USE OF SCALE CHARACTERS AND A DISCRIMINANT FUNCTION FOR CLASSIFYING SOCKEYE SALMON (*ONCORHYNCHUS NERKA*) BY CONTINENT OF ORIGIN

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ABSTRACT

The study of scale characters provides one method of determining the continental origins of salmon caught on the high seas. Three scale characters and a quadratic discriminant function were used to identify mature sockeye salmon (*Oncorhynchus nerka*) which originated in the North American and Asian continents. The fish were caught in the North Pacific Ocean and the Bering Sea. The method proved reliable.

Variability not associated with real continental differences did not invalidate the method. For 1956–62, average errors of classification were 19 percent for samples collected in Bristol Bay streams and 27 percent for those collected in Asian waters. The results from seven years of data were consistently good. The error of classification ranged from 11.7 to 26.1 percent for samples from Bristol Bay and 21.3 to 36.7 percent for those from Asia. The method confirmed the east-to-west distribution obtained from tagging—when applied to samples collected in 1962, it showed that Bristol Bay sockeye salmon predominated in the eastern Pacific Ocean and that Asian stocks predominated in the western Pacific. The results from the scale method agreed generally with those from a method based on morphological characters.

CONTENTS

INTRODUCTION

The U.S. Fish and Wildlife Service is attempting to determine for the International North Pacific Fisheries Commission (INPFC) the continental origins of sockeye salmon (*Oncorhynchus nerka*) caught in the North Pacific Ocean and Bering Sea. Studies on classifying sockeye salmon by continent of origin were summarized by Cleaver (1964). Useful information was provided by studies of tagging (Hartt, 1962, 1963, 1966), of parasites (Margolis, 1958), of morphological characters (Fukuhara *et al.*, 1962), and of scales. Studies on scales of sockeye salmon include those of Taguchi (1948) and Krogius (1958), who identified types of Asian sockeye salmon ; Clutter and Whitesel (1956) and Henry (1961), who reported on races from the Fraser River; and Mosher (1956a, 1956b, 1958, 1963), Anas (1956, 1962, 1964), Kubo (1958a, 1958b), and Kubo and Kosaka (1959), who reported on the continental origins of sockeye salmon caught in the Aleutian area of the North Pacific Ocean and Bering Sea.

The scale method has a number of advantages over the others. Scales are simple and inexpensive to collect in larger numbers at fishing and spawning sites. Fish need not be killed or mutilated to obtain samples. A collection of scales is compact and easy to store ; it becomes a permanent source of original data. In addition, large numbers of scales are required and collected routinely for other studies.

The scale characters and methods of statistical analysis used by the various authors differed. A comprehensive study of 32 scale characters indicated three to be useful in distinguishing North American from Asian sockeye salmon (Anas, 1962, 1964). In general, scales of sockeye salmon from Bristol Bay

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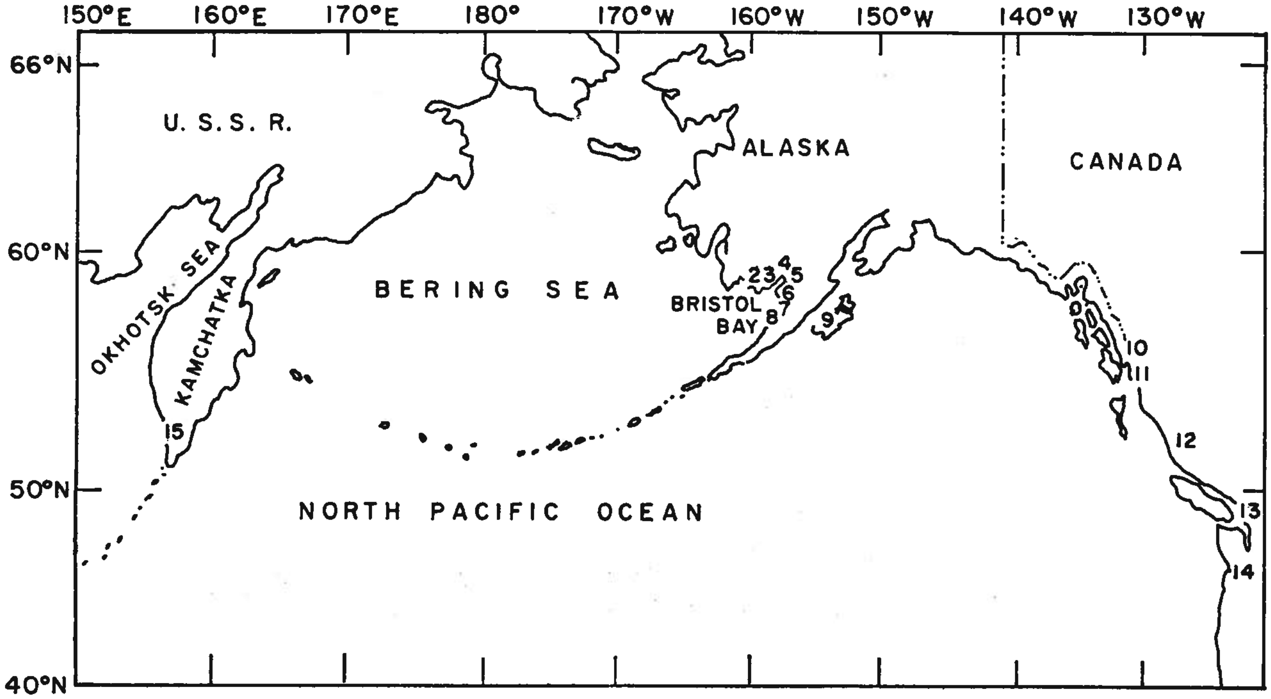

FIGURE 1. Inshore sampling localities for sockeye salmon, 1956–62.

1. Kuskokwim R.
2. Wood R.
3. Nushagak R.
4. Kvichak R.
5. Branch R.
6. Naknek R.
7. Egegik R.
8. Ugashik R.
9. Karluk R.
10. Nass R.
11. Skeena R.
12. Rivers Inlet
13. Fraser R.
14. Columbia R.
15. Ozernaya R.

have fewer circuli in the first half of the first ocean zone and wider distances between circuli 1 and 6 and circuli 13 and 18 in the first ocean zone than sockeye salmon of Asian origin.

This report describes and applies the latest scale method for classifying, by continent of origin, mature sockeye salmon caught in the Aleutian area of the North Pacific Ocean and Bering Sea. We first explain the technique of taking data for the three scale characters and examine the effects of certain sources of variation not associated with differences between continents. Selection of continental standard areas and a method of classification based on fish of known continental origin (Fig. 1) are presented next. Samples taken on the high seas during 1962 are then classified by continent of origin. Finally, to test the hypothesis that scales are useful for classifying samples of sockeye salmon of mixed continental origin, we compare the classification with an independent source of data.

DESCRIPTION OF TECHNIQUES

In sockeye salmon scales, a freshwater zone (1–3 years of lake residence) and a saltwater zone (1–4 years of ocean residence) are typical; a third zone (growth during lake or estuary residence in part of the year of seaward migration) is called " plus " growth. Depending on the number of years the fish spend in lake and ocean environments, the freshwater and saltwater zones may be further divided into the first freshwater zone, second freshwater zone, plus zone, first ocean zone, second ocean zone, and so forth. Each of these zones has certain characteristics, such as the number of circuli in the zone and the width of the zone.

Koo (1955) and Clutter and Whitesel (1956) recommended a " preferred scale " as the best for racial studies because scales in that particular area are the first to appear on the fish, and thus best reflect its total life history. The preferred scale is two rows above the lateral line, on the diagonal scale column which extends downward from the posterior insertion of the dorsal fin (Fig. 2).

Body zones A, B, and C (Fig. 2) were established by fishery scientists of Japan, Canada, and the United States during the 1957 Annual Meeting of INPFC. Zone A includes scale rows 1–4, above and below the lateral line, and extends from a point below the posterior insertion of the dorsal fin to a point midway between the posterior insertion of the dorsal fin and

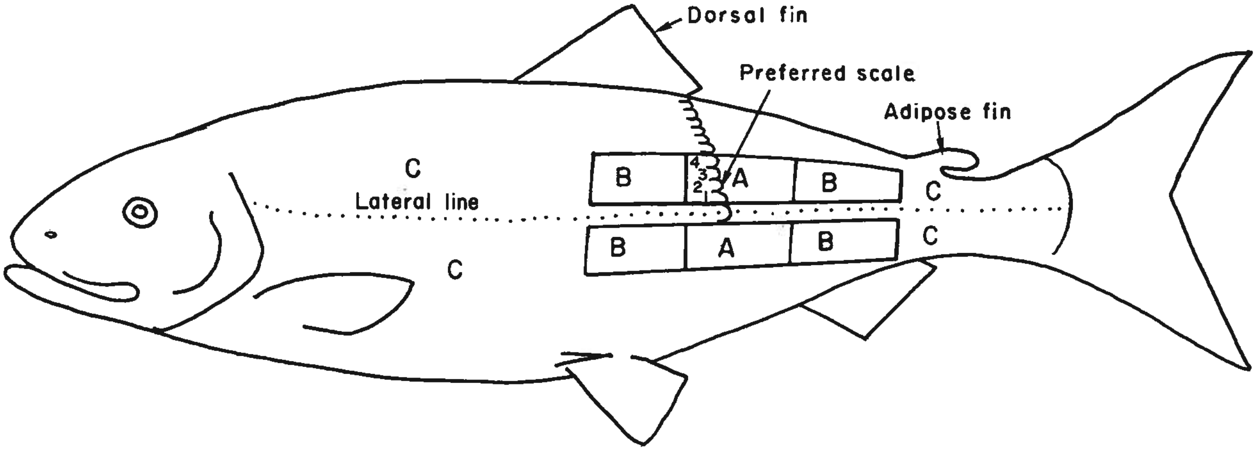

FIGURE 2. Location of " preferred scale", and body zones A, B, and C.

