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Pacific salmon, Oncorhynchus, concentrate certain gamma-emitting radionuclides (zinc-65, manganese-54, potassium-40, and cesium-137) in their viscera. In some cases the pattern of concentration of radionuclides seems related to the position of the fresh water plume of the Columbia River, a well known source of Zn^{65} in the northeast Pacific Ocean. Fishes whose migratory paths are far south of the river have more Zn^{65}, but less Mn^{54}.

In other cases concentrations can be at least partially explained by differences in feeding habits. The more carnivorous chinook and coho salmon accumulate the highest concentrations of Zn^{65}, Mn^{54} and Cs^{137}. On the other hand, the sockeye, a plankton feeder, has low radioactivity, with Mn^{54} the dominant radionuclide, some Zn^{65}, but no Cs^{137}. The few chum and pink salmon examined most nearly resembled the sockeye in radioactivity.

In southeastern Alaskan waters there is a distinct difference in

relative abundance of Zn^{65} and Mn^{54} in salmon. Manganese-54 is the dominant isotope in salmon of northern Alaskan waters, and Zn^{65} is more prominent in the spectra of fishes from Canadian and contingent United States waters. The Columbia River plume undoubtedly accounts for this increase in Zn^{65}.

To learn the effects of diet on concentration of radioactivity in salmon, stomach contents were removed and analyzed separately. Megalops crab larva concentrated Mn^{54} and Zn^{65}, whereas euphausiids concentrated only Zn^{65}. Spectra of herring and anchovies were similar to those of the salmon.

Separated visceral organs, shellfish, and steelhead trout were also analyzed. The same gamma emitters were present, but in differing amounts.

The radioactivity of salmon viscera clearly indicates that the influence of the Columbia River is widespread. There is some possibility that Zn^{65} and Mn^{54} may serve as ecological tools, complimenting tag studies as a means of tracing migrations.

ARTIFICIAL RADIONUCLIDES IN PACIFIC SALMON

by

NORMAN FREDERICK KUJALA

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ARTIFICIAL RADIONUCLIDES IN PACIFIC SALMON

INTRODUCTION

The Columbia River is a major source of radioactivity in the northeast Pacific Ocean because of the radionuclides introduced by the nuclear reactors at Hanford, Washington. One of these, zinc-65, is found in most marine organisms in waters off Oregon. When it was learned that the viscera of salmon from this area also contained relatively large amounts of Zn^{65}, the likelihood that viscera could be used to monitor the northern-most extension of Columbia River effluent was considered.

Salmon runs occur in coastal streams from California to Alaska, and commercial fisheries exist along the entire range. Thus, viscera could be obtained from salmon taken from 350 miles south to about 2000 miles north of the mouth of the Columbia River. Analysis of these samples should provide a measure of the decrease in Zn^{65} activity with distance from the Columbia River. These data should in turn help further our understanding of the movement of Columbia River water at sea in response to winds and currents. Hopefully, too, background information gained could eventually lead to a method of differentiating salmon of Asiatic stock from those originating in the streams of North America. Since the species are known to intermingle at times, a radioactive tag in the

American fish would help resolve an international problem.

This, then, was the purpose of the study. While not all objectives were realized, the affinity of salmon for radionuclides and the sensitivity of our techniques clearly demonstrate that the influence of the Columbia River extends far north of its anticipated limit.

Zinc-65 was not the only radionuclide present. Under some circumstances, manganese-54 was present in even larger amounts. Cesium-137 was also observed on occasion. Both Mn^{54} and Cs^{137} appear to originate primarily from fallout, rather than the Columbia River. Natural radioactive potassium-40 was also present in all samples.

Differences in the radionuclide content of various species were observed, and some of these differences seem to be related to diet. Some are clearly due to migration, or the lack of it. Therefore it seems likely that data of the type provided in this study could someday prove useful as an ecological tool, supplementing classical techniques already employed.

SCIENTIFIC BACKGROUND

Currents and Water Masses

A summary of the currents off the Pacific Coast of North America shows that the prevailing surface currents off the Oregon coast set toward the south in the summer (May through October) and toward the north during the winter months (Figure 1). Prevailing wind directions are directly correlated with surface currents (Pattullo and Burt, 1961).

Approaching the North American coast from the west, the North Pacific Drift splits at the Great Divergence (approximately 45° N and 135° W) into the Alaska current, flowing north, and the California current, flowing south (Ibid.). Close to the coast the Davidson current flows northward at the surface during the winter months (Burt and Wyatt, 1963).

Drift bottles released 25 miles off the mouth of the Columbia River during the winter have been picked up as far north as Afognak Island, Alaska (63° N and 152° W); Ketchikan, Alaska (56° N and 132° W); and Vancouver Island, Canada (50° N and 127° W)(Ibid.). The average minimum northward velocity determined from drift bottles was 0.4 nautical miles per hour. During the summer, drift bottles released in Oregon waters have been picked up as far south as

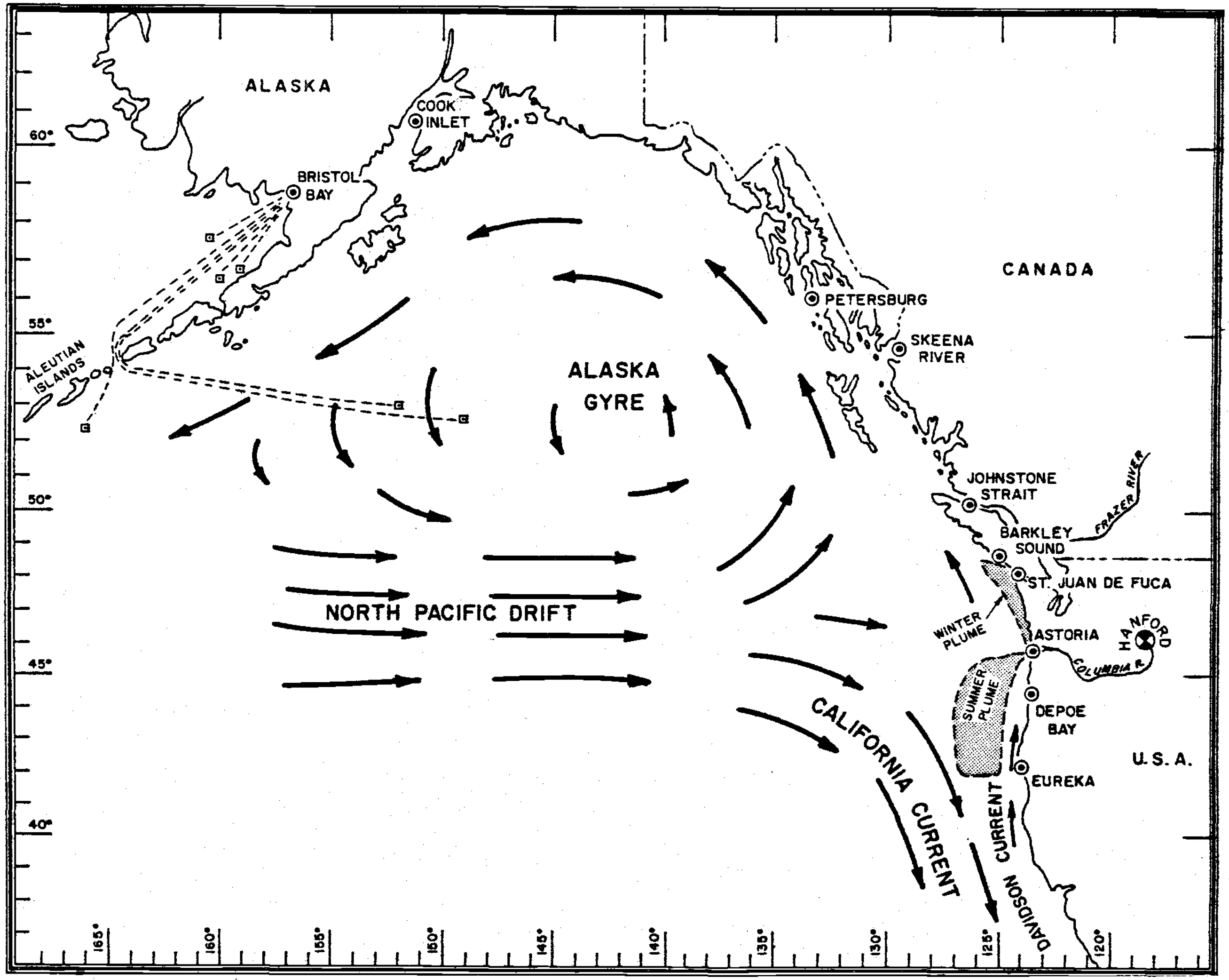

Figure 1. Northeast Pacific Ocean currents in relation to the Columbia River and collecting stations with Bristol Bay tagged fish migration routes.

Monterey Bay, California (37° N and 122° W). The average minimum southward velocity of about 0.3 knots was calculated from O. S. U. Oceanography Department returns.

Columbia River outflow into the ocean follows the prevailing current pattern; i. e., to the north in the winter and to the south in the summer (Figure 1). The Columbia River is present off the Oregon-California coast as a shallow fresh water plume during the summer. This plume, containing water with a salinity of less than 32.5‰, extends in a southwesterly direction over 300 miles off shore and as far south as Cape Mendocino, sometimes forming a pool 100,000 square miles in area (Barnes _et al._, 1964). The yearly maximal discharge of the Columbia, due to melting snows, also occurs in the summer (Kujala and Wyatt, 1961).

In the winter, surface waters are mixed to a greater depth, and the Columbia outflow is diminished, while coastal runoff is maximal. A seasonal change in the winds drives the Columbia plume northward and shoreward. Under these conditions, the plume is masked and not as easily detected by salinity measurements (Osterberg _et al._, 1964). Barnes (1964) reports that during the winter the plume lies inshore as a surface layer about 40 meters thick, and moves along the Washington coast north to the entrance of the Strait of Juan de Fuca, where it intermixes with the effluent waters from that Strait.

Currents and water masses of the Gulf of Alaska and Bering Sea have four significant features (Dodimead et al., 1963)

1. A major gyre with four subsidiary gyres: Bering Sea, Western Subarctic, Okhotsh Sea, and Alaskan. The Alaskan Gyre (Gulf of Alaska) extends along the southern side of the Aleutian Islands.
2. The confluence of the Oyashio and Kuroshio Currents in the Western Pacific.
3. The division of waters off the North American coast (Great Divergence).
4. A strong westward flowing current (Alaskan Stream) immediately south of the Aleutian Islands.

A part of the Oyashio current runs eastward and approaches within 60 miles south of the Aleutians in the vicinity of 180° longitude (Ibid.). The gyres listed are cyclonic (counterclockwise) in circulation. Hebard (1959) reported that Eastern Bering Sea and Bristol Bay currents are generally counterclockwise.

The Aleutian Chain is a barrier to circulation in the Eastern Bering Sea, and the main circulation between the North Pacific and Bering Sea occurs in Asiatic waters. Some Bering Sea water is lost to the Arctic Ocean through the Bering Strait, principally on the surface of the eastern side (Dodimead et al., 1963).

The movement of radioactivity at sea was reported by Lowman

(1952), who found that four months after nuclear tests at Eniwetok and Bikini the radioactivity had moved westward a distance of 1200 miles. This equals a drift of more than nine miles per day. Harley later reported the westward drift extended approximately 4300 miles from Bikini, giving essentially the same speed (Ibid.). These drift rates nearly equal the northward surface current flow off the Pacific Coast, calculated from drift bottle returns. In view of these investigations, it seems probable that Zn^{65} from the Columbia River can be transported into Alaskan waters by surface currents.

Life Histories of Pacific Salmon

All anadromous Pacific salmon spend from 18 months to six years in the ocean. Mature salmon return to their natal streams to spawn and die. A general description of each of the species is compiled in Table 1.

Migration routes published by the Washington Department of Fisheries (Moore *et al.*, 1960) show that chinook salmon migrate great distances, generally north of their natal streams (Figure 2). Coho salmon generally have shorter migratory paths, and the pattern is more random (Figure 3).

