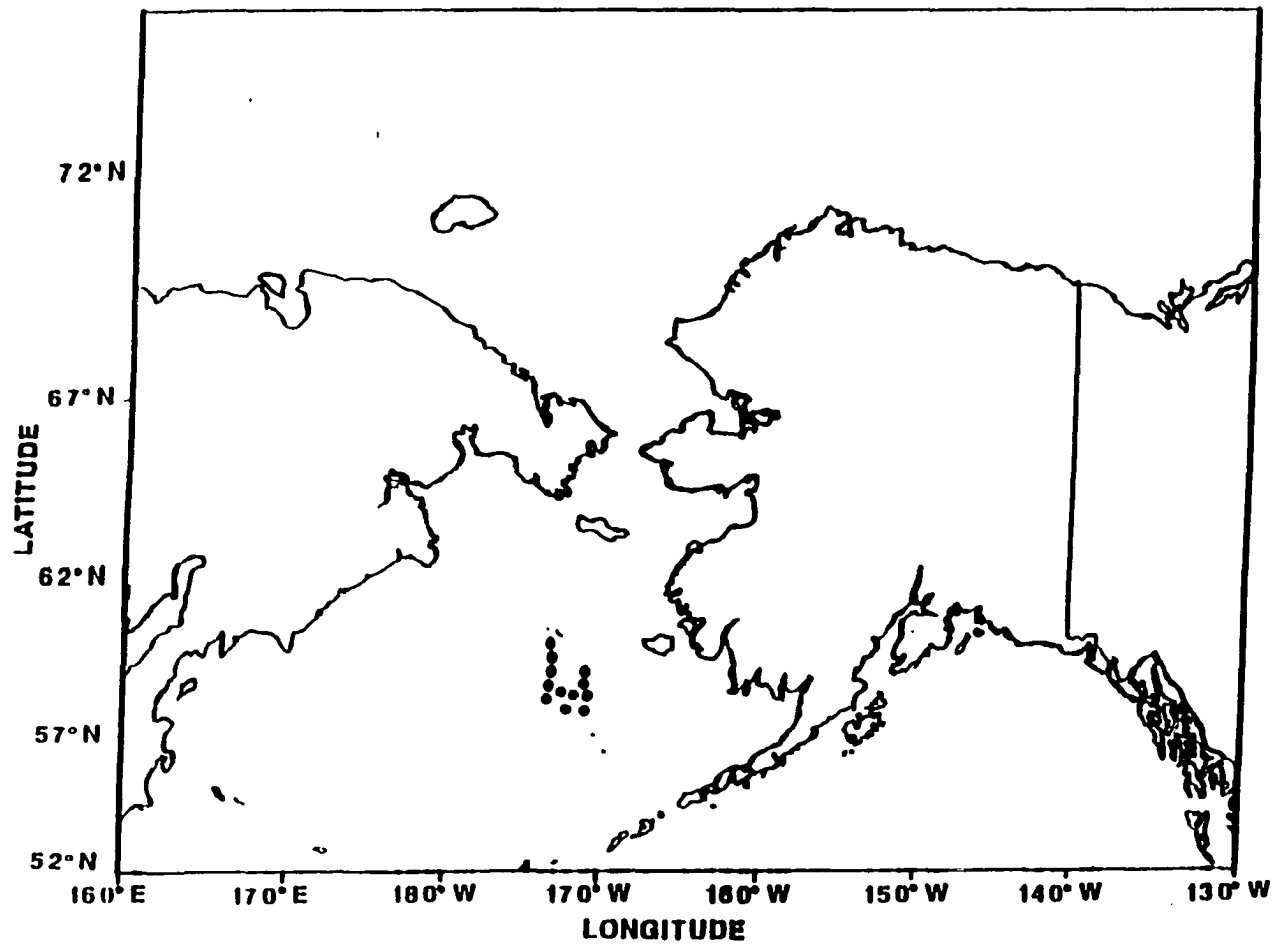


Figure 18. Collection sites for zooplankton samples taken aboard the R/V ALPHA HELIX, May, 1988 (IE88).

separated into major taxonomic groups and when possible sorted to species. Once sorted, individual taxon samples were frozen until processing in the laboratory. Additional sorting of frozen samples from TW88 and SU88 was conducted to species level in the laboratory. When sorting was impractical, zooplankton from a single net tow were frozen and treated as a "composite" sample.

Large copepods were sorted to species for cruises SU87 and SU89. Small and large copepods were sorted to species for cruises HX87, AK88 and SU88. For cruises where identification was impractical, calanoid copepods were divided into small, medium and large. Euphausiids were also sorted into small, medium and large sizes and euphausiid species were determined for cruises HX87, AK88, SU88.

Benthic samples were collected at some stations by deploying bottom trawls. Sorted organisms were taxonomically identified at sea and frozen for later analysis in the laboratory.

Zooplankton sample preparation

Sorted zooplankton samples were thawed and dried to a

constant weight at 90 °C. Samples were acidified with 10 percent hydrochloric acid to remove carbonates prior to drying. When possible, shells and exoskeletons of benthic organisms were removed prior to acidification and drying.

A subsample of approximately 15 mg of dried zooplankton (20 mg for copepod species) was ground with one gram of precombusted copper oxide (CuO). The ground sample was then placed in a 2 mm X 33 mm quartz tube and this tube placed in a 9 mm X 200 mm outer quartz tube. All air was evacuated on a vacuum manifold to a pressure <5 mTorr and the tubes sealed off with a propane-oxygen torch. The sealed tubes were then combusted in a muffle furnace at 870 °C for two hours and allowed to cool over several hours.

Combusted sample tubes were opened into a vacuum manifold using the procedure of Des Marais and Hayes (1976). The carbon dioxide and nitrogen gases were cryogenically separated and pumped into short borosilicate glass tubes and sealed off for later mass spectrometry.

Samples of tubed nitrogen (N₂) and carbon dioxide (CO₂) gas

were analyzed with a VG SIRA Series II mass spectrometer. The ratios of $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ were reported in conventional delta notation.

Statistical Treatment of Data

Kruskal-Wallis non-parametric tests were used to identify significant differences among locations for major taxonomic groups (Conover 1980, Zar 1984). Using a SAS/GLM computer statistical package, a non-parametric ANOVA on the ranked data was also employed to test for significant differences between the isotope ratios of taxonomic groups at given locations as well as between isotope ratios of each taxonomic group among locations (Conover and Iman, 1981). Major groups included copepods, euphausiids, amphipods, chaetognaths, crab larvae and shrimp larvae. Analysis for differences in major taxa between cruises were also conducted.

The study area was divided into regions of each sea based on sample sizes that could be statistically analysed. The regions for statistical analysis are listed by latitude and

longitude:

| | |
|------------------------------|----------------------------------|
| Canadian Beaufort Sea | (130.46-138.46 W, 69.00-71.95 N) |
| Eastern Alaskan Beaufort Sea | (139.47-143.70 W, 69.00-71.95 N) |
| Central Alaskan Beaufort Sea | (144.02-149.90 W, 69.00-71.95 N) |
| Western Alaskan Beaufort Sea | (152.65-156.50 W, 69.00-71.95 N) |
| Northern Chukchi Sea | (156.51-179.85 W, 70.00-71.50 N) |
| Eastern Chukchi Sea | (160.00-168.99 W, 66.35-69.99 N) |
| Western Chukchi Sea | (169.00-180.00 W, 66.35-69.99 N) |
| Eastern Bering Sea | (163.00-168.99 W, 63.00-66.27 N) |
| Central Bering Sea | (169.00-175.00 W, 63.00-66.27 N) |
| Western Bering Sea | (175.00W-179.85E, 53.93-67.00 N) |
| Southern Bering Sea | (170.67-172.86 W, 57.47-60.00 N) |

These regions are depicted in Figure 19. In a second analysis, the Canadian, Eastern Alaskan, Central Alaskan and Western Alaskan Beaufort seas were combined into the region Beaufort Sea. The Eastern and Western Chukchi seas were combined to form the Chukchi Sea. The Eastern, Central and Western Bering seas were combined into the Bering Sea. The Northern Chukchi Sea region and the Southern Bering Sea region

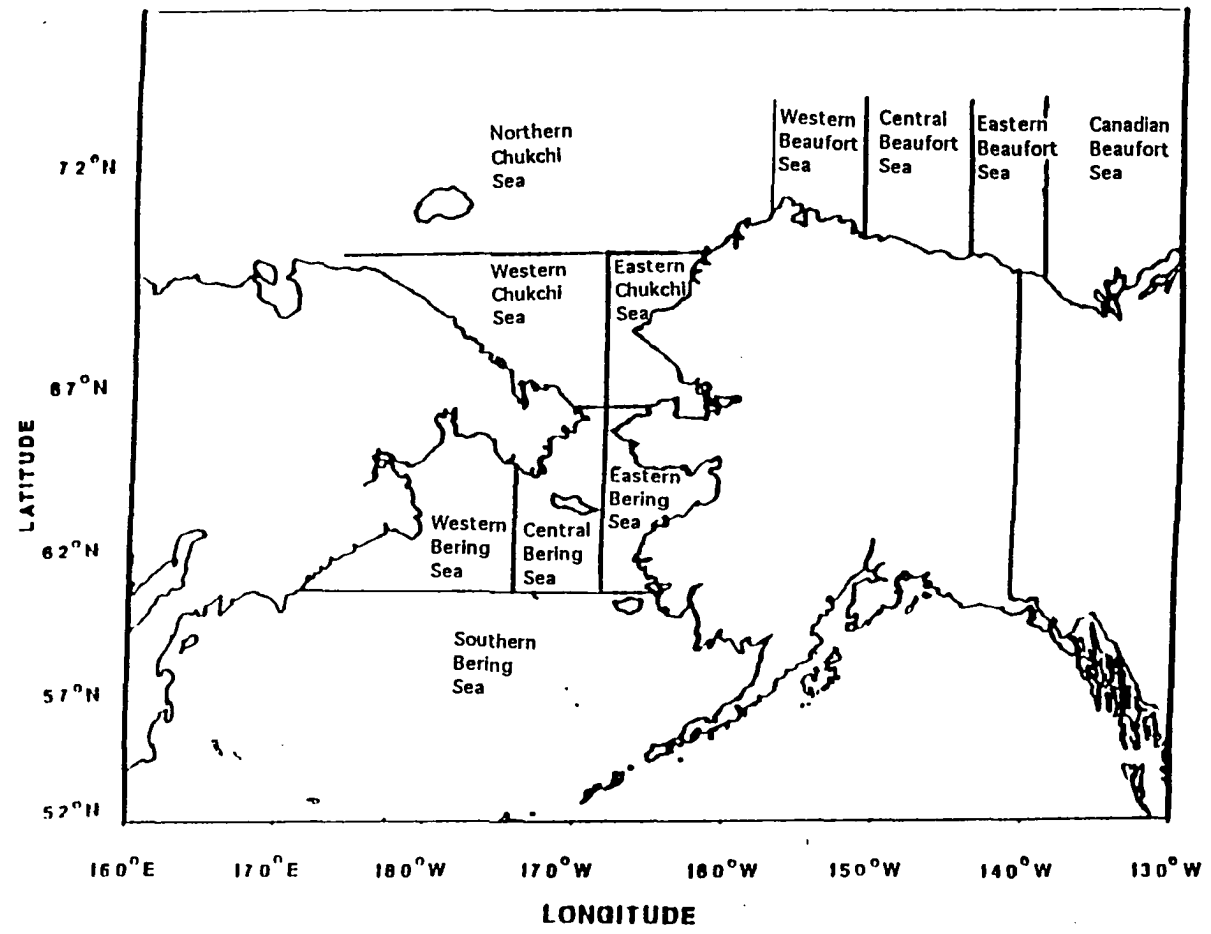


Figure 19. The eleven geographical regions designated for statistical analysis of zooplankton samples.

remained as in the previous analysis.

Bowhead Whale Tissue Collection

Bowhead whale tissue samples were collected from animals harvested by Alaskan native subsistence whalers of the coastal villages of Gambell, Point Hope, Wainwright, Nuiqsut, Barrow and Kaktovik, through cooperation of the whalers with the personnel of the Department of Wildlife Management, North Slope Borough.

Baleen plates and body tissues taken from 47 bowhead whales harvested between 1986 and 1990 are listed in Table 3.

Bowhead Whale Sample Preparation

Baleen plates were cleaned of gum tissue, algae and other foreign matter by soaking in water and scrubbing with steel wool. Each baleen plate was labeled along its length with tape at 2.5 cm intervals, beginning at the proximal end, and subsampled for isotopic analysis using a flexible shaft engraving tool. Approximately 15 mg of powdered baleen was ground with

TABLE 3. Bowhead whale samples (1986-1990).

| <u>WHALE NAME</u> | <u>HARVEST DATE</u> | <u>HARVEST LOCATION</u> | <u>SEX</u> | <u>BODY LENGTH</u> | <u>BALEEN LENGTH</u> | <u>COLLECTED SAMPLES</u> |
|------------------------------|---------------------|-------------------------|------------|--------------------|----------------------|---|
| <u>1986 HARVESTED WHALES</u> | | | | | | |
| 86B1 | 27/04/86 | BARROW | M | 8.2 m | 1.18m | BALEEN |
| 86B2 | 27/04/86 | BARROW | M | 8.7 m | 0.52 m | BALEEN, BLUBBER, MUSCLE |
| 86B3 | 30/04/86 | BARROW | F | 8.9 m | 1.60 m | BALEEN, MUSCLE |
| 86B4 | 01/05/86 | BARROW | M | 8.9 m | 1.30 m | BALEEN, MUSCLE |
| 86B5 | 04/05/86 | BARROW | M | 8.1 m | 0.85 m | BALEEN, MUSCLE, VISCERAL FAT |
| 86B6 | 05/05/86 | BARROW | F | 12.3 m | 2.30 m | BALEEN, MUSCLE, VISCERAL FAT |
| 86B7 | 06/05/86 | BARROW | M | 10.7 m | 2.01 m | BALEEN, MUSCLE, VISCERAL FAT |
| 86KK1 | 17/09/86 | KAKTOVIK | F | 7.6 m | 1.30 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER |
| 86KK2 | 17/09/86 | KAKTOVIK | F | 17.1 m | 3.80 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER |
| 86KK3 | 26/09/86 | KAKTOVIK | M | 10.4 m | 1.85 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER |
| 86WW1 | 05/05/86 | WAINWRIGHT | M | 15.9 m | 2.69 m | BALEEN, MUSCLE, VISCERAL FAT |
| 86WW2 | 10/05/86 | WAINWRIGHT | F | 17.7 m | 3.10 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER |
| <u>1987 HARVESTED WHALES</u> | | | | | | |
| 87B1 | 01/05/87 | BARROW | M | 9.3 m | 1.68 m | BALEEN |
| 87B2 | 02/05/87 | BARROW | F | 8.9 m | 1.50 m | BALEEN |
| 87B3 | 04/05/87 | BARROW | M | 11.0 m | 1.95 m | BALEEN |
| 87B4 | 20/05/87 | BARROW | F | 16.8 m | 3.17 m | BALEEN |
| 87B5 | 15/06/87 | BARROW | F | 15.7 m | 3.00 m | BALEEN |
| 87B5F | 15/06/87 | BARROW | FETUS | 4.0 m | 0.15 m | BALEEN, MUSCLE, BLUBBER |
| 87B6 | 22/10/87 | BARROW | F | 15.7 m | 3.15 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER, TENDON |
| 87B7 | 29/10/87 | BARROW | M | 8.5 m | 0.85 m | BALEEN, MUSCLE, VISCERAL FAT, BLUBBER |
| 87G2 | 24/04/87 | GAMBELL | F | 16.8 m | 3.45 m | BALEEN |
| 87H4 | 28/05/87 | POINT HOPE | M | 7.8 m | 0.68 m | BALEEN |
| 87N1 | 05/10/87 | NUIQSUT | F | 15.2 m | 3.30 m | BALEEN, MUSCLE, BLUBBER |
| 87WW2 | 08/05/87 | WAINWRIGHT | M | 13.5 m | 2.15 m | BALEEN |
| 87WW3 | 15/05/87 | WAINWRIGHT | F | 8.2 m | 2.08 m | BALEEN |

TABLE 3. (continued).

| <u>WHALE NAME</u> | <u>HARVEST DATE</u> | <u>HARVEST LOCATION</u> | <u>SEX</u> | <u>BODY LENGTH</u> | <u>BALEEN LENGTH</u> | <u>COLLECTED SAMPLES</u> |
|------------------------------|---------------------|-------------------------|------------|--------------------|----------------------|---|
| <u>1988 HARVESTED WHALES</u> | | | | | | |
| 88B1 | 24/04/88 | BARROW | F | 8.9 m | 0.98 m | BALEEN, MUSCLE, VISCERAL FAT |
| 88B2 | 25/04/88 | BARROW | M | 8.8 m | ----- | MUSCLE, VISCERAL FAT, BLUBBER |
| 88B3 | 25/04/88 | BARROW | F | 7.8 m | ----- | MUSCLE, VISCERAL FAT |
| 88B4 | 25/04/88 | BARROW | F | 9.0 m | 1.30 m | BALEEN, MUSCLE, TENDON |
| 88B6 | 02/05/88 | BARROW | F | 8.3 m | ----- | MUSCLE, VISCERAL FAT, TENDON, LIVER |
| 88B7 | 05/05/88 | BARROW | F | 8.2 m | 0.78 m | BALEEN, MUSCLE, VISCERAL FAT, LIVER |
| 88B8 | 06/05/88 | BARROW | F | 7.5 m | 1.30 m | BALEEN, MUSCLE, VISCERAL FAT, TENDON, LIVER |
| 88B9 | 15/09/88 | BARROW | M | 14.6 m | 2.53 m | BALEEN |
| 88B10 | 17/09/88 | BARROW | M | 15.1 m | 3.28 m | BALEEN |
| 88B11 | 17/09/88 | BARROW | F | 15.6 m | 3.40 m | BALEEN |
| 88G1 | 16/04/88 | GAMBELL | F | 15.7 m | 2.95 m | BALEEN |
| 88G2 | 25/04/88 | GAMBELL | F | 15.3 m | 2.75 m | BALEEN, MUSCLE |
| 88KK1 | 24/09/88 | KAKTOVIK | F | 14.9 m | 2.97 m | BALEEN |
| 88WW1 | 25/04/88 | WAINWRIGHT | F | 7.9 m | 0.75 m | BALEEN |
| 88WW2 | 26/04/88 | WAINWRIGHT | M | 9.1 m | 0.98 m | BALEEN |
| 88WW3 | 06/05/88 | WAINWRIGHT | F | 13.4 m | 2.07 m | BALEEN |
| <u>1990 HARVESTED WHALES</u> | | | | | | |
| 90B5 | 23/05/90 | BARROW | F | 15.9 m | 2.80 m | BALEEN |
| 90B8 | 02/10/90 | BARROW | M | 12.9 m | 2.43 m | BALEEN |
| 90G4 | 07/05/90 | GAMBELL | F | 15.2 m | 3.05 m | BALEEN |
| 90B7 | 01/10/90 | BARROW | F | 8.4 m | 1.40 m | BALEEN |

one gram of precombusted CuO and placed in the quartz tubes and treated as described for zooplankton preparation.

Frozen muscle, tendon and liver samples were trimmed to remove surface contaminants. Muscle, tendon and liver samples were subsampled into approximately 5 gm samples, which were then dried to constant weight at 90 °C. Solid tissues were ground with a mortar and pestle. Approximately 15 mg of powdered tissue were then ground with one gram of precombusted CuO. Blubber and visceral fats were also trimmed of surface contaminants and subsamples of approximately 5 gm were rendered to oils at 70 °C. Approximately 15 mg of the rendered oil were spotted on a small piece of precombusted glass fiber filter and then ground with one gram of precombusted CuO. Nitrogen was not collected from oil due to the very low concentrations present.

Statistical Treatment of Bowhead Whale Data

Cross-correlation analysis was used to determine the correlation coefficient between fall/winter baleen averages and

sea surface temperature anomalies. Sea surface temperature anomalies were determined using sea surface temperature data from the Bering Sea (55 N, 175 W) (J. Namias, Scripps Institute of Oceanography, pers. comm.).

CHAPTER 4. RESULTS

Zooplankton Isotope Ratios

Mass spectrometer results of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ for zooplankton and benthos are listed by cruise (Appendix 1, OCS Study MMS 92-0020). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages, standard deviations and maximum and minimum values for major taxonomic groups by region are given in Appendices 2 and 3. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data for major taxonomic groups by cruise are given in Appendices 4 and 5.

Regional Distribution: Carbon Isotope Results

Copepods

Copepods typically comprised over 50% of the total number of organisms from each net tow. Species included the following calanoid copepods: *Calanus marshallae*, *Pseudocalanus minutus*, *Eucalanus bungii bungii*, *Neocalanus plumchrus* and *Neocalanus cristatus*. *Metridia lucens*, a non-calanoid species,

was not included in statistical comparisons due to its small sample size ($n=3$). For statistical purposes, calanoid copepods were combined for each station and an average $\delta^{13}\text{C}$ value determined.

Copepod $\delta^{13}\text{C}$ values from 193 stations (Figure 20) showed significant differences among eleven geographical areas (ANOVA on ranked values, $F_{10,182}=22.54$, $P<0.0001$). Pairwise comparison revealed significant ($P\leq 0.05$) differences between regions. The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21. Copepods from the Eastern Beaufort Sea were significantly depleted relative to copepods from all other regions except the other Beaufort Sea regions (Figure 19). The Canadian Beaufort Sea copepods were significantly depleted relative to the Central Bering, Eastern Bering, Western and Eastern Chukchi seas. The Central Beaufort Sea copepods were depleted relative to those of the Western and Eastern Chukchi seas. The copepods from the Southern Bering Sea were significantly enriched relative to copepods from all other regions except the Western Chukchi Sea. In addition, the Western Chukchi copepods were enriched

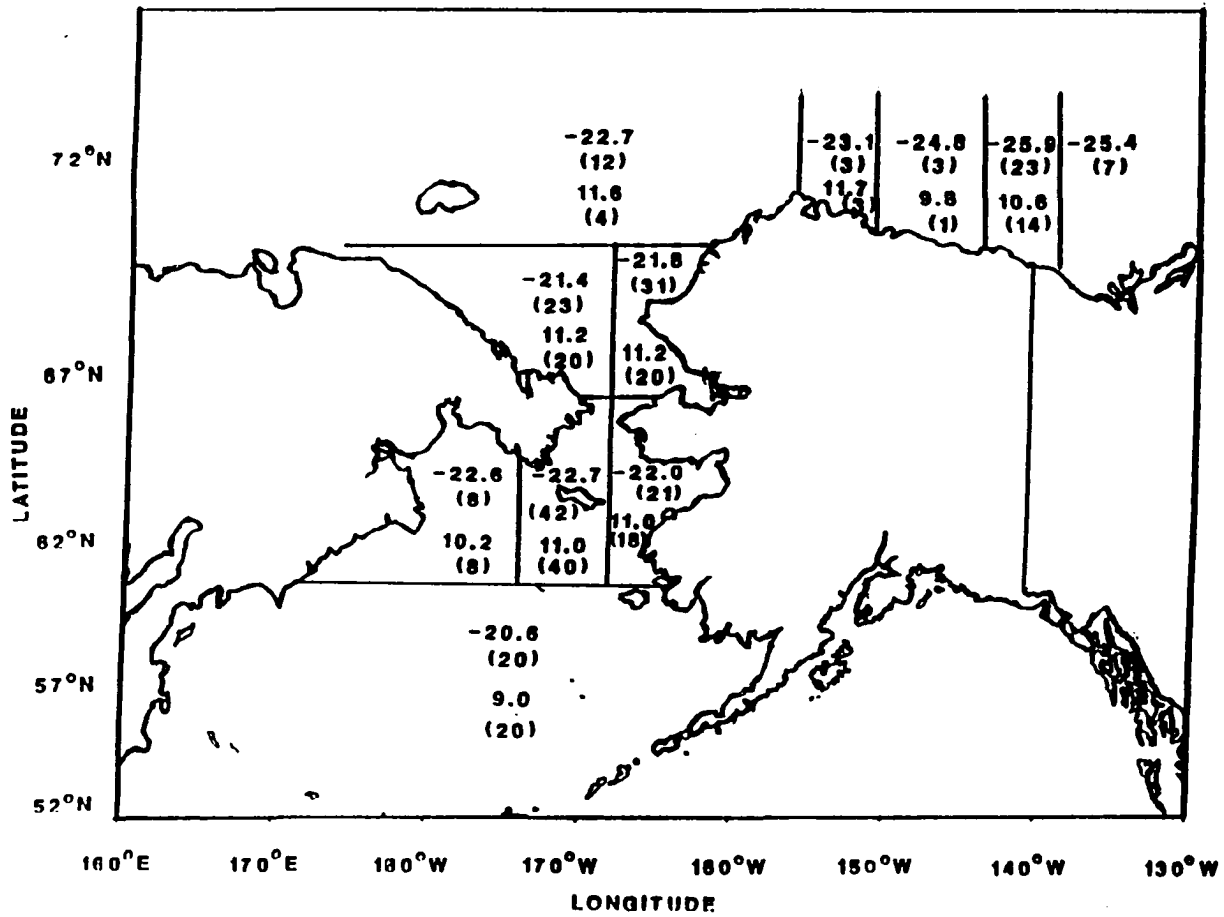


Figure 20. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for copepods by regions. Sample sizes are in parentheses.

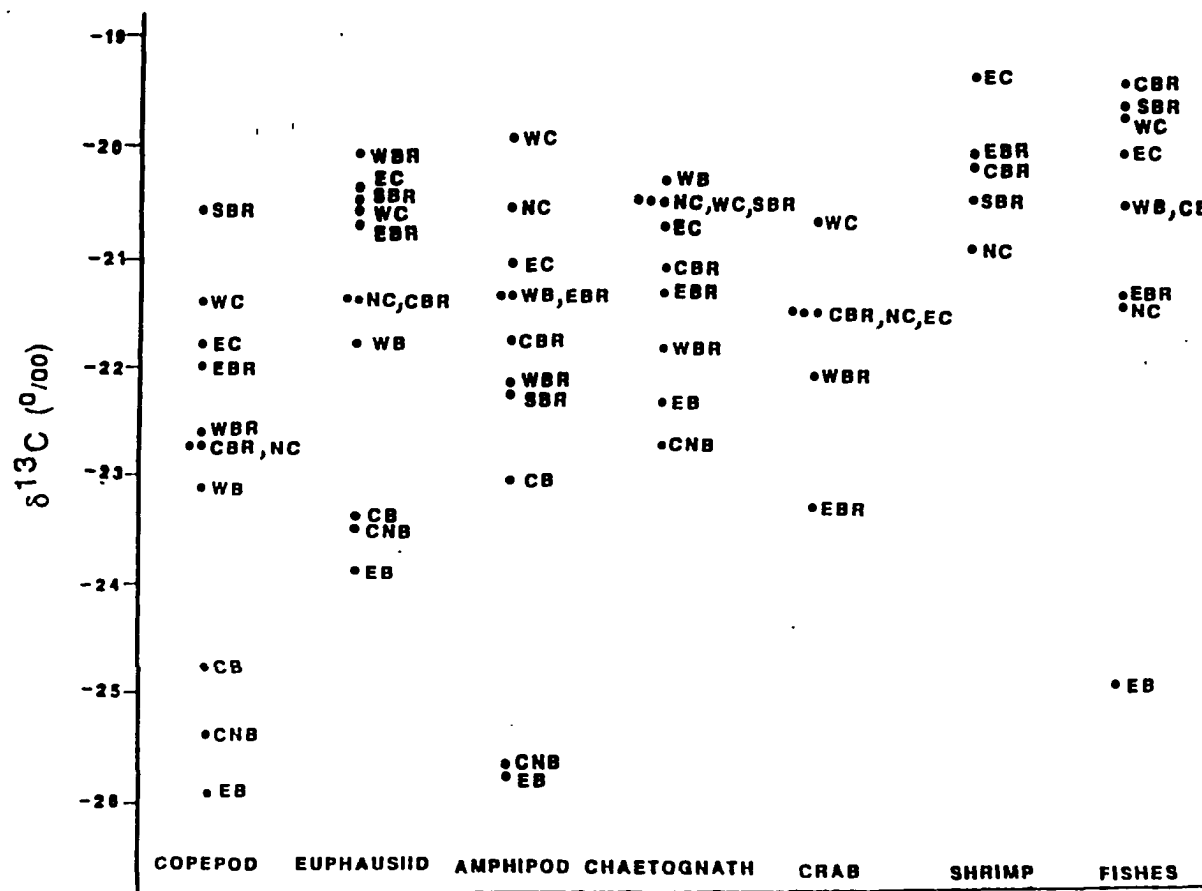


Figure 21. Average carbon stable isotopes ranked by region for major taxonomic groups. Abbreviations: EBR, CBR, SBR, WBR= eastern, central, southern and western Bering Sea respectively; EC, WC, NC= eastern, western and northern Chukchi Sea respectively; WB, EB, CB, CNB= western, eastern and central and Canadian Beaufort Sea respectively.

relative to those of the Northern Chukchi Sea and the Central Bering Sea.