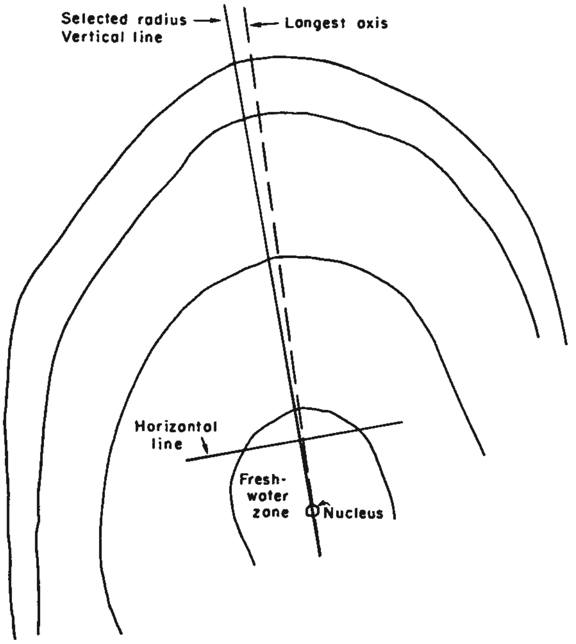

FIGURE 3. Sockeye salmon scale showing selected radius and longest axis.

the anterior insertion of the adipose fin. Zone B extends on both sides of zone A, from the midline of the dorsal fin to the anterior insertion of the adipose fin. Zone C includes all other scales. These definitions apply to both sides of the fish.

After 1957, scales were taken from zone A, mostly from above the lateral line. Prior to 1958 a few scales were taken from other body areas. Scales were taken from the left side of the body but also can be taken from the right.

Sockeye salmon scales were mounted on 3- by 5-inch gummed cards (Clausing, 1963) and impressed in cellulose acetate (0.020 inch thick) at a temperature of 135°C and a pressure of 4,200 pounds per square inch, as described by Koo (1955) and Clutter and Whitesel (1956). The scales were examined at 100X magnification on the projection device recommended by Mosher (1950).

The scale characters are read from a radius which defined a line that passes through the platelet or nucleus and lies close to, or on, the longest axis of the scale (Fig. 3). The selected radius fell along or near the longest radius of the freshwater growth field ; some latitude was given to care for the effects of strong asymmetry of some scales.

Broken circuli, or areas of poor impression, were sometimes too numerous to permit counts or measurements along the selected radius. A second radius was then selected, within ±10 degrees of the first—preferably as close as possible to the original radius and to the direction of the longest axis of the scale. The scale was discarded if no radius crossed through clearly defined circuli within 10 degrees of the first radius. Scales that were regenerated or damaged were not used.

Scales with eroded edges (eroded ocean zones are common in sockeye salmon when they approach spawning) were used if the erosion had not penetrated into the first ocean zone. All circuli that crossed or touched the selected radius were counted.

The following three characters of the first ocean zone, first used by Anas (1962), were used in the present study (Fig. 4).

1. The circulus count within the first half of the first ocean zone.
2. The distance between circuli 1 and 6 of the first ocean zone.
3. The distance between circuli 13 and 18 of the first ocean zone.

A transparent plastic card ruled with three equally

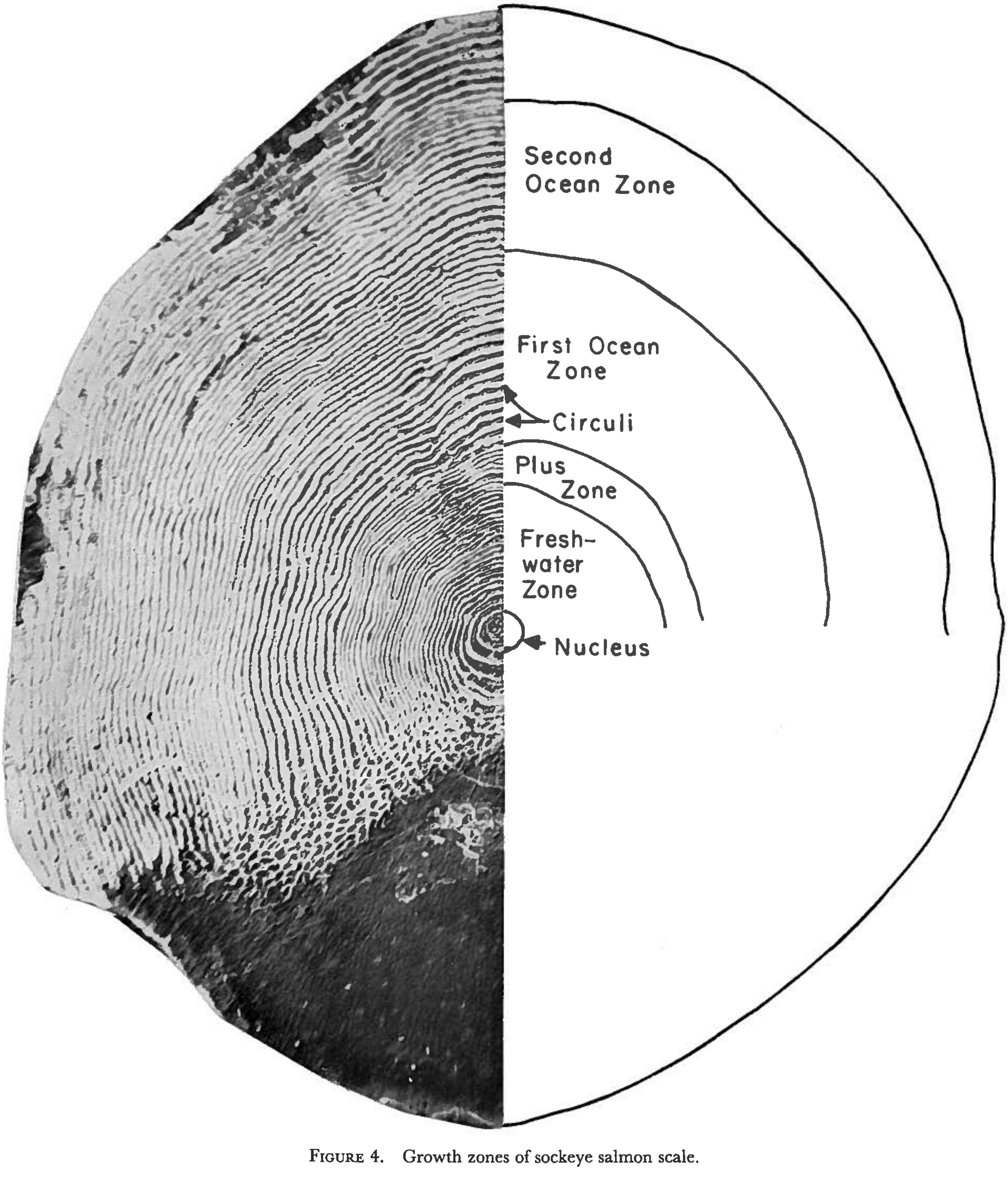

FIGURE 4. Growth zones of sockeye salmon scale.

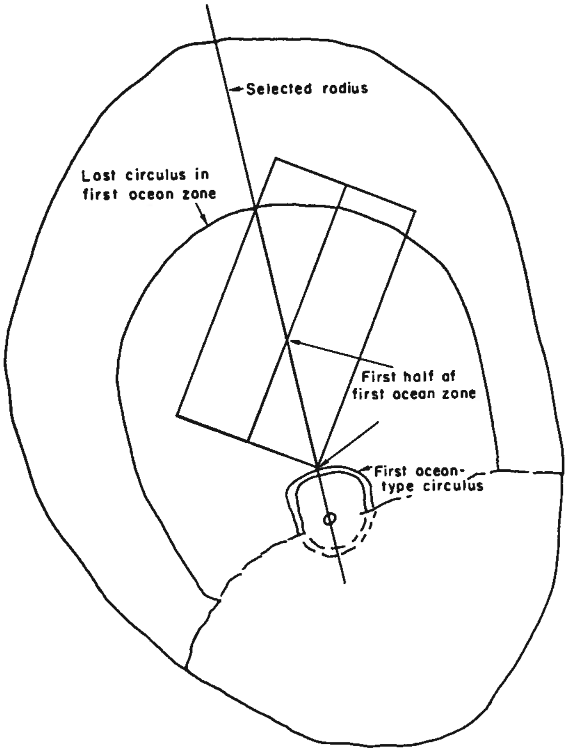

FIGURE 5. Illustration of use of a ruled plastic card for counting circuli in first half of first ocean zone.

spaced parallel lines was used to divide the first ocean zone into halves. After the bottom line was placed on the top edge of the first ocean-type circulus, the card was rotated until the top line fell on the top edge of the last circulus in the first ocean zone, at the selected radius (Fig. 5). Circuli between the bottom and middle lines of the card were then counted. A circulus that fell directly on the middle line was counted as a half-circulus.

In the first ocean zone the circuli are typically broader and the distances between circuli are greater than in the freshwater or plus zones. The width of the circuli and the distances between them, therefore, usually provide a visual method of picking the first circulus in the first ocean zone. The last circulus in the first ocean zone is the last one in a band of narrow, closely spaced circuli sometimes called the annulus (Clutter and Whitesel, 1956). Typically, the last circulus in the band is the narrowest one. The circuli near the annulus are likely to be incomplete, fused, or broken in the lateral fields of the scale. The broader circuli and wider interspaces in the second ocean zone are helpful in selecting the last circulus in the first ocean zone.

The distances between circuli 1 and 6 and circuli 13 and 18 were measured to the nearest millimeter.

On some scales we had to choose between " true " and " false " first-ocean annuli. By plotting the annuli by the Ford-Walford method (Walford, 1946) —i.e., plotting scale length at age " n " against scale length at age " $n+1$ ", scale length at age " $n+1$ " against scale length at age " $n+2$ ", etc.—from a number of scales that posed no problem, we noted that the ocean annuli fell on a nearly straight line, the slope of which differed little between the areas of collection or the ages of the fish (Figs. 6 and 7). (The one exception from the areas we tested was Rivers Inlet, British Columbia. Manzer *et al.* (1960) identified sockeye salmon from Rivers Inlet by the unique growth pattern of the circuli in the first ocean zone. No mature sockeye salmon of this type, however, were found in our study area.) For the occasional problem scale, therefore, we plotted the questionable first ocean annuli (in combination with the other ocean annuli for that scale) and selected as the true annulus the one that best fitted the expected straight-line relation.

SOURCES OF VARIATION

Before one can use scale data to evaluate a particular analytical technique for the separation of sockeye salmon by continent of origin, it is necessary to remove or to reduce the effect of extraneous sources of variability. These sources are discussed in the present section.