Tagging operations carried out on the high seas (Hartt, 1959) make it clear that sockeye, chum, and pink salmon have a more northerly range, and their migratory patterns are more east-west

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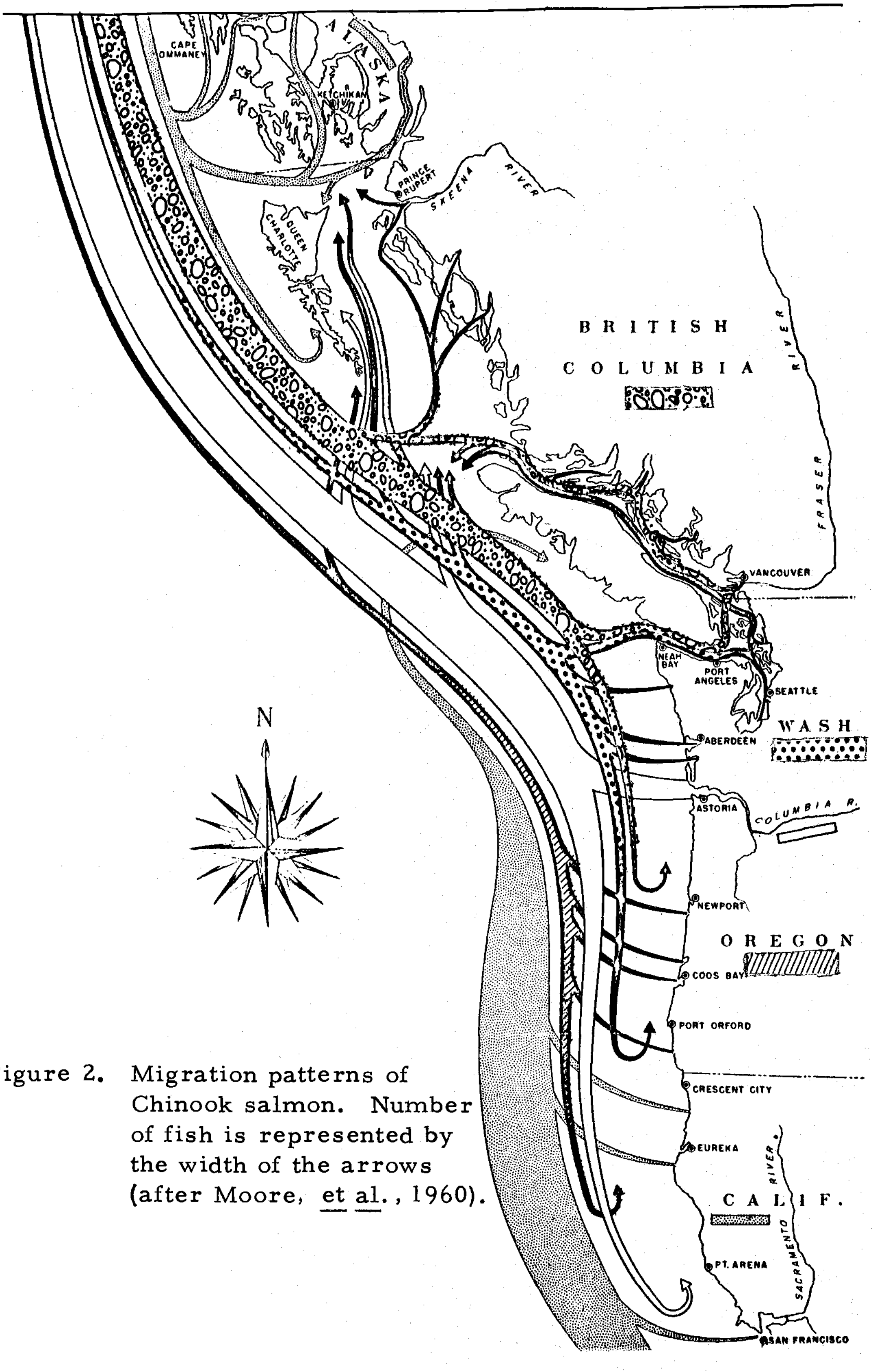

Figure 2. Migration patterns of Chinook salmon. Number of fish is represented by the width of the arrows (after Moore, et al., 1960).

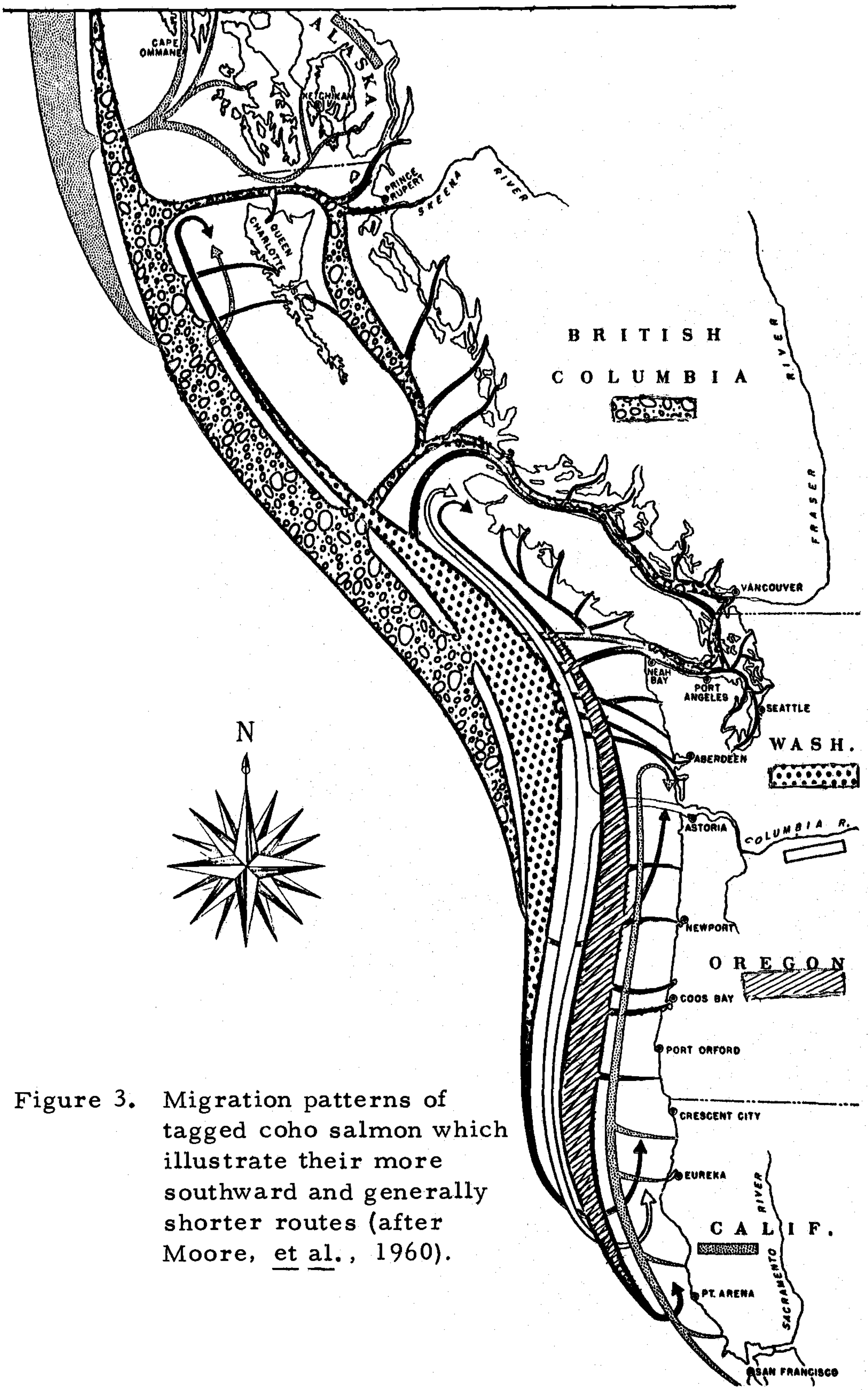

Figure 3. Migration patterns of tagged coho salmon which illustrate their more southward and generally shorter routes (after Moore, et al., 1960).

than the chinook or coho (Figures 4, 5, 6). However, Oregon and Washington chinook, coho, and even steelhead trout, migrate far enough north so that all six species occur near the Aleutian Chain (Figure 7). Ten sockeye salmon analyzed for radionuclides in this study were tagged fish. Their migratory paths (Figure 1) confirm previous determinations of ocean residence for sockeye in the Gulf of Alaska, and along the Aleutian Islands. It is apparent from the tag returns of Hartt that salmon migrate many thousands of miles, and stocks from Asia and North America intermingle in at least portions of their feeding grounds.

Pathways of Radionuclides in the Pacific Ocean

Zinc and manganese are present in enzymes essential to metabolism. Since organisms do not discriminate between different isotopes of a given element, if the radionuclide has the same physical and chemical form as the corresponding stable element, the two are accumulated according to their ratio of abundance. Sources, concentrations, and metabolic functions of zinc and manganese in marine organisms are reviewed below to help explain observed differences of radioactivity in salmon.

Zinc

Zinc-65 (245 day half-life) is a man-made, neutron-induced,

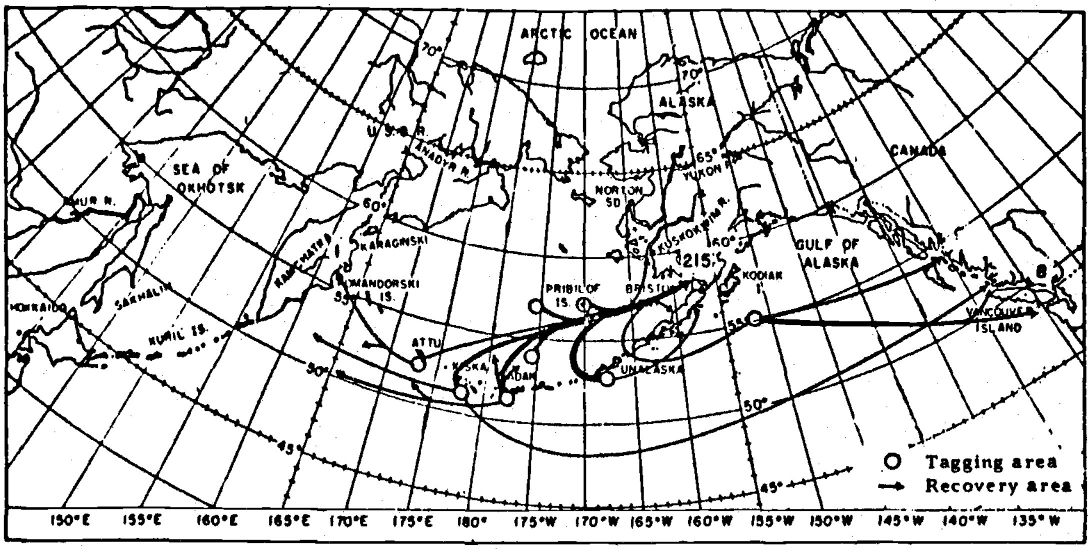

Figure 4. Migrations of tagged sockeye illustrate that American stocks are more numerous than those of Asia (after Hartt et al., 1959).

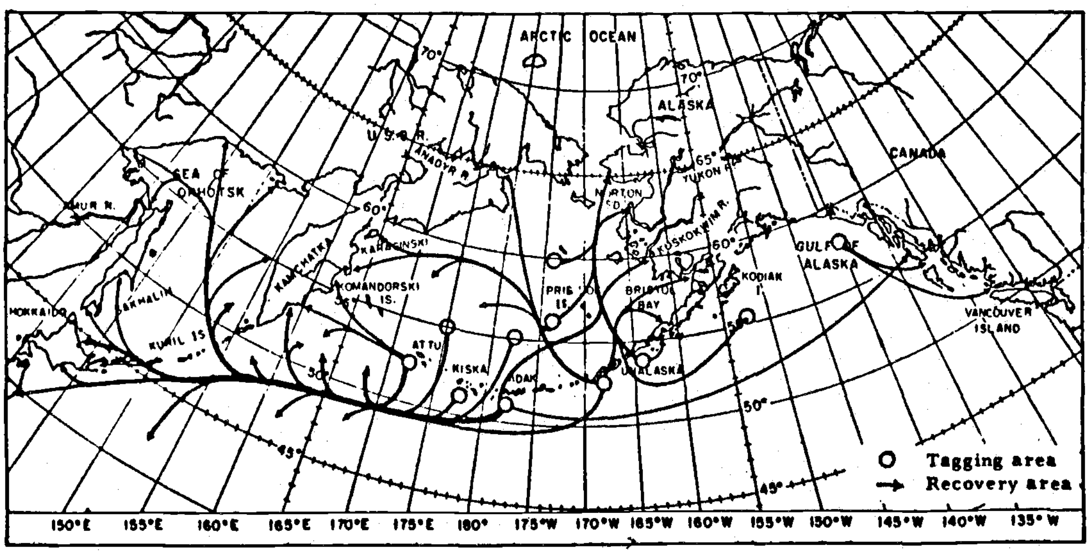

Figure 5. Migrations of tagged chum illustrate the predominance of Asian stocks in northern waters (after Hartt, et al., 1959).