Euphausiids

Species present for cruises HX87, AK88 and SU88 included *Thysanoessa raschii* and *Thysanoessa inermis*. Euphausiid $\delta^{13}\text{C}$ values for 127 stations (Figure 22) were significantly different among the eleven geographical areas (ANOVA on ranked values, $F_{10,116}=7.81$, $P<0.0001$), but no differences between sizes in a given region. Pairwise comparisons showed significant differences among regions.

The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21. Euphausiids from the Canadian, Central Alaskan and Eastern Alaskan Beaufort Sea regions were significantly ($P\leq 0.05$) depleted relative to those from the Southern Bering, Western Bering, Eastern Bering, Western Chukchi and Eastern Chukchi Sea regions. In addition, euphausiids from the Eastern Beaufort Sea region were significantly different from those of the Central Bering Sea.

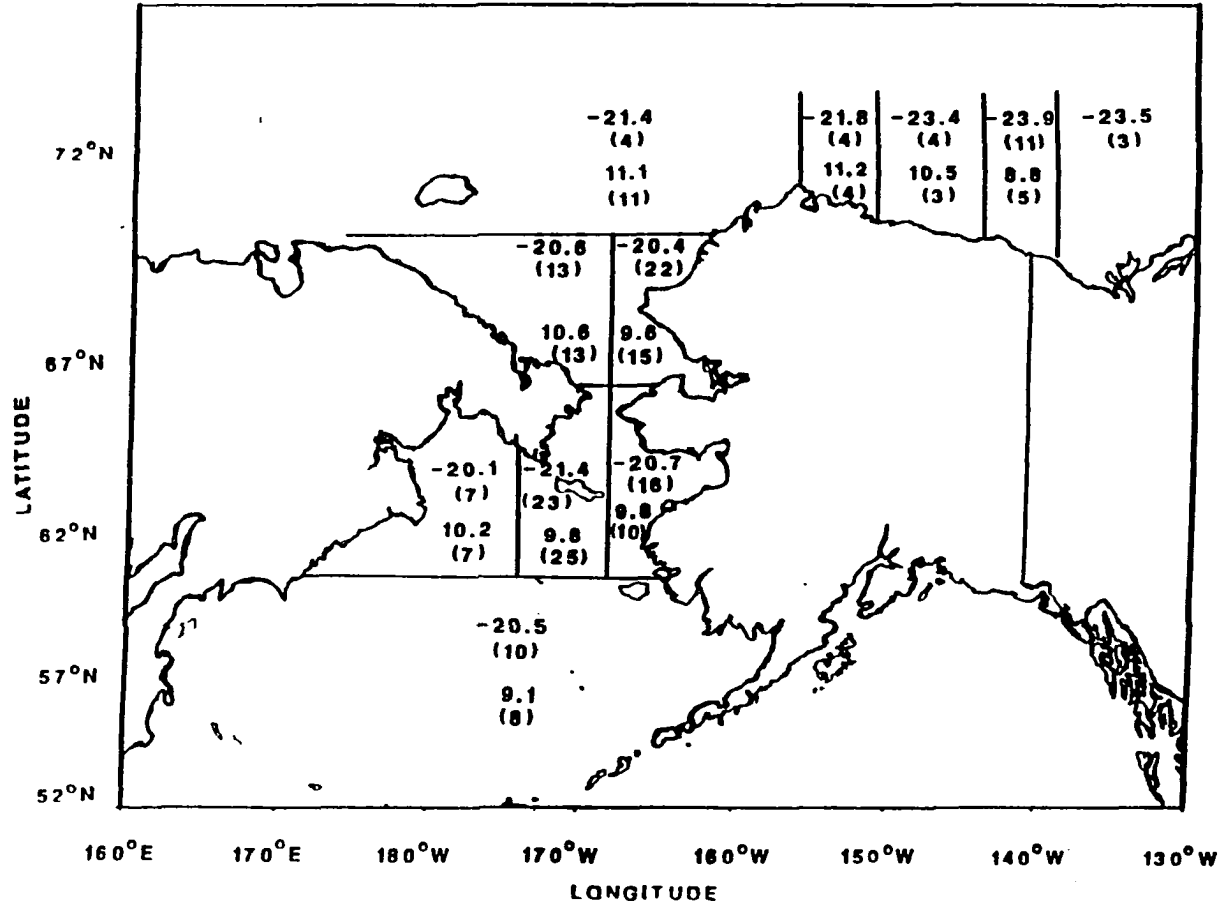


Figure 22. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for euphausiids by regions. Sample sizes are in parentheses.

Chaetognaths

Chaetognaths were all *Sagitta elegans* when identified (AK88 and SU88). Chaetognath $\delta^{13}\text{C}$ values for 122 stations (Figure 23) had significant differences ($P \leq 0.05$) among ten geographical areas (ANOVA on ranked values, $F_{9,112} = 5.65$, $P < 0.0001$). Pairwise comparisons showed significant differences between chaetognaths of the eleven regions. The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21. Chaetognaths from the Eastern Bering Sea were significantly different from those of the Southern Bering Sea. Chaetognaths from the Western Bering Sea were significantly different from those of the Northern, Eastern, Western Chukchi Sea and Southern Bering Sea regions.

Amphipods

Amphipods were typically Gammaridea and Hyperiidea from cruises AM86, PS86, HX87, SU87, AK88, TW88, SU88, SU89. *Ampelisca* sp. were present in two samples from cruise AK88, but these were not included in the analysis.

Amphipod $\delta^{13}\text{C}$ values for 82 stations (Figure 24) had

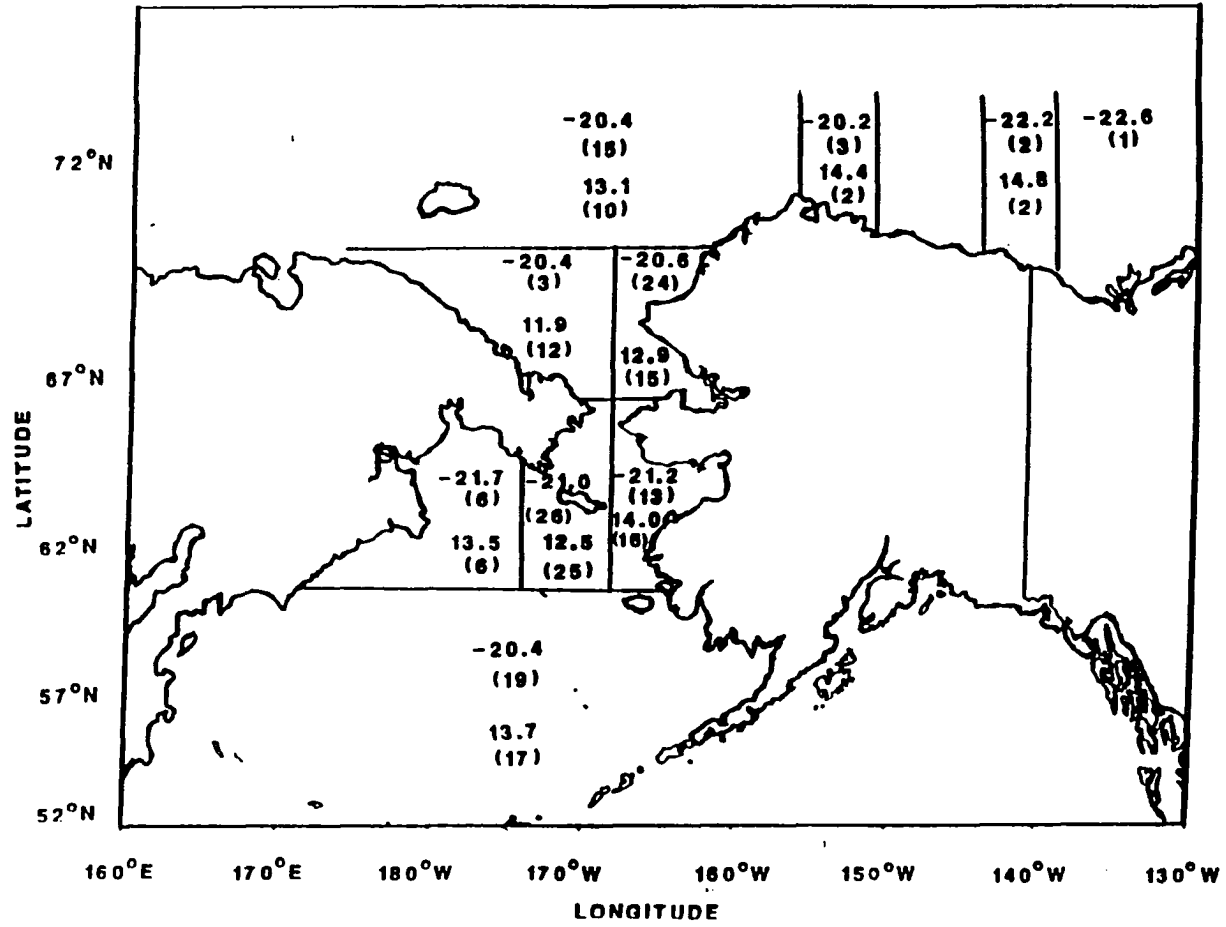


Figure 23. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for chaetognaths by regions. Sample sizes are in parentheses.

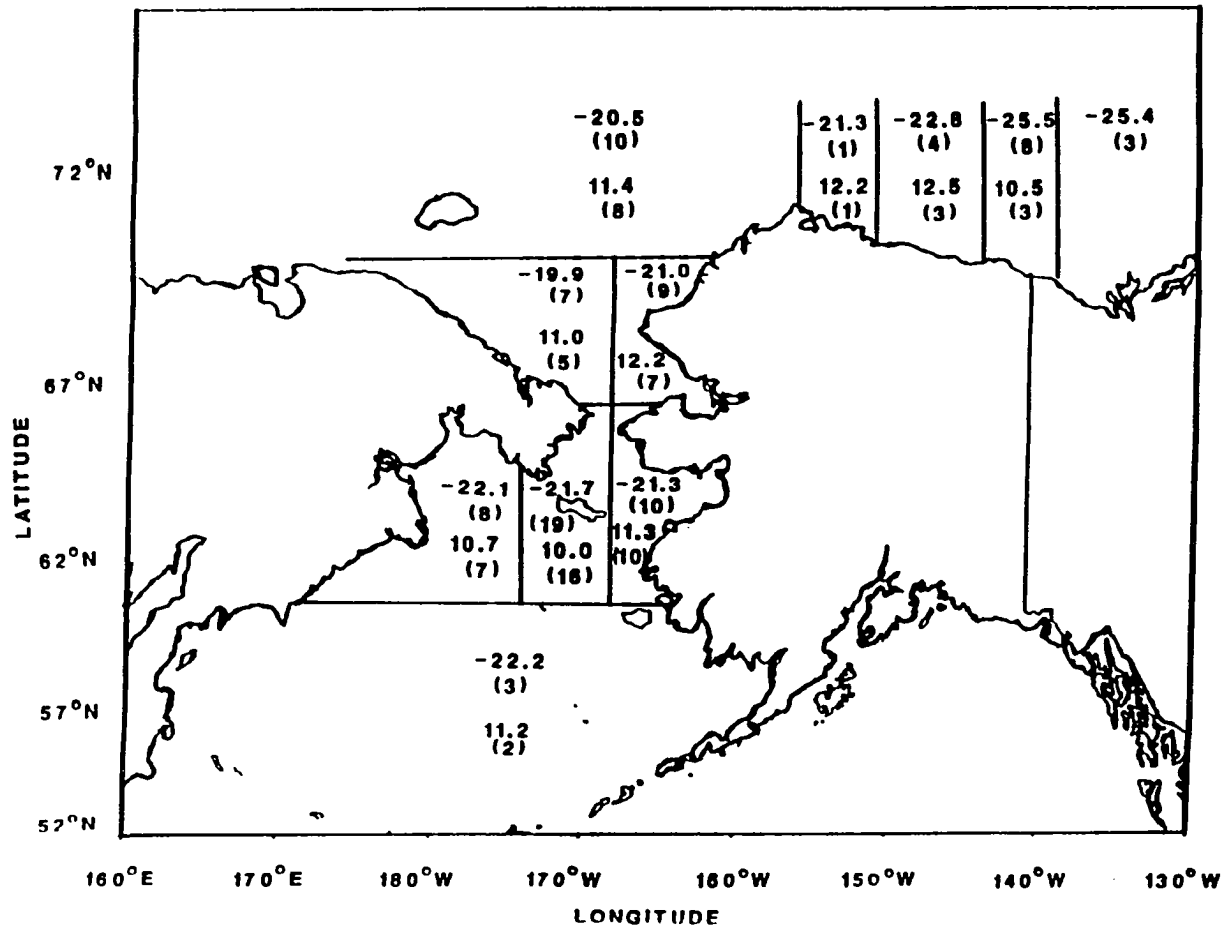


Figure 24. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for amphipods by regions. Sample sizes are in parentheses.

significant differences among the eleven geographical areas (ANOVA on ranked values, $F_{10,71}=4.68$, $P<0.0001$). Pairwise comparisons showed significant ($P\leq 0.05$) differences between amphipods of these regions. The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21. Amphipods from the Eastern Alaskan Beaufort Sea were significantly different from those of the Central Bering, Eastern Bering, Western Chukchi, Eastern Chukchi and Northern Chukchi seas. Amphipods from the Canadian Beaufort Sea were significantly different from those of the Western and Northern Chukchi seas.

Crabs

Planktonic crab megalopa and zoeae from the Chukchi and Bering seas were included in the analysis. No samples were collected from the Beaufort Sea. Taxa identified in cruises AK88 and SU88 were Anomuran zoeae, including *Pagurus* sp. and Brachyuran zoeae including *Chionoecetes* sp.

Crab $\delta^{13}\text{C}$ values for 36 stations (Figure 25) showed no significant ($P\leq 0.05$) differences among six geographical areas

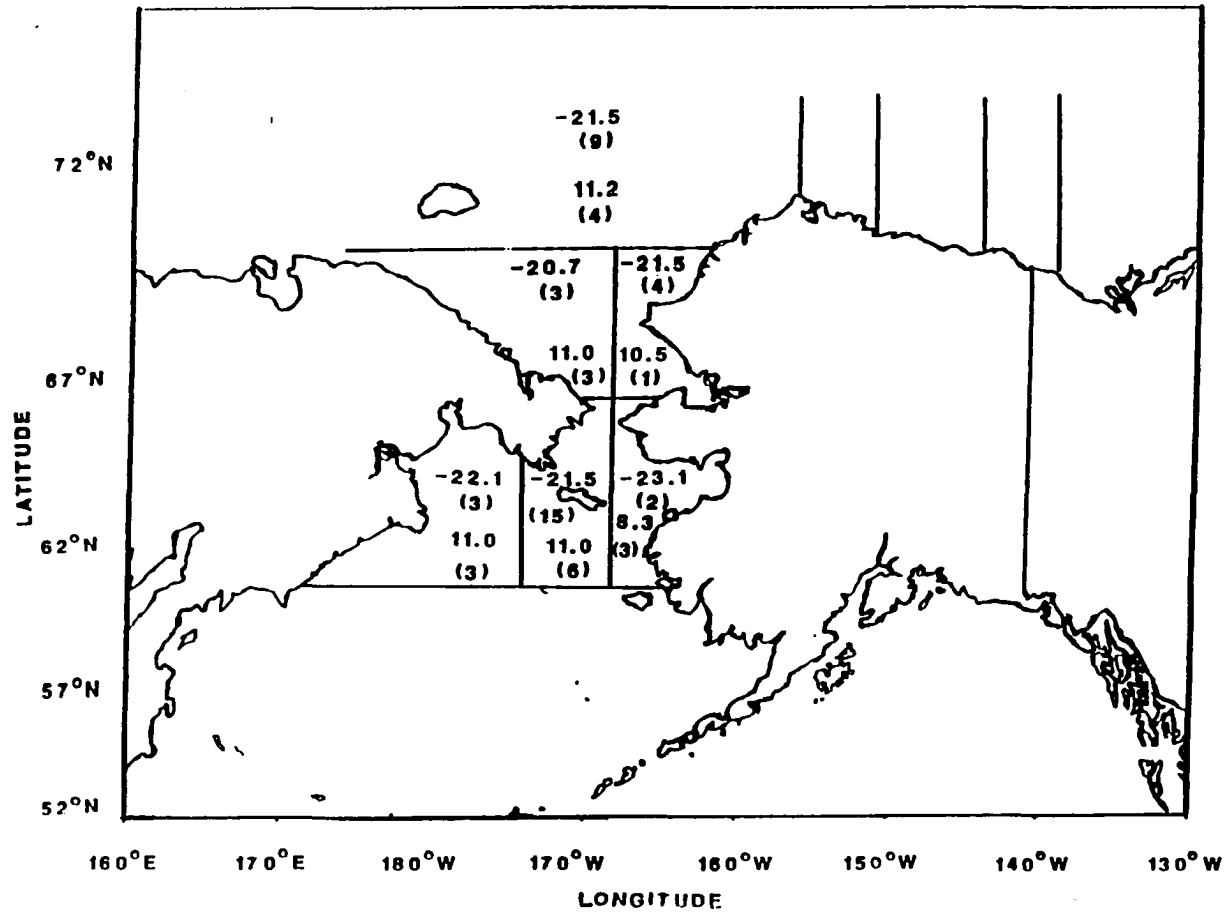


Figure 25. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for crab larvae by regions. Sample sizes are in parentheses.

(ANOVA on ranked values, $F_{5,30}=0.96$, $P<0.4605$). The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21.

Shrimp

Shrimp larvae for cruises AK88, TW88, SU88 were in the families Pandalidae and Hippolytidae. Shrimp larvae were not collected in the Beaufort Sea. Shrimp $\delta^{13}\text{C}$ values from 28 stations (Figure 26) had no significant ($P\leq 0.05$) differences among five geographical areas (ANOVA on ranked values, $F_{4,23}=2.01$, $P<0.1267$). The $\delta^{13}\text{C}$ averages are ranked by region in Figure 21.

Fishes

Some samples were not identified to species and are labeled simply fish or fish larvae. Identified samples include pollock (*Theragra chalcogramma*), sand lance (*Ammodytes hexapterus*), arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*), herring, snake prickleback (*Lumpenus*

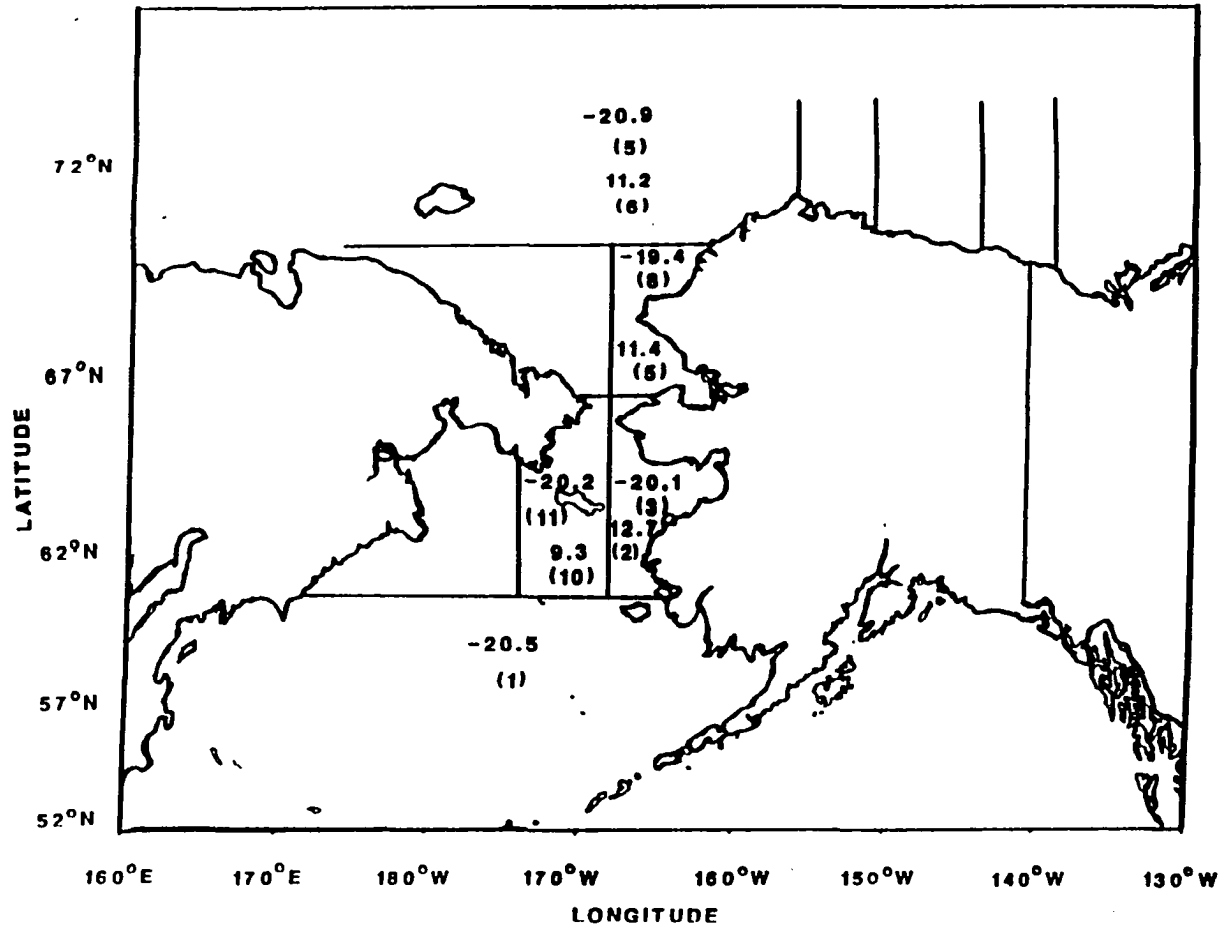


Figure 26. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for shrimp larvae by regions. Sample sizes are in parentheses.

sagitta), rainbow smelt (*Osmerus mordax*), starry flounder (*Platichthys stellatus*), arctic shanny (*Stichaeus punctatus*), great sculpin (*Myoxocephalus polyacanthocephalus*), armorhead sculpin (*Gymnocanthus galeatus*) and juvenile flounder. Figure 27 shows the distribution of $\delta^{13}\text{C}$ values with sample sizes for fishes by region. For statistical analysis, the Eastern, Western and Central Beaufort sea regions were combined into the Beaufort Sea; the Eastern and Western Chukchi were combined into the Chukchi; the Eastern and Central Bering were combined into the Bering Sea. Fish $\delta^{13}\text{C}$ values for 55 stations had significant differences among the 5 geographical regions (Beaufort Sea, Northern Chukchi Sea, Chukchi Sea, Bering Sea, Southern Bering Sea)(ANOVA on unranked values, $F_{5,49}=7.85$, $P<0.0001$). Beaufort Sea fishes were significantly ($P\leq 0.05$) depleted relative to those from the Northern Chukchi, Chukchi and Bering seas (Figure 21).

Regional Distribution: Nitrogen Isotope Results

Copepods

Figure 20 shows the distribution of $\delta^{15}\text{N}$ values size for

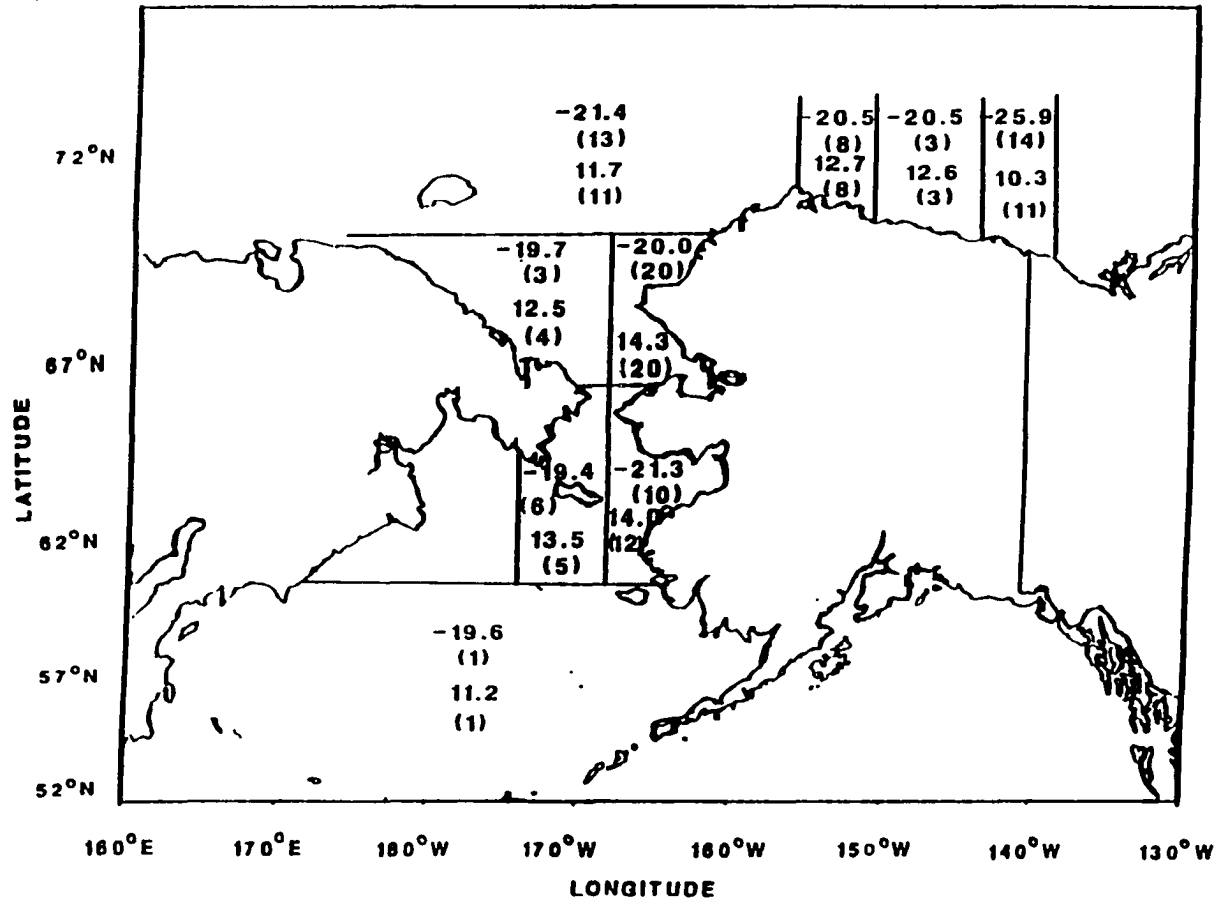


Figure 27. Mean $\delta^{13}\text{C}$ (negative) and mean $\delta^{15}\text{N}$ (positive) values are shown for fishes by regions. Sample sizes are in parentheses.

copepods by region. Copepod $\delta^{15}\text{N}$ values for 148 stations had significant differences among the eleven geographical areas (ANOVA on ranked values, $F_{9,138} = 2.44$, $P < 0.0131$). Copepod $\delta^{15}\text{N}$ values are significantly different only between the Southern Bering Sea ($n=20$) and the Central Bering Sea ($n=40$) and between the Eastern Chukchi Sea ($n=20$) and the Western Chukchi Sea ($n=20$) (Figure 28).