Variability due to errors in determining ages of sockeye salmon was not tested because adequate samples of marked salmon of known ages were not available. To determine ages each of two readers made independent readings for each fish. Disagreements between readers were resolved by a third, conference reading.

Samples used for tests of extraneous variability are listed in Appendix Table 1.

LOCATION ON BODY OF SAMPLED SCALES

To avoid spurious racial differences, scales should be taken from those body areas that minimize the variability in the values of the selected scale characters.

Examination of 135 scales from one fish showed that scales collected from zone A above the lateral line (see Fig. 2) and from both sides of the body had common means for all three scale characters ($P>0.05$). Scales from zone A that were collected from above and below the lateral line and from the left and right sides, however, had different means ($P<0.05$) for two of the three characters (Table 1). The means of scales from zones B and C differed from those of scales from zone A ($P<0.05$).

Before 1958, scales were not collected from precisely

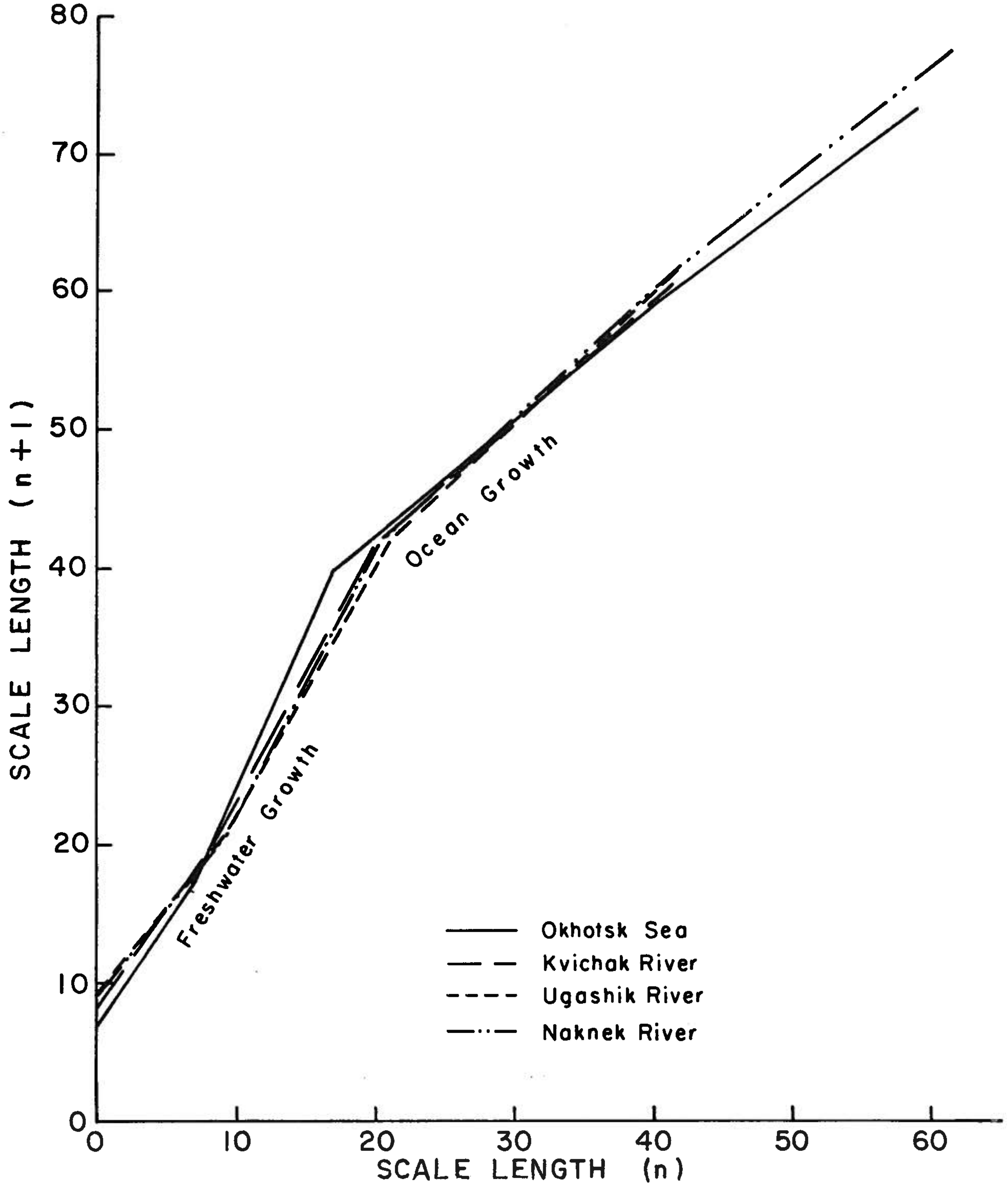

FIGURE 6. Scale length at age "n" plotted against scale length at age "n+1", scale length at age "n+1" plotted against scale length at age "n+2", etc., for sockeye salmon without plus growth.

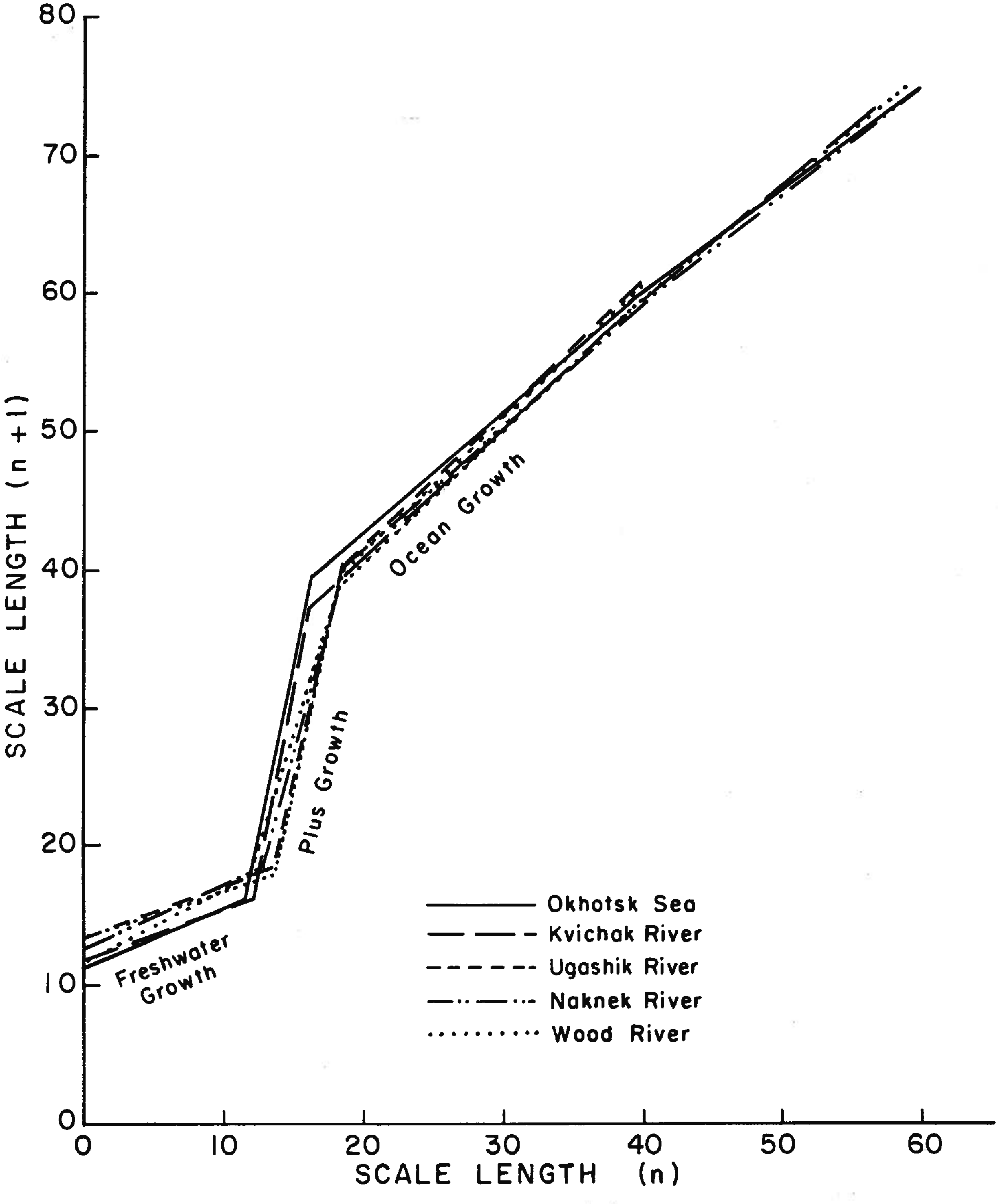

FIGURE 7. Scale length at age " n " plotted against scale length at age " n+1 ", scale length at age " n+1 " plotted against scale length at age " n+2 ", etc., for sockeye salmon with plus growth.

TABLE 1. Results of tests on means of three characters for scales taken from right and left sides of the body from zone A[1]. (Asterisk denotes significance at the 95 percent level; values given in table are *D*-values computed by Tukey's method of comparing all means as described by Snedecor, 1956.)

Scale character	Scales from above and below the lateral line		Scales from above the lateral line	
	Theoretical value (P=0.05)	Observed value	Theoretical value (P=0.05)	Observed value
Circulus count in first half of first ocean zone	8.344	9.444*	7.262	1.667
Distance between circuli 1 and 6 of first ocean zone	3.230	1.778	2.804	1.778
Distance between circuli 13 and 18 of first ocean zone	2.469	2.889*	2.144	1.223

[1] Zone A was subdivided into four areas above and four areas below the lateral line for a total of eight areas. This resulted in eight mean values, one for each area.

defined zones; the records do not specify whether a scale was collected above or below the lateral line. This study thus includes data from an unknown number of scales of zone A from below the lateral line. In practice, however, scales have seldom been taken below the lateral line. We assumed that about the same percentage of scales from below the lateral line were taken from specimens of each continent, and therefore that their presence introduced random variations rather than bias into the classification precedure.