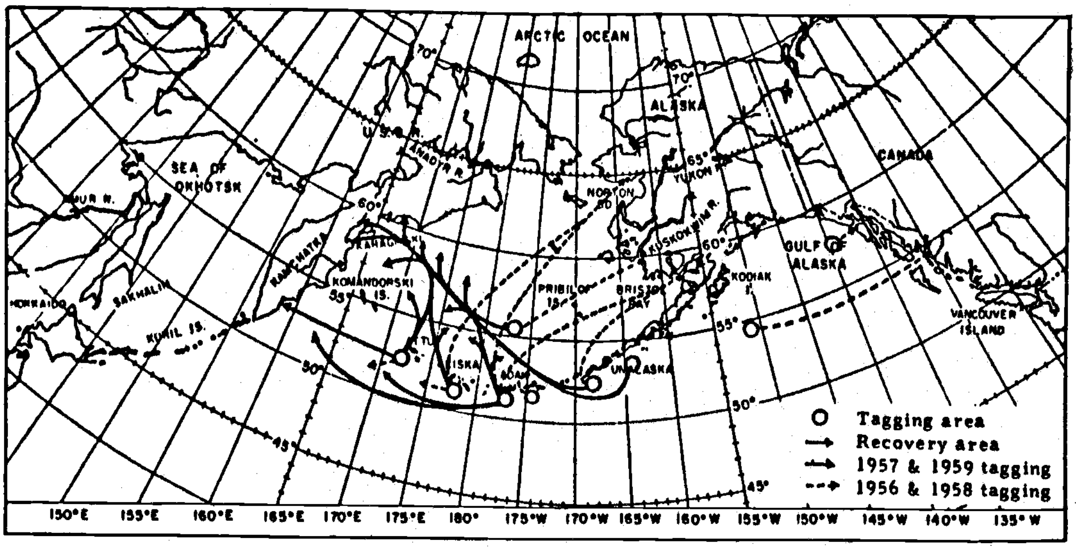

Figure 6. Migration of tagged pinks illustrates their origin depending on year class. Even-year classes are from North America and odd-year classes are from Asia (after Hartt et al., 1959).

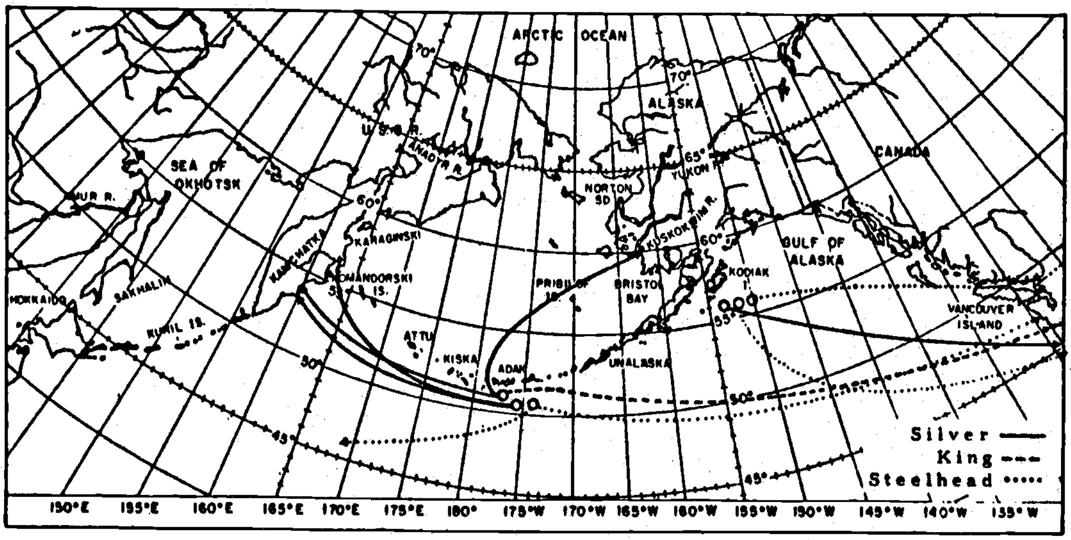

Figure 7. Migration of tagged silver, king and steelhead trout illustrates the intermingling of all species in the Gulf of Alaska and along the Aleutian Chain (after Hart et al., 1959).

gamma emitter, originating both from weapons testing and the cooling waters of atomic reactors. It is not a fission product. At the present time the principal source of Zn^{65} in the northeast Pacific Ocean is the Columbia River (Osterberg et al., 1964). An estimated 38 curies per day of Zn^{65} passes Vancouver, Washington in the Columbia, as a result of nuclear reactor operations at Hanford, Washington. A radioactive pool with an equilibrium value of 14,000 curies of Zn^{65} is maintained in the Pacific Ocean from this source (Nelson, 1961).

Zinc is an essential component of the enzyme carbonic anhydrase, which catalyzes the hydration of CO_2 in tissues such as gills, red blood cells, and vertebrate kidneys (Prosser, 1962; Rice, 1961). Zinc is also found in kidney phosphatase, pancreatic carboxypeptidase, glutamic and lactic dehydrogenases, and the alcohol dehydrogenase of yeast (Prosser, 1962).

Vinogradov (1953) states that in fishes zinc is concentrated in the same organs as iron; i.e., blood, liver, and spleen. Liver and spleen tissue may contain up to 10^{-2}% zinc. Zinc in the tissues of fishes also increases with age. Bertrand and Vladesco (1923) believe that zinc plays a physiological role in fertilization of fish eggs. Leiner and Leiner (1942) found that parts of the eye can concentrate as much as 10^{-10}% zinc. Yakusizi found zinc (0.33%) in the nuclei of erythrocytes, bound in carbonic anhydrase (Ibid.).

Bodansky (1920) reported 0.28 mg. of zinc per 100 gm. wet weight of redfish (sockeye), and Severy (1923) found 0.80 mg. of zinc per 100 gm. wet weight in the chinook salmon. Zinc is present in relatively large amounts in bivalve molluscs, especially *Pecten* and *Ostrea* (0.04% dry weight). Octopus urine contains 170 times as much zinc as does sea water. Crustacea have an average zinc concentration of $n \times 10^{-3}$% in the living matter. Zinc is also present in diatoms and marine algae (Vinogradov, 1953).

The average concentration of stable zinc in sea water varies from 0.005-0.014 gms. per ton (Rankama and Sahama, 1950). Chipman (1958) found a yearly average of 10.8 μg of zinc per liter of seawater at Beaufort, North Carolina. It is obvious that organisms concentrate zinc many times over the amount found in the water.

In view of the concentration factors of zinc in marine biota, it is not surprising that zinc-65 has been found in all levels of the food chain, from plankton to tuna and whales (Osterberg, 1962; Osterberg, Pearcy and Curl, 1964; Osterberg, Pearcy, and Kujala, 1964; Pearcy and Osterberg, 1964).

Manganese

Manganese-54 (310 day half-life) is associated principally with fallout from atomic weapons testing, although it is not a fission product. Manganese-54 is widespread, and marine organisms concentrating it have been detected in many parts of the Pacific Ocean (Folsom, _et al._, 1964).

Manganese occurs in many animals in concentrations from 5 to 10 mg. per 100 cc. of ash (Prosser, 1962). Prosser reports that it may act as a cofactor in oxidative phosphorylation, in L-malic dehydrogenase, and is a functional constituent of liver arganase. In some cases magnesium may substitute for manganese. In fishes, the amount of liver arginase is low in cod, salmon, bullhead, and trout, intermediate in herring, and very high in elasmobranchs.

In general, manganese occurs only in traces in fishes ($n \times 10^{-5}$% of the wet weight), with more in the marine invertebrates (Vinogradov, 1953). In fishes, most of the manganese is in the roe and the liver, with the least amount in the muscles (_Ibid._). Three determinations of manganese show 10.2 mg. Mn/100 g. ash in a coho; 0.9 mg. Mn/100 g ash in a salmon labeled "Fraser River Pink" (_Oncorhynchus kisutch_), and 1.5 mg. Mn/100 g ash in a sockeye (Riddell, 1936).

Other marine organisms containing manganese are plankton, molluscs, and crustacea. Vinogradov (1953) reported that diatoms (_Rhizosolenia_ and _Coscinodiscus_) of the Caspian Sea concentrated manganese, with values ranging from 4.0×10^{-5} to 2.4×10^{-2}% of dry matter. The surrounding seawater contained only $n \times 10^{-7}$% manganese. Thompson and Wilson (1935) found 0.07% manganese in the ash, or n × 10^{-2}% in the dry matter, of Puget Sound plankton (mostly diatoms). In oysters Galtsoff (1942) found high manganese content in the gills and ovaries, especially during periods of reproductive activity. It is also high in freshwater bivalves (Prosser, 1962). On the average, crustacea have about the same concentrations of zinc and manganese, n × 10^{-3}% of the living matter (Vinogradov, 1953). The concentration of manganese in the ocean is only 0.005 mg. per kg. (Sverdrup, et al., 1942); Revelle and Shafer, 1957), indicating that organisms concentrate this element many times over.

Manganese-54 is not a major gamma emitter in the Hanford reactor effluent. It has been measured in some marine organisms from Oregon waters, but it is not as abundant as Zn^{65}. Albacore liver, lantern fish, and rockfishes are examples of samples containing Mn^{54}.

Other Radionuclides

Cesium-137 (30 year half-life) is a nuclear fission product found in fallout. Unlike the other two elements, it is not considered biologically important, and relatively little is known about its distribution in marine organisms (Vinogradov, 1953). However, Cs-137 has been reported by Kolehmainen et al. (1964) in many species of fishes from Lapland lakes. Brown trout had up to 6.53 nanocuries of Cs^{137} per kilogram of fresh weight. This was three to five times more Cs^{137} than was found in the plankton on which they were feeding. Levels of Cs^{137} should be higher in animals from fresh water than from sea water, due to chemical competition from potassium in the latter.

Potassium-40, a naturally occurring radioisotope with a long half-life (1.2×10^9 years) was present in all salmon samples. However, its variations were not of concern in this study.

Other Investigations

The only previous investigation into gamma emitters in adult Pacific salmon, to my knowledge, was conducted by Watson and Rickard (1963). They measured the radioactivity of pink and chum salmon taken at Point Hope, Alaska, which borders the Chukchi Sea in the Arctic Ocean. They obtained the following results:

			Picocuries/g dry weight			
Location	Species		Zn^{65}	Mn^{54}	Cs^{137}	K^{40}
Lagoon	Chum	(entire minus gut contents)	0.22	0.074	0.69	13
Stream	Chum	"	0.26	0.00	0.066	12
Stream	Chum	"	0.19 ±0.053	0.022 ±0.015	0.057 ±0.0089	8.4 ±0.88
Lagoon	Pink	"	1.70	0.23	0.19	12
Stream	Pink	"	1.40 ±0.16	0.19 ±0.022	0.14 ±0.0099	13 ±1.5

These data, like mine, show that fishes from the Chukchi Sea are beyond the influence of Columbia River radioactivity.

Watson, Davis and Hanson (1961) measured some juvenile chinook caught at the mouth of the Columbia River in 1959. The fingerlings had Zn^{65} (62 pc/gm of dry wt.) but no Mn^{54} was detected.

METHODS

Collection of Samples

Salmon used in this study were caught by commercial fishermen in ten areas along the Pacific Coast. Collecting sites were Bristol Bay, Cook Inlet, and Petersburg, Alaska; Skeena River, Barkley Sound, Johnstone Strait, and the Straits of Juan de Fuca, Canada; Astoria and Depoe Bay, Oregon; and Eureka, California (Figure 1). The fishes were caught by gillnets, seines, or hook and line in salt water or at a river mouth. All were taken during the summer of 1964 (June 20 to August 5) except those from Depoe Bay, which were taken from October 15 to 20, 1964.

When salmon were caught the abdominal cavity was opened, and the entire visceral mass was removed, placed in a 32 oz. jar, and preserved with formalin. The preserved samples were shipped back to the Oregon State University laboratory for analysis by gamma ray spectrometry. Stomach samples were obtained from five species of Pacific salmon.

Sample Preparation

The sample tubes were counted 100 to 400 minutes in a Nuclear Data ND 130 AT gamma ray spectrometer (256 channels). Data from each sample were recorded in three ways:

1) The spectrum was plotted with an x-y recorder.

2) A memory readout tape was punched out on Tally paper tape.

3) A digital count for each of the 256 channels was recorded by IBM readout typewriter.

Photopeak counts for each sample were totaled for the three principal isotopes observed (Zn^{65}, Mn^{54} and K^{40}), and an IBM 1620 computer was used to calculate the radioactivity of each gamma emitter in picocuries per gram of dry weight at the time of collection. Later, a similar program was used to determine amounts of cesium-137 in some samples. Techniques followed in radioanalysis are given in more detail elsewhere (Osterberg, 1964).

RESULTS

Chinook

Average spectra of the viscera from two or more chinooks caught at six stations from Alaska to California are illustrated (Figure 8). Relative abundances of Zn^{65} and Mn^{54} are shown in Figure 9, with values listed in Table 2.

Table 2. Artificial radionuclides (pc/gm dry wt.) in Chinook salmon.