Other Zooplankton

The $\delta^{15}\text{N}$ values for euphausiids, chaetognaths, amphipods, crabs and shrimp are shown in Figures 22-26, respectively. Taxa, sample size and statistical parameters are listed in Table 4. For the five taxonomic groups listed, there were no significant differences among the regions tested (Figure 28).

Fishes

Fish $\delta^{15}\text{N}$ values from 51 stations (Figure 27) appear to have significant differences ($P \leq 0.05$) among the five geographical

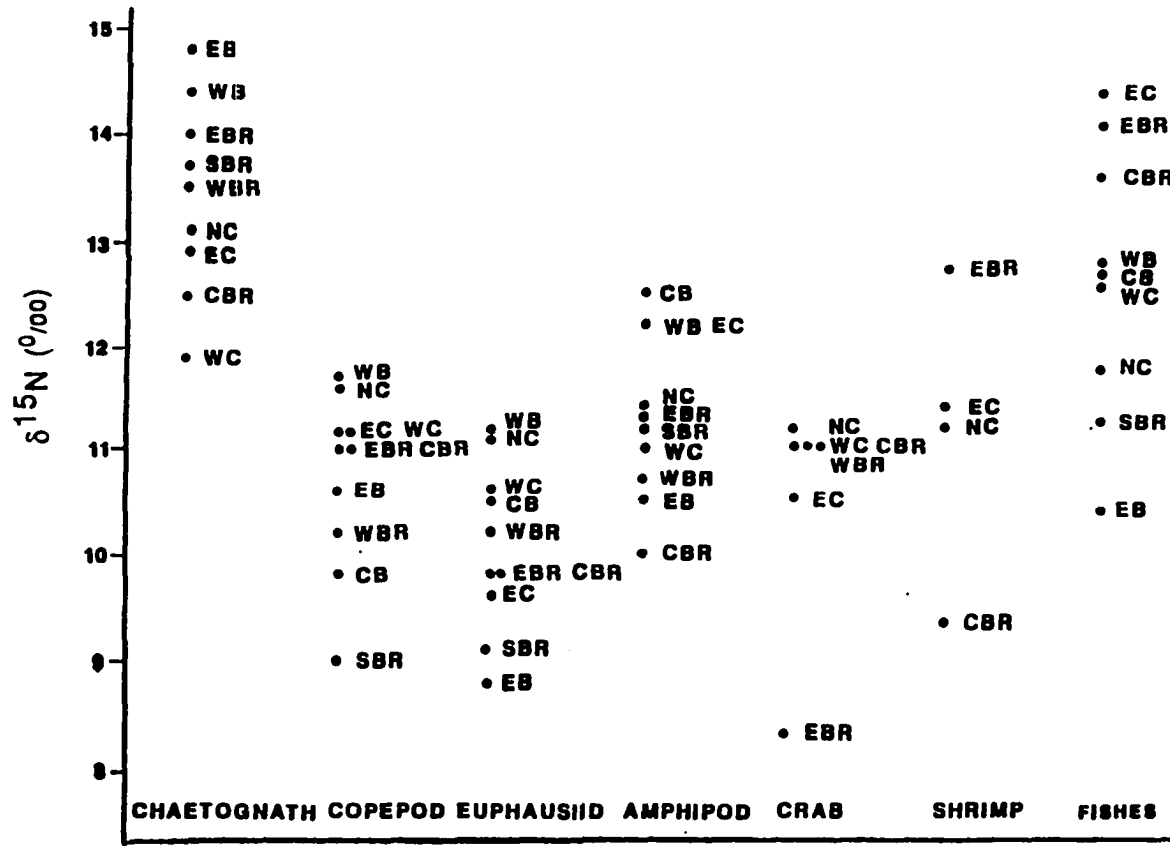


Figure 28. Average nitrogen stable isotopes ranked by region for major taxonomic groups. Abbreviations: EBR, CBR, SBR, WBR= eastern, central, southern and western Bering Sea respectively; EC, WC, NC= eastern, western and northern Chukchi Sea respectively; WB, EB, CB, CNB= western, eastern and central and Canadian Beaufort Sea respectively.

TABLE 4. $\delta^{15}\text{N}$ statistical analysis of major taxonomic groups among regions.

| <u>Taxa</u> | <u>N#</u> | <u>Statistical data</u> |
|--------------|-----------|--|
| Euphausiids | 101 | (ANOVA on ranked values, $F_{9,91}=1.61$, $P<0.1233$). |
| Chaetognaths | 105 | (ANOVA on ranked values, $F_{8,96}=2.17$, $P<0.0561$). |
| Amphipods | 62 | (ANOVA on ranked values, $F_{9,52}=1.30$, $P<0.2587$). |
| Crabs | 30 | (ANOVA on ranked values, $F_{5,24}=0.66$, $P<0.6539$). |
| Shrimps | 23 | (ANOVA on ranked values, $F_{3,19}=3.46$, $P<0.0568$). |

areas (Beaufort Sea, Northern Chukchi Sea, Chukchi Sea, Bering Sea, Southern Bering Sea) (ANOVA on unranked values, $F_{5,45}=5.69$, $P<0.0004$). The Beaufort Sea fishes were significantly depleted in ^{15}N , relative to those of the Bering and Chukchi seas (Figure 28).

Zooplankton isotope ratios between cruises

Zooplankton $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages, standard deviation, maximum and minimum values for Chukchi and Bering sea cruises for the major taxonomic groups (copepods, euphausiids, chaetognaths, amphipods) are given in Appendices 4 and 5. The carbon and nitrogen isotope ratios from zooplankton samples are shown in chronological order (by cruise) between the years 1987 to 1990 (Figures 29-32). SAS/GLM statistical analysis implementing non-parametric ANOVA analysis reveals statistical ($P\leq 0.05$) differences between seasons as indicated by cruises. The carbon isotope ratios reveal differences between seasons as well as between years.

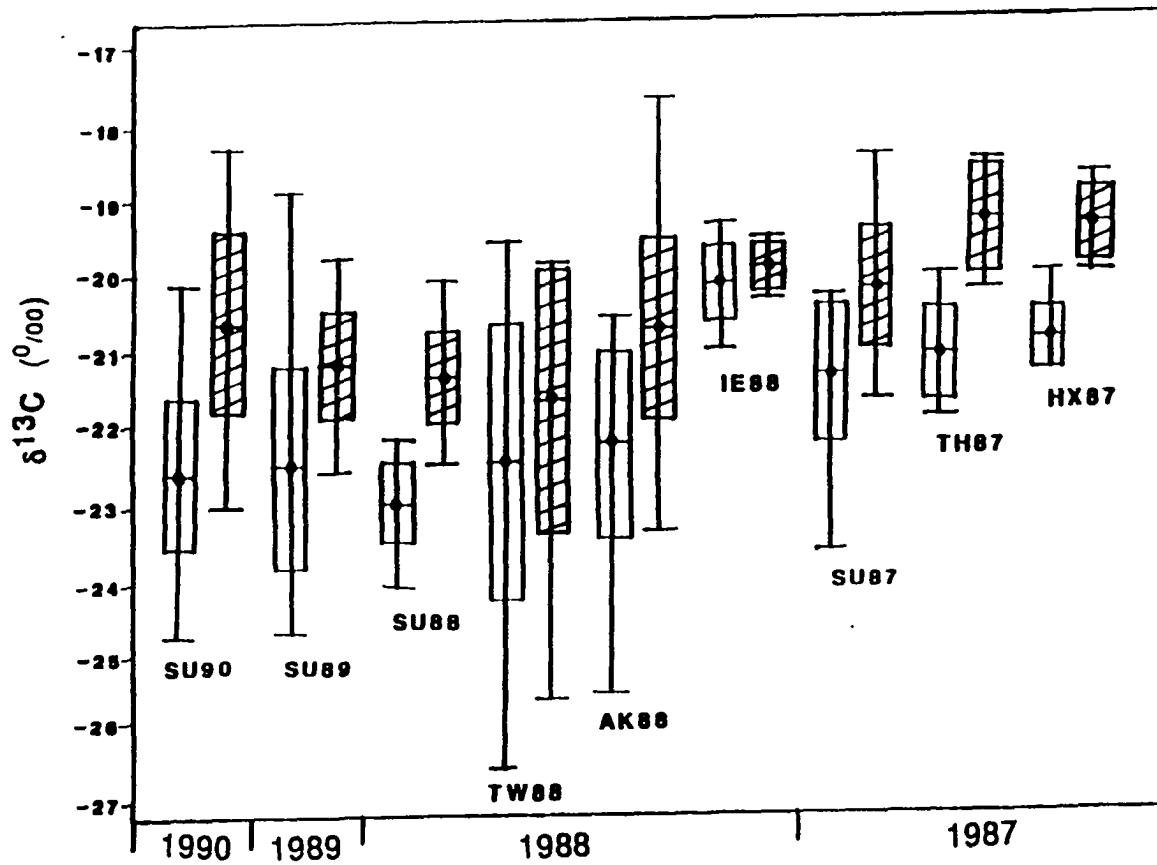


Figure 29. Average (bar), range (vertical line) and standard deviation (box) of carbon isotope ratios of copepods (open) and euphausiids (hatched) by cruise.

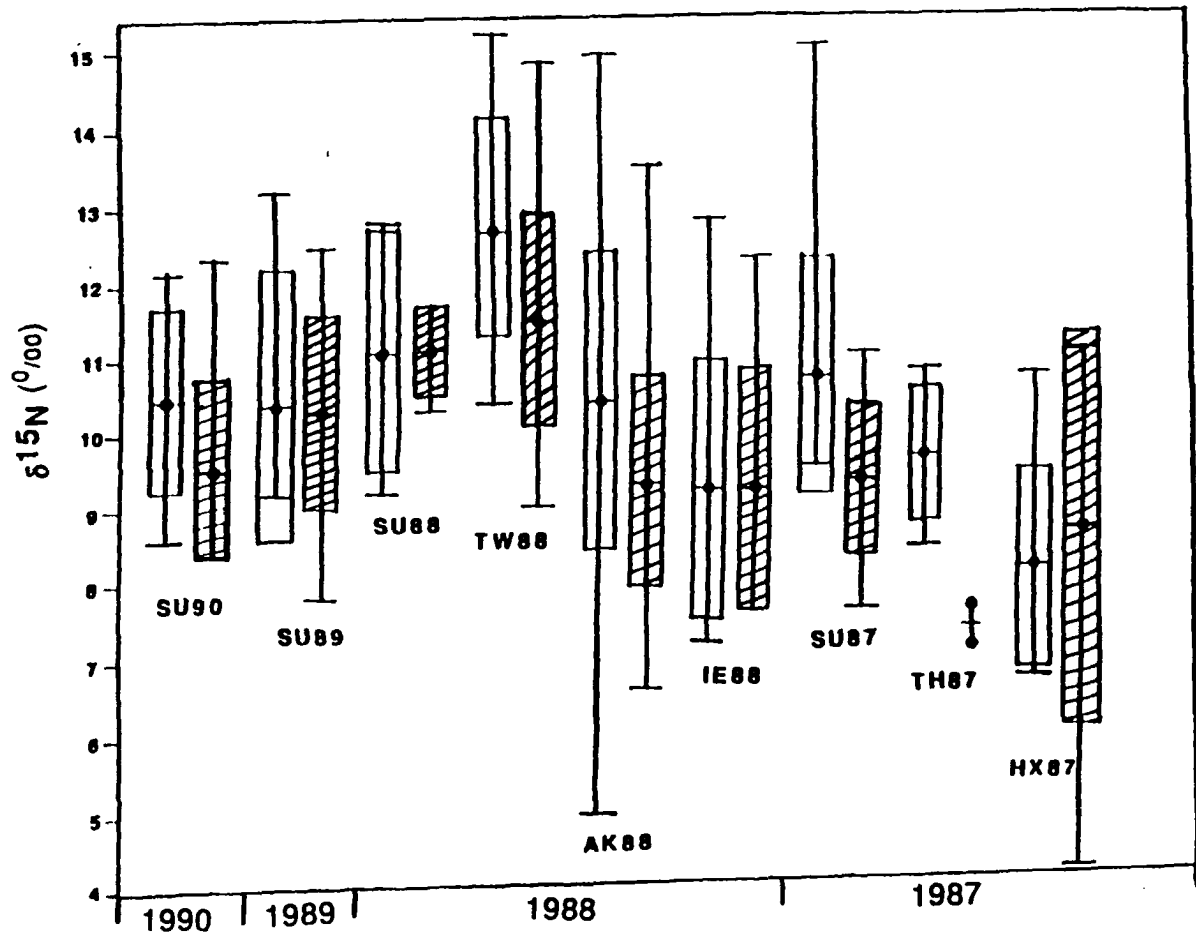


Figure 30. Average (bar), range (vertical line) and standard deviation (box) of nitrogen isotope ratios of copepods (open) and euphausiids (hatched) by cruise.

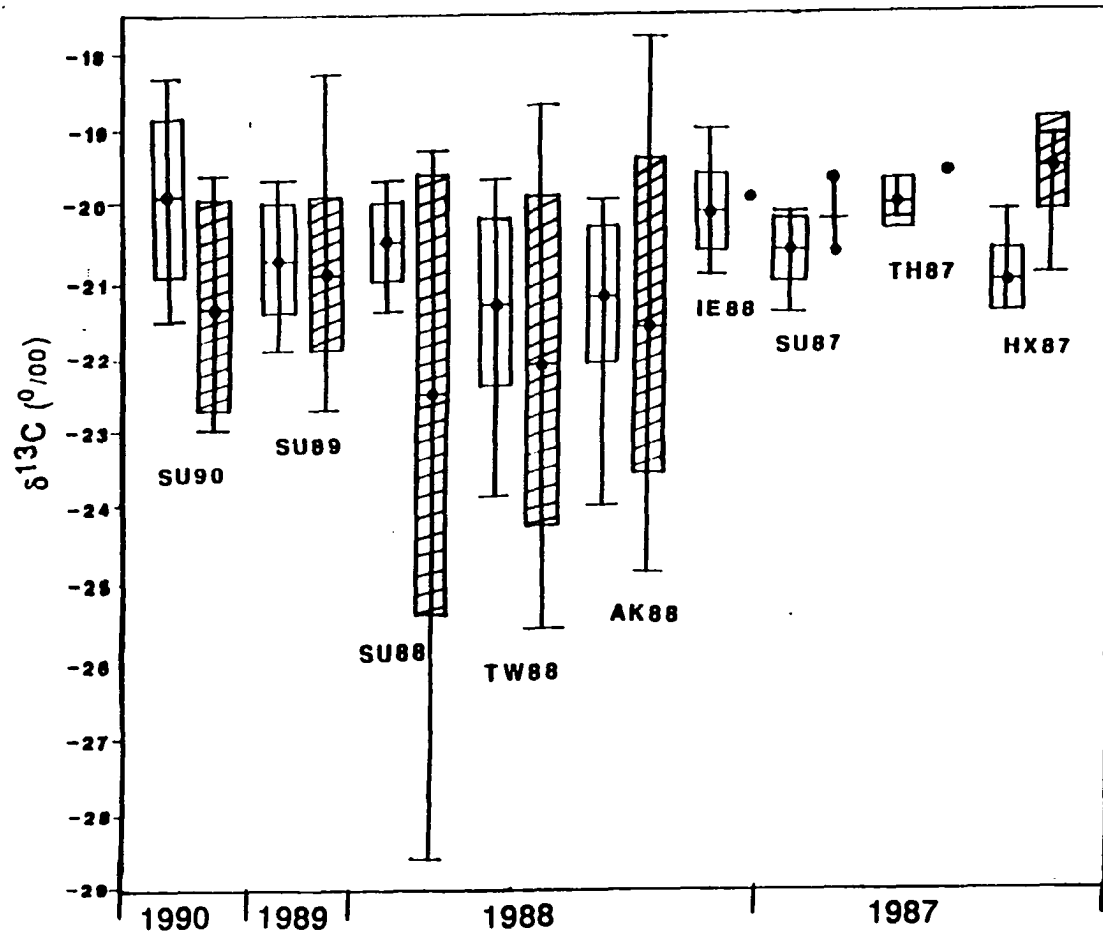


Figure 31. Average (bar), range (vertical line) and standard deviation (box) of carbon isotope ratios of chaetognaths (open) and amphipods (hatched) by cruise.

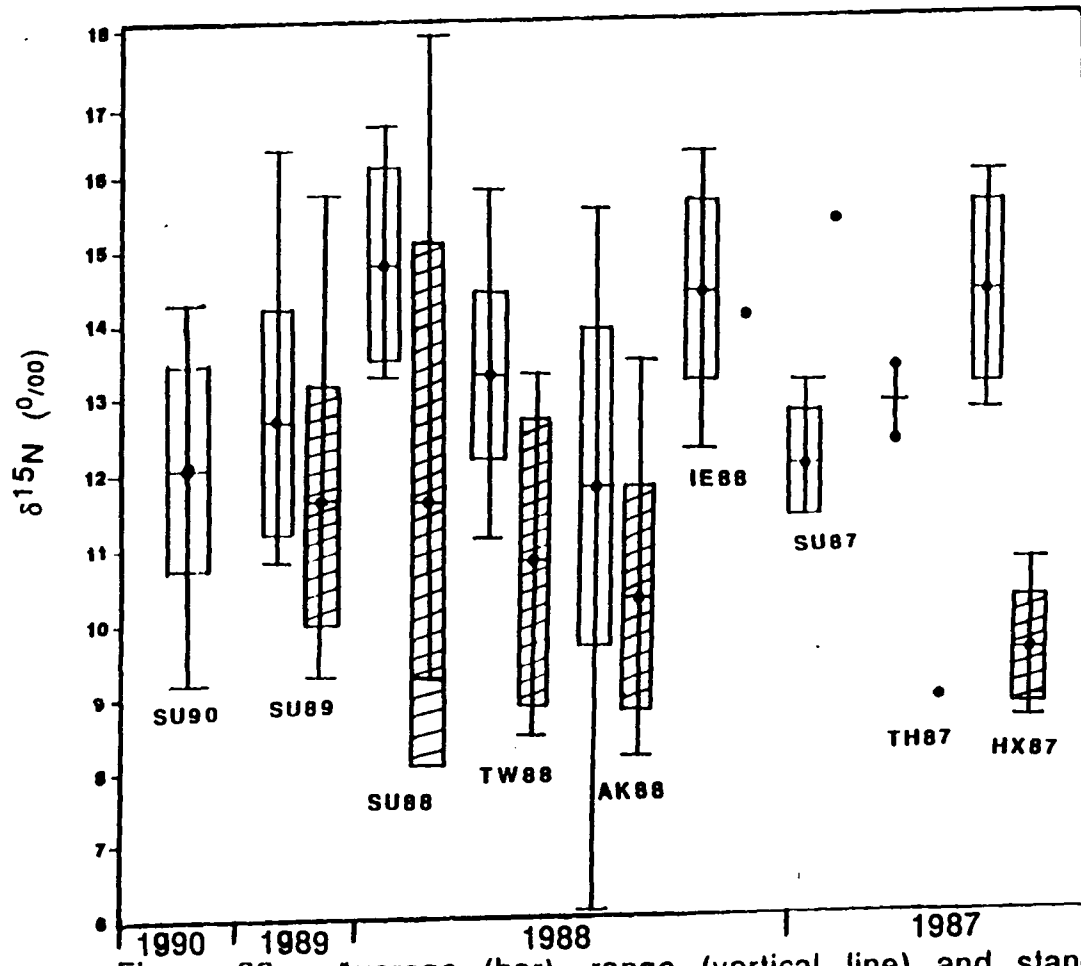


Figure 32. Average (bar), range (vertical line) and standard deviation (box) of nitrogen isotope ratios of chaetognaths (open) and amphipods (hatched) by cruise.

Copepods

Copepod $\delta^{13}\text{C}$ values from 193 stations were significantly different among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{12,180}=26.63$, $P<0.0001$) (Figure 29). Copepod $\delta^{13}\text{C}$ ratios for AK88, TW88, SU88 and SU89 were depleted relative to IE88, SU87, TH87, and HX87. SU87 copepods were depleted relative to those from IE88.

Copepod $\delta^{15}\text{N}$ values from 148 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{9,138}=10.05$, $P<0.0001$) (Figure 30). HX87 copepods were depleted relative to those from SU87, AK88, TW88, SU88, SU89. TW88 samples were significantly enriched relative to all other cruises.

Euphausiids

Euphausiid $\delta^{13}\text{C}$ values from 127 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{12,114}=12.30$, $P<0.0001$) (Figure 29). SU89, SU88 and

TW88 euphausiids were significantly depleted relative those from IE88, SU87, TH87 and HX87 with the exception that SU89 samples were not significantly different from SU87. AK88 euphausiids did not appear significantly different from those collected on other cruises.

Euphausiid $\delta^{15}\text{N}$ values from 101 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{9,91}=7.43$, $P<0.0001$) (Figure 30). TW88 was significantly enriched relative to AK88, IE88, SU87, TH87 and HX87.

Chaetognaths

Chaetognath $\delta^{13}\text{C}$ values from 122 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{9,112}=5.33$, $P<0.0001$) (Figure 31). IE88 and TH87 were significantly enriched relative to TW88 and AK88.

Chaetognath $\delta^{15}\text{N}$ values from 105 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked

values, $F_{8,96}=6.97$, $P<0.0001$) (Figure 32). AK88 was significantly enriched relative to SU88, TW88, IE88 and HX87. SU89 was significantly enriched relative to IE88.

Amphipods

Amphipod $\delta^{13}\text{C}$ values from 82 stations have significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{5,24}=12.669$, $P<0.0001$) (Figure 31). HX87 was significantly enriched relative to AK88, TW88 and SU88. For TH87 and IE88, only one sample was collected.

Amphipod $\delta^{15}\text{N}$ values from 62 stations have no significant differences among Chukchi/Bering sea cruises (ANOVA on ranked values, $F_{9,52}=3.15$, $P<0.0042$) (Figure 32).

Isotope Ratios of Bowhead Whale Tissues

Baleen plates and soft tissues from 47 bowhead whales were analysed for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (OCS Study MMS 92-0020). Table 5 summarizes average $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of baleen and soft

Table 5. Baleen and tissue $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for 1986-1990 bowhead whales. Dashes indicate no sample; tissue sample sizes and types are in parentheses: (B)=blubber, (T)=tendon, (L)=liver, (R)=renal visceral fat, (C)=cardiac visceral fat.

| WHALE | DATE | S | BODY | BALEEN | BALEEN | BALEEN | VISCERAL FAT | MUSCLE | MUSCLE | OTHER |
|--------|--------|-------|--------|--------|----------------------------|----------------------------|-----------------------|-----------------------|-----------------------|-----------------------------|
| | DDMMYY | E | LENGTH | LENGTH | AVG. $\delta^{13}\text{C}$ | AVG. $\delta^{15}\text{N}$ | $\delta^{13}\text{C}$ | $\delta^{13}\text{C}$ | $\delta^{15}\text{N}$ | $\delta^{13}\text{C}$ |
| | | X | (m) | (cm) | (‰) | (‰) | (‰) | (‰) | (‰) | (‰) |
| 86B1 | 270486 | M | 8.2 | 118 | -19.43 | 15.24 | --- | -19.43 | 15.24 | --- |
| 86B2 | 270486 | M | 8.7 | 52 | -18.74 | 15.82 | --- | -20.10 | 14.63 | -25.80 (B) |
| 86B3 | 300486 | F | 8.9 | 160 | -19.09 | 14.42 | --- | -20.70(2) | 12.64 | --- |
| 86B4 | 010586 | M | 8.9 | 130 | -18.77 | 14.68 | --- | -19.60 | 15.56 | --- |
| 86B5 | 040586 | M | 8.1 | 85 | -18.23 | 15.67 | -24.40 | -19.10 | 14.42 | --- |
| 86B6 | 050586 | F | 12.3 | 230 | -19.30 | 13.63 | -25.70 | -19.70 | 13.30 | --- |
| 86B7 | 060586 | M | 10.7 | 201 | -19.07 | 13.87 | -24.70 | -20.00(3) | 15.56 | --- |
| 86KK1 | 170986 | F | 7.6 | 130 | -19.00 | 14.28 | -27.60(2) | -21.40 | 13.91 | 26.02(3,B) |
| 86KK2 | 170986 | F | 17.1 | 380 | -17.80 | 14.39 | -25.00 | -19.20 | 13.86 | -25.35 |
| 86KK3 | 260986 | M | 10.4 | 185 | -19.30 | 14.45 | -27.00 | -21.40 | 14.96 | -26.50 |
| 86WW1 | 050586 | M | 15.9 | 269 | -17.26 | 14.01 | -25.00 | -18.80 | 14.38 | --- |
| 86WW2 | 100586 | F | 17.7 | 310 | -17.73 | 14.20 | -25.80 | -19.40 | 14.45 | -25.77 |
| 87B1 | 010587 | M | 9.3 | 168 | -19.42 | 13.88 | --- | --- | --- | --- |
| 87B2 | 020587 | F | 8.9 | 150 | -18.50 | 14.07 | --- | --- | --- | --- |
| 87B3-A | 040587 | M | 11.0 | 195 | -18.99 | 13.79 | --- | --- | --- | --- |
| 87B3-B | 040587 | M | 11.0 | 195 | -19.05 | 13.65 | --- | --- | --- | --- |
| 87B4 | 200587 | F | 16.8 | 317 | -18.43 | 14.08 | --- | --- | --- | --- |
| 87B5 | 150687 | F | 15.7 | 300 | -18.48 | 13.44 | --- | --- | --- | --- |
| 87B5F | 150687 | Fetus | 4.0 | 15 | -18.19 | 13.59 | --- | -18.94 | 14.23 | -19.47(B) |
| 87B6 | 221087 | F | 15.7 | 315 | -17.97 | 13.74 | -23.56 | -19.20(2) | 13.25 | -24.68(24,B) -15.75(2,T) |
| 87B7 | 291087 | M | 8.5 | 85 | -18.80 | 14.96 | -25.50 | -20.83 | 13.85 | -26.11(14,B) |
| 87G2 | 240487 | F | 16.8 | 345 | -18.23 | 14.20 | --- | --- | --- | --- |
| 87H4 | 280587 | M | 7.8 | 68 | -18.42 | 15.21 | --- | --- | --- | --- |
| 87N1 | 051087 | F | 15.2 | 330 | -18.74 | 13.67 | --- | -20.85(2) | 12.89 | -25.63(71,B) |
| 87WW2 | 080587 | M | 13.5 | 215 | -18.90 | 13.52 | --- | --- | --- | --- |
| 87WW3 | 150587 | F | 8.2 | 208 | -18.84 | 15.35 | --- | --- | --- | --- |
| 88B1 | 240488 | F | 8.9 | 98 | -18.56 | 15.32 | -24.99(2) | -20.16 | 14.55 | --- |
| 88B2 | 250488 | M | 8.8 | --- | --- | --- | -24.45 | -19.43 | 14.80 | -25.63(B) |
| 88B3 | 250488 | F | 7.8 | --- | --- | --- | -25.28 | -19.24 | --- | --- |
| 88B4 | 250488 | F | 9.0 | 130 | -18.63 | 15.02 | --- | -19.28(2) | 14.54 | -17.34(T) |
| 88B5 | 250488 | M | 8.9 | --- | --- | --- | --- | -19.43 | 13.80 | --- |
| 88B6 | 020588 | F | 8.3 | --- | --- | --- | -25.28(C) | -19.94(2) | 14.30 | -19.49(T) |
| | | | | | | | -25.69(R) | | | |
| 88B7 | 050588 | F | 8.2 | 78 | -18.86 | 14.91 | -25.71(R) | -20.30 | 14.43 | -21.11(L) |
| 88B8 | 060588 | F | 7.5 | 130 | -18.67 | 15.42 | -21.44(C) | -19.52 | 13.97 | -16.66(T) |
| | | | | | | | -25.59(R) | --- | --- | -20.22(L) |

TABLE 5. (continued).

| WHALE | DATE | SEX | BODY LENGTH (m) | BALEEN LENGTH (cm) | BALEEN AVG. $\delta^{13}\text{C}$ (‰) | BALEEN AVG. $\delta^{15}\text{N}$ (‰) | VISCERAL MUSCLE | | MUSCLE $\delta^{15}\text{N}$ (‰) | OTHER $\delta^{13}\text{C}$ (‰) |
|-------|--------|-----|-----------------|--------------------|---------------------------------------|---------------------------------------|-------------------------------|---------------------------|----------------------------------|---------------------------------|
| | | | | | | | FAT $\delta^{13}\text{C}$ (‰) | $\delta^{13}\text{C}$ (‰) | | |
| 88B9 | 150988 | M | 14.6 | 253 | -18.64 | --- | --- | --- | --- | --- |
| 88B10 | 170988 | M | 15.1 | 328 | -18.77 | --- | --- | --- | --- | --- |
| 88B11 | 170988 | F | 15.6 | 340 | -18.27 | --- | --- | --- | --- | --- |
| 88KK1 | 240988 | F | 14.9 | 297 | -18.71 | --- | --- | --- | --- | --- |
| 88WW1 | 250488 | F | 7.9 | 75 | -18.27 | 15.45 | --- | --- | --- | --- |
| 88WW2 | 260488 | M | 9.1 | 98 | -18.91 | --- | --- | --- | --- | --- |
| 88WW3 | 060588 | F | 13.4 | 207 | -19.73 | 13.94 | --- | --- | --- | --- |
| 88G1 | 160488 | F | 15.7 | 295 | -18.44 | 13.83 | --- | --- | --- | --- |
| 88G2 | 250488 | F | 15.3 | 275 | -18.41 | --- | --- | -19.06 | 13.90 | --- |
| 90B5 | 230590 | F | 15.9 | 280 | -18.36 | --- | --- | --- | --- | --- |
| 90B7 | 011090 | F | 8.4 | 140 | -18.81 | --- | --- | --- | --- | --- |
| 90B8 | 021090 | M | 12.9 | 243 | -19.25 | --- | --- | --- | --- | --- |
| 90G4 | 070590 | F | 15.2 | 305 | -18.44 | --- | --- | --- | --- | --- |

tissues for each whale. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for 2.5 cm intervals along the baleen plates have been plotted for each whale (Figure 33). Tissue results reported by Schell et al. (1989) are shown in Figure 12 and additional tissue results are added in Figure 34. As reported by Schell et al. (1989), whales harvested in spring had $\delta^{13}\text{C}$ muscle values ranging from -18.8 to -20.7‰. Of six whales harvested in the fall, 86KK1, 86KK3, 87B7, and 87N1 had $\delta^{13}\text{C}$ values ranging between -20.8 to -21.4‰. Whales 86KK1, 86KK3 and 87B7 were small whales while 87N1 was a large female. The other two large female whales harvested in the fall, 87B6 and 86KK2, had $\delta^{13}\text{C}$ muscle values of -19.2‰, similar to spring whales. Visceral fat $\delta^{13}\text{C}$ values showed small whales 86KK1 and 86KK3 to range from -27.0 to -27.6‰ (Schell et al. 1989). Fall harvested whales 86KK2, 87B6 and 87B7 had $\delta^{13}\text{C}$ visceral fat values ranging from -23.6 to -25.5‰, similar to spring whales.