SELECTION OF READING RADIUS

A one-way analysis of variance test indicated that, for 30 preferred scales of sockeye salmon from the Kvichak River in North America and 30 from the Okhotsk Sea in Asia, the mean values for the three scale characters did not differ significantly for angles that were 15 degrees on each side of the selected radius ($P > 0.05$). Because the scale radius can be selected within the 15 degrees (as shown by the small standard deviation in Table 2) we assumed that selection of the scale radius in this study was an insignificant source of variability. (As mentioned earlier, scales were discarded if the second radius chosen on questionable scales differed more than 10 degrees from the first.)

TABLE 2. Average and standard deviations for picking a given scale radius on replicated trials.

Freshwater age	Sample size	Average deviation	Standard deviation
Year	*Number*	*Degree*	*Degree*
2	10	+0.9	3.81
3	10	+0.5	3.23
4	10	+1.1	3.87

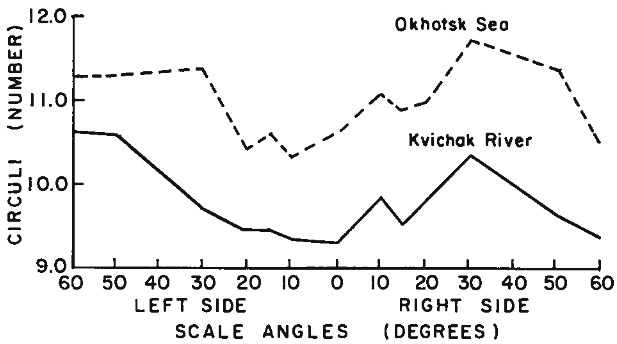

FIGURE 8. Mean number of circuli in first half of first ocean zone along radii at angles up to 60 degrees on each side of selected radius (at 0 degrees) for sockeye salmon from the Kvichak River and the Okhotsk Sea.

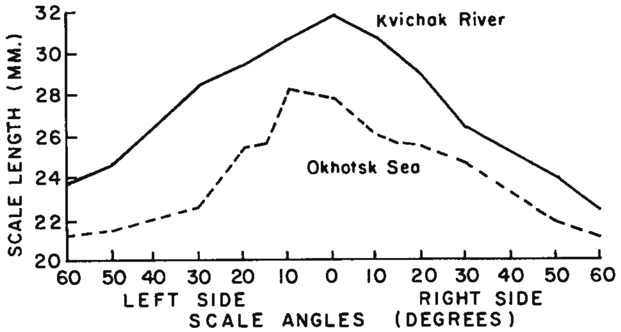

FIGURE 9. Mean distances between circuli 1 and 6 of the first ocean zone measured along scale radii at angles up to 60 degrees on each side of selected radius (at 0 degrees) for sockeye salmon from the Kvichak River and the Okhotsk Sea.

The racial separation between samples from the Kvichak River and the Okhotsk Sea can be estimated by summing the differences in the mean values of the three scale characters for each of the tested angles. We concluded from inspection of Figures 8–10 that our selected radius gave as good racial separation as any of the other tested radii.

SCALE READERS

The performance of three trained scale readers was tested to estimate variability among them. Inde-

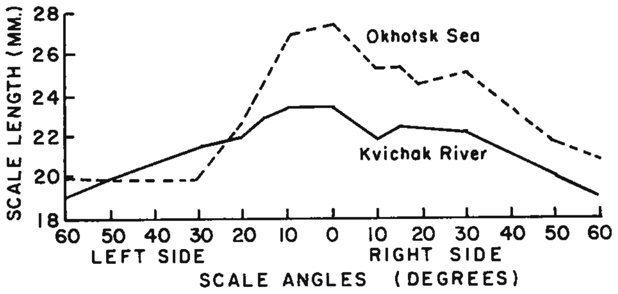

Figure 10. Mean distances between circuli 13 and 18 of the first ocean zone measured along scale radii at angles up to 60 degrees on each side of selected radius (at 0 degrees) for sockeye salmon from the Kvichak River and the Okhotsk Sea.

pendent test situations were set up to examine: (1) the consistency with which different readers selected a common radius, (2) the variability between readers in taking data for each of the three characters, and (3) the relative merits of single and duplicate readings.

The three readers chose radii within ±10 degrees of each other 95 percent of the time. It is unlikely, therefore, that selection of different radii by different readers introduced serious random error or bias.

The variance component for scales within geographical areas (rather than the within-reader component) was used to determine whether or not the readers contributed significant variability to the scale characters. Thus, if the component of variance for scales within areas was considerably larger than the component due to readers, the readers were assumed not to be a significant source of variability. This assumption is valid because, for our scale data, the variance of scales-within-area is included as part of the total error term when values of scale characters are determined.

Analysis of variance tests of three readers, six areas, and three scale characters showed that the variance components for readers and for interaction involving readers were small compared to the component for scales within areas (Appendix Tables 2 and 3). Readers, therefore, were evidently not a significant source of variation.

Expected variances (estimated from the components of Appendix Table 3) were computed to determine the merit of reading the same scale twice (Appendix Table 4). There was a slight decrease in the variability when two readings were averaged; duplicate readings reduced the variability very little, however, over that of a single reading.

The foregoing analyses indicated that the different readers introduced little bias or random variation. Scales from each sample were assigned in equal numbers to the three scale readers to distribute this small variation evenly among all areas.

Sampling Date and Gear

Most of the collections from Bristol Bay were made during the peak of the runs to obtain samples that were representative of the particular inshore area. A few were taken at other periods to find whether samples from non-peak periods were equally suitable.

When sampling dates were tested by analysis of variance (Appendix Table 5), only one of 21 F-values was significant ($P<0.05$). Date of collection, therefore, was not considered a significant source of variability. Samples from each stream in Bristol Bay, regardless of sampling date, were combined in the remainder of the analysis. Samples of Asian origin collected on different dates were not combined because they probably contained mixed stocks.

Sockeye salmon from the high seas were collected in strings of gill nets ($2\frac{1}{2}$-, $3\frac{1}{4}$-, $4\frac{1}{2}$-, and $5\frac{1}{4}$-inch mesh, stretched measure). If salmon from one continent were consistently larger than those from the other, size selectivity of nets could cause error in our final classification by continent of origin. On the other hand, size selectivity would introduce little error if the particular scale characters were independent of the size of the fish of known origin.

The effect of size selectivity by fishing gear was tested by computing correlation coefficients within age groups and geographical areas between each of the scale characters and fish length. Data were from scales of 845 fish collected in 15 samples from tributaries of Bristol Bay in 1956–59 (Appendix Table 1). Variability in scale characters that could be attributed to fish length was less than one percent ($\bar{r}^2$ values in Appendix Table 6). Selectivity by fishing gear, therefore, was not considered a significant source of variability.

Less direct evidence also is available. Lander and Tanonaka (1964, Tables 2 and 5) found that: (1) the average length of Western Alaskan sockeye salmon differed little from that of Asian fish sampled at the same time, in the same area, and from the same ocean age group; and (2) the four mesh sizes as fished together in 1956–60 took representative length samples of fish available to the nets.

Age, Year Class, and Sex

Age, year class, and sex were examined as possible sources of variation. For this purpose we analyzed samples of 29 or more fish collected in 1956–60 from principal tributaries of Bristol Bay.

Analysis of variance tests showed that sex (Appendix

Table 7) and presence or absence of plus growth associated with age (Appendix Table 8) were not significant sources of variation ($P > 0.05$). The F-values for year class (Appendix Table 9), freshwater age (Appendix Table 10), and ocean age (Appendix Table 11), however, were significant ($P < 0.05$).

Summary of Effects of Nonrandom Variation

The foregoing analyses indicated that use of scales from above and below the lateral line of zone A may have added some variability that could not be avoided because of the way in which the scales were collected. Different year classes and ages of sockeye salmon also contributed significant variability to the scale characters. The variation associated with plus growth, date of collection, fishing gear, sexual dimorphism, readers, and selection of a radius were not significant.

Errors of classification would be minimized if each age group within a year class were classified separately. The costs of sampling, however, prohibited analysis by individual age groups ; therefore, we decided to use a method in which ages are pooled. This method, which would provide adequate sample sizes, will work if the differences between the values of the scale characters for Asian and North American sockeye salmon were large enough to offset the differences due to year classes and age groups within continents. If samples of known continental origin in a given year can be classified with small error from pooled age groups, the technique of combined age groups would be useful. If samples of known continental origin cannot be classified with small error, however, individual age groups must be examined or the technique abandoned.