Collection location	No. per ave.	Zn^{65}	Mn^{54}
Bristol Bay, Alaska	6	1.77	1.71
Petersburg, Alaska	3	3.45	0.45
Skeena River, Canada	4	3.45	0.18
St. Juan de Fuca, Canada	2	44.88	0.08
Astoria, Oregon	7	49.15	0.04
Eureka, California	4	81.87	0.72

Data in Table 2 show that Zn^{65} and Mn^{54} were very low, and nearly equal in Bristol Bay. This area is the farthest from the Columbia River. At Petersburg and the Skeena River, the Zn^{65} was twice as high as in salmon from Bristol Bay, but the Mn^{54} was much less. In salmon from the Straits of Juan de Fuca, closer to the Columbia River, the Zn^{65} increased markedly, while Mn^{54}

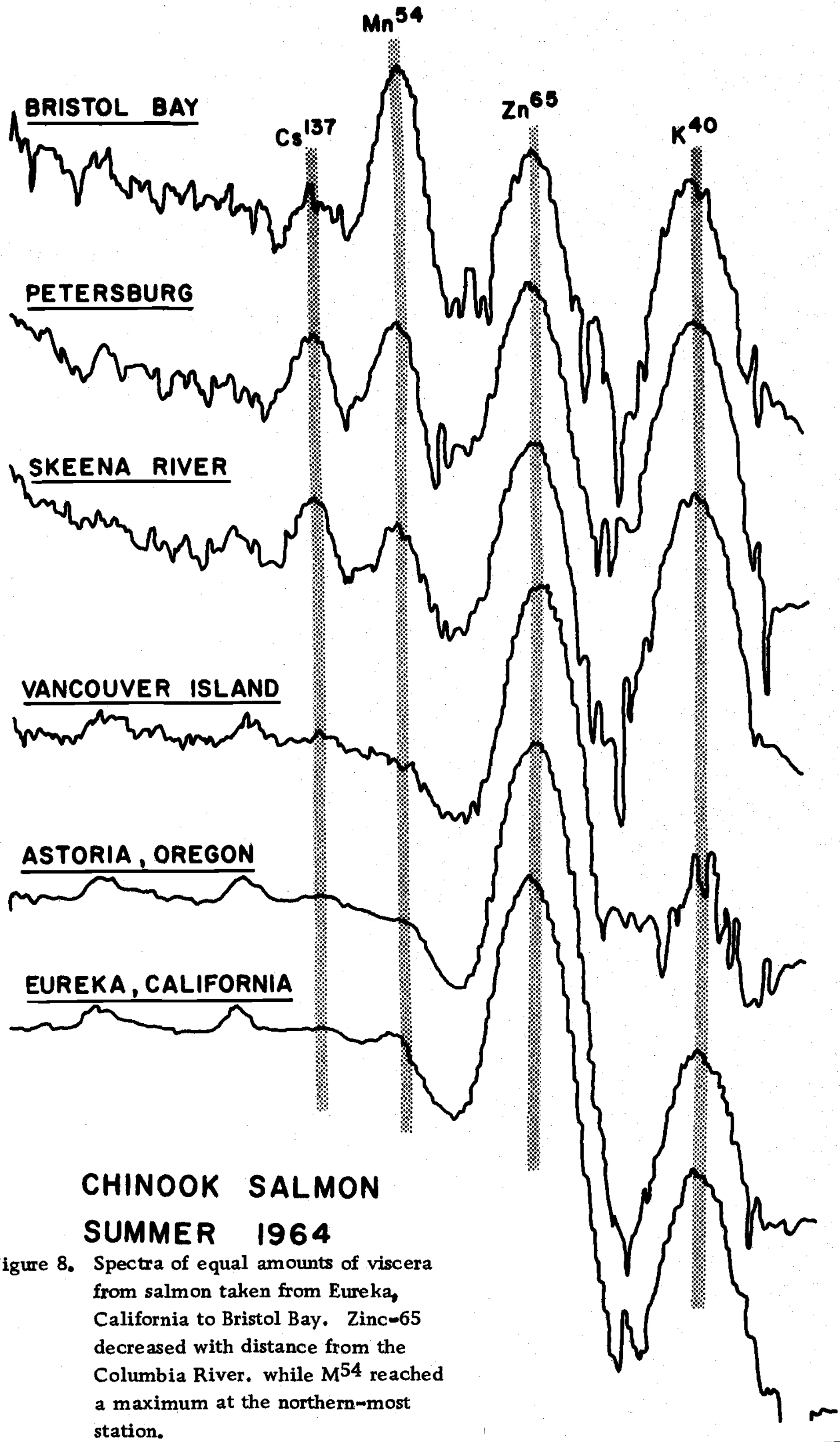

Figure 8. Spectra of equal amounts of viscera from salmon taken from Eureka, California to Bristol Bay. Zinc-65 decreased with distance from the Columbia River, while M^{54} reached a maximum at the northern-most station.

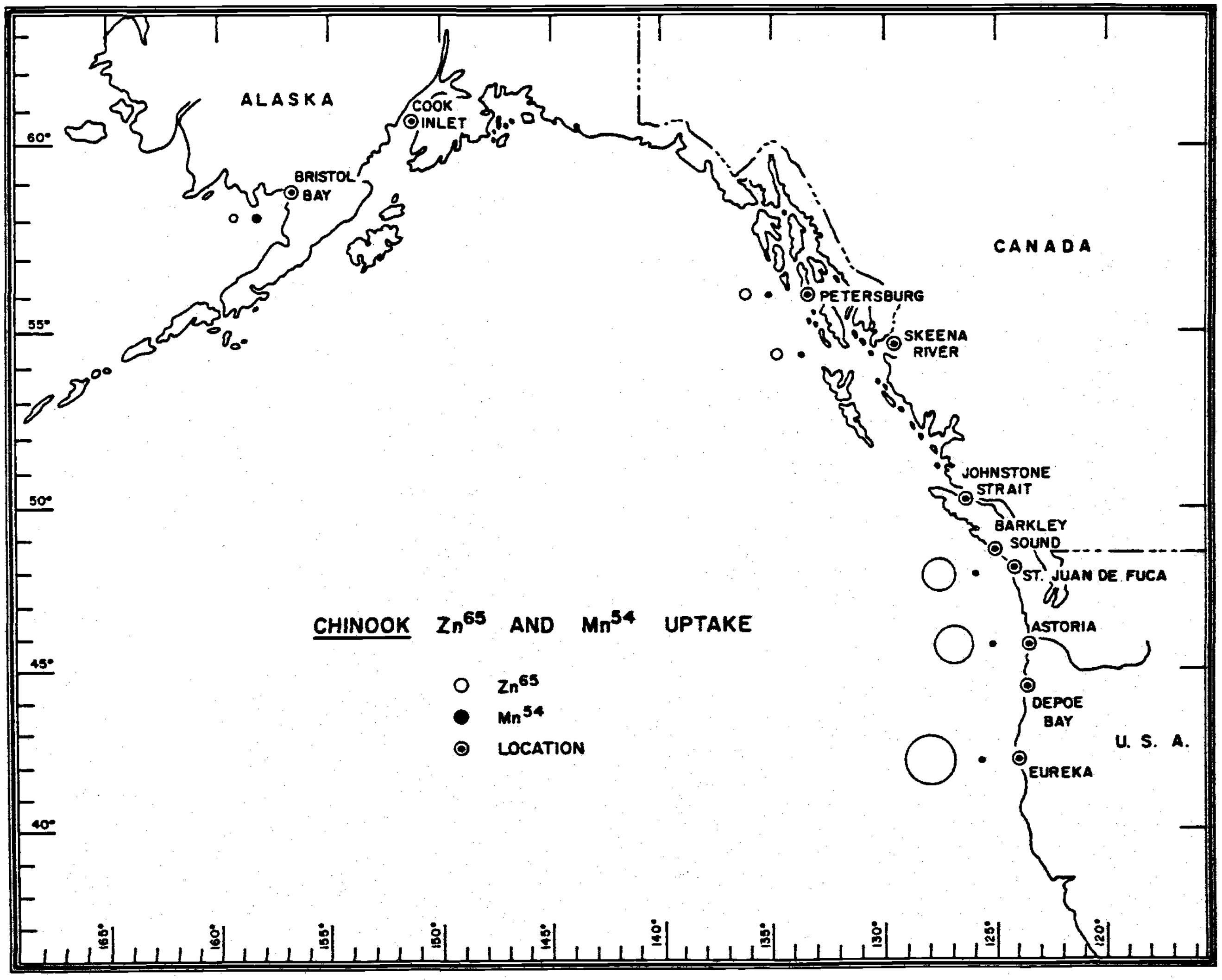

Figure 9. Relative amounts of radioactivity in chinook salmon are represented by the size of the circles offshore from each collecting location. Units are picocuries/gram dry weight.

remained in trace amounts. At the mouth of the Columbia River, near Astoria, the level of Zn^{65} increased slightly. Averaging of the eight Astoria samples obscured the Mn^{54} and Cs^{137} present in three of the samples. At Eureka, California, the southern-most sampling area, four chinook had more Zn^{65} than the salmon collected at any other location. These chinook were caught approximately 350 nautical miles south of the Columbia River mouth. A trace of Mn^{54} was also present.

The spectra of chinook taken at Astoria were of two distinct types. One, type B, showed a high level of Zn^{65} only; the other, type A, had lower Zn^{65} and measurable amounts of Mn^{54} and Cs^{137} (Figure 10).

Sockeye

Figures 11 and 12 illustrate the relative concentrations of Zn^{65} and Mn^{54} in sockeye viscera from six coastal areas in summer. Actual values obtained for all gamma emitters are listed in Table 3. Concentrations of Zn^{65} and Mn^{54} were lower in sockeye than in chinook, and the Zn^{65}-Mn^{54} ratio in sockeye was about the same in all but one of the areas sampled. Manganese-54 predominated in all samples except those from Barkley Sound, where Zn^{65} was slightly higher.

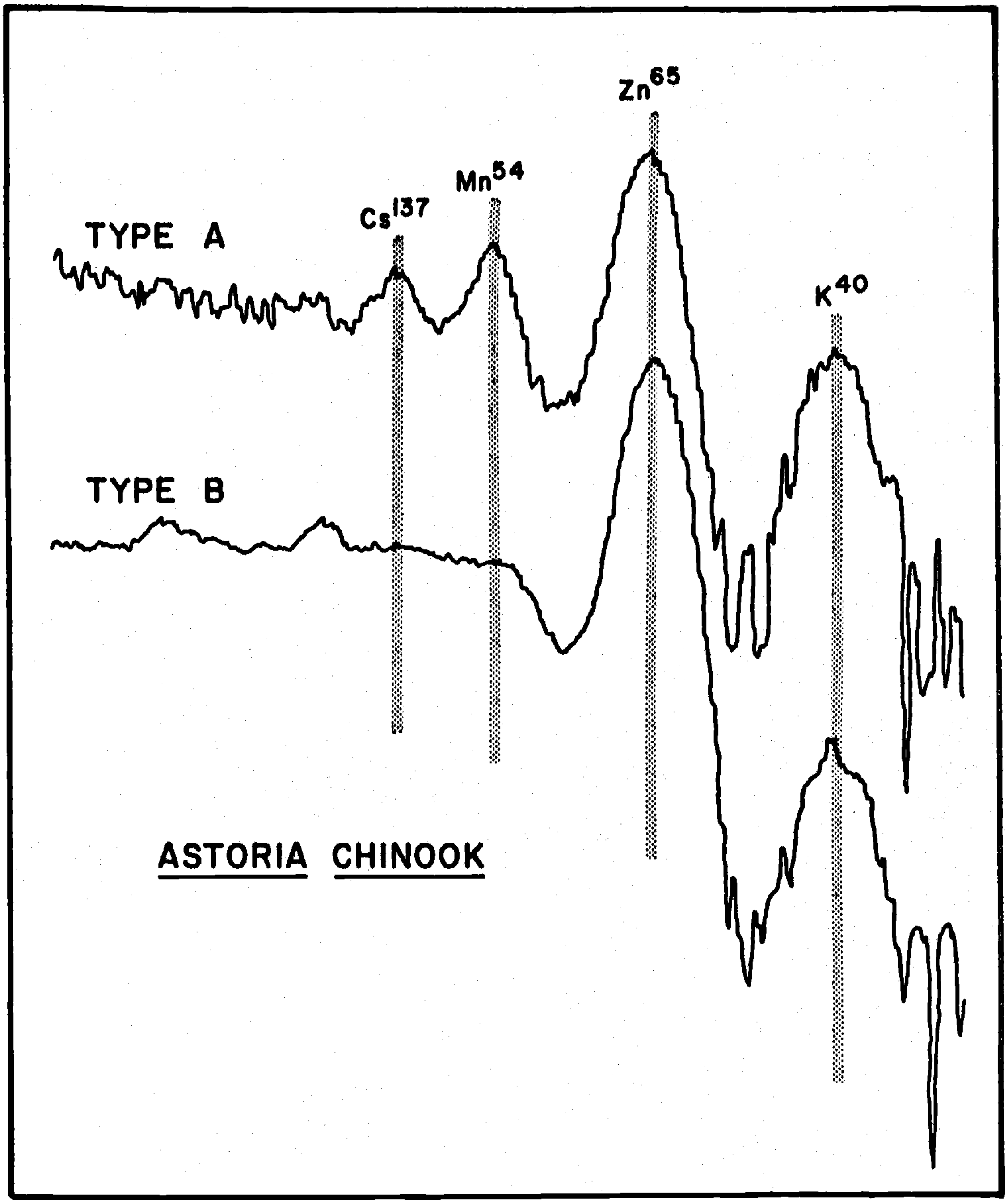

Figure 10. Two types of chinook spectra, possibly indicating different ocean migration routes.