Fall-winter Baleen Isotope Ratios

Figure 35 shows the carbon isotope ratio trace of an adult

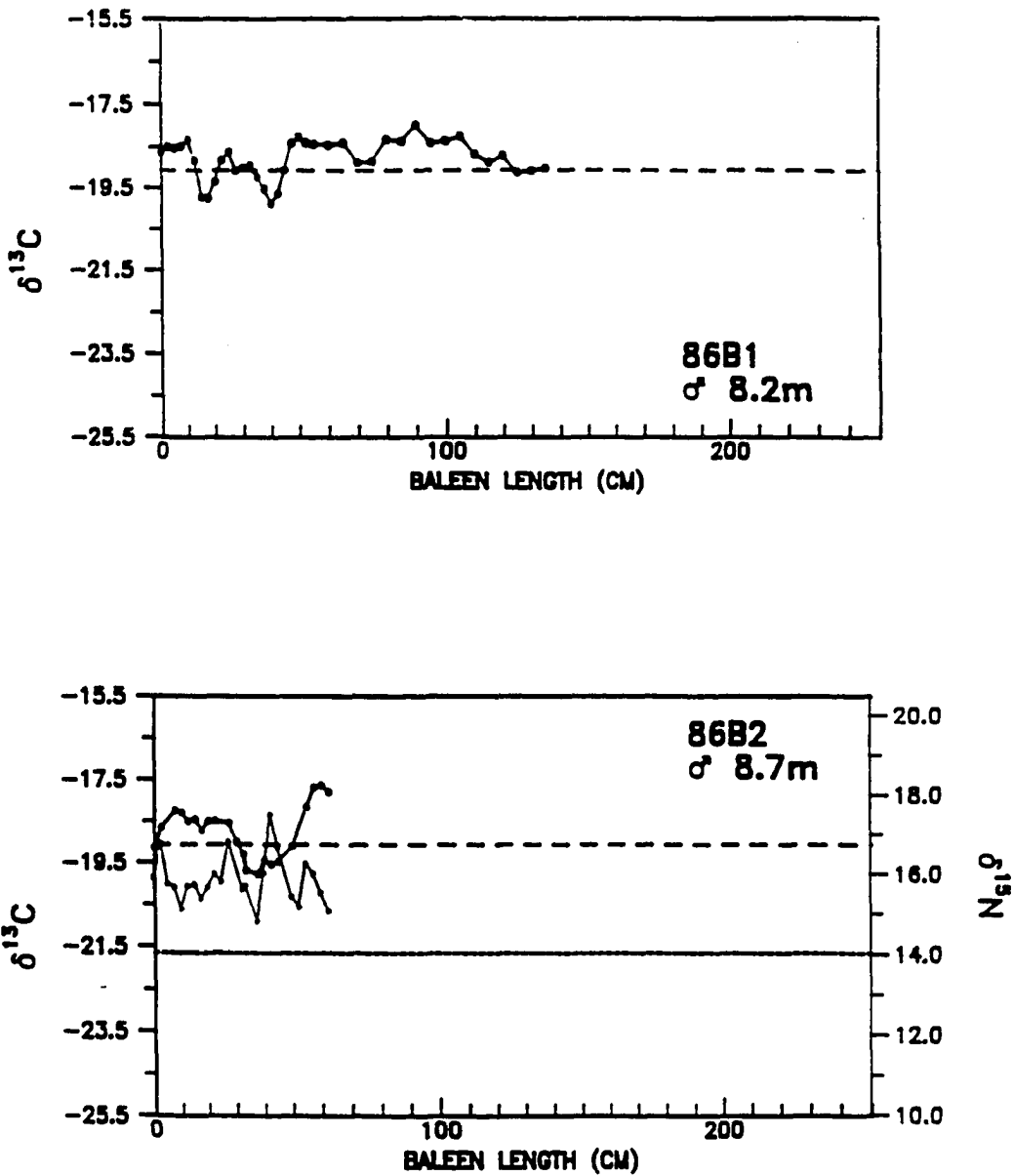


Figure 33. Carbon and nitrogen isotope ratios along the length of baleen plates from bowhead whales (*Balaena mysticetus*) harvested between 1986 and 1990. Base of plate (newest baleen) is at left in all traces. Dates of take are listed in Table 3. Carbon trace (●—●), Nitrogen trace (▲—▲).

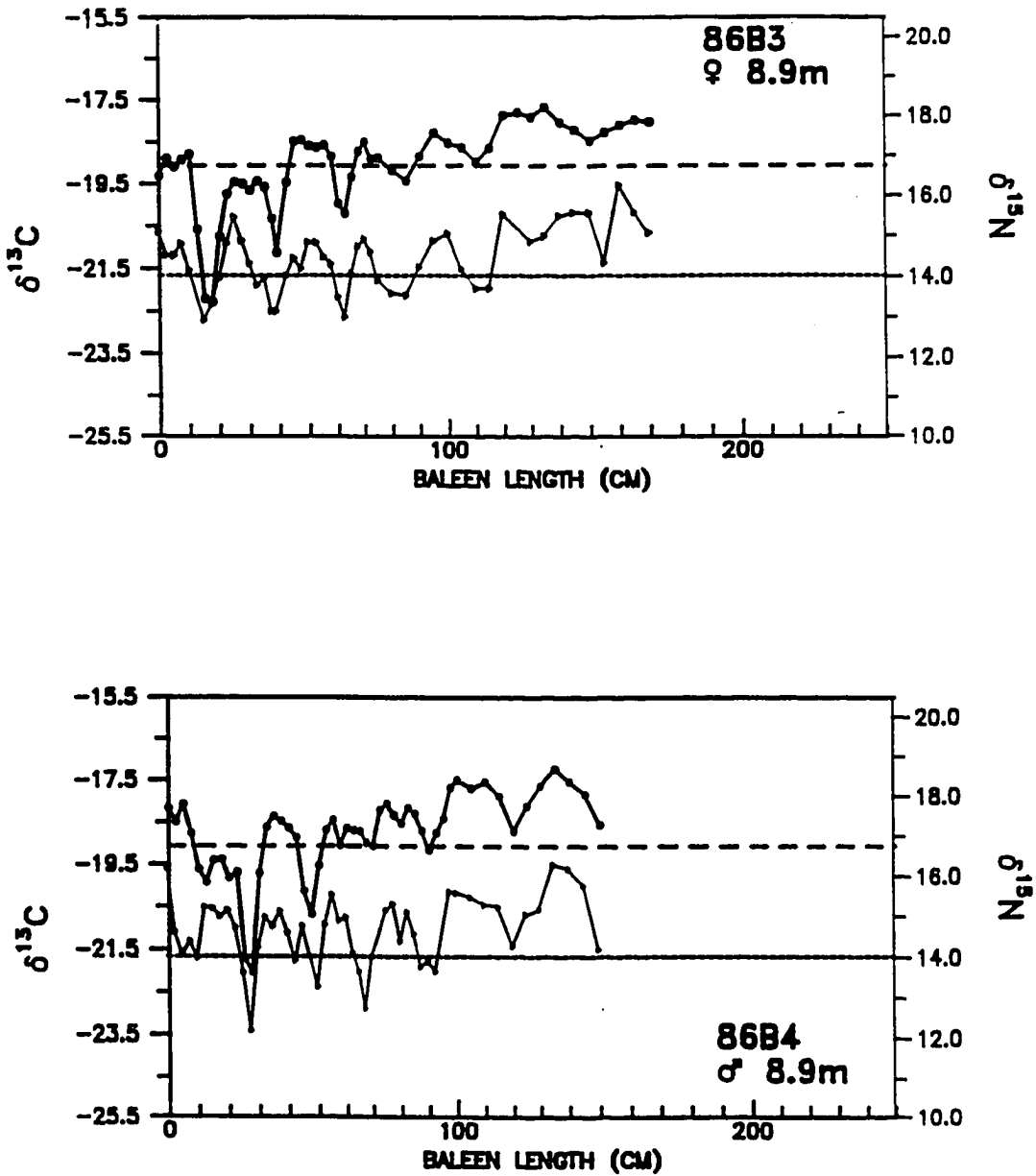


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

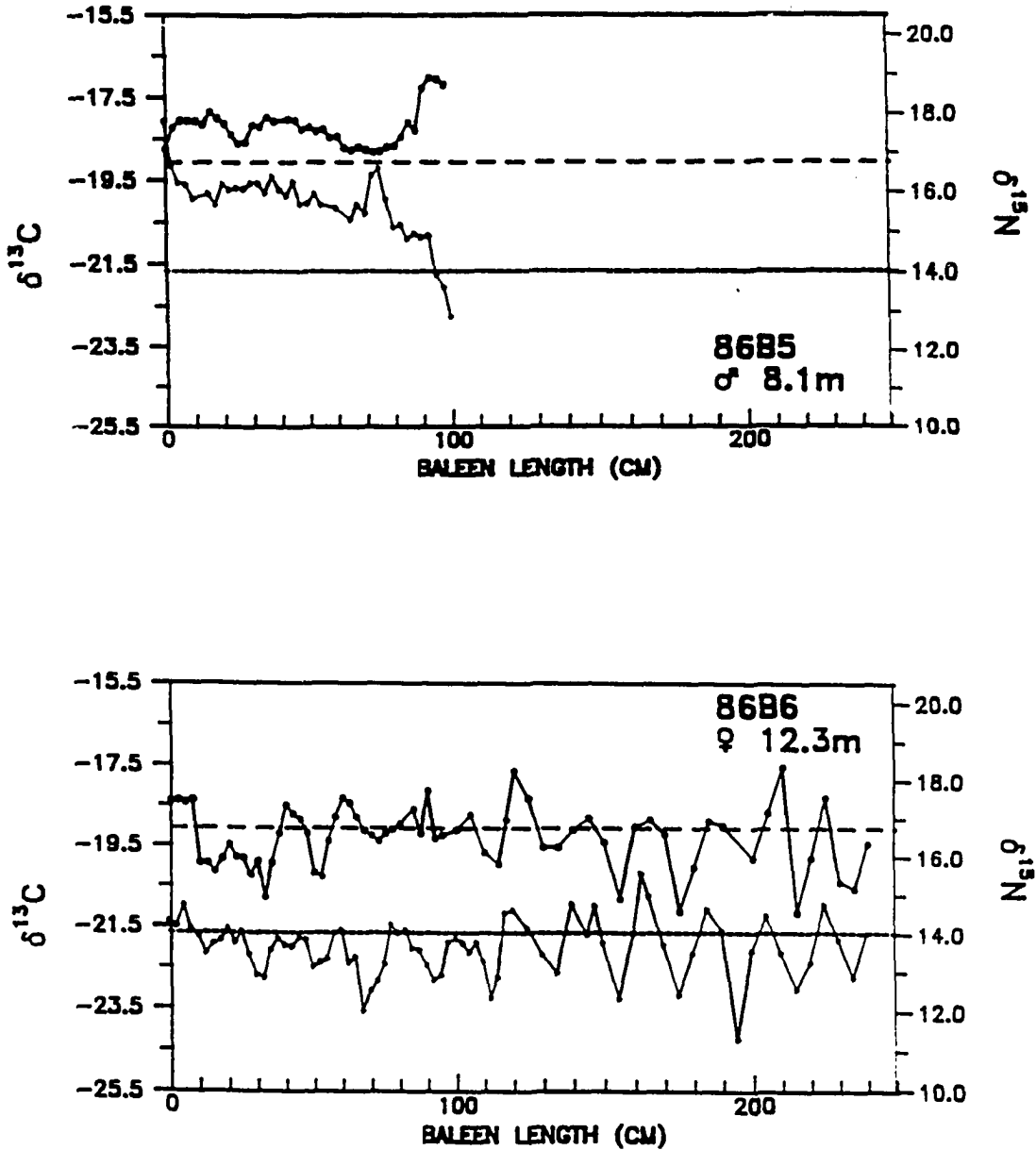


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

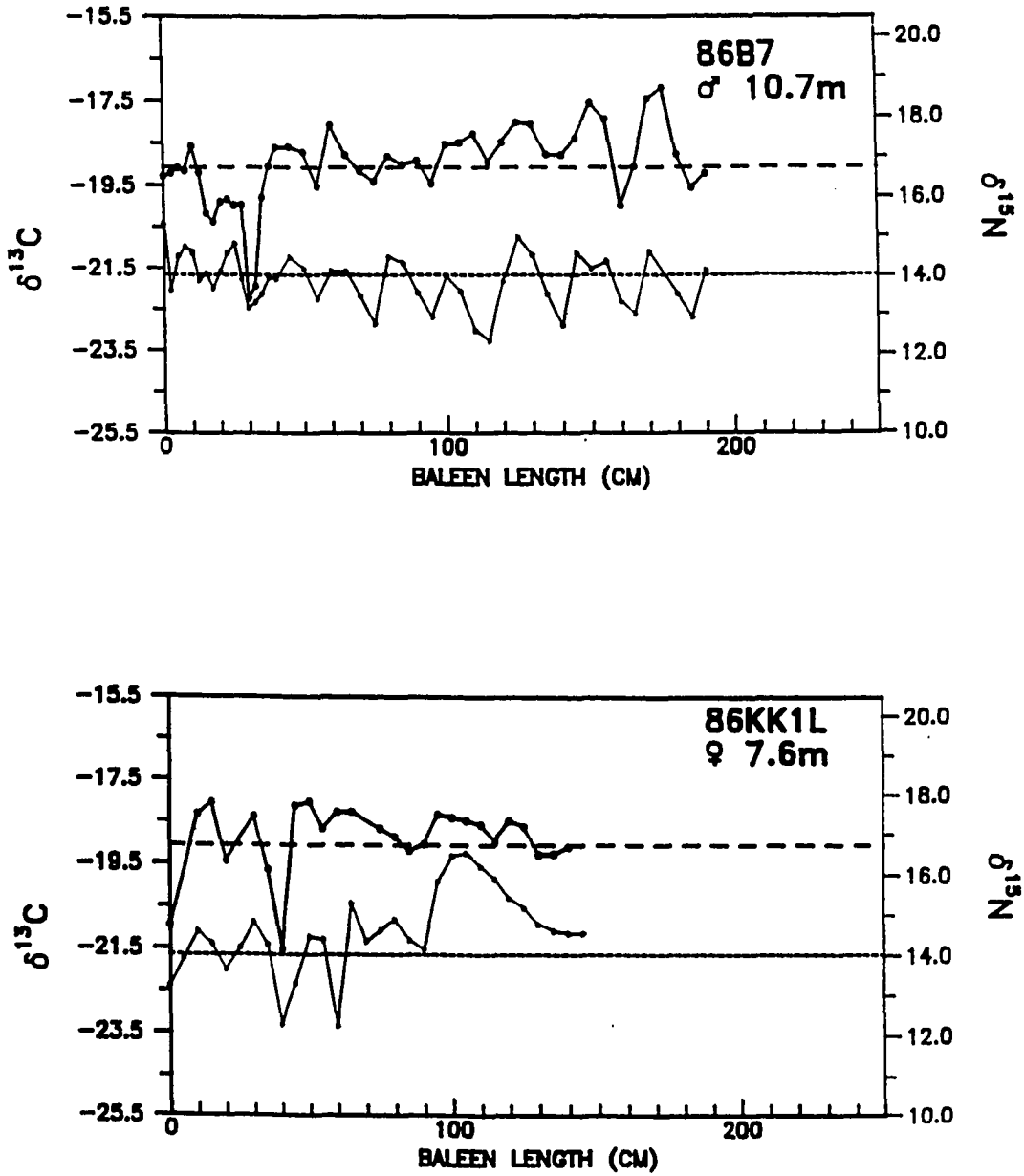


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

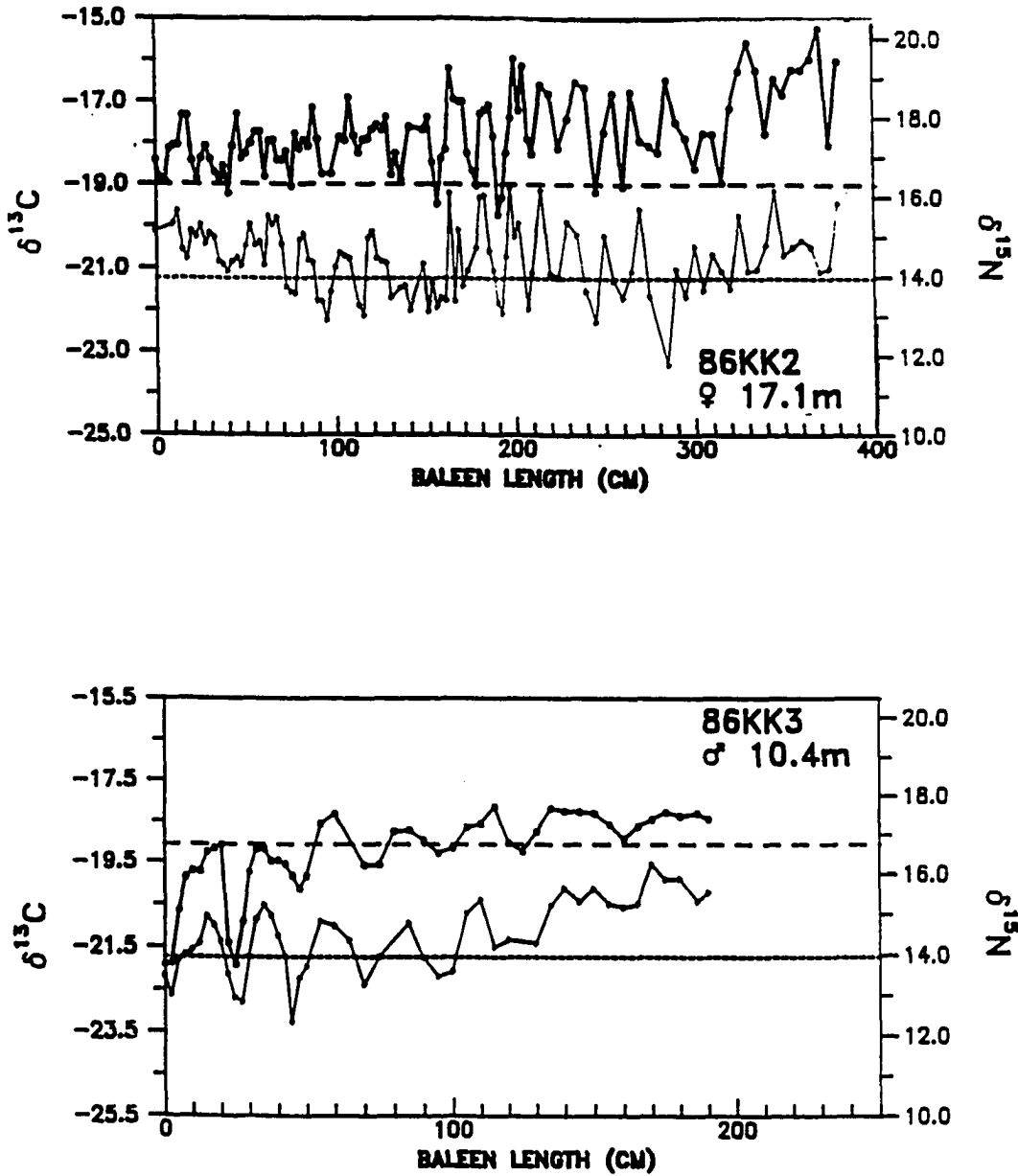


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

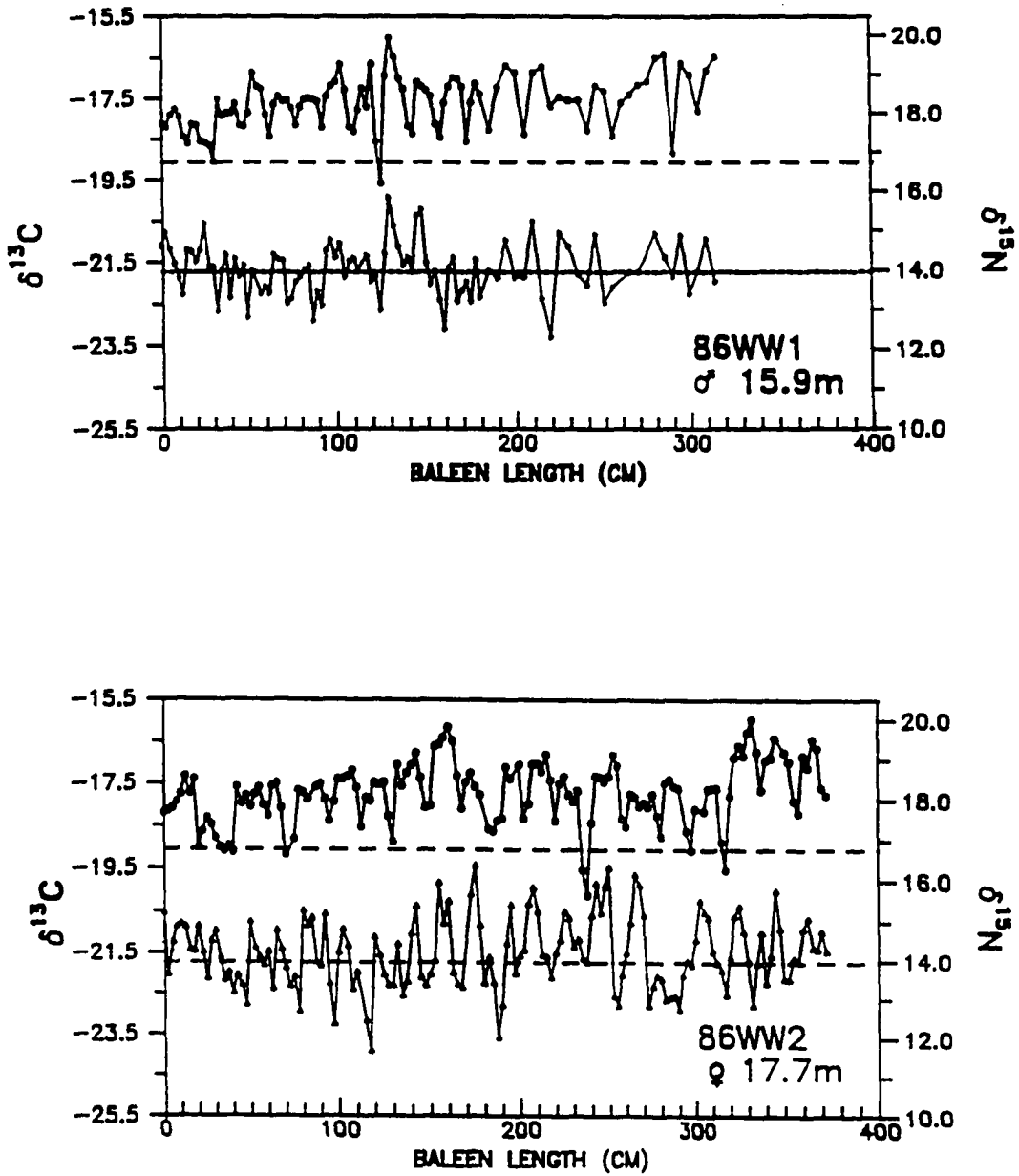


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

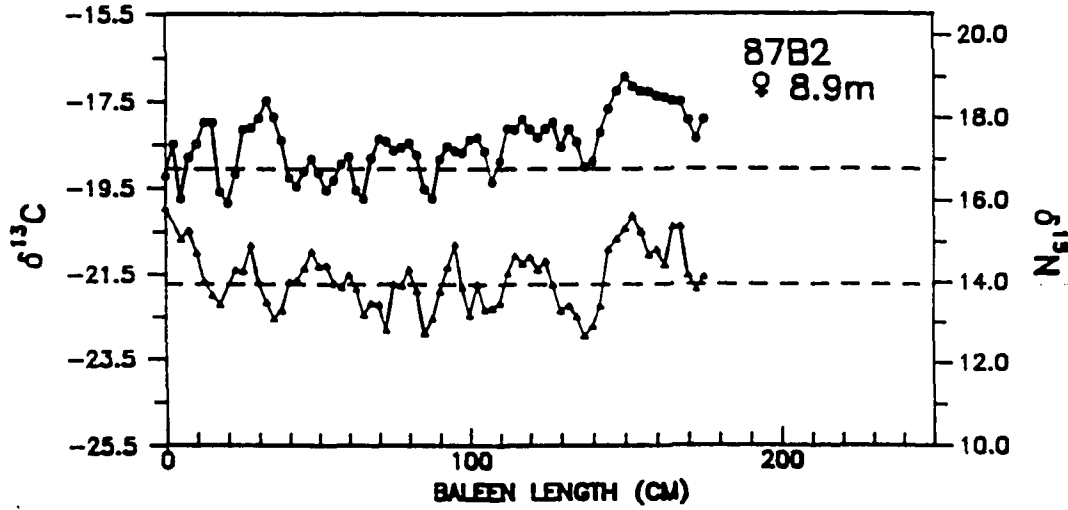
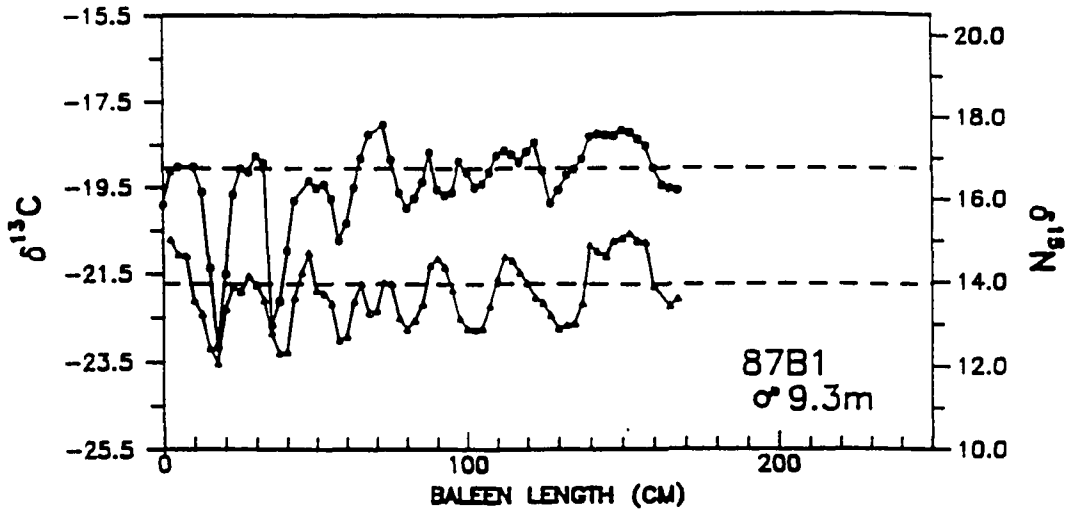