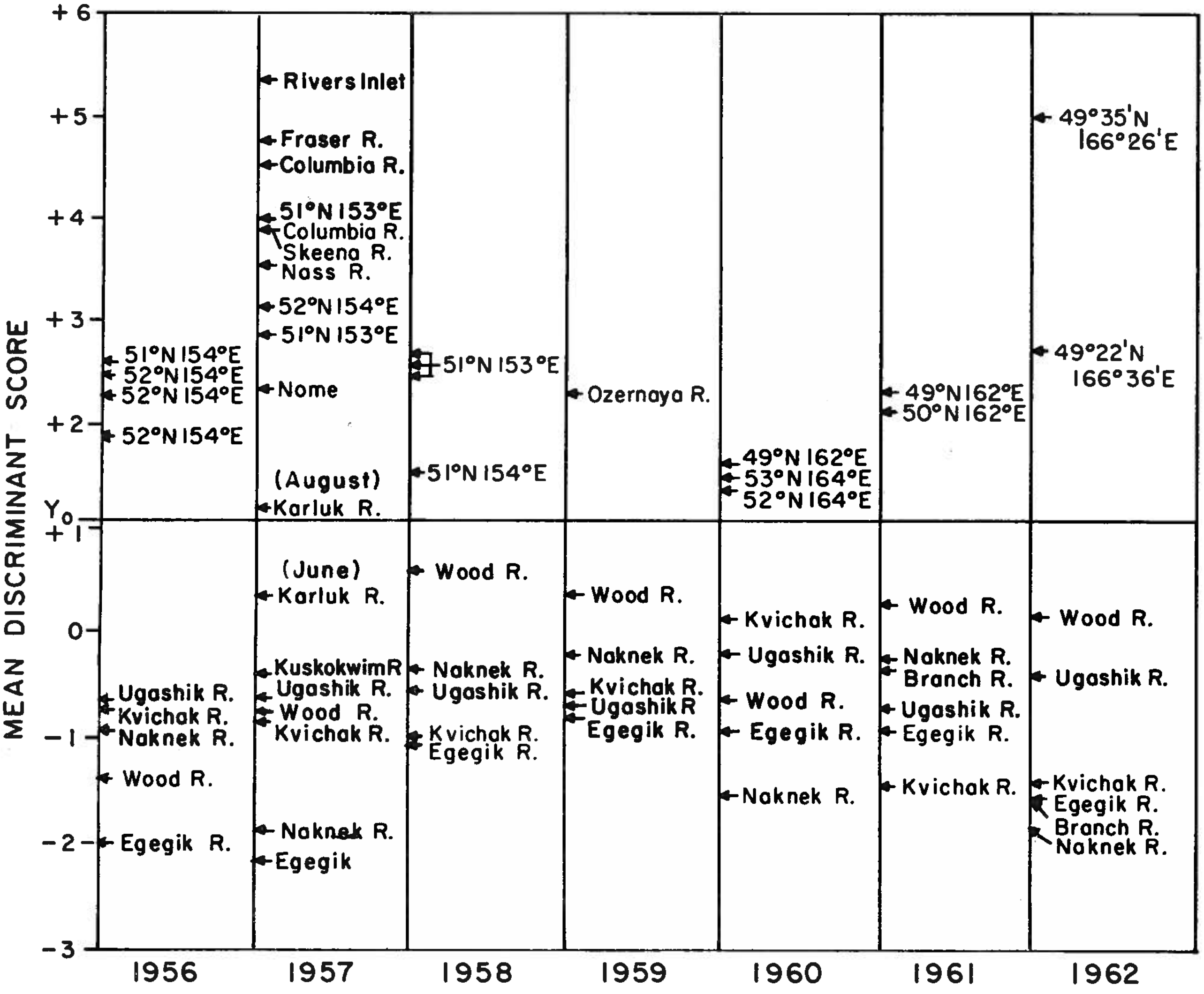

Figure 11. Linear comparison of mean discriminant scores for samples collected from Bristol Bay and Asian coastal areas, 1956–62, and other North American areas, 1957. The discriminant function was computed from data collected in 1957.

To evaluate the effects of variation due to year class and age, samples from Asia and North America with mixed age groups should be classified as to their continent of origin. If the results are promising, the method could then be evaluated further by comparing the results from use of scale characters with those of another method—one based on morphological characters. First, however, an analytical technique and samples from the areas of origin must be selected.

SELECTION OF ANALYTICAL TECHNIQUE

Mosher (1963) examined bivariate frequencies of certain scale characters (counts of total circuli in the first ocean zone and in the combined freshwater and plus growth zones for freshwater ages 2 and 3, and widths of the first ocean and combined freshwater zones for freshwater age 4 fish) as well as age composition data to classify sockeye salmon taken on the high seas in 1956–57 by continent of origin. Age composition, however, had not yielded consistent results (Mosher, 1956a; Kubo, 1958a). The method of bivariate frequencies does not require the two assumptions of normal distribution and common variance-covariance matrices. Mosher's method, however, had certain disadvantages: (1) the use of a table of frequencies for each freshwater age group led to low frequencies in some of the cells upon which classification decisions were based, (2) data were lacking in some of the cells for samples from the reference areas, and (3) the method was inconvenient to use with more than two characters.

Linear and Quadratic Discriminant Functions

Fisher (1936) introduced the discriminant function as a method of classifying individuals from a mixed sample into their two natal groups. In this method, a set of counts or measurements from an individual is reduced to a single value by which the individual is classified as being from one group or the other. In his work on the general problem of discrimination between two normally distributed populations of a given character, Smith (1947) confirmed the results of earlier workers who found that the best discriminant function is based on the difference between the logarithms of the two distribution functions. He showed that Fisher's linear discriminant function is a special case in which the variance-covariance matrices of the distributions are the same and gave an example of the more complex quadratic function which does not require the assumption of common variance-covariance matrices. Rao (1952) also worked on the linear discriminant function and reported examples. Isaacson (1954) pointed out that linear discriminant functions computed from uncommon variance-covariance matrices based on large sample sizes should give good results. Fukuhara *et al.* (1962) successfully used a linear discriminant function based on morphological data to classify mature sockeye salmon caught on the high seas by their continent of origin.

Correct use of the linear discriminant function, then, requires the three important assumptions that: (1) frequency distributions of the data are multivariate normal, (2) the data should have common variance-covariance matrices, and (3) each individual to be classified must be from one of the groups to which individuals are being assigned. The advantage of the quadratic discriminant function proposed by Smith is that common variance-covariance matrices are not required.

We selected the method of discriminant functions for analysis of our scale data because: (1) any of a number of racial characters can be used conveniently, (2) the correlation between successive characters is removed during the analysis, (3) in an earlier scale study it clearly differentiated Bristol Bay sockeye salmon from those of Asian origin, and (4) it was used successfully with morphological data to differentiate Western Alaskan from Asian mature sockeye salmon caught on the high seas.

Definition of Continental Standards

An important consideration in the use of the discriminant function is the selection of the reference areas that make up the two continental standards—Asia and North America. Fukuhara *et al.* (1962) discussed this problem in detail and assumed that, "... most specimens in the high-seas samples to be classified are of western Alaska or southwestern Kamchatka origin." This assumption is based on: (1) a list of the most productive streams in Asia and North America, (2) tagging experiments (Hartt, 1962, 1963, 1966; Hall *et al.*, 1964; Kondo *et al.*, 1965), and (3) parasitic infection of sockeye salmon with species that are for the most part restricted to streams in Kamchatka and parts of the North American continent (Margolis, 1958).

An earlier analysis of scale characters (Anas, 1964) showed that most sockeye salmon from Bristol Bay river systems are distinct from those of Asian coastal areas. Sockeye salmon from Nome (Salmon Lake) and the sampling areas around the Gulf of Alaska are similar to the Asian type (Fig. 11); if present in high seas samples, they would be classified as Asian. Independent tagging studies, however, show that mature sockeye salmon from these North American areas are relatively scarce in high seas samples collected in the Aleutian area (Hartt, 1962).

The area of origin of samples that form the two

TABLE 3. Differences in mean discriminant values per unit standard deviation between Bristol Bay and Asian sockeye salmon for comparison of computed linear discriminant functions for 1956–62[1].

Function computed for:	Year of collection							Mean difference	Percentage error of classification
	1956	1957	1958	1959	1960	1961	1962		
1956	1.64	2.09	1.20	1.27	0.94	0.92	1.20	1.32	25.5
1957	1.58	2.16	1.30	1.42	1.14	1.10	1.56	1.46	23.3
1958	1.20	1.92	1.48	1.48	1.27	1.35	2.02	1.53	22.0
1959	1.34	2.02	1.46	1.51	1.24	1.20	1.83	1.51	23.0
1960	1.25	1.96	1.47	1.45	1.28	1.42	2.06	1.55	21.9
1961	0.90	1.57	1.22	0.95	1.11	1.68	2.04	1.35	24.9
1962	0.98	1.70	1.41	1.25	1.23	1.58	2.17	1.47	23.2
1956–62	1.36	2.04	1.44	1.43	1.27	1.42	2.00	1.56	21.7

[1] $\frac{L_A - L_B}{D}$ where: L_A = mean discriminant score for Asia.
L_B = mean discriminant score for Bristol Bay.
D = standard deviation of discriminant scores.

continental standards in this report (Appendix Table 12) is the same as used by Fukuhara *et al.* (1962). Asian samples taken off the southwest and southeast coasts of the Kamchatkan peninsula by Japanese mothership and research vessels (1956–58, 1960–62) were used in the Asian standard. Asian river samples were available only in 1959. Kamchatka River sockeye salmon, which make up an estimated 25 percent of the total Asian runs, are not represented in the samples available for our study. North American standard samples were restricted to those taken from Bristol Bay (1956–62).

Classification of Samples from Continental Standard Areas

The samples used to represent Asian and Bristol Bay sockeye salmon were large every year (Appendix Table 12). We accordingly adopted Isaacson's 1954 conclusion that the linear function based on large sample sizes should give good results and computed linear discriminant functions from data collected each year in 1956–62. One function was computed for each year and a separate function was computed from the pooled data; calculations were as shown by Rao (1952). Each of these functions was used to classify fish collected in 1956–62. The linear discriminant function computed from identical scale characters as given by Anas (1964) for data collected in 1957 was retained here for comparison.

The error of classification ideally should be weighted to the relative abundance of the various populations composing each high seas sample because the goal of the classificatory procedure is to assess the true proportions of the Asian and North American sockeye salmon in each sample. This adjustment for relative abundance could not be made, however. Therefore, the average error of classification—weighted according to the relative abundance of fish from various Bristol Bay rivers—was calculated (Appendix Table 12) for each year (Fukuhara *et al.*, 1962). A similar type of weighted average error of classification was not possible for the Asian standard.

The observed proportion of Bristol Bay type sockeye salmon in each sample was corrected for those fish of Asian origin classified incorrectly as Bristol Bay type and for Bristol Bay type classified incorrectly as Asian type (Worlund, 1960). The formula for this correction is:

$$P=\frac{r_a-P_{ba}}{P_{aa}-P_{ba}} \qquad \text{Equation 1}$$

where P = corrected percentage of North American type
r_a = observed percentage of Bristol Bay type
P_{ba} = percentage of Asian type misclassified as Bristol Bay type
P_{aa} = percentage of Bristol Bay type classified correctly

The mean discriminant values per unit standard deviation (equal to Rao's D-values) were computed for data collected each year in 1956–62 to find a suitable general linear function (Table 3). These values represent the discriminating power of the functions; large values are indicated with small errors of classification. The function associated with the largest mean difference would be the best function. Because of the way in which the functions are computed, the best linear function for any group of data is the function computed from those data—as can be seen in the diagonal elements of the table. The mean differences which ranged from 1.32 (1956) to 1.56 (1956–62), or 25.5 and 21.7 percent error of classification, respectively, indicate that differences, if any, between the general efficiencies of the functions were small—a difference of only 3.8 percent in error of classification between the most efficient and least efficient functions. Also, since no apparent trend was

TABLE 4. Summary of chi-square values for testing homogeneity of Bristol Bay and Asian variance-covariance matrices for data collected in 1957 and in 1956–62 (pooled).