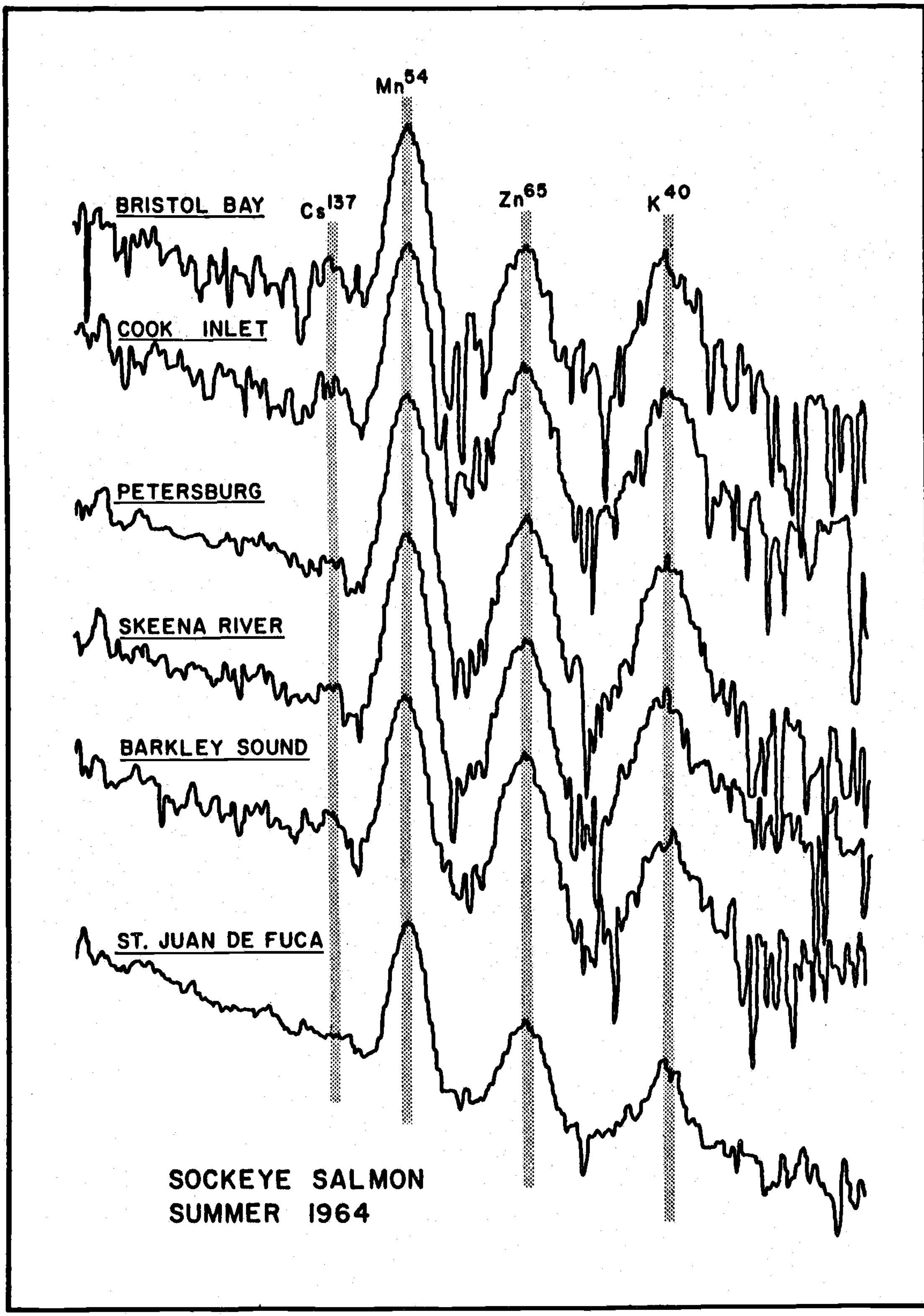

Figure 11. The sockeye spectra are similar in all areas the areas sampled. Mn^{54} is the predominant isotope.

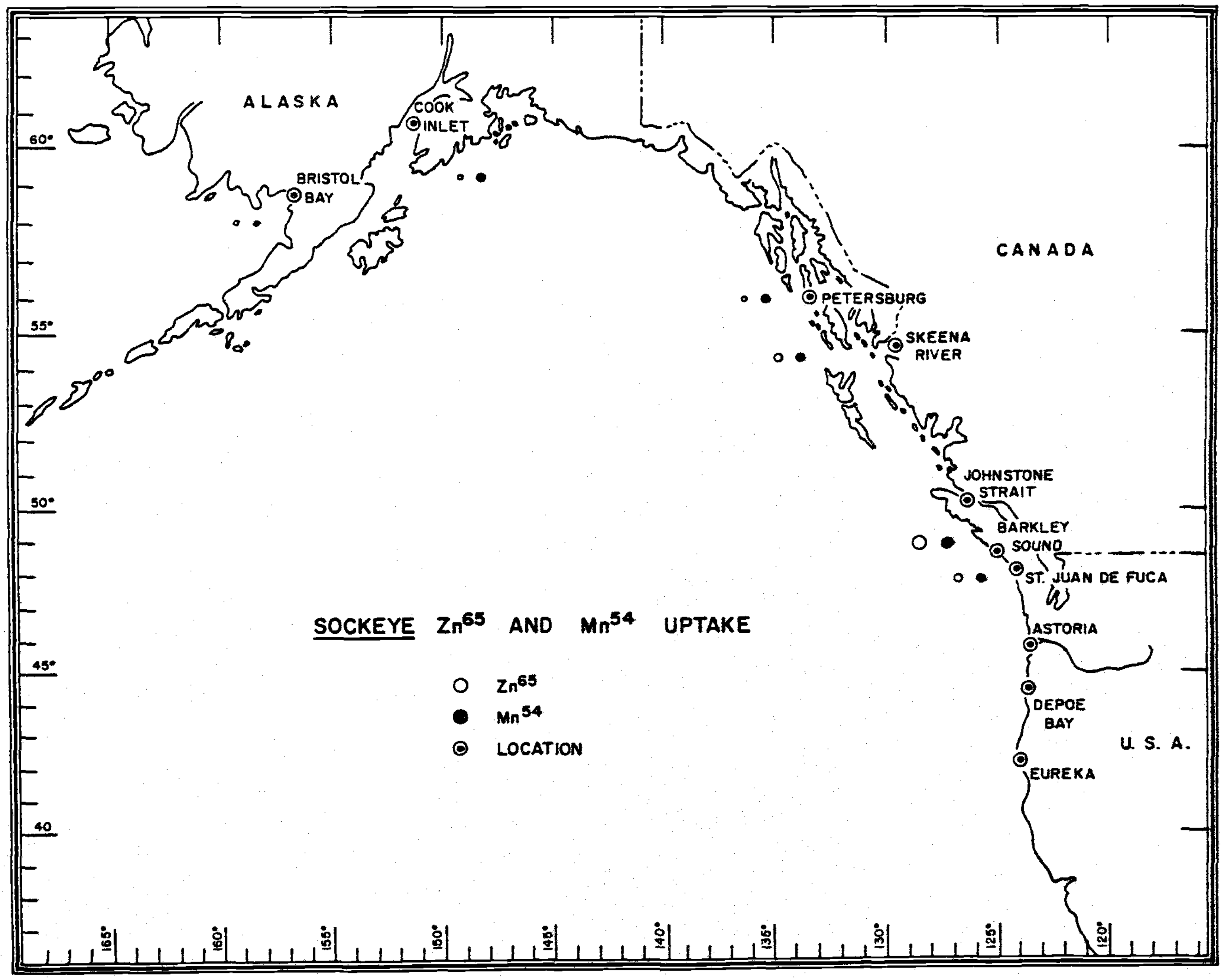

Figure 12. This chart illustrates the low similar radioactivity in all the sockeye samples and no definite increase in Zn^{65} closer to the Columbia River.

Table 3. Artificial radionuclides (pc/gm dry wt.) in sockeye salmon.

Collection location	No. per ave.	Zn^{65}	Mn^{54}
Bristol Bay, Alaska	5	0.86	1.47
Cook Inlet, Alaska	6	1.52	2.70
Petersburg, Alaska	5	1.18	1.91
Skeena River, Canada	5	1.94	2.65
Barkley Sd., Canada	8	5.52	3.24
St. Juan de Fuca, Canada	5	2.28	3.00

Coho

Viscera of coho salmon provided a slightly different picture of coastal distribution of Zn^{65} and Mn^{54} (Figures 13 and 14). The northern-most coho samples were collected at Cook Inlet in Central Alaska, where accumulation of Mn^{54} was the highest of any salmon analyzed (Figure 14). Farther south, between Petersburg and the Skeena River, a distinct reversal occurred and Zn^{65} predominated (Table 4). Coho had higher concentrations of Zn^{65} and Mn^{54} than either chinook or sockeye at this location. Petersburg samples contained more Mn^{54} but less Zn^{65} than Skeena River samples. In the Straits of Juan de Fuca, the Zn^{65} concentration in coho viscera increased, and was similar to the concentration in chinook. On the other hand, the average Mn^{54} concentration was higher in coho than in the chinook. The highest average concentration of

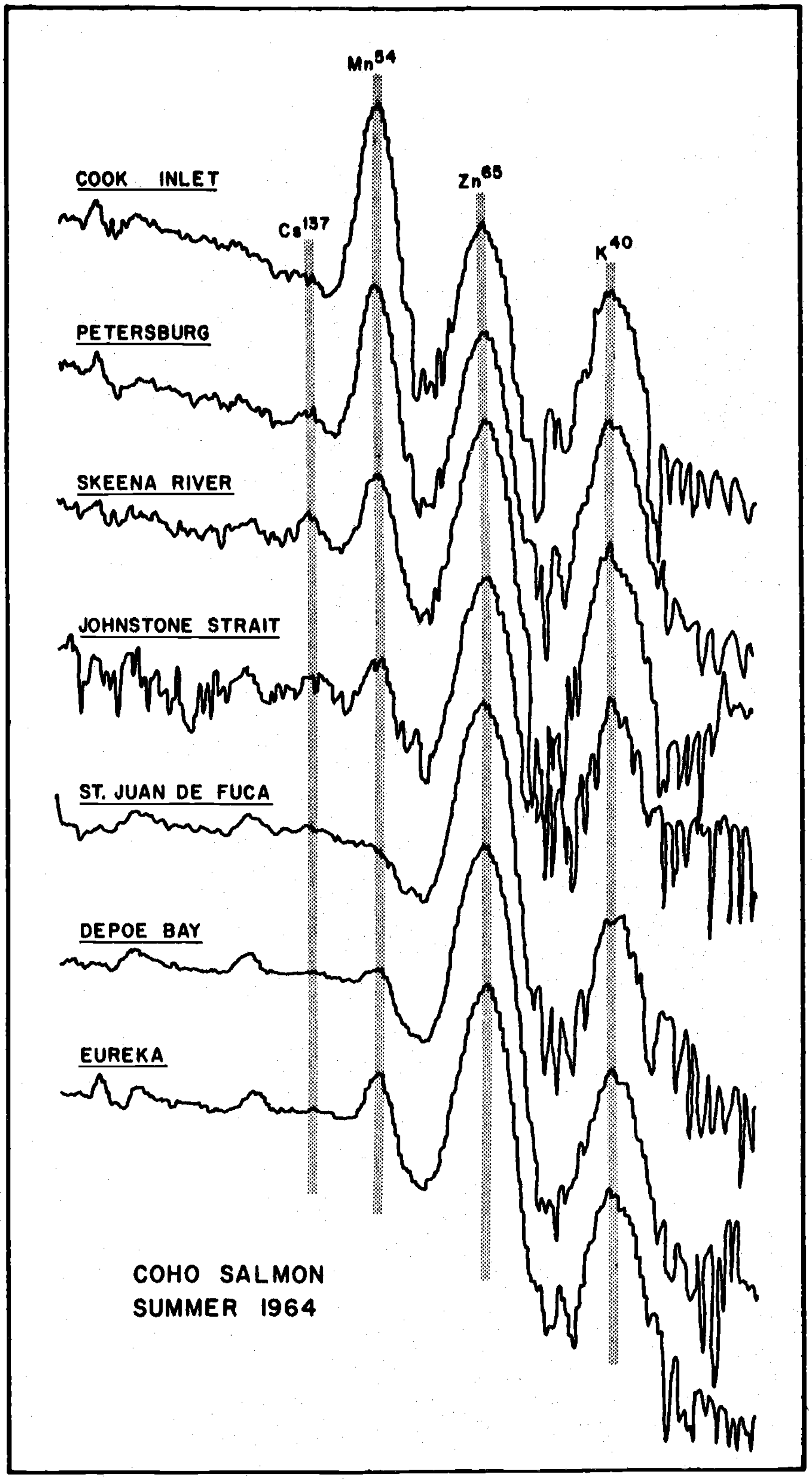

Figure 13. Coho spectra are similar to chinook spectra, with a distinct reversal of the dominant isotope from Cook Inlet to Eureka.