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

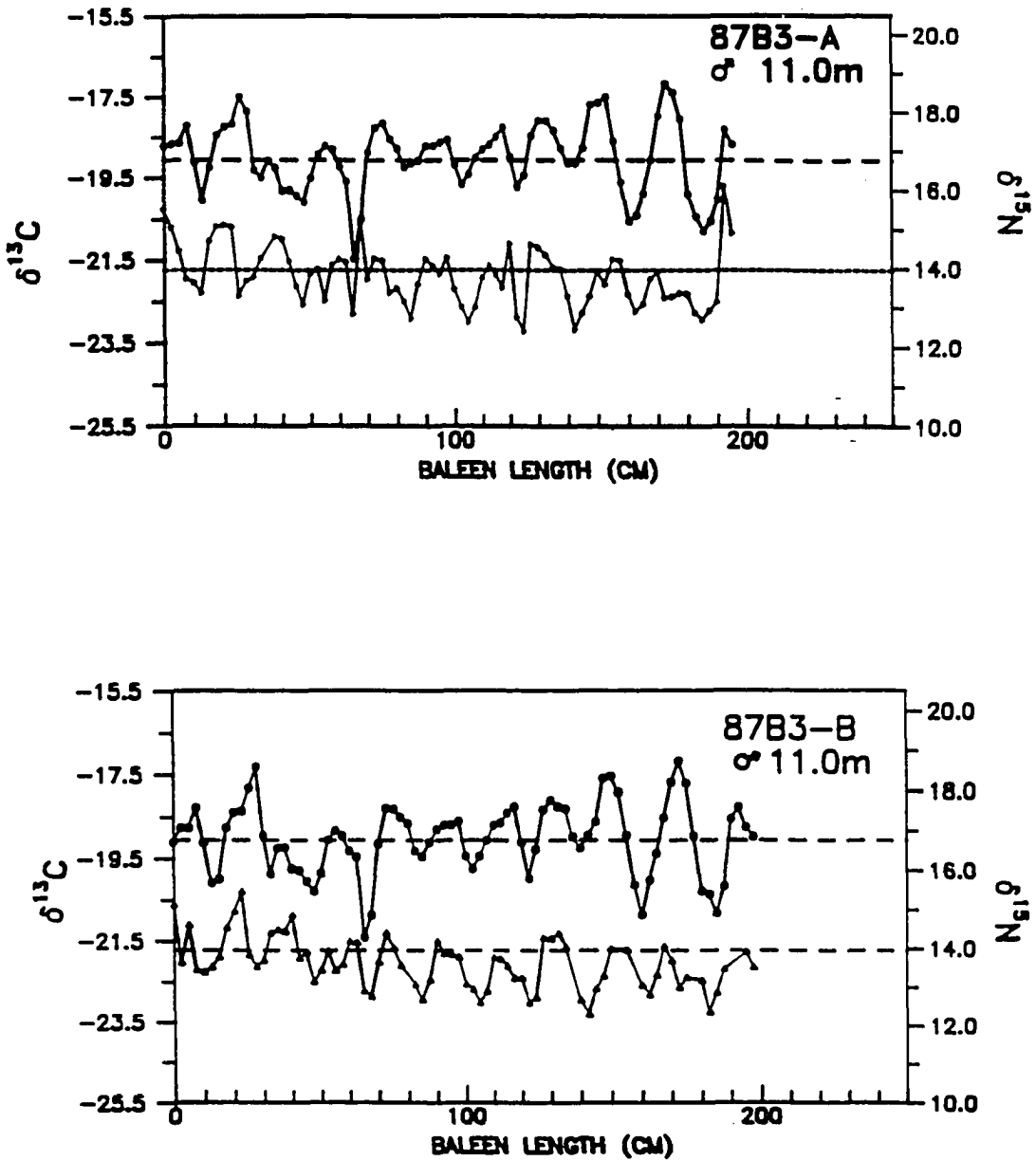


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

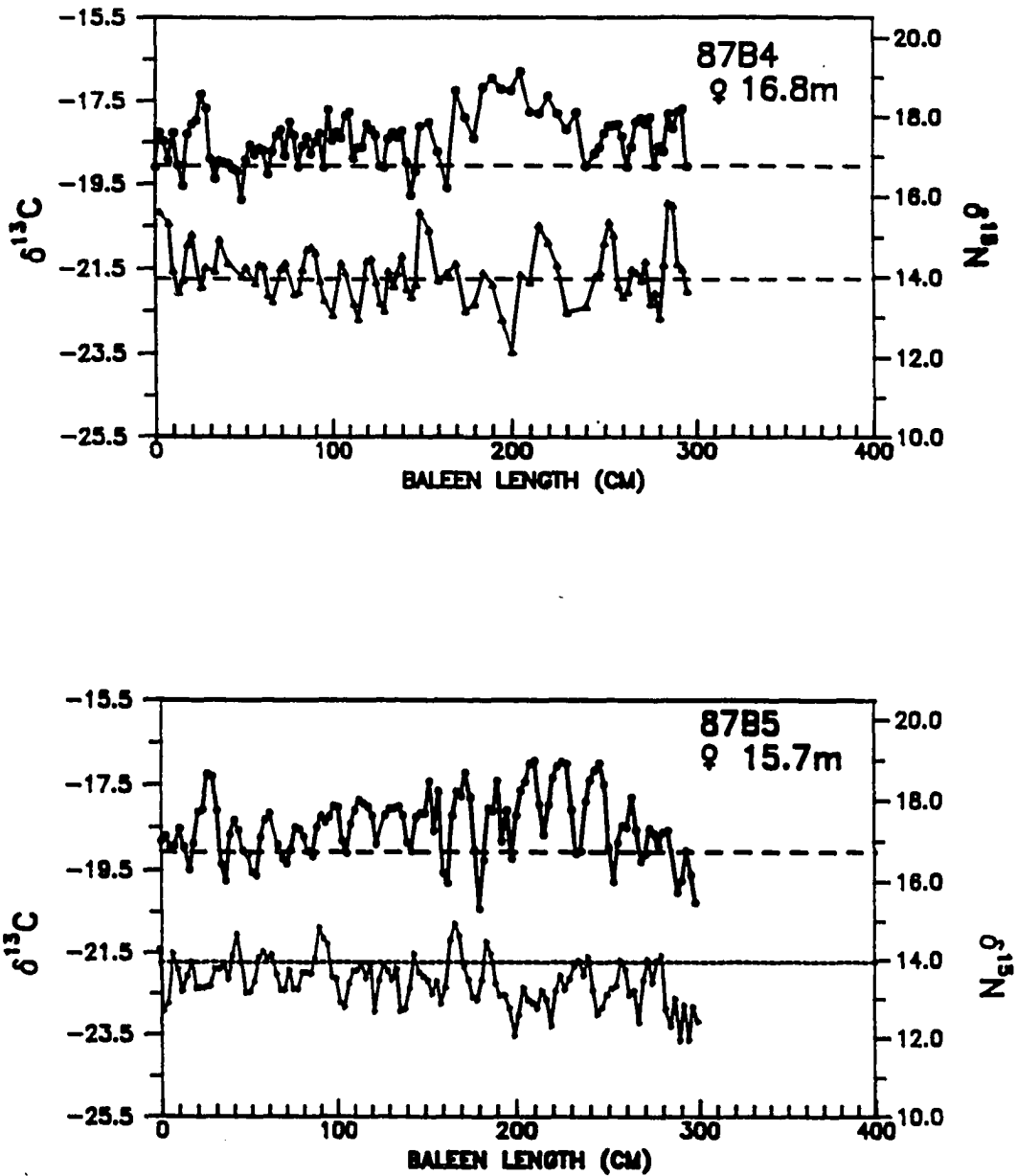


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

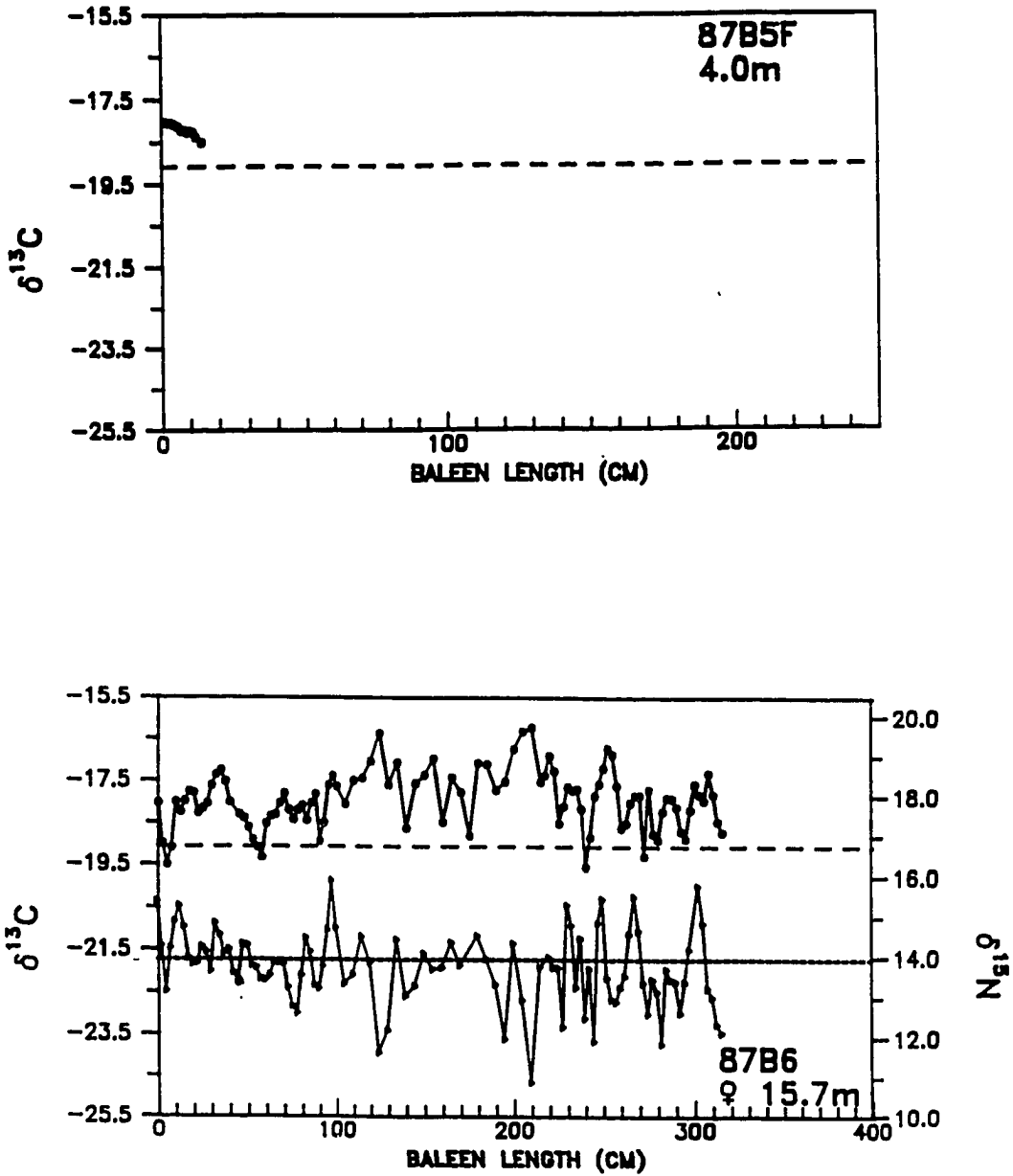


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

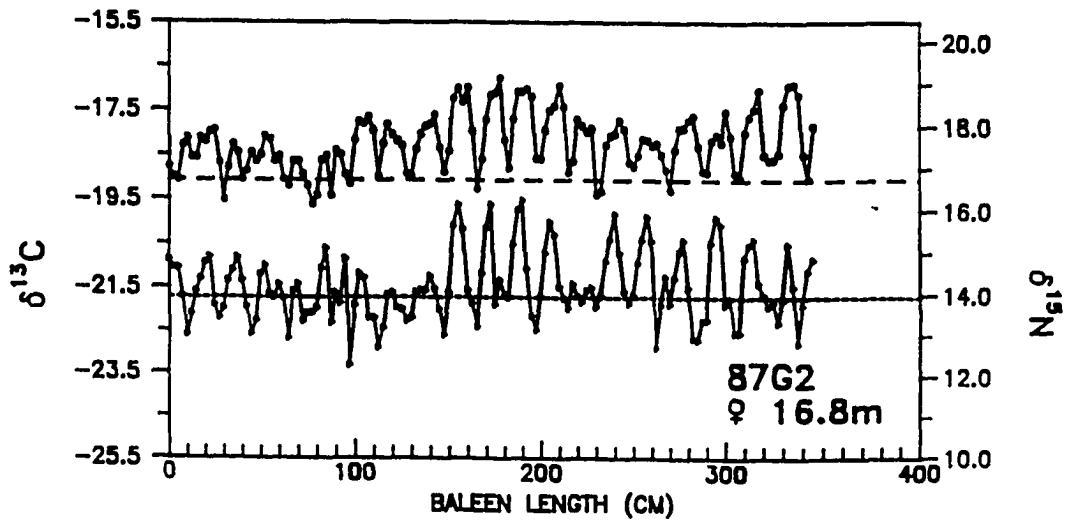
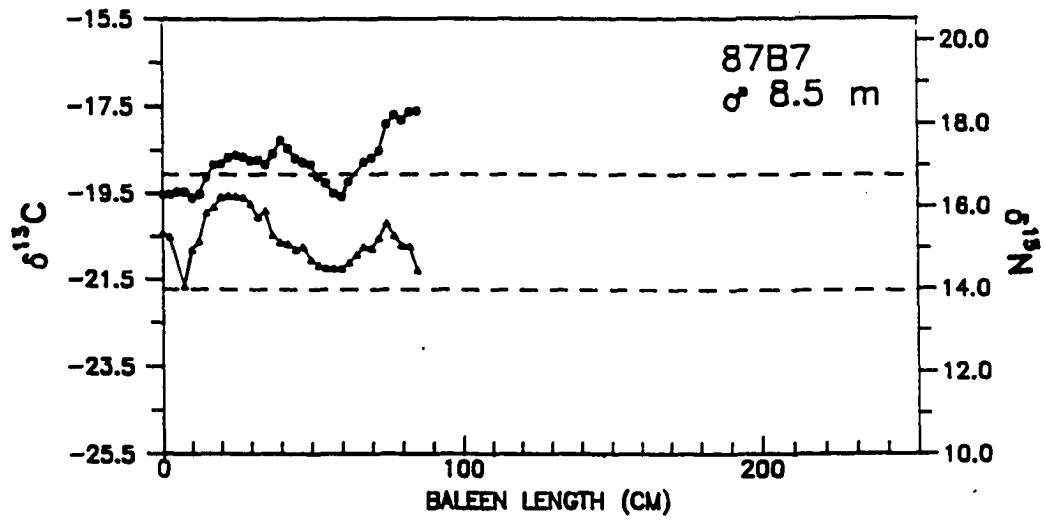


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

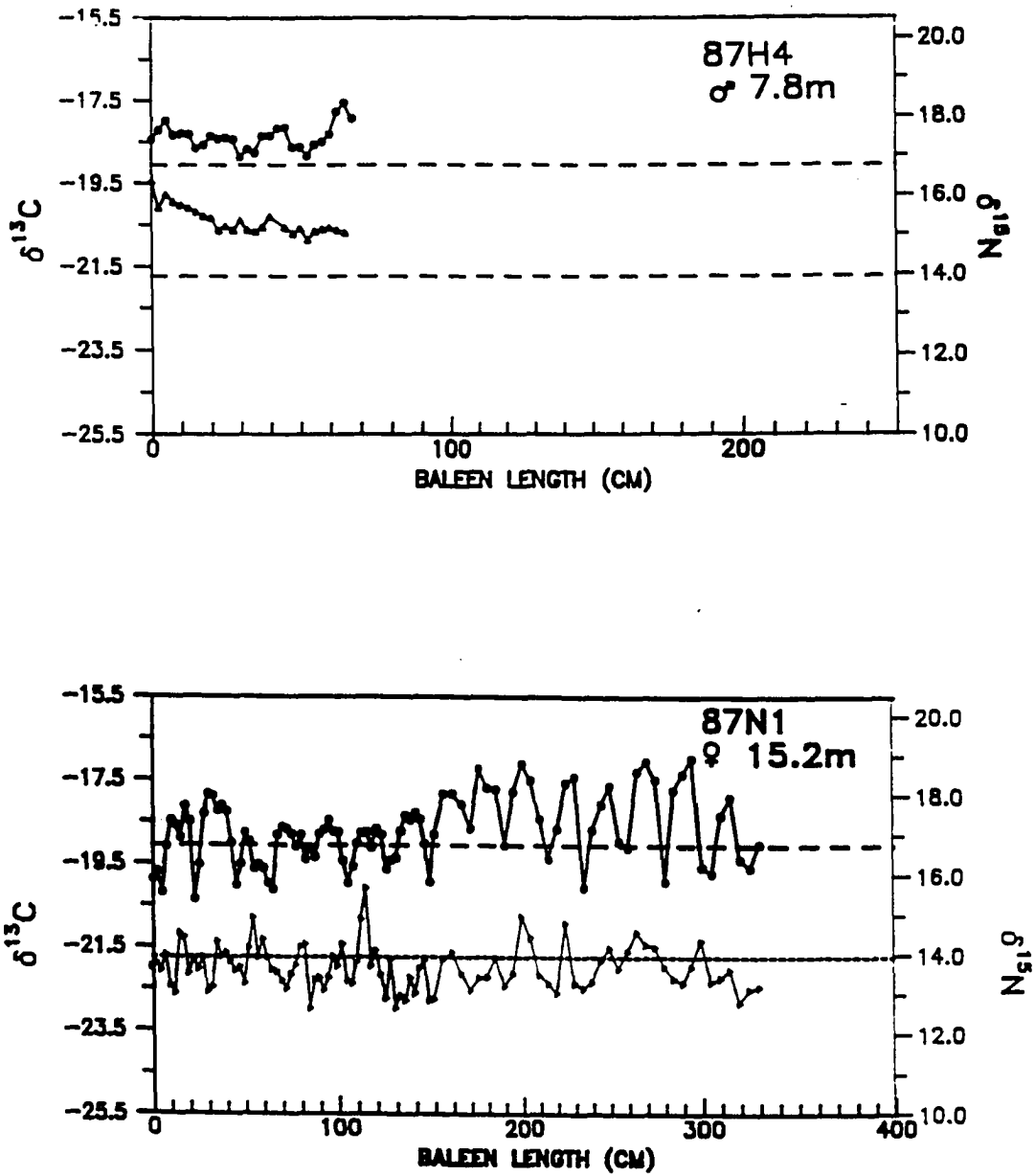


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

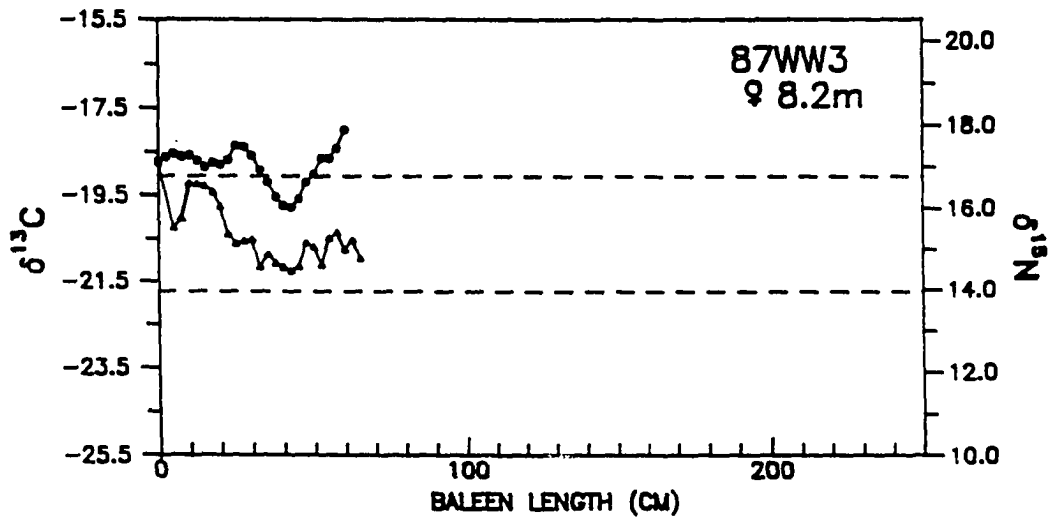
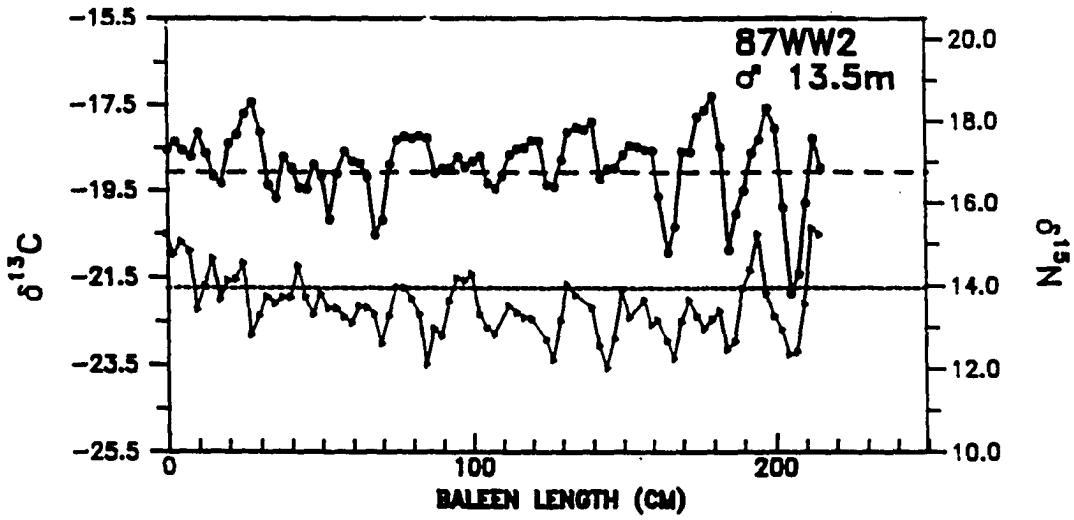


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

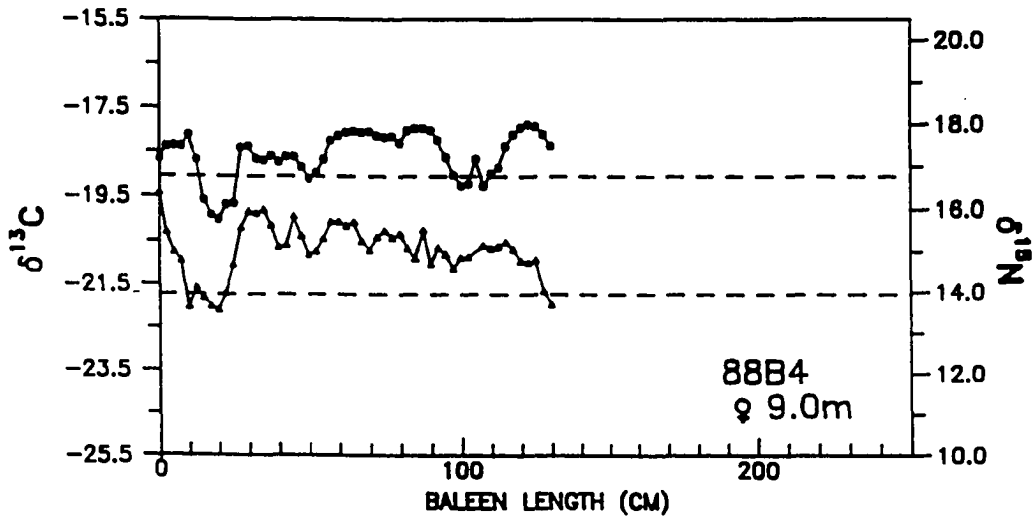
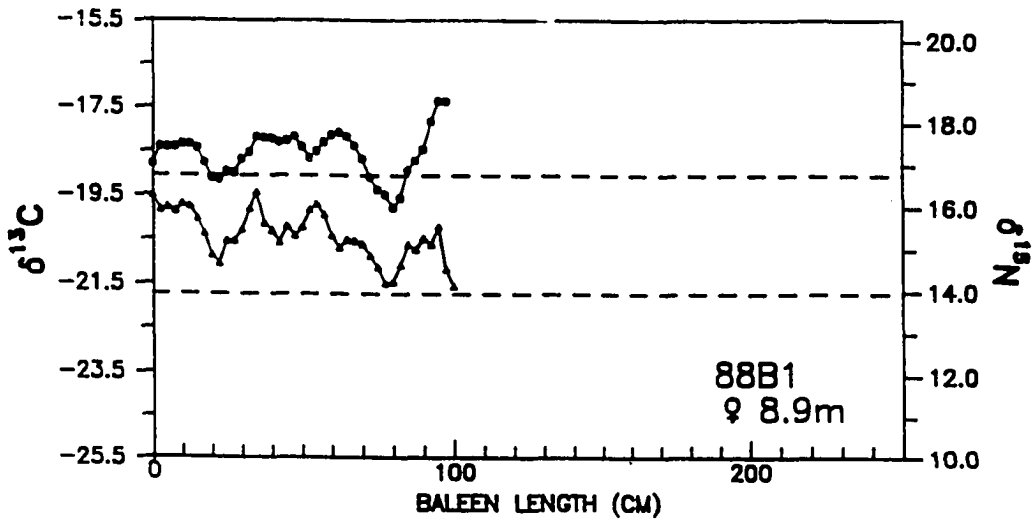