	Chi-square value for matrices by use of:			
	1957 function		1956–62 function	
Area	Theoretical ($P=0.05$)	Observed	Theoretical ($P=0.05$)	Observed
Bristol Bay	36.42	27.19	250.99	543.89**
Okhotsk Sea	21.03	17.36	166.03	42.13
Pooled areas	12.59	122.09**	—	—

** $P<0.01$.

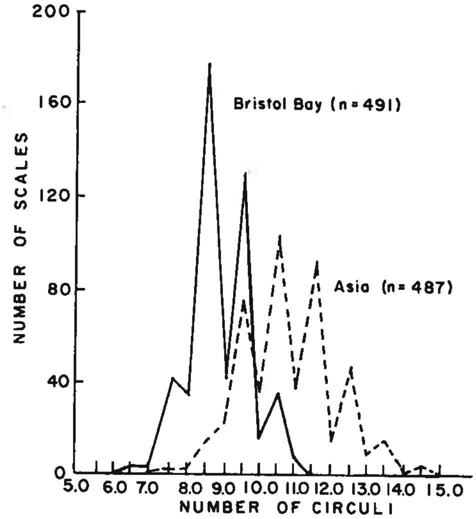

FIGURE 12. Frequency of circulus counts in the first half of the first ocean zone for samples collected from Bristol Bay and Asia, 1957.

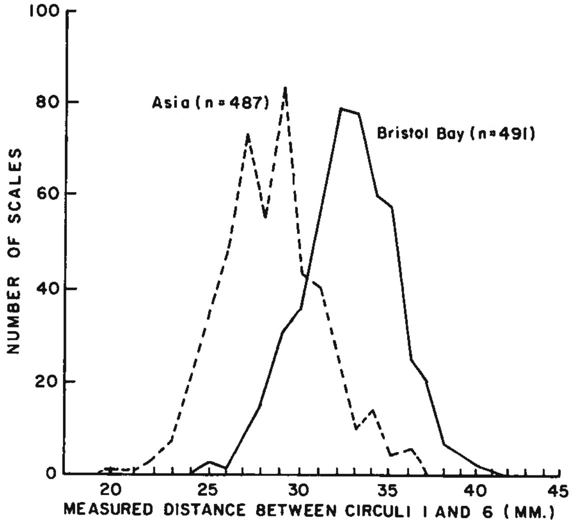

FIGURE 13. Frequency of measured distances between circuli 1 and 6 of the first ocean zone for samples collected from Bristol Bay and Asia, 1957.

evident in the table it can be concluded that any one of the functions would be about as effective as the others. The pooled-years function was selected as the most suitable general linear function for our purpose.

Multivariate normality of data and common variance-covariance matrices were assumed in the computation of the linear discriminant function. Table 4

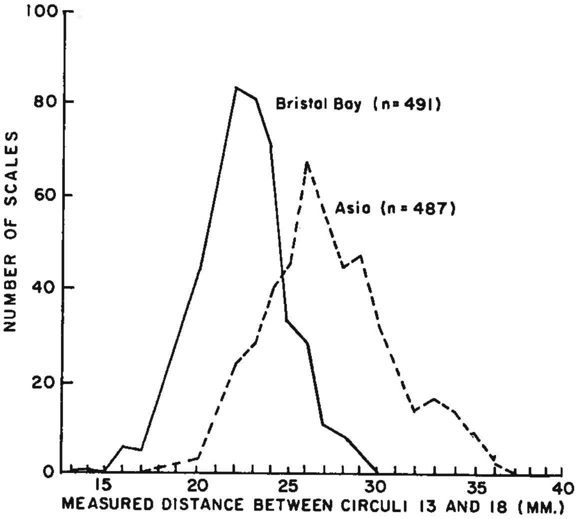

FIGURE 14. Frequency of measured distances between circuli 13 and 18 of the first ocean zone for samples collected from Bristol Bay and Asia, 1957.

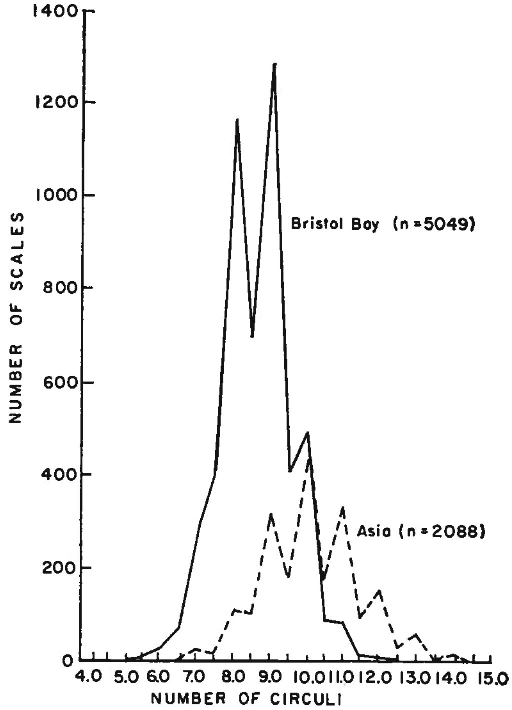

FIGURE 15. Frequency of circulus counts in the first half of the first ocean zone for samples collected from Bristol Bay and Asia, 1956–62.

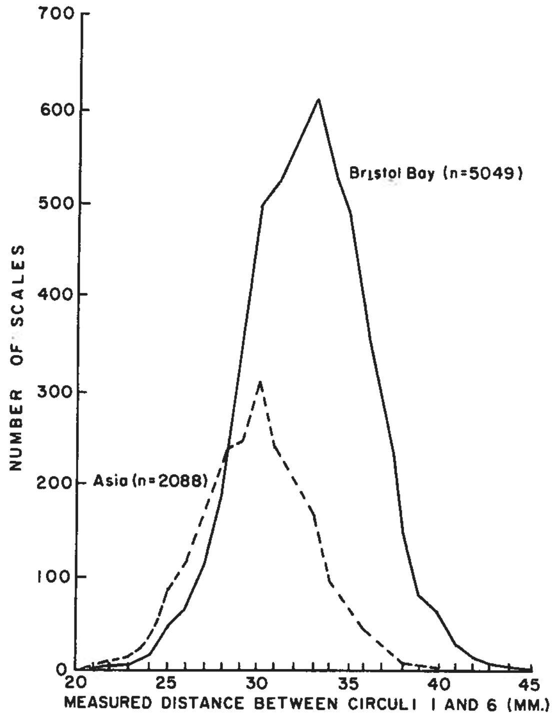

FIGURE 16. Frequency of measured distances between circuli 1 and 6 of the first ocean zone for samples collected from Bristol Bay and Asia, 1956–62.

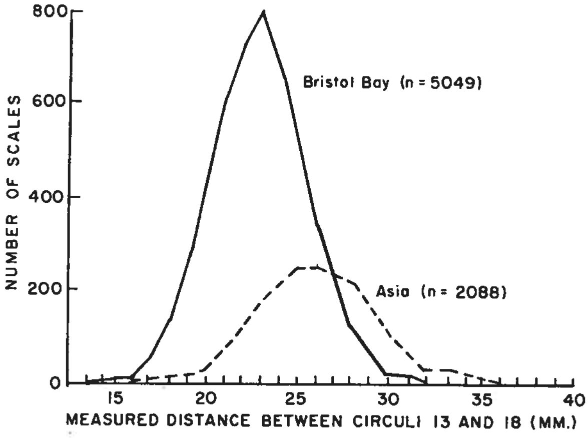

FIGURE 17. Frequency of measured distances between circuli 13 and 18 of the first ocean zone for samples collected from Bristol Bay and Asia, 1956–62.

shows, however, that the variance-covariance matrices within Bristol Bay were not common in the pooled data ; the several samples used to form the matrices for Bristol Bay and Asia separately were common for data collected in 1957. Only the Asian matrices were common for the pooled years, 1956–62.

The frequency distributions of the individual scale characters for the 1956–62 pooled data appear to have normal distributions (Figs. 12–17). A digit bias, however, is evident for the circulus counts in the first half of the first ocean zone (Figs. 12 and 15). We believe the data are from normal distributions and that the preference for half-circuli does not nullify the assumption of normality. Normality of the individual characters alone does not assure joint multivariate normality but does provide provisional evidence of joint normality.

The preference for the half-circulus counts could be caused by circuli falling more often on the lines inscribed on the clear plastic counting card than between them. The preference occurred for both Bristol Bay and Asian sockeye salmon ; it would be difficult to remove this preference entirely. We may even have increased the digit bias by counting the circuli in each sixth of the distance in the first half of the first ocean zone and summing the counts. In the future, circuli in the first half of the first ocean zone should be counted without subdivision.

A linear discriminant function can be computed even though the assumptions of common variance-covariance matrices and normality of data were not entirely satisfied. The efficiency of the function will be decreased accordingly. This approach was used in the present study, and empirical tests were used to measure the efficiency of the functions. Fukuhara *et al.* (1962) used the same approach but tested the assumptions more extensively.

Returning now to the analytical procedure, we next computed the parallel quadratic discriminant functions (1957 data and the pooled 1956–62 data) and, for the same inshore samples, compared the results with those from the linear functions. Smith (1947) calculated a quadratic discriminant function, but because computations are not common in the literature, ours is given in Appendix Table 13. Multivariate normality is assumed for the quadratic discriminant function ; common variance-covariance matrices are not.

The linear and quadratic functions are :

Linear (1957) :

$$L=0.0487X-0.4455Y+0.4116Z-1.0506 \qquad \text{Equation 2}$$

Linear (1956–62) :

$$L=0.0960X-0.1404Y+0.1975Z-9.8789 \qquad \text{Equation 3}$$

Quadratic (1957) :

$$L=0.007X^2+0.023Y^2+0.069Z^2-0.010XY-0.014XZ-0.108YZ-1.212X-0.768Y+2.356Z+38.993 \qquad \text{Equation 4}$$

Quadratic (1956–62) :

$$L=0.0053X^2-0.0159Y^2+0.0276Z^2+0.0002XY+0.0006XZ+0.0366YZ-0.8824X-0.2146Y$$

TABLE 5. Misclassification of Bristol Bay and Asian sockeye salmon by two linear and two quadratic discriminant functions, 1956–62.