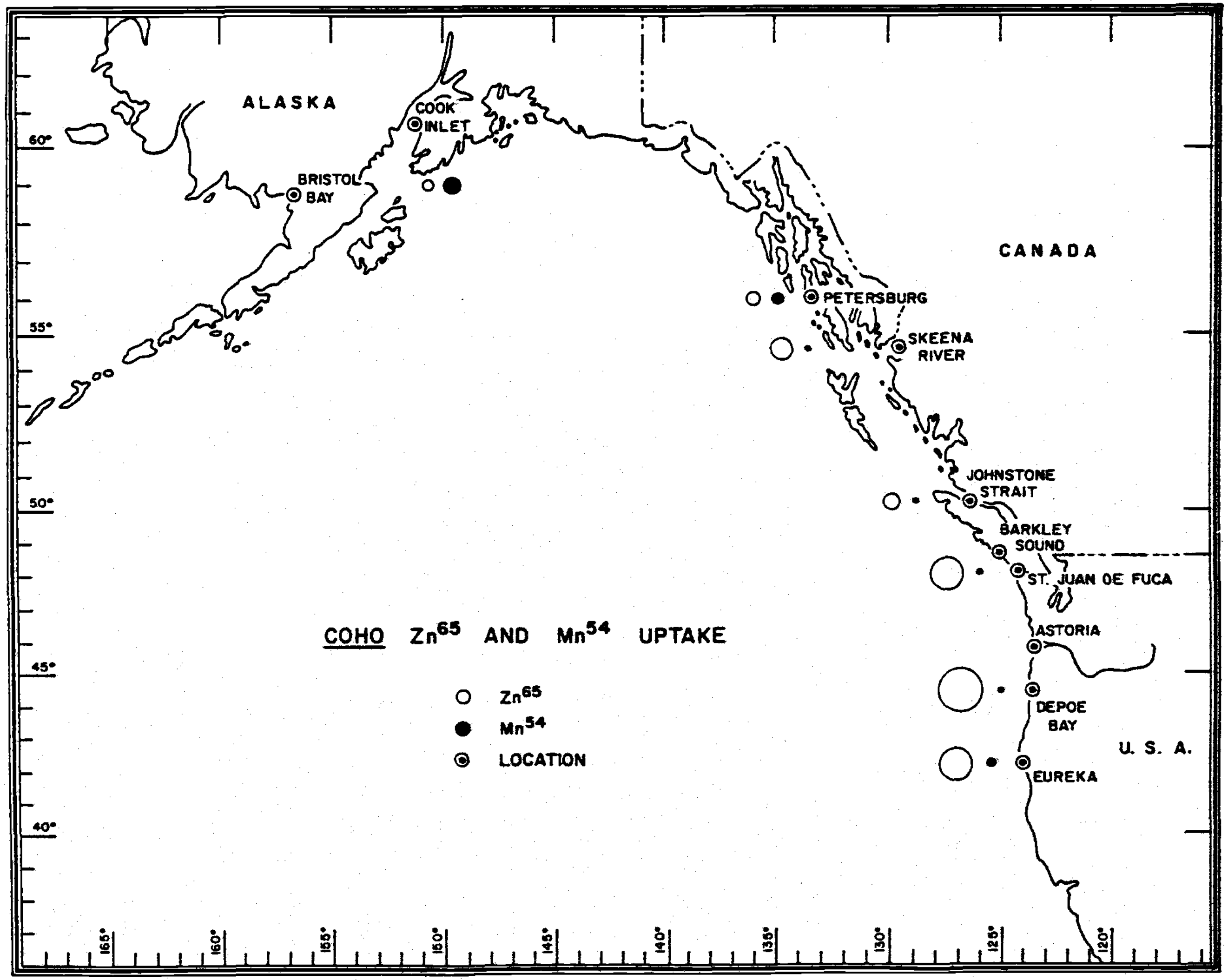

Figure 14. Principal features are the high Mn^{54} concentrations in Cook Inlet samples and the increasing amount Zn^{65} closer to the Columbia River.

Zn^{65} in coho was found at Depoe Bay, but the samples were obtained three months later in the year than the rest of the samples. Depoe Bay is about 75 miles south of the Columbia River. Coho taken at Eureka, the most southern collecting site, were nearly as radioactive as those from Depoe Bay.

Table 4. Artificial radionuclides (pc/gm dry wt.) in coho salmon.

Collection location	No. per ave.	Zn^{65}	Mn^{54}
Cook Inlet, Alaska	5	3.61	8.80
Petersburg, Alaska	5	6.45	4.93
Skeena River, Canada	4	15.02	0.90
Johnstone St., Canada	4	8.74	0.49
St. Juan de Fuca, Canada	4	43.71	1.40
Depoe Bay, Oregon	9	59.28	0.85
Eureka, California	3	44.98	1.73

Pink and Chum

Pink and chum salmon were collected at Cook Inlet and Petersburg, Alaska (Table 5).

Table 5. Artificial radionuclides in pink and chum in pc/g dry weight.

Collection location	Pink			Chum		
	No. per ave.	Zn^{65}	Mn^{54}	No. per ave.	Zn^{65}	Mn^{54}
Cook Inlet, Alaska	-	-	-	3	3.73	3.52
Petersburg, Alaska	3	5.17	1.49	2	2.76	2.60

The small pink salmon (two-year life span) taken at Petersburg concentrated more Zn^{65} than chum and sockeye from that area.

Petersburg	Zn^{65}	Mn^{54}
Pink	5.17 pc/g	1.49 pc/g
Sockeye	1.18	1.91
Chum	2.76	2.60

The chum salmon had concentrations similar to but slightly higher than the sockeye, i.e., nearly equal amounts of the two isotopes. Pink salmon spectra more closely resembles the coho.

No cesium-137 was measured in either the pink or chum.

The foregoing spectra have illustrated the differences or similarities of one salmon species taken from different locations, showing the effect of environment on concentrations of radionuclides in the viscera. It was also desirable to know the variations of radioactivity in the several species collected at the same station at the same time. This was not possible, since, as was noted, some species of salmon follow different migratory routes, and spawn at different times of the year. However, Petersburg is centrally located, and all five species of salmon were taken there at fairly short intervals in time; thus, comparisons were made at this location.

A comparison of spectra of all salmon species from Petersburg showed some differences (Figure 15). Most notable were the lower Mn^{54} peak and higher Cs^{137} peak in the spectrum of the chinooks.

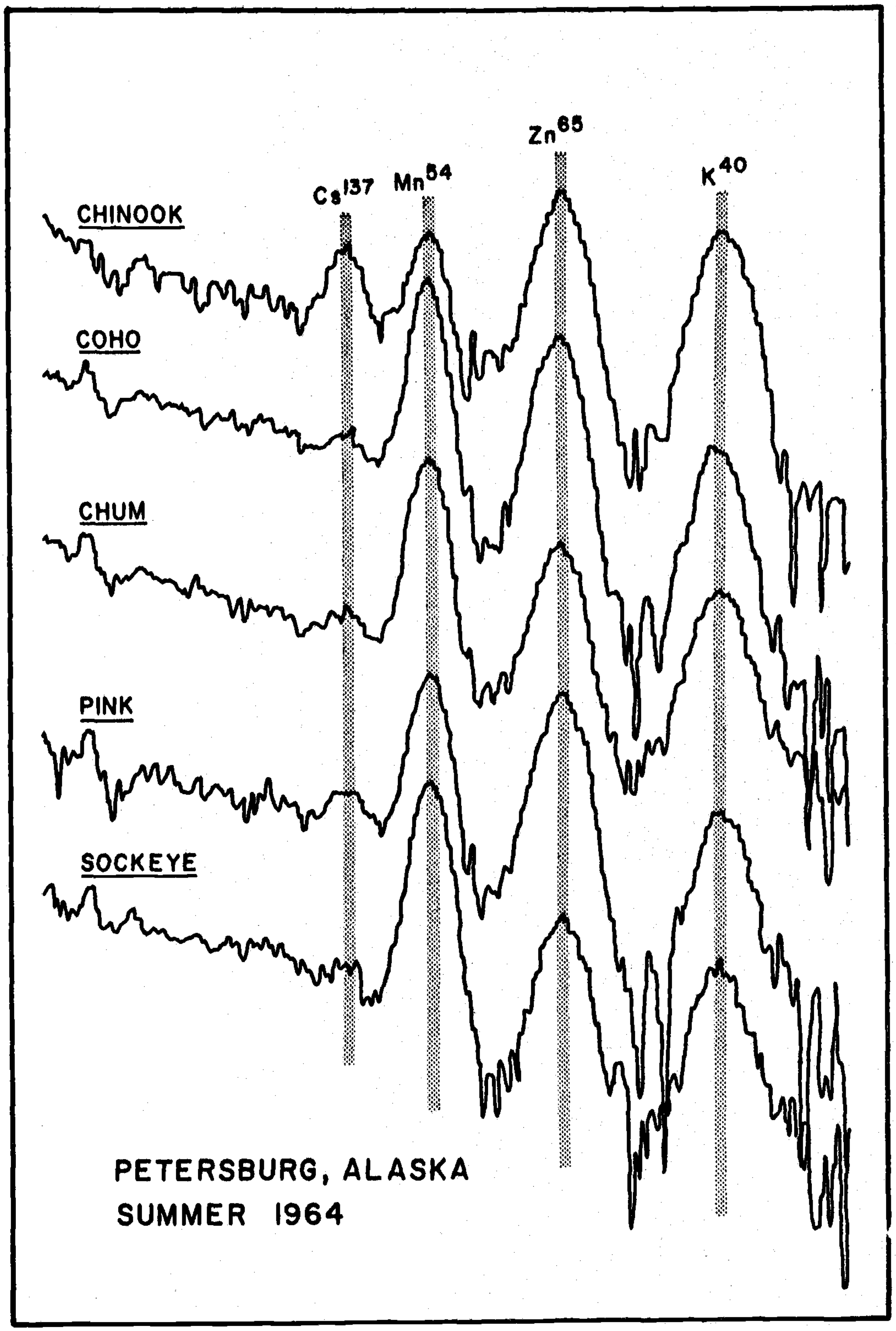

Figure 15. Spectra of all five species taken in the same area illustrate the differences by species especially accumulation of Cs^{137} in chinook.

Visceral Organs

Viscera of several salmon were separated, and the organs were counted individually to determine if any part might have an affinity for a particular radionuclide. Organs analyzed were the liver, pyloric caeca, empty stomach, ovaries or testes, and gills. Two difficulties were encountered:

1) Sample size was often too small for definitive results.
2) The relatively high levels of Zn^{65} present in some samples made analysis of Mn^{54} difficult.

A definite affinity for a particular isotope was difficult to demonstrate. However, the liver and ovaries seemed to concentrate Mn^{54} more than the other visceral organs. This might be expected because Vinogradov (1953) found higher concentrations of stable manganese in the liver and roe of fishes. The gills of two Petersburg coho salmon actually contained the most Mn^{54} of the different organs counted (ave. 12.1 pc/gm). In 1963 some Depoe Bay coho examined showed the highest concentrations of Zn^{65} in the pyloric caeca (ave. 151.21 pc/gm). No other definite concentrations by any visceral organ or salmon species was noted.

Stomach Contents

The majority of salmon stomachs analyzed were empty, or nearly empty, because most were caught during their spawning migrations, and had discontinued feeding. However, stomach contents of ten coho and chinook salmon were separated, identified, and analyzed for artificial radionuclides. Principal components of the diet of these salmon were herring, anchovies, euphausiids, crab larvae, and rockfishes.

Levels of radioactivity of the stomach contents were generally similar to those of the stomachs from which they were removed. Herring taken from three coho stomachs obtained in the Petersburg area had Zn^{65} and Mn^{54} concentrations similar to their coho predator (Table 6). Zinc-65 was the dominant radioisotope in the herring averaging $\sim$9 pc/gm.