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

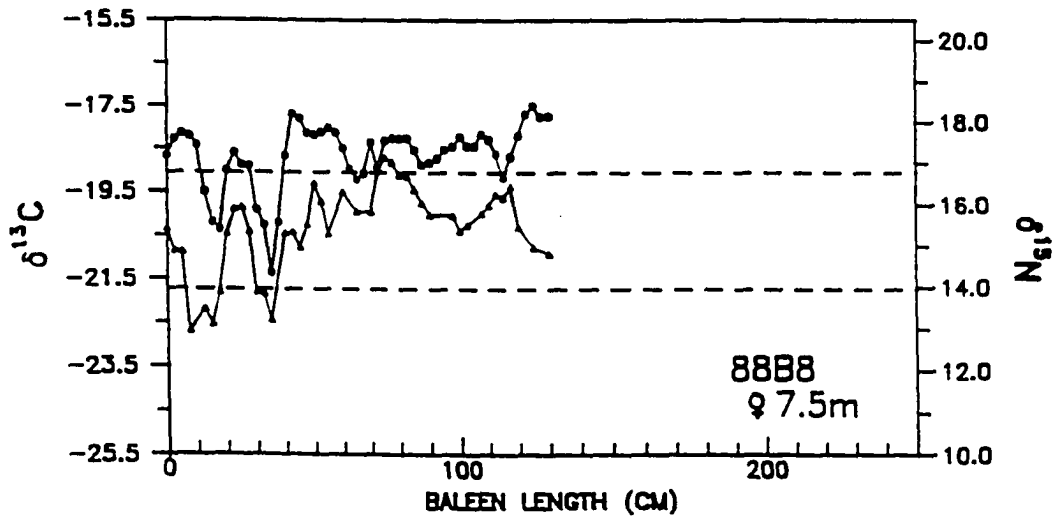
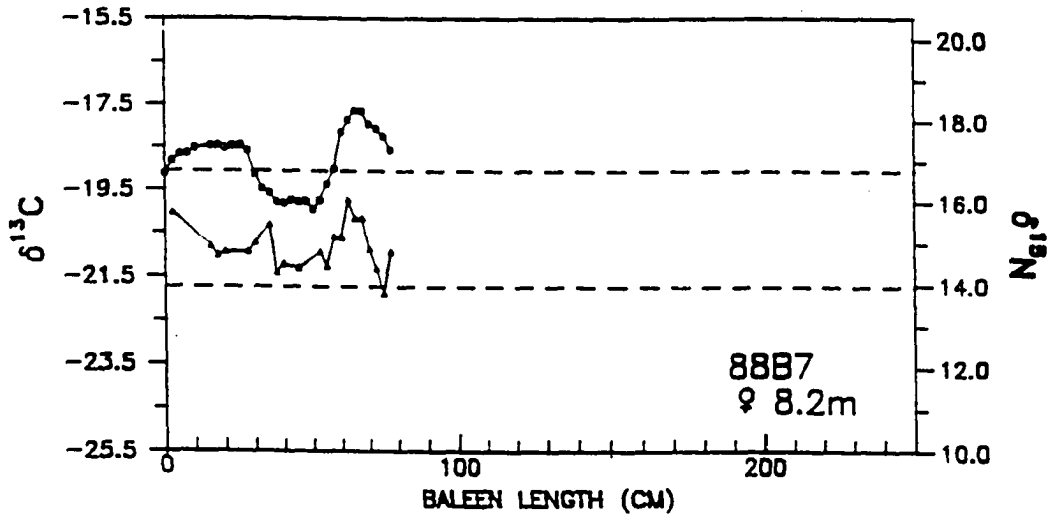


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

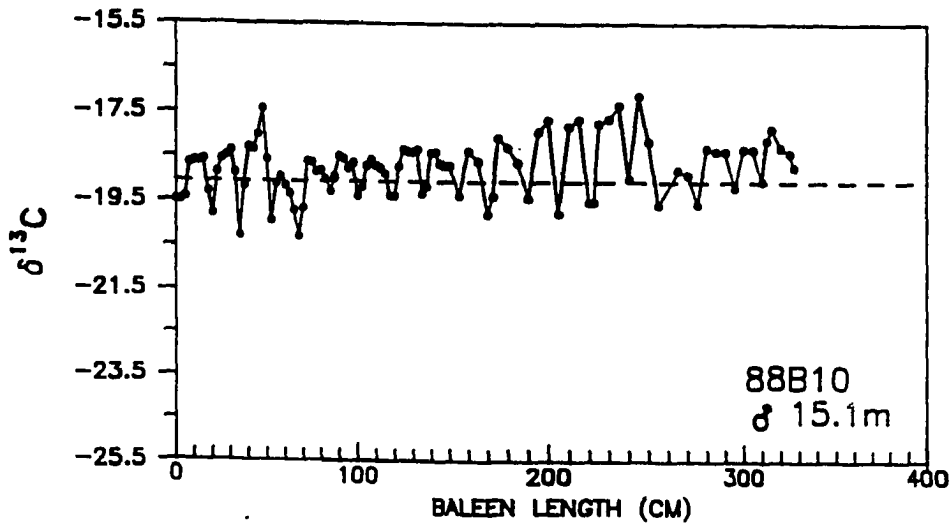
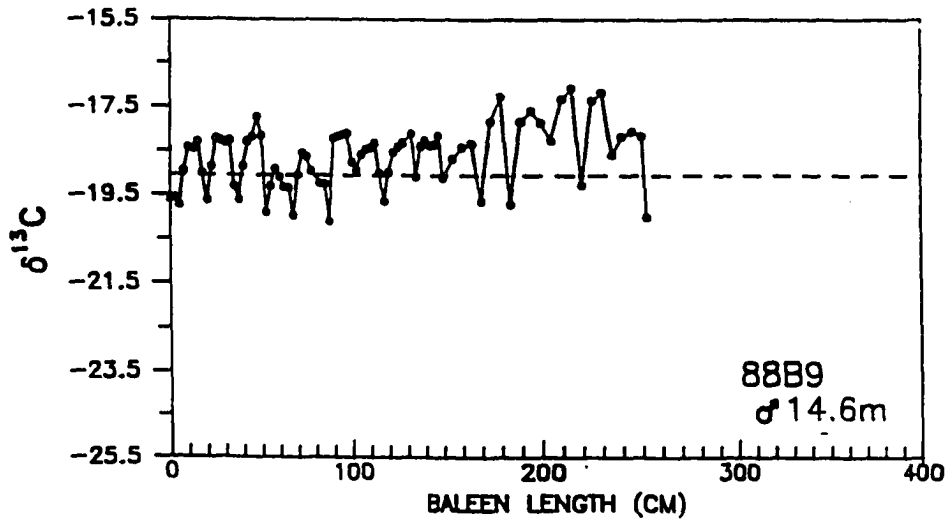


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

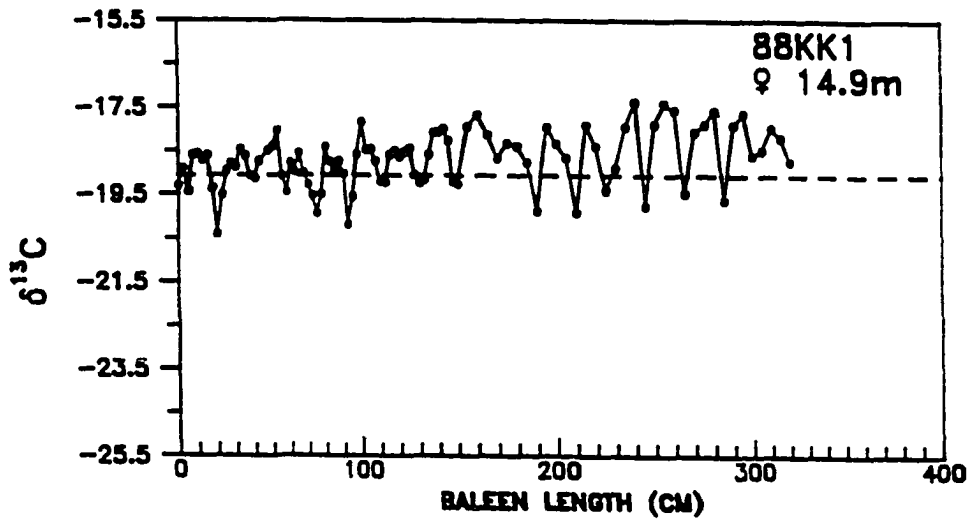
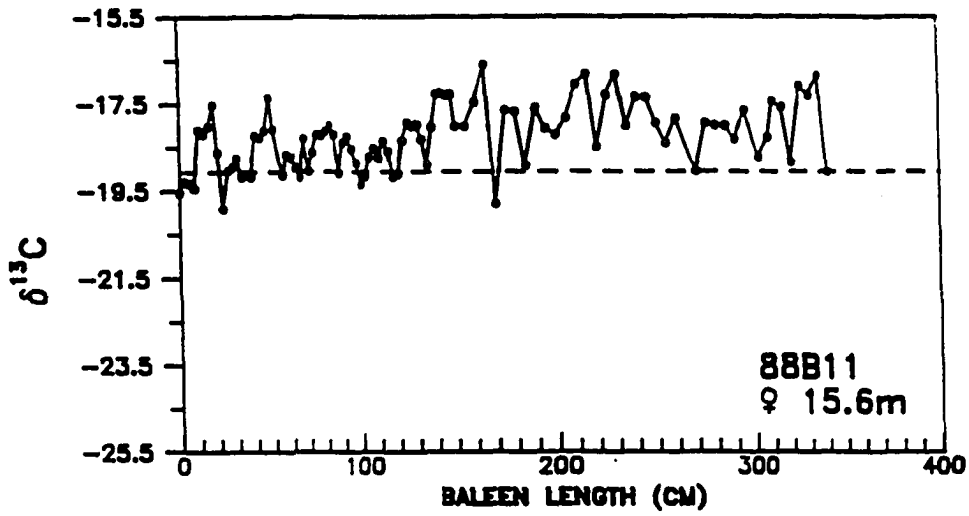


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

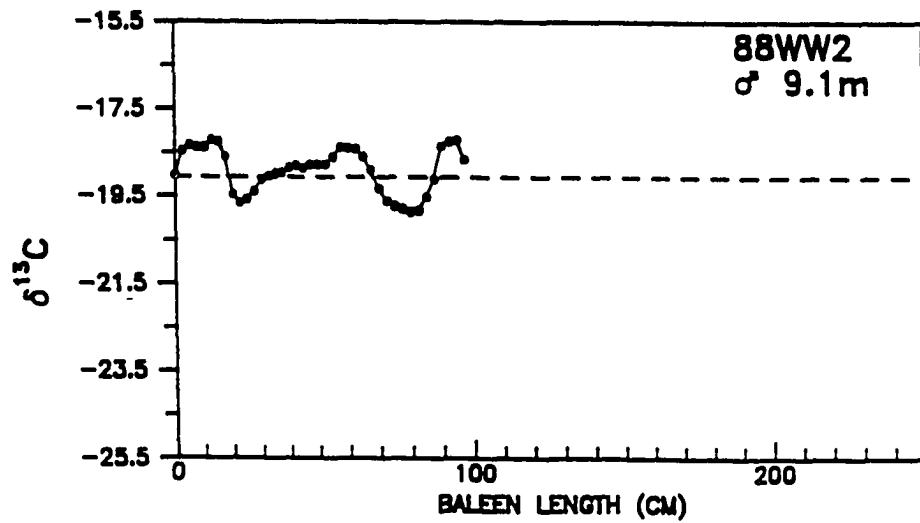
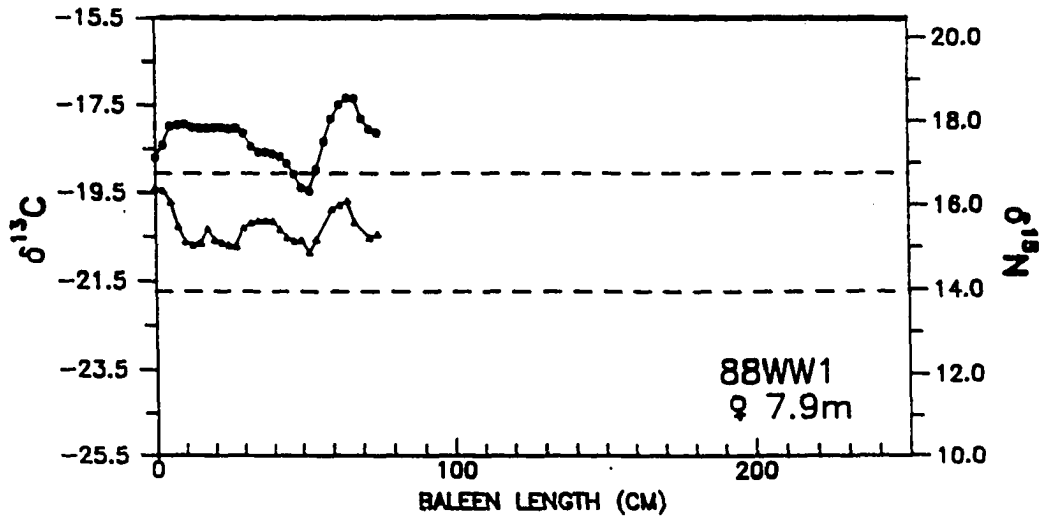


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

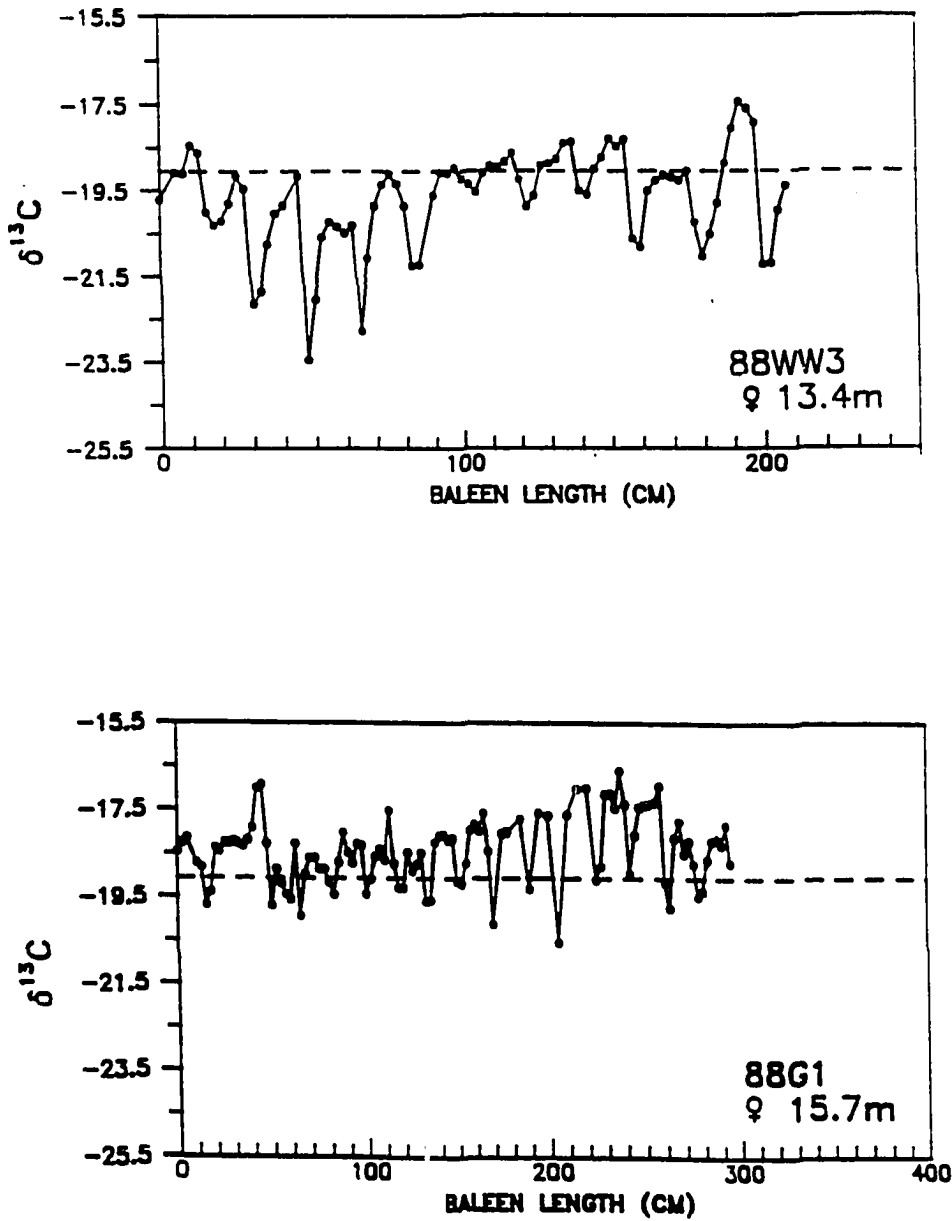


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

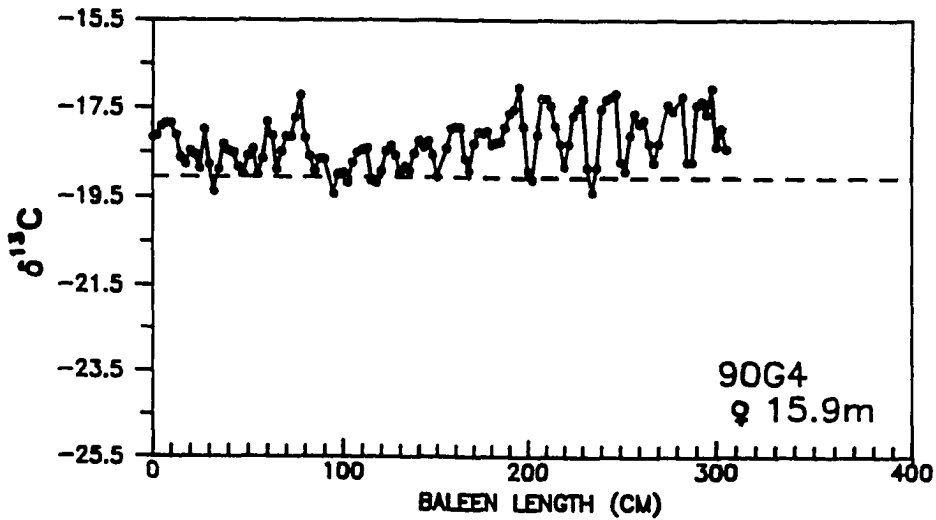
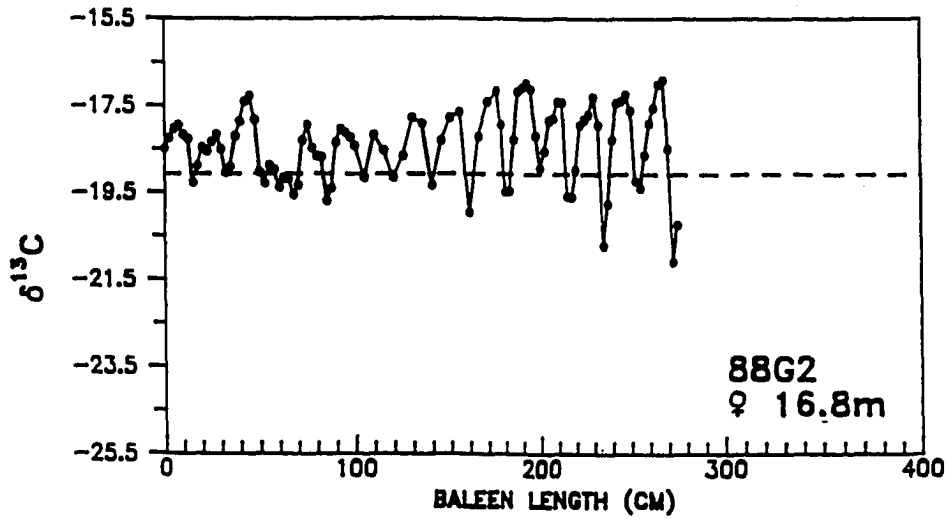


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

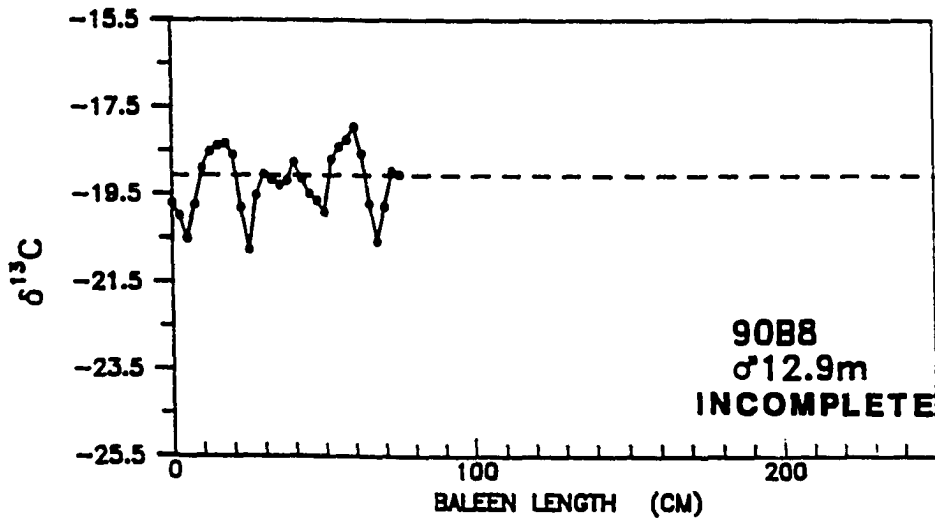
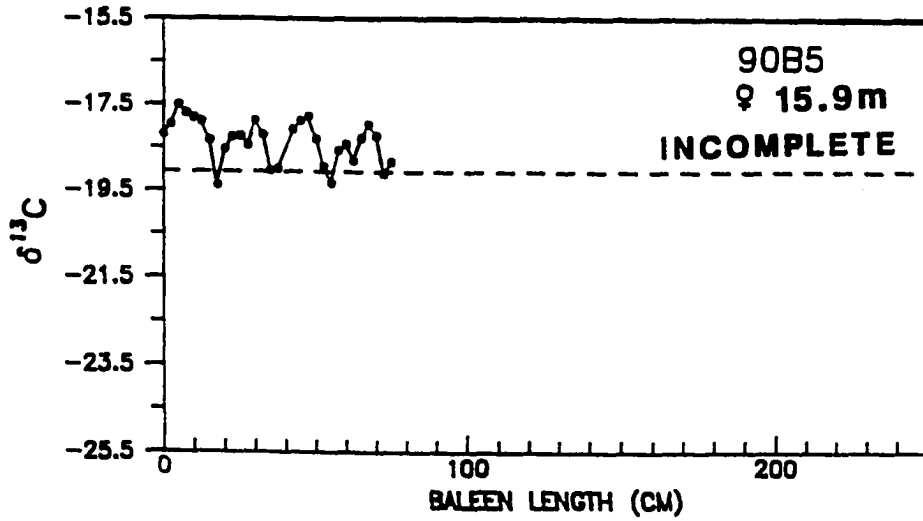


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

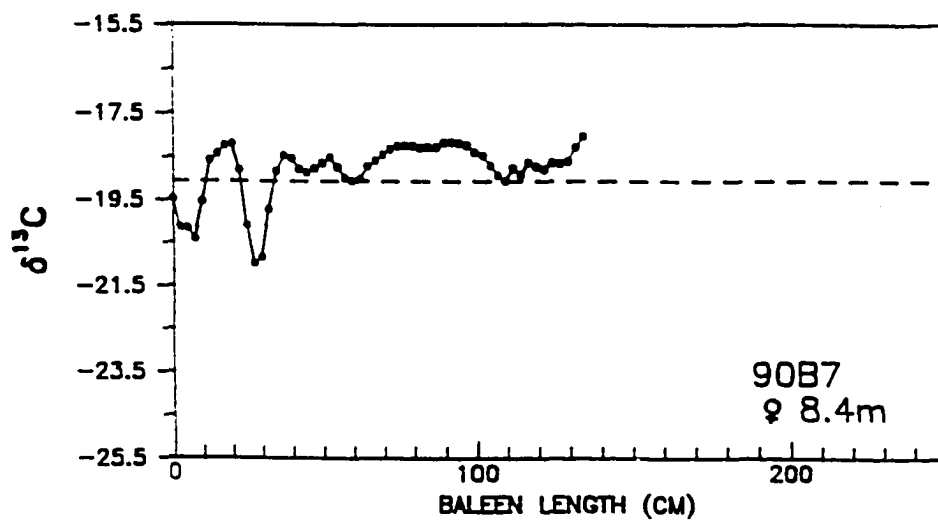


Figure 33. Baleen carbon and nitrogen isotope traces (continued).

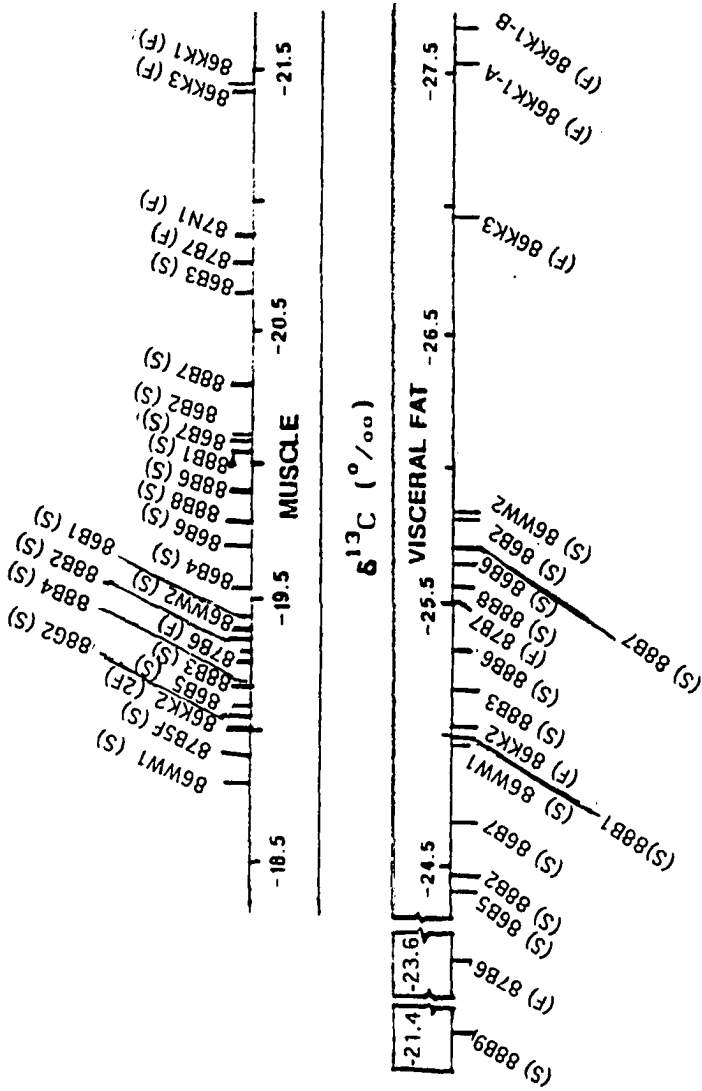


Figure 34. Bowhead whale muscle and visceral fat $\delta^{13}C$ values for whales harvested in the fall (F) and spring (S), 1986-1988.