Year of collection	Function		Misclassification of:	
			Bristol Bay salmon[1]	Asian salmon
			Percent	*Percent*
1956	Linear	1957	13.9	29.8
	„	1956–62	14.0	36.2
	Quadratic	1957	12.7	32.2
	„	1956–62	12.6	36.3
1957	Linear	1957	11.4	18.3
	„	1956–62	14.7	20.3
	Quadratic	1957	9.9	20.3
	„	1956–62	11.7	21.3
1958	Linear	1957	26.4	31.4
	„	1956–62	22.9	31.7
	Quadratic	1957	25.8	32.6
	„	1956–62	22.9	29.8
1959	Linear	1957	25.4	24.7
	„	1956–62	26.6	21.6
	Quadratic	1957	25.1	25.8
	„	1956–62	25.3	21.6
1960	Linear	1957	27.5	37.1
	„	1956–62	27.3	35.4
	Quadratic	1957	26.0	40.5
	„	1956–62	26.1	36.7
1961	Linear	1957	21.7	27.2
	„	1956–62	20.4	24.4
	Quadratic	1957	20.4	29.2
	„	1956–62	18.8	27.2
1962	Linear	1957	16.1	21.7
	„	1956–62	15.8	10.1
	Quadratic	1957	17.4	18.7
	„	1956–62	16.5	13.7
Mean	Linear	1957	20.3	27.2
	„	1956–62	20.2	25.7
	Quadratic	1957	19.6	28.5
	„	1956–62	19.1	26.7

[1] Adjusted by multiplying observed misclassification by fraction escaping to each Bristol Bay stream sampled.

$$-2.1620Z+63.7242 \qquad \text{Equation 5}$$

In equations 2–5:

L=discriminant score (which determines continent of origin)

X=the circulus count within the first half of the first ocean zone (X10)

Y=the measured distance between circuli 1 and 6 of the first ocean zone (in mm)

Z=the measured distance between circuli 13 and 18 of the first ocean zone (in mm)

Positive values of L signified Asian type fish, and negative values of L signified Bristol Bay type fish; fish with L values of zero were not classified.

Results of classifying Bristol Bay and Asian sockeye salmon collected between 1956 and 1962 by the 1957 and by the pooled-years linear and quadratic functions are given in Table 5 and Appendix Table 12. On the average, the pooled-years quadratic function is best for classifying Bristol Bay sockeye salmon and the pooled-years linear function is best for classifying Asian sockeye salmon. With the exception of 1962, the results are similar for all four functions. For 1962, the pooled-years linear and quadratic functions classified age 3.2[1] Asian type sockeye salmon more efficiently. The percentages of age 3.2 fish misclassified were 18 percent for the pooled-years quadratic function, and 35 percent for the 1957 linear function.

The adequacy of our sample size for the degree of precision desired was assessed in the following manner. Assuming the percentage errors of classification (P) for each continent to be approximately normally distributed about the true P, the inshore sample size required for 95 percent confidence is:

$$n=4_{pq}/d^2 \qquad \text{Equation 6}$$

In equation 6:

n=required sample size
p=probability of correct classification
q=probability of incorrect classification
d=allowable error in classification

The largest misclassification for Asian samples by the 1956–62 quadratic function was 36.7 percent in 1960; the largest for Bristol Bay samples was 26.1 percent, also in 1960 (Table 5). When 36.7 percent was regarded as the largest misclassification expected, five percent as the maximum error allowed, and 85 percent of collected scales assumed readable, the solution of equation 6 gave a sample size of about 438 fish from each continent. Sample sizes in Appendix Table 12 show that for some years a precision of five percent was not attained for Asian sockeye salmon (1959 to 1961; precision of 8.4, 7.4, 7.3 percent, respectively). The average precision for Bristol Bay samples was 2.9 percent and for Asian samples, 5.7 percent.

We concluded that the 1956–62 pooled-years linear and quadratic discriminant functions were satisfactory for use with our three scale characters. The function

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[1] Age designations of salmon in this report follow the system of Koo (1962). The number of winters-at-sea marks on the scale is preceded by a decimal point (age .1—one winter at sea, etc.) The number of winters-in-freshwater marks precedes the decimal point. Year class is the sum of the two numbers plus one year for the time the eggs were in gravel. For example, an age 1.2 fish has one freshwater annulus, two winters in the ocean, and is in its fourth year. This age corresponds to age 4_2 in the Gilbert and Rich (1927) system.

computed each year would have been best for that year's data, but we are looking for a function that can be used year after year. Acceptable errors of classification and consistent results were evident for all seven years of collected data with both pooled functions. The quadratic function has the added advantage of not requiring common variance-covariance matrices (shown in Table 4 to be unequal). The 1956–62 pooled-years quadratic function, therefore, was selected as the most appropriate function for our data. This function was used to classify samples of mature sockeye salmon caught at sea in 1962 to continent of origin.

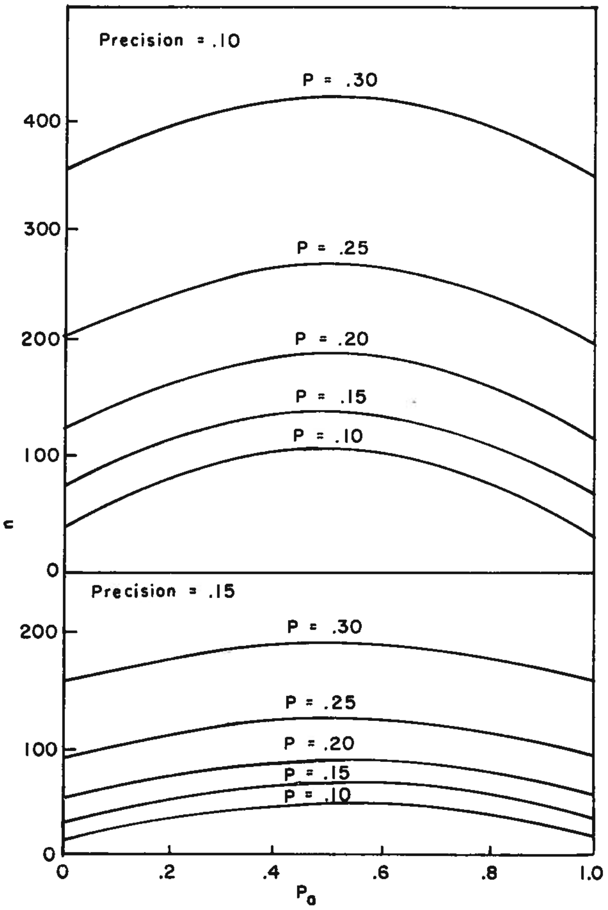

FIGURE 18. The relation between n, P_a, and P for precision of 0.10 (upper panel) and 0.15 (lower panel) (adapted from Worlund, 1960), where:

n=size of mixed (high seas) samples of two populations

P_a=true proportion of fish from Area A in mixed population

P=expected error of classification for (inshore) reference samples

Precision=expected precision in estimated proportion from Area A.

CLASSIFICATION OF 1962 HIGH SEAS SAMPLES

Before actually classifying samples of sockeye salmon collected at sea in 1962, we tested the adequacy of the sample sizes by the method of Worlund (1960) to determine the precision expected in estimates of continental composition.

" *P* " in Figure 18 is the expected error of classification for the inshore samples; for our data, P=16.53 for Bristol Bay sockeye salmon and P=13.68 for Asian sockeye salmon (end of Appendix Table 12). With 90 percent confidence, a precision of 0.10 was too strict; so we used a precision of 0.15. With no intermingling and a precision of 0.15, samples sizes of 30 were adequate. About 60 fish were required for this precision when Bristol Bay and Asian sockeye salmon were intermingled in equal numbers. Most of the samples collected in 1962 were large enough to attain adequate precision of 0.15 (Table 6.) The proportions of Bristol Bay type sockeye salmon from the 1956–62 quadratic function were computed for 78 samples that contained 30 or more mature fish. (Samples were collected from May 25 to July 13, 1962, from gillnet catches by Japanese motherships and research vessels and by U.S. research vessels). The observed proportions were adjusted by a method of Worlund and Fredin (1962).

Asian type sockeye salmon predominated in the western Pacific Ocean, and Bristol Bay type sockeye salmon predominated in the eastern Pacific Ocean (Table 7). Mature Asian type sockeye salmon predominated from 162°E to 171°E. The eastward limit of a substantial proportion of Asian type sockeye salmon was 180°. Bristol Bay type sockeye salmon predominated from 175°W to 173°E. The westward limit of substantial proportions of Bristol Bay type sockeye salmon was 173°E, but sample 40 (from 170°E) contained 40.4 percent Bristol Bay type sockeye salmon, and sample 50 (collected at 171°E) contained 55.8 percent. Considerable intermingling of mature fish of both continental types apparently occurred between 170°E and 180°. The samples were, however, taken largely in the month of June.

COMPARISON BETWEEN SCALE AND MORPHOLOGICAL DATA

Results were compared to determine whether the use of scales was as effective as the use of morphological characters for classifying sockeye salmon. The two methods are related in that the assumptions underlying the selection of the continental standards are the same. The main differences are in: (1) choice of racial characters, (2) use of a quadratic function for the scale method and a linear function for the morphological

TABLE 6. Estimated proportion of mature sockeye salmon from Bristol Bay in samples containing more than 30 fish collected at sea in 1962.