At Depoe Bay the herring and anchovies found in two coho stomachs were somewhat similar to their predator and much higher in Zn^{65} ($\sim$52 pc/gm) than the Petersburg stomach contents (Table 6). The anchovies had also concentrated significant amounts of Mn^{54} as had coho that had eaten them. Only one other coho of the nine Depoe Bay samples had a measureable amount of Mn^{54}.

Farther south, the stomach contents of five salmon caught at Eureka had the highest concentrations of Zn^{65} along the coast ($\sim$100 pc/gm) as did their predator (Table 6). Other interesting Zn^{65} concentrations were noticed in the Eureka sample. One coho contained Dungeness crab megalops (Cancer magister). Two chinooks

Table 6. Stomach contents and corresponding viscera results.

Zn^{65} and Mn^{54} of stomach contents (picocuries/gm. of dry weight)				Zn^{65} and Mn^{54} of corresponding salmon viscera (picocuries/gm. of dry weight)		
Species	Location	Zn^{65}	Mn^{54}	Species	Zn^{65}	Mn^{54}
Herring, Clupea sp.	Petersburg	4.06	0.85	Coho	6.43	3.03
"	"	7.70	2.81	"	5.30	4.10
"	"	14.57	3.80	"	7.39	4.48
"	Depoe Bay	52.28	0.22	"	33.03	0.14
Anchovies, Engraulis sp.	"	52.76	1.91	"	99.57	3.27
Euphausia sp.	Eureka	43.04	0.57	Chinook	39.88	0.27
"	"	*25.50	*0.13	Chinook	111.04	2.02
"	"	*5.55	*0.44	} Coho	46.72	4.11
Megalops, Cancer magister	"	*11.61	*2.08			
"	"	124.11	8.18	Coho	54.24	0.14
Young rockfishes (5) Sebastodes sp.	"	122.50	5.71	"	34.00	0.94
Tapeworms (parasites)	Bristol Bay	7.98	5.20	Chinook	1.67	4.69

*Values in pc./gm. of wet weight which may be multiplied by five to give an estimate of similar dry weight values.

were full of euphausiids (Euphausia sp.), small shrimp-like crustacea. A fourth coho had gorged itself on both megalops and euphausiids, and the fifth coho had eaten five small rockfishes. The euphausiids concentrated only Zn^{65}, and the megalops crab larvae concentrated both Zn^{65} and Mn^{54}. The spectra for these two food items are shown in Figure 16. The rockfishes were exceedingly high in both Zn^{65} and Mn^{54} (Table 6).

A comparison of Zn^{65} and Mn^{54} in salmon visceral mass and prey did not often indicate an increased concentration in the salmon. For instance, crab megalops had 124.11 pc/g of Zn^{65} and 8.18 pc/g of Mn^{54}, whereas the viscera of the coho which had eaten them contained only two-fifths as much Zn^{65} (54.24 pc/g) and one-fiftieth as much Mn^{54} (0.14 pc/g). In most cases, the Zn^{65} concentrations were higher in the prey than in the predator (Table 6). However, in the oven-drying process (60° C), small organisms were dried more thoroughly in 24 hours than the much larger salmon viscera samples. This difference could account for higher values in pc/g dry weight in the stomach contents.

Other Analyses

Shellfish, crab larva and steelhead trout were other items analyzed in an attempt to determine the pathways of some of the

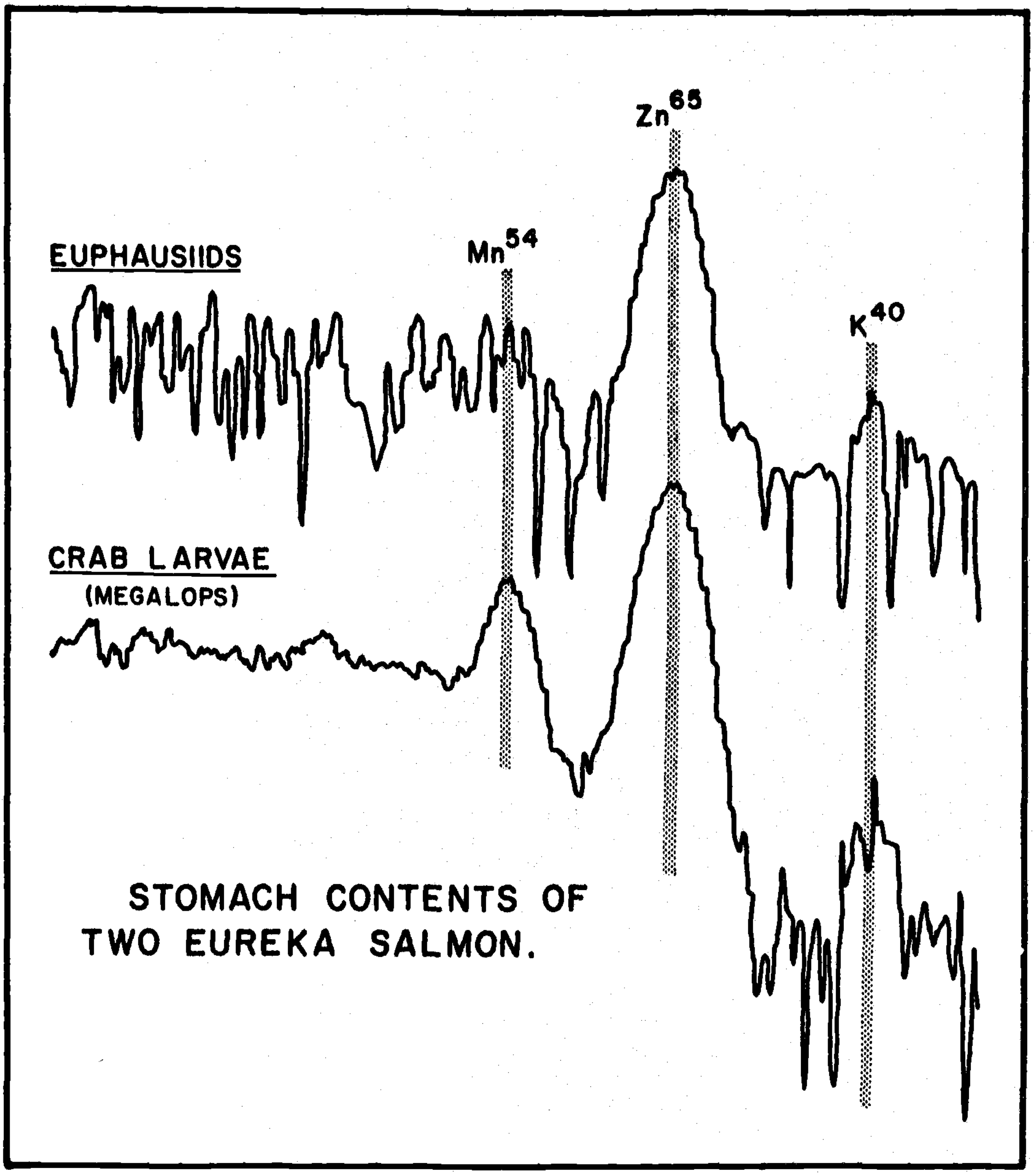

Figure 16. The two spectra illustrate the differences in radioisotope concentration by salmon food organisms. Zn^{65} and Mn^{54} in crab larvae and only Zn^{65} in euphausiids in the same area.

artificial radionuclides (Table 7).

The shellfish were counted to determine background radioactivity of the area in which the migrating salmon were caught. Unfortunately, shellfish were secured in only three areas where the salmon were taken. However, mussels (Mytilus californianus) have been measured previously along the Pacific coast by Watson et al. (1961) and Osterberg (1965). These authors indicated that the mussels off the coast of Oregon and California showed a gradual drop in Zn^{65} concentration with increase in distance southward from the Columbia River. Similarly, the Zn^{65} content decreased north of the Columbia River.

In my study, the six mussels, Mytilus sp., taken at Bristol Bay were shucked and dried for counting. Levels of radioactivity were so low they were barely detectable and the standard deviation increased to ±50%.

The 21 mussels from Petersburg contained traces of Zn^{65}, Mn^{54}, and Cs^{137} (Table 7). Similar amounts were found in clams (Siliqua spp. and Clinocardium spp.) collected farther north at Cook Inlet. Crab larvae (megalops stage) collected in Cook Inlet also contained traces of Zn^{65} and Mn^{54}. These low values may indicate the background radioactivity present in the North Pacific due to fallout, rather than from the influence of the Columbia River.

The steelhead trout (Salmo gairdneri) is a sea-going, close

Table 7. Related items radioanalysis.

Sample	No.	Collection location	Picocuries/gram of dry weight		
			Zn^{65}	Mn^{54}	Cs^{137}
Mussels, Mytilus sp.	6	Bristol Bay, Alaska	*1.48	*0.67	nd
Mussels, Mytilus sp.	21	Petersburg, Alaska	0.80	0.54	0.28
Razor clam, Siliqua sp.	1	Cook Inlet, Alaska	0.32	0.25	nd
Cockles, Clinocardium sp.	3	"	0.84	0.33	nd
Crab megalops			0.39	0.14	nd
Steelhead trout, Salmo gairdneri	1M	Alsea River, Oregon	2.92	1.25	nd
Steelhead trout, Salmo gairdneri	1M	"	3.60	1.34	nd

*± 50%.

relative of the Pacific salmon. Two viscera samples of this species, caught December, 1964 in the Alsea River, Oregon, were analyzed. Concentrations of Zn^{65} and Mn^{54} in the two male steelhead were much lower than in chinook and coho taken in Oregon waters.

DISCUSSION

When this thesis problem was conceived, it was hoped that several species of salmon could be collected concurrently from many of the areas which have commercial fisheries. This was not practical because the salmon runs do not occur simultaneously. For example, summer collections at Cook Inlet, Alaska were too late to sample the chinook runs, which had already been completed. Other gaps in the data appear where collections failed, but, fortunately, these gaps are few and some major features can be seen in the pattern of radionuclide concentration in salmon.

Chinook

There are several trends in the concentration of radionuclides in chinook salmon. First, low but nearly equal levels of Zn^{65} and Mn^{54} ($<$ 2.0 pc) were present in the Bristol Bay samples. Bristol Bay is north of the Aleutian Islands (Figure 1). These islands provide a barrier to intensive intermixing of Alaskan current surface waters with those of Bristol Bay and the Bering Sea (Dodimead, et al., 1963). Information on the migration routes of Bristol Bay chinook is scarce, but International North Pacific Fisheries Commission tag returns indicate that chinook are abundant in the Bering Sea during early summer, and in the vicinity of the central Aleutians later in the summer. Assuming that the Bristol Bay chinook spends its ocean life in the central North Pacific and Bering Sea, low Zn^{65} concentrations in the fish would be expected because of the great distance from the Columbia River (2500 miles).

There are no plausible explanations for the Mn^{54} concentrations at this time, although it may be noted that samples from northern waters with low Zn^{65} concentrations had the highest Mn^{54} concentrations. It is apparent that the Zn^{65} and Mn^{54} had different origins.

The second major factor in radionuclide concentration in chinook was that a marked decrease in Zn^{65} levels and the ratio of Zn^{65} to Mn^{54} occurred in fish caught between the Skeena River and Straits of Juan de Fuca. The distinct changeover in the dominant radionuclide may indicate that the southeastern Alaska area is the northern limit of Columbia River influence. There was less Zn^{65} in food organisms in Alaskan waters than in waters influenced by the river; hence, salmon feeding solely on food not affected by the river would concentrate less Zn^{65}. Chinook from the Straits of Juan de Fuca definitely had higher Zn^{65} levels, indicating their association with Columbia River water. Columbia River water is detectable in this area during the winter (Barnes, 1964).

The highest Zn^{65} concentrations occurred in chinook caught 350 miles south of the Columbia River, off Eureka, California. The best explanation for these high concentrations is that these fish spend nearly all of their adult life associated with Columbia River plume water, and eat the food organisms found in the plume. Osterberg et al. (1964), found higher Zn^{65} concentrations in euphausiids 100 miles south of the Columbia River in summer than those collected 15 miles off the mouth of the river. This indicates a lag in maximum Zn^{65} concentration. As mentioned previously, radiozinc is also found in mussels (Mytilus californianus) from as far south as northern California. However, there are pockets of lower Zn^{65} concentrations in mussels associated with areas of upwelling along the coast near the Oregon-California border (Osterberg, 1965).

Columbia River plume waters have been traced as far as San Francisco, California 600 miles south of the river's mouth (Reid, et al., 1958). Animals that make up the diet of salmon (euphausiids, copepods, crustacean larva, small fishes) are found in surface waters most affected by plume water. Sacramento River chinook, the major salmon species in the Eureka troll fishery, migrate north towards the Columbia River until they reverse direction and return to spawn (Figure 2).