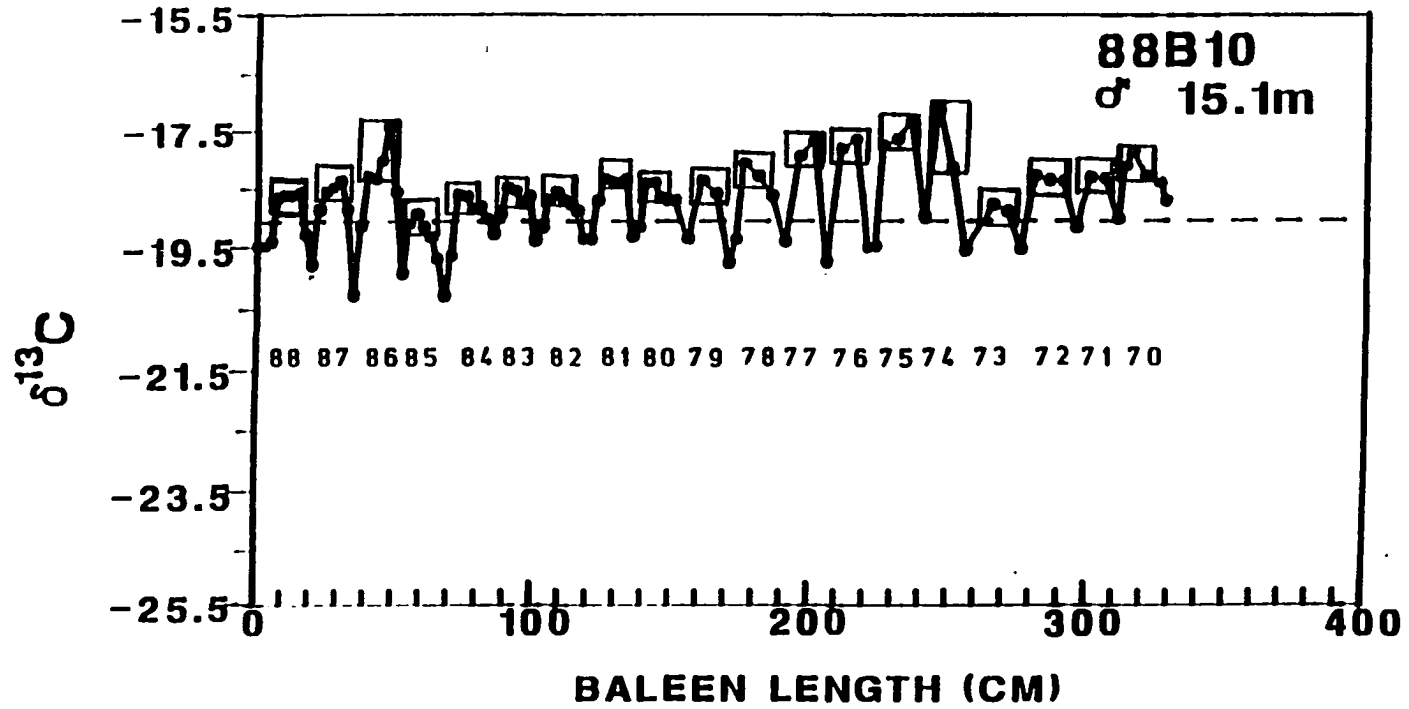


Figure 35. Carbon isotope trace of an adult bowhead whale (88B10). Boxes show isotope ratio values derived from fall-winter feeding in the Bering/Chukchi seas.

whale (88B10). The trace spans the period 1969 to 1988. The boxes show the isotope ratio values laid down during the periods the whale was in the Bering/Chukchi seas. Whales harvested in the spring have new baleen enriched in $\delta^{13}\text{C}$, indicating previous feeding during the fall and/or winter in the Chukchi/Bering seas.

Whales killed in the fall have new baleen growth that is ^{13}C -depleted as the baleen reflects the relatively ^{13}C -depleted prey of the Beaufort Sea summer feeding grounds. It would be expected that if the whale fed only in the summer, that the $\delta^{13}\text{C}$ values of the tissues would reflect only the $\delta^{13}\text{C}$ values of the Beaufort Sea zooplankton prey. The annual $\delta^{13}\text{C}$ oscillations reveal, however, that the depleted region is less than one-third of the yearly baleen growth and is equivalent to the fraction of the year the whales reside in the Beaufort Sea. This suggests that baleen growth continues through the fall and winter at an approximately constant rate (within the sampling precision).

These fall-winter values display multi-year trends of changing isotope ratios, punctuated by years showing abrupt shifts. These trends are evident in the baleen of all of the adult

whales sampled (16 whales).

From the traces of stable isotope values along the baleen plates, fall/winter baleen values were listed by year for the adult whales (Appendix 6). Fall/winter values were averaged for the 16 whales (Figure 36, Appendix 7) and plotted for the years 1973 to 1990.

Bering Sea Surface Temperature Anomalies

Figure 36 shows the isotope ratio values from baleen plate records for fall-winter feeding by all whales between 1973 and 1990. With the exception of isotope ratios in 1985-1986, the trend follows a relatively smooth pattern of ^{13}C -depletion from 1975 to 1985 and increasing enrichment in recent years. Also shown in Figure 36 are the sea surface temperature anomalies for the Bering Sea over this same period. Fall/winter averages are plotted opposite nine-month and five-year running mean Bering Sea surface temperature anomalies recorded at 55 degrees North and 175 degrees West. Although a pronounced 2.4 year temperature cycle is evident in warm years, as shown by the 9

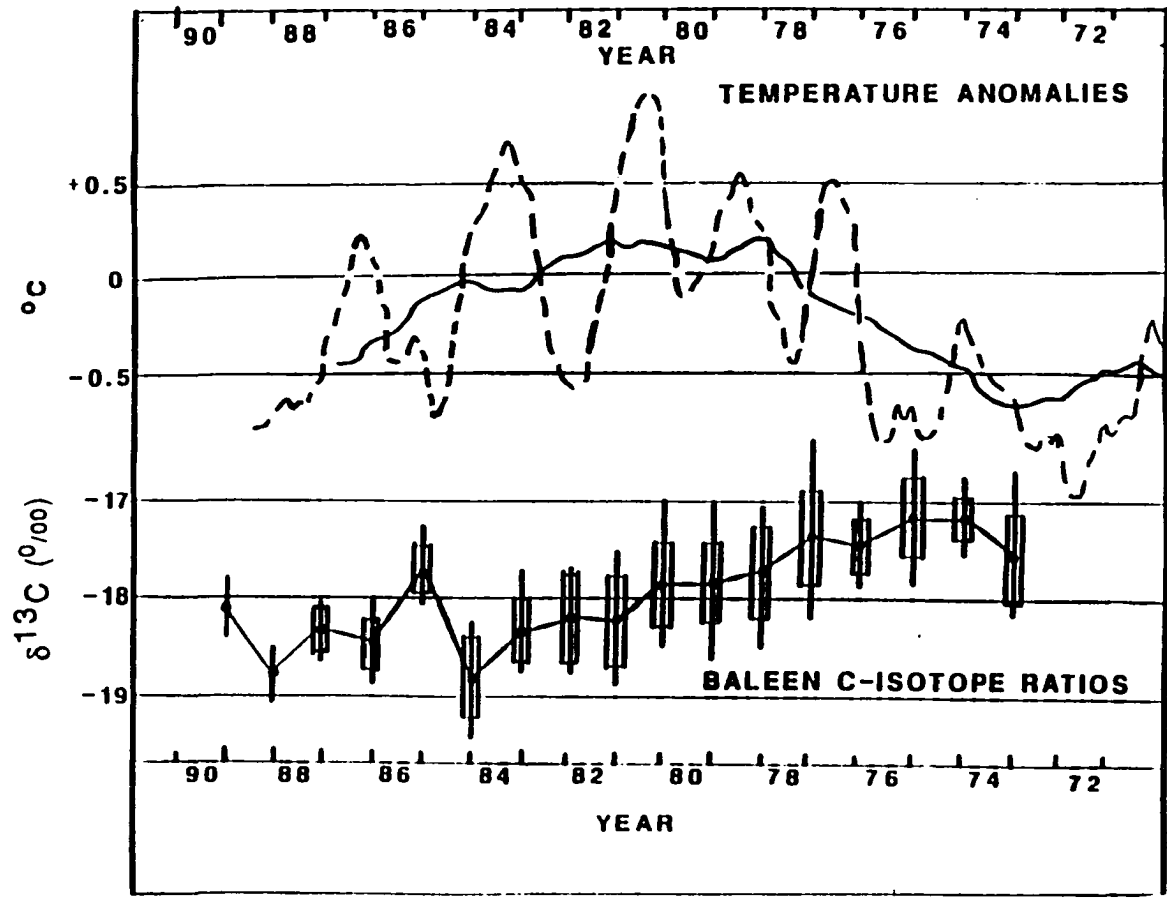


Figure 36. Carbon isotope ratio values from baleen plate records for fall-winter feeding by 16 adult bowhead whales. Also shown are sea surface temperature anomalies depicted by a 9 month running mean (dashed) and a 5 year running mean (solid).

month running mean, the isotope record reflects only the inverse of the long-term trend as evident in the five year running mean.

Five-year running mean sea surface temperature anomalies for the spring and summer months (April-September) were averaged (Appendix 8) and plotted opposite fall/winter baleen $\delta^{13}\text{C}$ averages (Figure 37). Cross-correlation analysis between spring/summer sea surface temperature anomalies and fall/winter baleen $\delta^{13}\text{C}$ averages indicates an inverse correlation (Figure 38). The correlation is strongest ($r \sim -0.75$) when baleen $\delta^{13}\text{C}$ averages lag sea surface temperature changes by approximately one to two years. At the one to two year lag, the inverse correlation is close to the 90% confidence level.

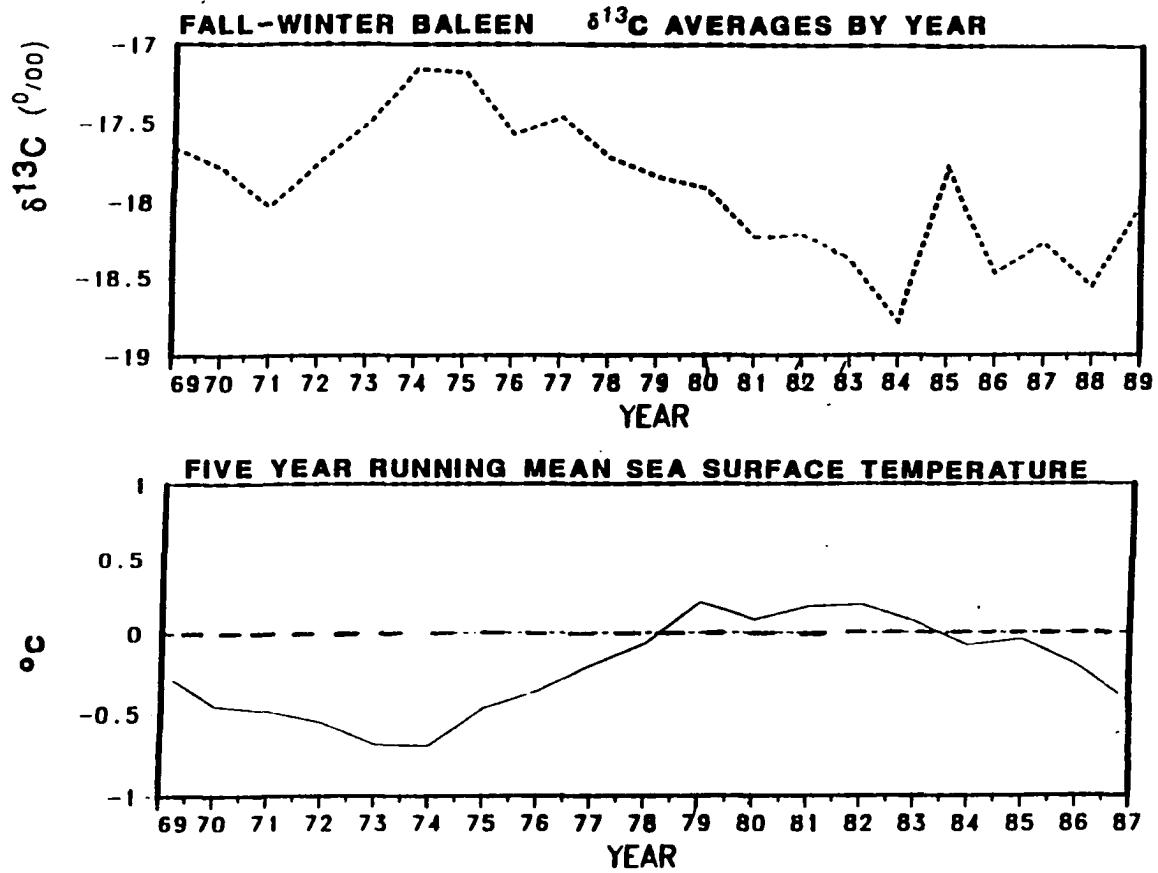


Figure 37. Five year running mean sea surface temperature averages (April-September) and fall-winter baleen $\delta^{13}\text{C}$ averages by year.

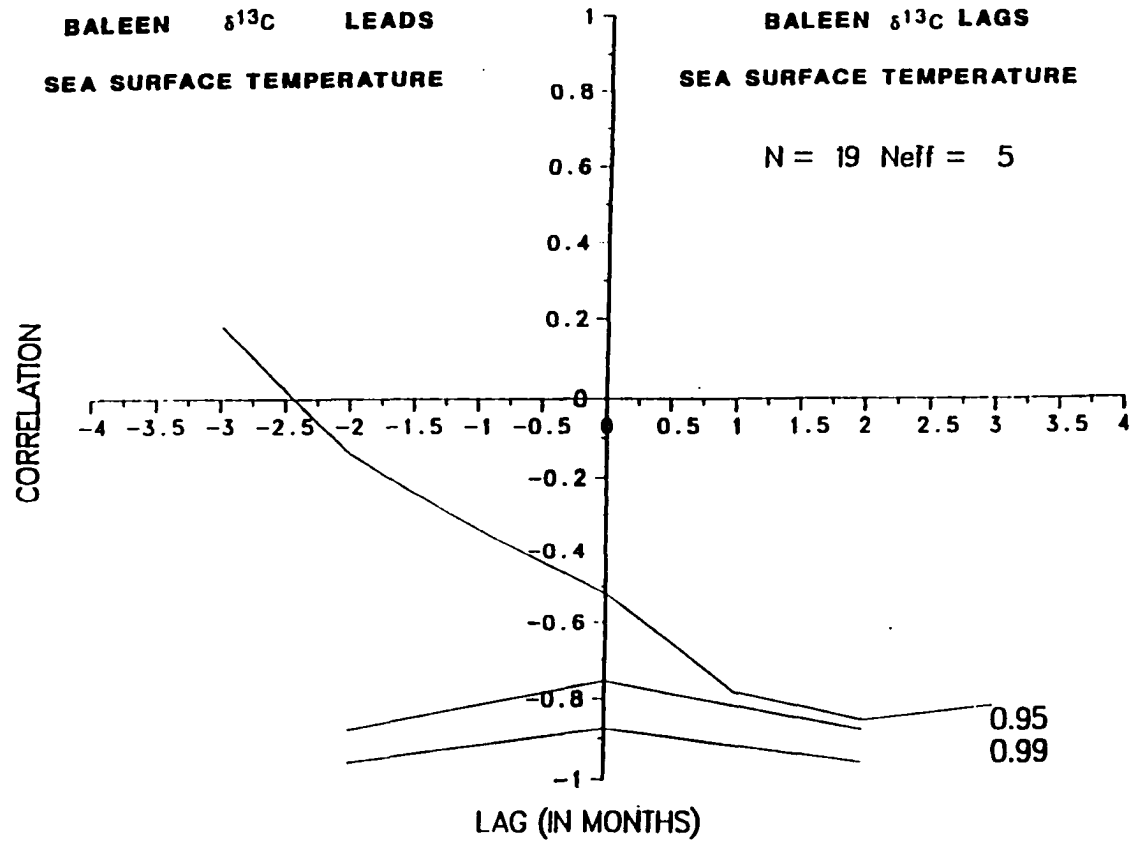


Figure 38. Baleen fall-winter $\delta^{13}\text{C}$ averages inversely correlate to 5-year running mean sea surface temperatures. Baleen $\delta^{13}\text{C}$ lags sea surface temperature by approximately 2 years, approaching 95% confidence level.

CHAPTER 5. DISCUSSION

Carbon Isotope Ratio Latitudinal Gradient

The statistical analyses of carbon isotope data shows trends in zooplankton enrichment from the Beaufort Sea to the Chukchi/Bering seas. These findings concur with similar findings of Saupe et al. (1989). The Canadian, Eastern Alaskan and Central Alaskan Beaufort seas zooplankton are the most ^{13}C -depleted and the Chukchi and Bering seas tend to be the most enriched.

This evidence further supports the latitudinal trend of ^{13}C -depletion at higher latitudes and enrichment at lower latitudes. However, due to the small sample size in the Western Beaufort Sea, the significant differences listed between the Western Beaufort and Eastern, Canadian and Central Beaufort seas may not be as strong as indicated.

Seasonal and Interannual Variation in Zooplankton $\delta^{13}\text{C}$

In 1988, copepods, euphausiids and amphipods collected on the spring ice-edge cruise (May) are significantly ^{13}C -enriched relative to those collected in late summer and early fall (July-October).

Several Chukchi/Bering sea cruises taken from September to October 1987-1990, within the same general geographic regions, show a weak trend of ^{13}C -depletion in zooplankton between years. This trend, however weak, may be an indication of interannual change in zooplankton $\delta^{13}\text{C}$.

The trend in $\delta^{13}\text{C}$ depletion of zooplankton between 1987 and 1990 is likely due to a combination of seasonal and inter-annual effects. Changes in $\delta^{13}\text{C}$ of phytoplankton stocks with ice-retreat and bloom stages would be reflected in seasonal differences in $\delta^{13}\text{C}$ of zooplankton as well as zooplankton species. This slight variability between years may be a result of physical parameters, including temperature change, affecting primary production or biomass diversity between years which may alter the $\delta^{13}\text{C}$ of pooled zooplankton samples.

Carbon Isotope Ratio Trends in Baleen

Carbon isotope ratios in consumers are established by the primary producers in the ecosystem (in this case, phytoplankton). Subsequent changes within a food chain are the result of fractionation caused by metabolism within the organism and are usually small (<1ppt). Thus the carbon isotopic composition of bowhead whales is a surrogate for the isotopic composition of the primary producers in areas where the animals feed, assuming that the growth of baleen is continuous. The Bering/Chukchi seas are the source of most of the food supporting bowhead whales. The whales feed during late fall and winter on small zooplankton that serve as integrators of the previous season's primary production.

The slight trend in ^{13}C -depletion of zooplankton stocks noted above is in contrast to the slight trend of ^{13}C -enrichment in fall-winter baleen over the same time period (Figure 36). I expected that the weak trend in zooplankton ^{13}C -depletion between years would be reflected in a similar weak trend in baleen $\delta^{13}\text{C}$. However, since the winter baleen reflects the

primary producers 87-88, 88-89 and 89-90 are testable. This small sample size does not reflect a clear trend in either enrichment or depletion in either baleen or zooplankton $\delta^{13}\text{C}$. The fall/winter baleen $\delta^{13}\text{C}$ averages show a trend in ^{13}C -depletion between 1973 and 1984. In following years, baleen $\delta^{13}\text{C}$ appears to have a trend in ^{13}C -enrichment (1985 to 1990) with an intense increase in ^{13}C -enrichment in 1985.

Assuming growth of baleen is continuous, it is possible that $\delta^{13}\text{C}$ values of zooplankton sampled during the September-October cruises are not characteristic of the zooplankton the whales consume later in the fall-winter months (November to December). Whales may be concentrating their feeding in regions not extensively covered in this study and may also alter their feeding strategy by foraging in different areas. This may be due to changes in abundance and possibly location of different zooplankton species between years.

$\delta^{15}\text{N}$ Oscillations in Baleen

For major taxonomic groups, there is no marked

geographic gradient in $\delta^{15}\text{N}$ throughout the study area. Rather, $\delta^{15}\text{N}$ enrichment appears to occur solely with increasing trophic level as indicated by chaetognaths and fish ^{15}N -enrichment, relative to other zooplankton.

The oscillations in $\delta^{15}\text{N}$ present in baleen are large, often greater than $\delta^{13}\text{C}$ oscillations. The $\delta^{15}\text{N}$ oscillations in baleen plates range from approximately 13‰ to 15‰. The ^{15}N enrichment correlates with the ^{13}C enrichment and therefore may be associated with fall-winter feeding.

It is difficult to explain $\delta^{15}\text{N}$ oscillations over the seasons if whales consume only zooplankton prey. However, it is possible that they consume other organisms that are in the water column. A shift to include higher trophic level food sources in winter might account for the observed shifts in $\delta^{15}\text{N}$. When feeding in the Bering Sea, the winter whale habitat include deeper, off-shore food sources. An increase in larval or juvenile fish consumption in the Bering/Chukchi seas may also enrich the $\delta^{15}\text{N}$ of the baleen. Fishes, which are found in stomach contents

of whales, are often schooling zooplankton for their own consumption and may be an incidental catch. If fish are contributing to the ^{15}N enrichment, they would most likely be slow and small, perhaps juvenile pollock or sand-lance. It is also possible that the whales are consuming quantities of other seasonally abundant higher trophic organisms, including jellyfish, which are also $\delta^{15}\text{N}$ enriched (OCS Study MMS 92-0020).

Alternatively, the $\delta^{15}\text{N}$ oscillations may be purely internal physiological characteristics of the whale and not dependent upon food source $\delta^{15}\text{N}$. Further studies on whale feeding ecology in the Bering Sea would help determine the extent of whale feeding during the winter and the diversity of its prey.

CHAPTER 6. CONCLUSIONS

1. Trophic level enrichments in $\delta^{15}\text{N}$ suggest the observed $\delta^{15}\text{N}$ oscillations in bowhead whale baleen may be due to changes in the trophic level of prey or physiological cycles in the whales rather than geographical gradients of $\delta^{15}\text{N}$ within prey taxa. Increased consumption of fishes or other ^{15}N -enriched prey in the Chukchi/Bering seas during the winter months is a plausible explanation for these ^{15}N enrichments, which coincide with fall/winter feeding as indicated by carbon isotope patterns.

2. Zooplankton sampled on cruises between 1987 and 1990 show a slight trend in depletion of $\delta^{13}\text{C}$ from the early cruises to the later cruises. This trend may be due to inter-annual environmental changes affecting $\delta^{13}\text{C}$ of phytoplankton.

3. The $\delta^{13}\text{C}$ of baleen laid down in the fall-winter months is

inversely correlated to long-term sea surface temperature trends in the Bering Sea. If it can be shown that the long-term changes in $\delta^{13}\text{C}$ in baleen are related to primary productivity, this record can be helpful in assessing past climatic change and as a measure of biological response induced by future warming of the arctic/subarctic marine ecosystem.

APPENDIX 1. Zooplankton $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results from
M. W. BRADSTREET COLLECTIONS (ZOO85)

| SPECIES | ST. | DAY | MO. | YR. | LAT. | LONG. | $\delta^{13}\text{C}$ |
|--------------------|-----|-----|-----|-----|-------|--------|-----------------------|
| EUPHAUSIID: | | | | | | | |
| T. RASCHII | 9 | 18 | 9 | 85 | 69.70 | 141.00 | -23.58 |
| T. RASCHII | 8 | 7 | 9 | 85 | 70.20 | 142.70 | -19.67 |
| AMPHIPODA: | | | | | | | |
| P. LIBELLULA | 11 | 7 | 9 | 85 | 70.10 | 142.70 | -26.87 |
| P. LIBELLULA | 12 | 7 | 9 | 85 | 70.20 | 142.70 | -25.81 |
| P. LIBELLULA | 10 | 6 | 9 | 85 | 70.50 | 143.10 | -27.05 |
| COPEPODA: | | | | | | | |
| COPEPODA | 4 | 18 | 9 | 85 | 69.70 | 141.00 | -27.23 |
| COPEPODA | 5 | 7 | 9 | 85 | 70.20 | 142.70 | -24.66 |
| COPEPODA | 3 | 7 | 9 | 85 | 70.10 | 142.70 | -25.76 |
| COPEPODA | 1 | 7 | 9 | 85 | 70.20 | 142.70 | -20.05 |
| COPEPODA | 2 | 7 | 9 | 85 | 70.20 | 142.70 | -26.19 |
| COPEPODA | 7 | 7 | 9 | 85 | 70.10 | 142.70 | -26.03 |
| COPEPODA | 6 | 6 | 9 | 85 | 70.50 | 143.10 | -25.38 |

APPENDIX 2. $\delta^{13}\text{C}$ means, standard deviations and range for taxonomic groups by region.

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|---------------------|----------------|-------------------|--------------------|
| Canadian | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | -25.4 | -23.5 | -22.6 |
| Std. dev. | ± 1.1 | ± 0.4 | |
| Maximum | -23.6 | -23.2 | |
| Minimum | -26.7 | -24.0 | |
| n | 7 | 3 | 1 |
| Eastern Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | -25.9 | -23.9 | -22.2 |
| Std. dev. | ± 1.2 | ± 1.9 | |
| Maximum | -22.9 | -19.7 | -21.9 |
| Minimum | -28.1 | -26.2 | -22.5 |
| n | 23 | 11 | 2 |
| Central Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | -24.8 | -23.4 | N/A |
| Std. dev. | ± 0.3 | ± 0.5 | |
| Maximum | -24.5 | -22.9 | |
| Minimum | -25.1 | -24.1 | |
| n | 3 | 4 | |
| Western Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | -23.1 | -21.8 | -20.2 |
| Std. dev. | ± 1.0 | ± 0.9 | ± 0.3 |
| Maximum | -22.4 | -21.0 | -20.0 |
| Minimum | -24.2 | -23.0 | -20.5 |
| n | 3 | 4 | 3 |

APPENDIX 2. (continued).

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|--------------------|----------------|-------------------|--------------------|
| Northern | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | -22.7 | -21.4 | -20.4 |
| Std. dev. | ±1.3 | ±0.5 | ±0.5 |
| Maximum | -18.9 | -20.6 | -19.7 |
| Minimum | -24.3 | -22.5 | -21.4 |
| n | 12 | 14 | 15 |
| Eastern | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | -21.8 | -20.4 | -20.6 |
| Std. dev. | ±1.0 | ±1.1 | ±0.6 |
| Maximum | -20.1 | -18.5 | -19.7 |
| Minimum | -23.7 | -22.6 | -22.2 |
| n | 31 | 22 | 24 |
| Western | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | -21.4 | -20.6 | -20.4 |
| Std. dev. | ±0.7 | ±0.6 | ±0.6 |
| Maximum | -20.4 | -19.9 | -19.7 |
| Minimum | -22.9 | -21.7 | -21.5 |
| n | 23 | 13 | 13 |
| Eastern | | | |
| <u>Bering Sea</u> | | | |
| Mean | -22.0 | -20.7 | -21.2 |
| Std. dev. | ±1.2 | ±1.1 | ±1.0 |
| Maximum | -20.5 | -18.8 | -20.2 |
| Minimum | -24.7 | -22.6 | -23.9 |
| n | 21 | 16 | 13 |

APPENDIX 2. (continued).

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|--------------------------|----------------|-------------------|--------------------|
| Western | | | |
| <u>Bering Sea</u> | | | |
| Mean | -22.6 | -20.1 | -21.7 |
| Std. dev. | ±1.4 | ±1.5 | ±0.6 |
| Maximum | -20.6 | -17.7 | -21.2 |
| Minimum | -24.3 | -21.9 | -22.6 |
| n | 8 | 7 | 6 |
| | | | |
| Central | | | |
| <u>Bering Sea</u> | | | |
| Mean | -22.7 | -21.4 | -21.0 |
| Std. dev. | ±1.5 | ±1.7 | ±0.7 |
| Maximum | -19.6 | -19.6 | -19.7 |
| Minimum | -26.6 | -25.9 | -23.6 |
| n | 42 | 23 | 26 |
| | | | |
| Southern | | | |
| <u>Bering Sea</u> | | | |
| Mean | -20.6 | -20.5 | -20.5 |
| Std. dev. | ±1.5 | ±1.2 | ±0.5 |
| Maximum | -19.4 | -19.6 | -19.7 |
| Minimum | -25.8 | -23.4 | -21.4 |
| n | 20 | 10 | 15 |

APPENDIX 2 (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|---------------------|-----------------|-------------|---------------|-------------|
| Canadian | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | -25.4 | N/A | N/A | N/A |
| Std. dev. | ±1.2 | | | |
| Maximum | -24.1 | | | |
| Minimum | -26.2 | | | |
| n | 3 | | | |
| Eastern Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | -25.5 | N/A | N/A | -25.9 |
| Std. dev. | ±1.4 | | | ±1.5 |
| Maximum | -23.7 | | | -22.5 |
| Minimum | -27.1 | | | -28.0 |
| n | 8 | | | 14 |
| Central Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | -22.8 | N/A | N/A | -20.5 |
| Std. dev. | ±0.3 | | | ±0.5 |
| Maximum | -22.5 | | | -20.0 |
| Minimum | -23.1 | | | -21.1 |
| n | 4 | | | 3 |
| Western Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | -21.3 | N/A | N/A | -20.5 |
| Std. dev. | | | | ±0.7 |
| Maximum | | | | -19.0 |
| Minimum | | | | -21.3 |
| n | 1 | | | 8 |

APPENDIX 2 (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|-----------------------------|-----------------|-------------|---------------|-------------|
| <u>Northern Chukchi Sea</u> | | | | |
| Mean | -20.5 | -21.5 | -20.9 | -21.4 |
| Std. dev. | ±0.7 | ±0.6 | ±0.2 | ±2.1 |
| Maximum | -19.3 | -20.1 | -20.5 | -19.3 |
| Minimum | -21.3 | -22.2 | -21.0 | -27.0 |
| n | 10 | 9 | 5 | 13 |
| <u>Eastern Chukchi Sea</u> | | | | |
| Mean | -21.0 | -21.5 | -19.4 | -20.0 |
| Std. dev. | ±1.5 | ±1.7 | ±1.2 | ±2.1 |
| Maximum | -18.7 | -20.5 | -17.2 | -15.1 |
| Minimum | -23.2 | -24.0 | -20.6 | -24.9 |
| n | 9 | 4 | 8 | 20 |
| <u>Western Chukchi Sea</u> | | | | |
| Mean | -19.9 | -20.7 | N/A | -19.7 |
| Std. dev. | ±1.5 | ±0.7 | | ±1.5 |
| Maximum | -17.8 | -19.9 | | -13.8 |
| Minimum | -21.5 | -21.1 | | -21.8 |
| n | 7 | 3 | | 3 |
| <u>Eastern Bering Sea</u> | | | | |
| Mean | -21.3 | -23.1 | -20.1 | -21.3 |
| Std. dev. | ±2.8 | | ±0.4 | ±1.5 |
| Maximum | -19.3 | -21.9 | -19.7 | -18.8 |
| Minimum | -28.6 | -24.3 | -20.5 | -22.8 |
| n | 10 | 2 | 3 | 10 |

APPENDIX 2 (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|-------------------|-----------------|-------------|---------------|-------------|
| Central | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | -21.7 | -21.5 | -20.2 | -19.4 |
| Std. dev. | ±2.0 | ±1.6 | ±1.1 | ±2.2 |
| Maximum | -18.3 | -17.7 | -18.2 | -17.6 |
| Minimum | -25.6 | -24.0 | -22.1 | -23.9 |
| n | 19 | 15 | 11 | 6 |
| Western | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | -22.1 | -22.1 | N/A | N/A |
| Std. dev. | ±1.6 | ±1.5 | | |
| Maximum | -20.0 | -20.4 | | |
| Minimum | -24.8 | -23.3 | | |
| n | 8 | 3 | | |
| Southern | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | -22.2 | N/A | -20.5 | -19.6 |
| Std. dev. | ±2.5 | | | |
| Maximum | -19.9 | | | |
| Minimum | -24.9 | | | |
| n | 3 | | 1 | 1 |

APPENDIX 3. $\delta^{15}\text{N}$ means, standard deviations and range for taxonomic groups by region.

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|------------------------|----------------|-------------------|--------------------|
| Canadian | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | N/A | N/A | N/A |
| Std. dev. | | | |
| Maximum | | | |
| Minimum | | | |
| n | | | |
| Eastern Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | 10.6 | 8.8 | 14.8 |
| Std. dev. | ± 1.4 | ± 2.5 | |
| Maximum | 13.8 | 11.8 | 14.9 |
| Minimum | 8.6 | 6.1 | 14.6 |
| n | 14 | 5 | 2 |
| Central Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | 9.8 | 10.5 | N/A |
| Std. dev. | | ± 0.7 | |
| Maximum | | 11.3 | |
| Minimum | | 10.0 | |
| n | 1 | 3 | |
| Western Alaskan | | | |
| <u>Beaufort Sea</u> | | | |
| Mean | 11.7 | 11.2 | 13.1 |
| Std. dev. | ± 0.4 | ± 0.8 | ± 1.5 |
| Maximum | 12.0 | 12.5 | 16.3 |
| Minimum | 11.3 | 9.4 | 11.0 |
| n | 3 | 11 | 10 |

APPENDIX 3. (continued).

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|---------------------------|----------------|-------------------|--------------------|
| Northern | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | 11.6 | 11.1 | 13.1 |
| Std. dev. | ±0.6 | ±0.8 | ±1.5 |
| Maximum | 12.4 | 12.5 | 16.3 |
| Minimum | 10.9 | 9.4 | 11.0 |
| n | 4 | 11 | 10 |
| Eastern | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | 11.2 | 9.6 | 12.9 |
| Std. dev. | ±1.9 | ±1.7 | ±1.4 |
| Maximum | 15.1 | 13.6 | 15.8 |
| Minimum | 8.4 | 7.1 | 10.8 |
| n | 20 | 15 | 15 |
| Western | | | |
| <u>Chukchi Sea</u> | | | |
| Mean | 11.2 | 10.6 | 11.9 |
| Std. dev. | ±1.8 | ±1.9 | ±1.3 |
| Maximum | 15.2 | 14.8 | 13.5 |
| Minimum | 8.0 | 8.4 | 8.8 |
| n | 20 | 13 | 12 |
| Eastern | | | |
| <u>Bering Sea</u> | | | |
| Mean | 11.0 | 9.8 | 14.0 |
| Std. dev. | ±2.2 | ±2.3 | ±1.4 |
| Maximum | 14.7 | 12.4 | 16.6 |
| Minimum | 6.7 | 4.1 | 11.4 |
| n | 18 | 10 | 16 |

APPENDIX 3. (continued).

| <u>REGION</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> |
|-------------------|----------------|-------------------|--------------------|
| Central | | | |
| <u>Bering Sea</u> | | | |
| Mean | 11.0 | 9.8 | 12.5 |
| Std. dev. | ±2.2 | ±1.6 | ±1.4 |
| Maximum | 14.9 | 13.1 | 15.8 |
| Minimum | 5.0 | 6.6 | 10.0 |
| n | 40 | 25 | 25 |
| Western | | | |
| <u>Bering Sea</u> | | | |
| Mean | 10.2 | 10.2 | 13.5 |
| Std. dev. | ±1.8 | ±1.8 | ±1.9 |
| Maximum | 13.5 | 13.5 | 15.5 |
| Minimum | 7.9 | 8.3 | 11.0 |
| n | 8 | 7 | 6 |
| Southern | | | |
| <u>Bering Sea</u> | | | |
| Mean | 9.0 | 9.1 | 13.7 |
| Std. dev. | ±1.9 | ±1.5 | ±1.5 |
| Maximum | 12.8 | 12.3 | 16.3 |
| Minimum | 5.0 | 7.6 | 11.0 |
| n | 20 | 8 | 10 |

APPENDIX 3. (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|----------------------------|-----------------|-------------|---------------|-------------|
| Canadian | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | N/A | N/A | N/A | N/A |
| Std. dev. | | | | |
| Maximum | | | | |
| Minimum | | | | |
| n | | | | |
| Eastern Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | 10.5 | N/A | N/A | 10.3 |
| Std. dev. | ±2.3 | | | ±1.4 |
| Maximum | 12.3 | | | 13.1 |
| Minimum | 7.9 | | | 8.7 |
| n | 3 | | | 11 |
| Central Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | 12.4 | N/A | N/A | 12.6 |
| Std. dev. | ±0.5 | | | ±0.3 |
| Maximum | 12.7 | | | 13.0 |
| Minimum | 11.8 | | | 12.2 |
| n | 3 | | | 3 |
| Western Alaskan | | | | |
| <u>Beaufort Sea</u> | | | | |
| Mean | 12.2 | N/A | N/A | 12.7 |
| Std. dev. | | | | ±0.4 |
| Maximum | | | | 13.1 |
| Minimum | | | | 11.8 |
| n | 1 | | | 8 |

APPENDIX 3. (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|-----------------------------|-----------------|-------------|---------------|-------------|
| <u>Northern Chukchi Sea</u> | | | | |
| Mean | 11.4 | 11.2 | 11.2 | 11.7 |
| Std. dev. | ±1.0 | ±0.6 | ±2.1 | ±1.2 |
| Maximum | 13.0 | 11.9 | 15.0 | 13.9 |
| Minimum | 9.8 | 10.4 | 9.5 | 8.6 |
| n | 8 | 4 | 6 | 11 |
| <u>Eastern Chukchi Sea</u> | | | | |
| Mean | 12.2 | 10.5 | 11.4 | 14.3 |
| Std. dev. | ±2.7 | | ±1.5 | ±1.5 |
| Maximum | 15.7 | | 13.6 | 17.2 |
| Minimum | 9.3 | | 9.5 | 11.7 |
| n | 7 | 1 | 6 | 20 |
| <u>Western Chukchi Sea</u> | | | | |
| Mean | 11.0 | 11.0 | N/A | 12.5 |
| Std. dev. | ±1.6 | ±0.5 | | ±1.1 |
| Maximum | 13.5 | 11.5 | | 13.7 |
| Minimum | 9.3 | 10.6 | | 10.7 |
| n | 5 | 3 | | 4 |
| <u>Eastern Bering Sea</u> | | | | |
| Mean | 11.3 | 8.3 | 12.7 | 14.0 |
| Std. dev. | ±2.6 | ±3.6 | | ±1.3 |
| Maximum | 17.8 | 11.8 | 14.6 | 16.2 |
| Minimum | 9.0 | 4.6 | 10.7 | 11.2 |
| n | 10 | 3 | 2 | 12 |

APPENDIX 3. (continued).

| <u>REGION</u> | <u>AMPHIPOD</u> | <u>CRAB</u> | <u>SHRIMP</u> | <u>FISH</u> |
|-------------------|-----------------|-------------|---------------|-------------|
| Central | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | 10.0 | 11.0 | 9.3 | 13.5 |
| Std. dev. | ±1.5 | ±1.9 | ±1.4 | ±2.0 |
| Maximum | 13.3 | 15.9 | 12.4 | 15.7 |
| Minimum | 8.2 | 8.7 | 7.7 | 10.1 |
| n | 16 | 16 | 10 | 5 |
| Western | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | 10.7 | 11.0 | N/A | N/A |
| Std. dev. | ±1.2 | ±1.5 | | |
| Maximum | 12.0 | 12.6 | | |
| Minimum | 8.5 | 9.7 | | |
| n | 7 | 3 | | |
| Southern | | | | |
| <u>Bering Sea</u> | | | | |
| Mean | 11.2 | N/A | N/A | 11.2 |
| Std. dev. | | | | |
| Maximum | 14.1 | | | |
| Minimum | 8.2 | | | |
| n | 2 | | | 1 |

APPENDIX 4. Average $\delta^{13}\text{C}$ values for zooplankton collected in the Chukchi and Bering seas (1987-1990).

| <u>CRUISE</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> | <u>AMPHIPOD</u> |
|---------------|----------------|-------------------|--------------------|-----------------|
| <u>HX87</u> | | | | |
| Mean | -21.0 | -19.5 | -21.0 | -19.5 |
| Std. dev. | 0.3 | 0.5 | 0.4 | 0.6 |
| Maximum | -20.7 | -18.8 | -20.1 | -19.1 |
| Minimum | -21.5 | -20.1 | -21.4 | -20.9 |
| n | 7 | 5 | 6 | 7 |
| <u>TH87</u> | | | | |
| Mean | -21.2 | -19.4 | -20.0 | -19.6 |
| Std. dev. | 0.6 | 0.7 | 0.3 | |
| Maximum | -20.1 | -18.6 | -19.7 | |
| Minimum | -22.0 | -20.3 | -20.2 | |
| n | 11 | 6 | 6 | 1 |
| <u>SU87</u> | | | | |
| Mean | -21.4 | -20.3 | -20.6 | -20.2 |
| Std. dev. | 0.9 | 0.8 | 0.4 | |
| Maximum | -20.4 | -18.5 | -20.1 | -19.7 |
| Minimum | -23.7 | -21.8 | -21.4 | -20.6 |
| n | 20 | 11 | 14 | 2 |
| <u>IE88</u> | | | | |
| Mean | -20.2 | -20.0 | -20.1 | -19.9 |
| Std. dev. | 0.5 | 0.3 | 0.5 | |
| Maximum | -19.4 | -19.6 | -19.0 | |
| Minimum | -21.1 | -20.4 | -20.9 | |
| n | 18 | 8 | 17 | 1 |

APPENDIX 4. (continued).

| <u>CRUISE</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> | <u>AMPHIPOD</u> |
|---------------|----------------|-------------------|--------------------|-----------------|
| <u>AK88</u> | | | | |
| Mean | -22.3 | -20.8 | -21.2 | -21.6 |
| Std. dev. | 1.2 | 1.2 | 0.9 | 2.0 |
| Maximum | -20.6 | -17.7 | -19.9 | -17.8 |
| Minimum | -25.8 | -23.4 | -24.0 | -24.9 |
| n | 39 | 27 | 23 | 21 |
| <u>TW88</u> | | | | |
| Mean | -22.5 | -21.7 | -21.3 | -22.1 |
| Std. dev. | 1.8 | 1.7 | 1.1 | 2.2 |
| Maximum | -19.6 | -19.9 | -19.7 | -18.7 |
| Minimum | -26.6 | -25.9 | -23.9 | -25.6 |
| n | 29 | 18 | 17 | 8 |
| <u>SU88</u> | | | | |
| Mean | -23.0 | -21.4 | -20.5 | -22.5 |
| Std. dev. | 0.5 | 0.6 | 0.5 | 2.9 |
| Maximum | -22.2 | -20.1 | -19.7 | -19.3 |
| Minimum | -24.1 | -22.5 | -21.4 | -28.6 |
| n | 16 | 13 | 11 | 8 |
| <u>SU89</u> | | | | |
| Mean | -22.5 | -21.2 | -20.7 | -20.9 |
| Std. dev. | 1.3 | 0.7 | 0.7 | 1.0 |
| Maximum | -18.9 | -19.8 | -19.7 | -18.3 |
| Minimum | -24.7 | -22.6 | -21.9 | -22.7 |
| n | 17 | 17 | 22 | 18 |
| <u>SU90</u> | | | | |
| Mean | -22.6 | -20.6 | -19.9 | -21.3 |
| Std. dev. | 1.0 | 1.2 | 1.0 | 1.4 |
| Maximum | -20.1 | -18.3 | -18.3 | -19.6 |
| Minimum | -24.8 | -23.0 | -21.5 | -23.0 |
| n | 32 | 14 | 19 | 4 |

APPENDIX 5. Average $\delta^{15}\text{N}$ values for zooplankton collected in the Chukchi and Bering seas (1987-1990).

| <u>CRUISE</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> | <u>AMPHIPOD</u> |
|---------------|----------------|-------------------|--------------------|-----------------|
| <u>HX87</u> | | | | |
| Mean | 8.1 | 8.6 | 14.4 | 9.6 |
| Std. dev. | 1.3 | 2.6 | 1.2 | 0.7 |
| Maximum | 6.7 | 11.0 | 16.0 | 10.8 |
| Minimum | 10.7 | 4.1 | 12.8 | 8.7 |
| n | 7 | 5 | 6 | 7 |
| <u>TH87</u> | | | | |
| Mean | 9.6 | 7.4 | 12.9 | 9.0 |
| Std. dev. | 0.9 | | | |
| Maximum | 10.8 | 7.6 | 13.4 | |
| Minimum | 8.4 | 7.1 | 12.4 | |
| n | 5 | 2 | 2 | 1 |
| <u>SU87</u> | | | | |
| Mean | 10.7 | 9.3 | 12.1 | 15.4 |
| Std. dev. | 1.6 | 1.0 | 0.7 | |
| Maximum | 15.0 | 11.0 | 13.2 | |
| Minimum | 9.5 | 7.6 | 11.4 | |
| n | 12 | 7 | 6 | 1 |
| <u>IE88</u> | | | | |
| Mean | 9.2 | 9.2 | 14.4 | 14.1 |
| Std. dev. | 1.7 | 1.6 | 1.2 | |
| Maximum | 12.8 | 12.3 | 16.3 | |
| Minimum | 7.2 | 7.6 | 12.3 | |
| n | 18 | 7 | 15 | 1 |

APPENDIX 5. (continued).

| <u>CRUISE</u> | <u>COPEPOD</u> | <u>EUPHAUSIID</u> | <u>CHAETOGNATH</u> | <u>AMPHIPOD</u> |
|---------------|----------------|-------------------|--------------------|-----------------|
| <u>AK88</u> | | | | |
| Mean | 10.4 | 9.3 | 11.8 | 10.3 |
| Std. dev. | 2.0 | 1.4 | 2.1 | 1.5 |
| Maximum | 14.9 | 13.5 | 15.5 | 13.5 |
| Minimum | 5.0 | 6.6 | 6.0 | 8.2 |
| n | 36 | 27 | 22 | 16 |
| <u>TW88</u> | | | | |
| Mean | 12.7 | 11.5 | 13.3 | 10.8 |
| Std. dev. | 1.4 | 1.4 | 1.1 | 1.9 |
| Maximum | 15.2 | 14.8 | 15.8 | 13.3 |
| Minimum | 10.4 | 9.0 | 11.1 | 8.5 |
| n | 33 | 20 | 22 | 7 |
| <u>SU88</u> | | | | |
| Mean | 11.1 | 11.1 | 14.8 | 11.6 |
| Std. dev. | 1.6 | 0.6 | 1.3 | 3.5 |
| Maximum | 12.8 | 11.7 | 16.6 | 17.8 |
| Minimum | 9.2 | 10.3 | 13.3 | 9.3 |
| n | 4 | 5 | 6 | 5 |
| <u>SU89</u> | | | | |
| Mean | 10.4 | 10.3 | 12.7 | 11.6 |
| Std. dev. | 1.8 | 1.3 | 1.5 | 1.6 |
| Maximum | 13.2 | 12.5 | 16.3 | 15.7 |
| Minimum | 9.2 | 7.8 | 10.8 | 9.3 |
| n | 15 | 16 | 22 | 17 |
| <u>SU90</u> | | | | |
| Mean | 10.5 | 9.6 | 12.0 | N/A |
| Std. dev. | 1.2 | 1.2 | 0.9 | |
| Maximum | 12.2 | 12.4 | 13.9 | |
| Minimum | 8.6 | 8.4 | 10.6 | |
| n | 6 | 10 | 18 | |

APPENDIX 6. Fall-winter baleen $\delta^{13}\text{C}$ values for 17 adult bowhead whales by year.

| <u>WHALE</u> | <u>1989-90</u> | <u>1988-89</u> | <u>1987-88</u> | <u>1986-87</u> | <u>1985-86</u> | <u>1984-85</u> | <u>1983-84</u> |
|--------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 90B8 | -17.88 | -18.48 | -18.22 | | | | |
| 90G4 | -18.42 | -19.04 | -18.44 | -18.20 | -18.01 | | |
| 90B5 | -17.73 | -18.17 | -17.91 | -18.14 | | | |
| 88B11 | | | -17.92 | -18.92 | -17.86 | -18.72 | -18.13 |
| 88KK1 | | | -18.64 | -18.66 | -18.32 | -18.78 | -18.72 |
| 88B9 | | | -18.41 | -18.28 | -18.04 | -19.13 | -18.72 |
| 88B10 | | | -18.61 | -18.48 | -17.93 | -19.08 | -18.72 |
| 88G1 | | | -18.21 | -18.36 | -17.29 | -19.40 | -19.17 |
| 88G2 | | | -18.06 | -18.33 | -17.50 | -19.25 | -18.24 |
| 87N1 | | | | -18.54 | -17.99 | -19.09 | -18.71 |
| 87G2 | | | | -18.80 | -18.06 | -18.59 | -18.25 |
| 87B6 | | | | -18.00 | -17.38 | -18.44 | -18.05 |
| 87B5 | | | | -18.87 | -17.55 | -18.53 | -18.41 |
| 87B4 | | | | -18.56 | -17.67 | -19.06 | -18.68 |
| 86KK2 | | | | | -17.59 | -18.29 | -17.83 |
| 86WW2 | | | | | -17.61 | -18.48 | -17.89 |
| 86WW1 | | | | | -17.88 | -18.26 | -17.89 |

| <u>WHALE</u> | <u>1982-83</u> | <u>1981-82</u> | <u>1980-81</u> | <u>1979-80</u> | <u>1978-79</u> | <u>1977-78</u> | <u>1976-77</u> |
|--------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 90B8 | | | | | | | |
| 90G4 | | | | | | | |
| 90B5 | | | | | | | |
| 88B11 | -18.42 | -18.55 | -17.99 | -17.29 | -17.05 | -17.68 | -17.83 |
| 88KK1 | -18.27 | -18.54 | -18.05 | -17.92 | -18.36 | -18.15 | -18.16 |
| 88B9 | -18.14 | -18.42 | -18.43 | -18.30 | -18.39 | -17.55 | -17.77 |
| 88B10 | -18.61 | -18.67 | -18.39 | -18.59 | -18.49 | -18.19 | -17.81 |
| 88G1 | -18.44 | -18.22 | -18.72 | -18.12 | -17.81 | -17.93 | -17.61 |
| 88G2 | -18.13 | -18.35 | -17.84 | -17.91 | -17.48 | -17.06 | -17.53 |
| 87N1 | -18.63 | -18.85 | -18.37 | -17.92 | -17.42 | -17.31 | -17.50 |
| 87G2 | -18.74 | -18.45 | -17.74 | -18.02 | -17.77 | -17.11 | -17.01 |
| 87B6 | -18.11 | -17.55 | -16.95 | -17.34 | -17.30 | -17.61 | -17.10 |
| 87B5 | -18.60 | -18.10 | -17.95 | -18.06 | -17.93 | -17.56 | -17.87 |
| 87B4 | -18.18 | -18.53 | -17.97 | -18.20 | -18.30 | -18.08 | -17.58 |
| 86KK2 | -18.11 | -17.73 | -17.57 | -17.55 | -17.57 | -16.73 | -17.21 |
| 86WW2 | -17.77 | -17.72 | -17.31 | -17.50 | -17.03 | -16.38 | -17.54 |
| 86WW1 | -17.11 | -17.52 | -17.50 | -17.02 | -17.21 | -17.08 | -17.39 |

APPENDIX 6. (continued).

| <u>WHALE</u> | <u>1975-76</u> | <u>1974-75</u> | <u>1973-74</u> | <u>1972-73</u> | <u>1971-72</u> | <u>1970-71</u> | <u>1969-70</u> |
|--------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 90B8 | | | | | | | |
| 90G4 | | | | | | | |
| 90B5 | | | | | | | |
| 88B11 | -16.95 | -17.08 | -17.36 | -17.85 | -18.00 | -17.66 | -17.52 |
| 88KK1 | -17.66 | -17.49 | -17.74 | -17.77 | -18.08 | | |
| 88B9 | -17.19 | -17.27 | -18.14 | | | | |
| 88B10 | -17.74 | -17.58 | -18.14 | -18.86 | -18.36 | -18.33 | -18.08 |
| 88G1 | -17.21 | -17.06 | -17.21 | -18.13 | -18.28 | | |
| 88G2 | -17.60 | -17.35 | -17.15 | | | | |
| 87N1 | -17.86 | -17.28 | -17.36 | -18.13 | | | |
| 87G2 | -17.06 | -17.29 | -17.85 | -17.89 | -18.20 | -17.75 | -17.93 |
| 87B6 | -16.44 | -17.19 | -17.68 | -16.94 | -17.91 | -18.01 | -17.81 |
| 87B5 | -17.13 | -17.02 | -17.19 | -18.28 | -18.65 | -19.48 | |
| 87B4 | -17.07 | -17.03 | -17.61 | -17.99 | -18.17 | -17.95 | -17.73 |
| 86KK2 | -16.45 | -16.72 | -16.60 | -16.81 | -17.36 | -16.99 | -17.78 |
| 86WW2 | -17.19 | -17.02 | -17.79 | -17.07 | -18.01 | -17.49 | -17.62 |
| 86WW1 | -16.94 | -16.81 | -17.23 | -17.26 | -17.29 | -16.46 | -16.78 |

APPENDIX 7. Fall-winter baleen $\delta^{13}\text{C}$ values averaged by year.

| YEAR | $\delta^{13}\text{C}$ AVERAGE | STANDARD DEVIATION | $\delta^{13}\text{C}$ MAXIMUM | $\delta^{13}\text{C}$ MINIMUM | n |
|-------------|---|-------------------------------|---|---|----------|
| 1989-90 | -18.01 | 0.30 | -17.73 | -18.42 | 3 |
| 1988-89 | -18.56 | 0.36 | -18.17 | -19.04 | 3 |
| 1987-88 | -18.27 | 0.26 | -17.91 | -18.64 | 9 |
| 1986-87 | -18.47 | 0.28 | -18.00 | -18.92 | 13 |
| 1985-86 | -17.78 | 0.28 | -17.29 | -18.32 | 15 |
| 1984-85 | -18.79 | 0.36 | -18.26 | -19.40 | 14 |
| 1983-84 | -18.39 | 0.39 | -17.83 | -19.17 | 14 |
| 1982-83 | -18.23 | 0.41 | -17.11 | -18.74 | 14 |
| 1981-82 | -18.23 | 0.42 | -17.52 | -18.85 | 14 |
| 1980-81 | -17.91 | 0.46 | -16.95 | -18.72 | 14 |
| 1979-80 | -17.84 | 0.42 | -17.02 | -18.59 | 14 |
| 1978-79 | -17.72 | 0.49 | -17.03 | -18.49 | 14 |
| 1977-78 | -17.46 | 0.52 | -16.38 | -18.19 | 14 |
| 1976-77 | -17.57 | 0.31 | -17.01 | -18.16 | 14 |
| 1975-76 | -17.18 | 0.41 | -16.44 | -17.86 | 14 |
| 1974-75 | -17.16 | 0.23 | -16.72 | -17.58 | 14 |
| 1973-74 | -17.50 | 0.41 | -16.60 | -18.14 | 14 |
| 1972-73 | -17.75 | 0.59 | -16.81 | -18.86 | 12 |
| 1971-72 | -18.03 | 0.38 | -17.29 | -18.65 | 11 |
| 1970-71 | -17.79 | 0.80 | -16.46 | -19.48 | 9 |
| 1969-70 | -17.66 | 0.37 | -16.78 | -18.08 | 8 |

APPENDIX 8. Five year running mean sea surface temperature anomalies averaged from April to September (1969-1987).

| <u>Year</u> | <u>Five year running mean sea surface temperature anomalies average (April-September)</u> |
|-------------|---|
| 1969 | -0.250 |
| 1970 | -0.457 |
| 1971 | -0.490 |
| 1972 | -0.558 |
| 1973 | -0.693 |
| 1974 | -0.701 |
| 1975 | -0.469 |
| 1976 | -0.368 |
| 1977 | -0.209 |
| 1978 | -0.070 |
| 1979 | +0.199 |
| 1980 | +0.088 |
| 1981 | +0.172 |
| 1982 | +0.184 |
| 1983 | +0.074 |
| 1984 | -0.083 |
| 1985 | -0.044 |
| 1986 | -0.202 |
| 1987 | -0.435 |

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