Two "types" of chinook were present at Astoria, from an analysis of the radionuclide spectra: Type A (Zn^{65}, Mn^{54}, Cs^{137}) and Type B (Zn^{65} only, in much higher concentration than Type A). Columbia River chinook taken at Astoria might be expected to have high Zn^{65} concentrations, as do other marine organisms in the area

(Osterberg et al., 1964). However, the two "types" from eight salmon counted were distinctly different (Figure 10). Perhaps the difference can be explained by variations in migration routes, feeding habits, or residence time in Columbia River water. No noticeable correlation to size or sex was discernible (size 12 to 34 pounds).

It is possible that principal ocean migration routes were different; i.e., Type A may have migrated the greatest distance northward out of the influence of the Columbia River, whereas Type B may not have migrated northward far enough to escape the effects of the radioactive effluent. Having remained in it for most of their lives, Type B fish would have accumulated higher levels of Zn^{65}. Recent studies tend to substantiate this theory. Tag returns indicate that many Columbia River chinook confine their ocean life to the area between the mouth of the river and Vancouver Island. On the other hand, some Columbia chinook migrate great distances into northern waters along the Aleutian chain (Loeffel, 1965).

Still another possibility is that the high Zn^{65} Type B chinook had been associated with Columbia River water near the river mouth for a longer period than Type A, before actually migrating upstream. Greene (1909) observed that fall chinook took as long as 30 days to pass through brackish water. They spent considerable time swimming back and forth in tidewater to acclimate to fresh water.

Cesium-137 was found in measurable amounts in chinook samples. The preferential accumulation of Cs^{137} in some chinooks is not readily explained. Perhaps the longer average life span (4-7 years) of the chinook, relative to other Pacific salmon, is important with radionuclides having a long half-life. Cesium-137 has a 30-year half-life. Also, there may be a trophic level effect, since the chinook is the most predaceous of the salmon. Pendleton (1964) found a 3.4 fold increase in concentration of Cs^{137} in higher trophic levels in a terrestrial environment.

Sockeye

The similarity of the spectra of sockeye samples from all collecting areas along the Pacific Coast was striking. Low levels of both Mn^{54} and Zn^{65} (with Mn^{54} usually dominant), and no marked increase in Zn^{65} in samples taken close to the Columbia River, characterized sockeye data (Figures 5 and 6, and Table 2). Lower levels of Zn^{65} and Mn^{54} in all sockeye may be due to the similar ocean life in the Gulf of Alaska or Central North Pacific beyond the range of measureable Columbia River influence. Lower levels of Zn^{65} and Mn^{54} than in chinook and coho may be due to feeding on a lower trophic level. Sockeye feed more on amphipods, euphausiids, copepods and crustacean larva. Chinook and coho eat more small fishes.

The migration routes and time spent in far northern waters by the sockeye could explain the lack of Zn^{65} in samples taken in the Straits of Juan de Fuca (only 200 miles north of the Columbia River). Tag returns indicate that the Gulf of Alaska is the principal feeding ground of the Canadian sockeye (I. N. P. F. C., 1961). Their feeding would diminish upon approaching the spawning grounds near the Straits of Juan de Fuca. Moiseev (1961) observed that Asian sockeye quit feeding when approaching the Asian coast, close to their natal stream.

Manganese-54 is the principal artificial radionuclide in the majority of the sockeye samples. The slightly higher Mn^{54} concentrations relative to Zn^{65} (Table 2), can be explained by the remoteness of the sockeye's feeding grounds from the influence of the Columbia River. Feeding habits, which differ from those of other species, also may be important. Manganese-54 from fallout is widespread. For example, pelagic albacore also accumulate Mn^{54} (Osterberg, 1965).

No evidence for Cs^{137} was found in the sockeye samples. Perhaps this was due to the different feeding habits or the shorter life span of the sockeye when it is compared with the chinook.

Concentrations of Zn^{65} and Mn^{54} differed with sex in sockeye. Females showed an affinity for Mn^{54}, while males perhaps showed a slightly greater affinity for Zn^{65} (Table 8). All of the 20 female sockeye analyzed had concentrated more Mn^{54} relative to Zn^{65}.

Table 8. Sockeye sexual affinity for Zn^{65} and Mn^{54}.

Location	No. analyzed	Females		No. analyzed	Males	
		$Mn^{54} > Zn^{65}$	$Zn^{65} > Mn^{54}$		$Mn^{54} > Zn^{65}$	$Zn^{65} > Mn^{54}$
Bristol Bay, Alaska	3	3	0	2	1	1
Cook Inlet, Alaska	5	5	0	1	1	0
Petersburg, Alaska	2	2	0	3	2	1
Skeena River, Canada	3	3	0	2	1	1
Barkley Sound, Canada	3	3	0	5	0	5
St. Juan de Fuca, Canada	4	4	0	2	1	1
TOTAL		20	0		6	9

On the other hand, nine males principally concentrated Zn^{65}, while six males contained mostly Mn^{54}. This might be explained by Vinogradov's (1953) findings that female fishes tend to accumulate manganese in the roe, whereas males tend to concentrate zinc in the testes. To check this, ovaries and testes were removed from the viscera and analyzed separately. However, problems arose which prevented definitive results. Viscera which contained nearly equal amounts of Mn^{54} and Zn^{65} were needed. Bristol Bay samples most nearly fulfilled this requirement. However, levels of radioactivity were low in these samples. The testes or ovaries that were separated contained very little Mn^{54} or Zn^{65}. The low counting rate on these organs increased the probable error of counting beyond acceptability. Samples from areas other than Bristol Bay showed considerable amounts of Zn^{65} in all the organs, but Mn^{54} was in such small quantity and could not be measured. Of the five Pacific salmon species investigated, only the sockeye showed sexual differences in uptake of radionuclides.

Coho

At Cook Inlet, Mn^{54} was the dominant isotope in coho. Coho from this station contained the highest concentrations of any species at any location.

No apparent reason can be given for the high levels of Mn^{54} in

Cook Inlet coho (average of 8.80 pc). Coho in that area generally migrate west along the Aleutian Chain (I. N. P. F. C., 1961). Their feeding habits resemble those of the chinook, but coho are not as selective (Heg and Van Hyning, 1951). Perhaps the coho had been feeding extensively on organisms rich in Mn^{54}; for example, the crab megalops and young rockfishes collected at Eureka, California, had high levels of Mn^{54}. Also, the coho is noted for its rapid summer growth rate in the ocean (Ibid.). This might result in a higher concentration of Mn^{54}.

A definite reversal in relative abundance of Mn^{54} and Zn^{65} was seen in the southeastern Alaska area. In coho from Cook Inlet, the Mn^{54} concentration was higher than Zn^{65}, as mentioned before. At Petersburg, farther south, the two isotopes were nearly in equal concentrations, with Zn^{65} slightly higher. Four hundred miles farther south, at the Skeena River, Mn^{54} was reduced to a trace and Zn^{65} concentration more than doubled (see Table 4).

These differences might be explained by the migration routes mentioned earlier. The southeastern Alaska coho has a generally random pattern of local movement (Moore, et al., 1960). This movement could be within the limits of the influence of Columbia River waters. Absolute delineation of the effects of Columbia River effluent is difficult, however, because there is a widespread background of low Zn^{65} level throughout the world due to nuclear testing

(Osterberg, et al., 1964). For example, 21 mussels (Mytilus sp.) from Petersburg showed a trace of Zn^{65}, and Mn^{54} (less than 1.0 pc/g of dry wt., minus the shells). Mussels from farther south in Canada were not obtained for examination.

Toward the south, in Canadian waters, the Zn^{65} content in coho continued to increase, and only a trace of Mn^{54} was present. This definite increase in Zn^{65} content in Canadian coho undoubtedly was a direct result of Columbia River discharge. The migrations of Canadian coho are primarily local and southward towards the Columbia River mouth (Figure 3). Similarly, Washington coho are found in Canadian waters as far north as Queen Charlotte Islands, and some Oregon coho as far north as Vancouver Island. British Columbia coho mix with those from Washington streams around Vancouver Island (Moore, et al., 1960).

Coho samples taken in the Eureka area contained nearly as much Zn^{65} (44.98 pc/g) as samples taken closer to the mouth of the Columbia River.

The Washington Department of Fisheries (Moore et al., 1960) reported that coho reared in Oregon streams contributed substantially to the California troll fishery, and, to a lesser extent, the Washington fishery. Therefore, the coho caught off Eureka were probably natives of Oregon and had been associated with the Columbia plume both during their southward migration and their northward return to the spawning grounds (Figure 7).

Manganese-54 diminished in samples having high Zn^{65} concentrations. The lower Mn^{54} concentrations found in coho from more southern waters (i.e., Vancouver Island to Eureka) was also noticeable in chinook. There is no plausible explanation for this phenomenon at this time. However, Osterberg (1964) noted that tuna with high levels of Zn^{65} seemed to have less Mn^{54} than fish with lower amounts of Zn^{65}.

Cesium-137 appeared in three Canadian coho. This may be the result of the diet of the coho, which most nearly resembles that of the chinook; that is, it may be a trophic level effect.

There was a distinct difference in concentration of radionuclides by salmon species caught in the area of the Straits of Juan de Fuca. Sockeye had mostly Mn^{54}, but chinook and coho contained more Zn^{65} (Table 2, 3, and 4). Different migration routes and natal streams might explain the variation of Zn^{65} concentrations in the species. The sockeye return to the Fraser River after spending most of their ocean life in the Gulf of Alaska, where there is little Columbia River influence. The chinook probably hatched in the Columbia River basin. These were immature fish (6 or 7 lb.) which had spent their entire lives under the influence of Columbia River waters. The coho may have originated in British Columbia or Washington. They generally range from the Queen Charlotte Islands to northern California, well within the influence of the Columbia River.

Pink and Chum

The pink salmon has a two year life span and is the smallest species taken in the Petersburg area. High concentrations of Zn^{65} in pink salmon may have been due to omnivorous feeding habits of the fish. Aron and Allen (1956) found fish more frequently in the diet of pink than either sockeye or chum, which are considered to have similar feeding habits. The higher Zn^{65} concentrations in pink salmon may also indicate a more extensive southward migration.

The chum salmon had nearly equal concentrations of Mn^{54} and Zn^{65}. These concentrations are somewhat higher than those in sockeye. The two species have similar diets, although the chum is not quite as omnivorous, feeding more on fishes (Allen, 1956). Migration routes of pink and chum normally are into far northern Pacific waters beyond the influence of the Columbia River.

SUMMARY

Viscera of salmon from a major portion of the northeast Pacific Ocean fisheries contained artificial radionuclides. The gamma emitters zinc-65 (245 days) and manganese-54 (310 days) were found in most samples. Cesium-137 (30 years) was present only in the more predaceous chinook salmon.

Levels of Zn^{65} were low in northern Alaskan waters, but increased greatly in fish taken from nearer the Columbia River mouth. Zinc-65 is a major contaminant in the Columbia River, where it appears as a result of nuclear reactors at Hanford, Washington. Zinc-65 also is present over most of the world in fallout; however, levels from this source are much lower. Nevertheless, the ubiquity of Zn^{65} makes it difficult to determine the absolute northern limit of Columbia River penetration. A transition zone, between relative concentrations of Zn^{65} and Mn^{54}, appears off southern Alaska. South of these stations, Zn^{65} levels in fish increase rapidly as the Columbia River is approached. Conversely, Mn^{54} becomes less obvious in fish high in Zn^{65}. There is little doubt that Mn^{54} comes from a different source than the Zn^{65}; i.e., Mn^{54} is principally from fallout.

Another difficulty in defining the northernmost intrusion of Columbia River water with certainty lies in the migratory and

feeding patterns of salmon. Thus, there is a question of whether salmon obtained their radioactivity in waters away from the area of capture. Since most salmon are taken while approaching their spawning grounds, and normally do not feed at this time, their radioactivity may reflect activity in a previous environment, rather than at the point of capture. Nevertheless, salmon which feed off Oregon, Washington, and Canada contain higher levels of Zn^{65} than those whose migrations are restricted to Alaskan waters. If it can be shown that Asiatic stocks remain north and west of the Columbia River intrusion, their radioactivity may very well be appreciably lower than those from North America. If so, this radioactive tag could be used to differentiate the two stocks, which intermingle on the high seas. Further work will be required to establish this point.

Levels of radioactivity of salmon from off Oregon tend to be somewhat higher than has been reported in plankton and nekton from the same region. This may be biased by the fact that radioanalyses of salmon were confined largely to viscera. The liver and other internal organs are normally richer in trace metals than other parts of the body.

There was no indication in any of our samples that levels of radioactivity were high enough to endanger either the health of the fish or those of its human consumers. On the contrary, cesium-137 was much lower in salmon than in most terrestrial animals that provide the bulk of protein in the diet of man. This is in part due to the abundance of potassium in sea water. Potassium is chemically similar to cesium, and tends to compete against it in the marine environment.

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