Sample no.	Location		Date	Sample size	Proportion of Bristol Bay type salmon			
							90 percent confidence intervals	
	Lat.	Long.			Observed	Corrected		
				Number	*Percent*	*Percent*	*Lower*	*Upper*
1	50N	162E	7– 7	33	3.0	0	0	14.1
2	50N	165E	7– 1	36	25.0	16.2	0	33.2
3	50N	165E	7– 3	43	23.3	13.8	0	29.0
4	50N	165E	7– 5	31	16.1	3.5	0	19.1
5	49N	166E	6–19	54	14.81	1.6	0	13.1
6	49N	166E	6–21	48	16.7	4.3	0	17.0
7	50N	166E	6–12	82	20.73	10.1	0	20.6
8	50N	166E	7– 1	42	14.3	0.9	0	13.6
9	50N	166E	7– 5	30	13.3	0	0	14.8
10	49N	167E	6–12	88	11.4	0	0	8.6
11	53N	167E	6–16	137	23.4	13.9	5.4	22.4
12	48N	168E	6–10	47	19.1	7.8	0	21.3
13	48N	168E	6–10	50	8.0	0	0	11.5
14	48N	168E	6–11	55	20.0	9.1	0	21.8
15	48N	168E	6–12	92	18.5	6.9	0	16.4
16	48N	168E	6–12	79	20.2	9.4	0	20.1
17	48N	168E	6–14	48	14.6	1.3	0	13.3
18	48N	168E	6–14	54	18.5	6.9	0	19.4
19	48N	168E	6–16	48	22.9	13.2	0	27.5
20	48N	168E	6–17	45	11.1	0	0	12.1
21	48N	168E	6–18	83	24.1	14.9	3.8	26.0
22	48N	168E	6–18	91	25.3	16.6	5.9	27.3
23	48N	168E	6–18	75	14.7	1.4	0	11.0
24	49N	168E	6–12	101	18.8	7.3	0	16.5
25	49N	168E	6–11	53	26.4	18.2	3.9	32.5
26	49N	168E	6–12	81	19.8	8.8	0	19.2
27	49N	168E	6–13	46	30.4	24.0	8.0	40.0
28	50N	168E	6–29	38	28.9	21.8	4.5	39.1
29	47N	169E	5–25	68	27.9	20.4	7.6	33.3
30	47N	169E	5–25	75	14.7	1.4	0	11.0
31	47N	169E	5–26	52	34.6	30.0	14.4	45.6
32	47N	169E	5–27	51	11.8	0	0	11.3
33	48N	169E	6–13	45	22.2	12.2	0	26.8
34	48N	169E	6–16	43	14.0	0.5	0	13.0
35	49N	169E	6–15	100	29.0	21.9	11.2	32.6
36	49N	169E	6–17	39	15.4	2.5	0	16.1
37	50N	169E	6–23	51	13.7	0	0	11.4
38	50N	169E	6–23	41	12.2	0	0	12.7
39	50N	169E	6–25	44	20.5	9.8	0	24.1
40	46N	170E	5–25	167	41.9	40.4	31.4	49.4
41	47N	170E	5–26	50	16.0	3.3	0	15.5
42	47N	170E	5–27	57	17.5	5.5	0	17.4
43	47N	170E	6–12	52	11.5	0	0	11.2
44	50N	170E	6–25	36	22.2	12.2	0	28.5
45	51N	170E	6– 3	66	31.8	26.0	12.5	39.5
46	51N	170E	6–27	44	15.9	3.2	0	16.2
47	52N	170E	5–25	76	30.6	24.2	11.7	36.7
48	52N	170E	6– 1	46	28.3	20.9	5.2	36.6
49	52N	170E	5–25	77	35.1	30.7	17.9	43.5
50	50N	171E	5–25	76	52.6	55.8	42.3	69.3
51	51N	171E	6–25	33	33.3	28.1	8.8	47.4

Continued . . .

TABLE 6. Continued.

Sample no.	Location		Date	Sample size	Proportion of Bristol Bay type salmon			
	Lat.	Long.			Observed	Corrected	90 percent confidence intervals	
				Number	*Percent*	*Percent*	*Lower*	*Upper*
52	51N	171E	6–27	35	14.3	0.9	0	14.8
53	51N	171E	6–10	127	37.0	33.4	23.3	43.5
54	51N	171E	6–28	33	21.2	10.8	0	27.6
55	51N	173E	6– 4	30	83.3	99.8	83.7	100.0
56	50N	174E	5–31	81	48.1	49.3	36.2	62.4
57	51N	174E	5–31	64	65.6	74.4	60.4	88.4
58	51N	174E	6– 7	51	66.7	76.0	60.4	91.6
59	50N	176E	6– 6	75	25.2	16.6	4.7	28.4
60	51N	176E	6– 5	37	56.8	61.8	42.6	81.0
61	51N	176E	6– 6	97	81.4	97.0	87.7	100.0
62	51N	177E	6– 6	91	83.5	100.0	90.8	100.0
63	51N	176E	6– 7	51	72.5	84.3	69.6	99.0
64	50N	177E	6– 6	85	72.9	84.9	73.6	96.3
65	51N	177E	6– 6	67	67.2	76.7	63.2	90.2
66	51N	177E	6– 6	98	77.6	91.5	81.6	100.0
67	50N	180	6– 2	122	42.6	41.4	30.8	52.0
68	51N	179W	6– 1	74	79.7	94.6	83.6	100.0
69	51N	178W	6– 1	81	69.1	79.5	67.4	91.6
70	54N	177W	6–16	54	79.6	94.5	81.6	100.0
71	51N	176W	5–31	101	71.3	82.6	71.9	93.2
72	51N	176W	6– 1	49	71.4	82.7	67.5	97.9
73	51N	176W	6– 2	54	74.1	86.6	72.5	100.0
74	51N	176W	6– 2	57	68.4	78.4	63.9	92.9
75	51N	176W	6– 4	57	79.0	93.5	80.8	100.0
76	51N	176W	6–11	47	72.3	84.0	68.6	99.4
77	51N	175W	5–31	109	71.6	82.9	72.8	93.1
78	51N	175W	6– 1	55	70.9	82.0	67.6	96.4

TABLE 7. Average distribution (percentage) of mature Bristol Bay type sockeye salmon in 1962 samples from the Aleutian area as determined by use of the 1956–62 quadratic discriminant function.

	Month and latitude														
	May					June					July				
Long.	45N–46N	47N–48N	49N–50N	51N–52N	53N–54N	45N–46N	47N–48N	49N–50N	51N–52N	53N–54N	45N–46N	47N–48N	49N–50N	51N–52N	53N–54N
162E	—	—	—	—	—	—	—	—	—	—	—	—	0	—	—
163E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
164E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
165E	—	—	—	—	—	—	—	—	—	—	—	—	11.2	—	—
166E	—	—	—	—	—	—	—	5.3	—	—	—	—	0.4	—	—
167E	—	—	—	—	—	—	—	0	—	13.9	—	—	—	—	—
168E	—	—	—	—	—	—	7.3	16.0	—	—	—	—	—	—	—
169E	—	13.0	—	—	—	—	6.4	6.8	—	—	—	—	—	—	—
170E	40.4	4.4	—	27.4	—	—	0	12.2	16.7	—	—	—	—	—	—
171E	—	—	55.8	—	—	—	—	—	18.3	—	—	—	—	—	—
172E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
173E	—	—	—	—	—	—	—	—	99.8	—	—	—	—	—	—
174E	—	—	49.3	74.4	—	—	—	—	76.0	—	—	—	—	—	—
175E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
176E	—	—	—	—	—	—	—	16.6	81.0	—	—	—	—	—	—
177E	—	—	—	—	—	—	—	84.9	89.4	—	—	—	—	—	—
178E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
179E	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
180	—	—	—	—	—	—	—	41.4	—	—	—	—	—	—	—
179W	—	—	—	—	—	—	—	—	94.6	—	—	—	—	—	—
178W	—	—	—	—	—	—	—	—	79.5	—	—	—	—	—	—
177W	—	—	—	—	—	—	—	—	—	94.5	—	—	—	—	—
176W	—	—	—	82.6	—	—	—	—	84.6	—	—	—	—	—	—
175W	—	—	—	82.9	—	—	—	—	82.0	—	—	—	—	—	—

TABLE 8. Classification of Bristol Bay and Asian sockeye salmon collected in 1956–62 by scale characters (1956–62 quadratic discriminant function) and by morphological characteristics (1956–57 linear discriminant function).

	Relative number of sockeye salmon misclassified by:			
	Scales		Morphology[1]	
Year	Bristol Bay	Asia	Bristol Bay	Asia
	Percent	*Percent*	*Percent*	*Percent*
1956–57	12.2	28.8	17.7	23.8
1958	22.9	31.7	22.6	28.8
1959	25.3	21.6	23.6	36.6
1960	26.1	35.4	21.8	27.0
1961	18.8	24.4	17.0	36.9
1962	16.5	16.8[2]	19.2	35.4
Average	20.3	26.5	20.3	31.4

[1] Results computed by Morphology Program staff members, Bureau of Commercial Fisheries Biological Laboratory, Seattle, Washington.

[2] This percentage disagrees with that for Asian sockeye in Appendix Tables 3–6 because different samples were used as continental references in the scale and morphological studies; in this table, the morphological study reference samples were classified by the scale method.

method, and (3) pooling of the 1956–62 inshore data to compute the quadratic function for scales, but use of only the 1956 inshore data to compute the linear function for morphological characters. Results of classifying sockeye salmon collected in 1956–62 (Table 8) indicate that, on the average, the scale method is five percent better for classifying Asian fish and exactly the same for classifying Bristol Bay fish. Morphological characters classified Bristol Bay and Asian types of sockeye salmon more efficiently in 1956–60; scale characters were better in 1961 and 1962.

For the 1962 high seas samples, results from the best scale method (use of the 1956–62 quadratic function) were compared with the results from morphological characters as reported by Landrum and Dark (1964) for 39 samples collected on the same dates and from the same geographical areas (Table 9). (Most of the scale samples were from whole fish samples processed at the Bureau of Commercial Fisheries Biological Laboratory, Seattle, Washington.) The correlation between the estimates obtained from the two methods was significant ($P<0.01$) and positive. For the observed values $r=0.93$ and for the corrected values $r=0.94$, see Table 9 and Figures 19 and 20.

Both methods show, for a limited number of samples,

TABLE 9. Classification of mature Bristol Bay type sockeye salmon collected at sea in 1962 by scale and morphological techniques.

				Scales			Morphology		
					Bristol Bay type			Bristol Bay type	
Sample no.	Lat.	Long.	Sample date	Sample size	As classified	Corrected	Sample size	As classified	Corrected
					Percent	*Percent*		*Percent*	*Percent*
1	50N	166E	6–12	82	20.73	10.1	113	33.63	0
2	49N	167E	6–12	88	11.36	0	113	37.17	3.9
3	53N	167E	6–16	137	23.36	13.9	213	36.62	2.7
4	49N	168E	6–12	81	19.75	8.7	103	38.83	7.6
5	48N	168E	6–18	75	14.67	1.4	87	35.63	0
6	48N	168E	6–18	71	19.72	8.6	95	42.11	14.8
7	48N	168E	6–12	79	20.25	9.4	110	35.45	0.1
8	48N	168E	6–12	69	15.94	3.2	88	28.41	0
9	47N	169E	5–25	77	23.38	13.9	92	33.70	0
10	47N	169E	5–25	87	13.79	0.2	96	29.17	0
11	46N	170E	5–25	167	58.08	63.6	196	65.82	67.0
12	47N	170E	6–12	52	11.54	0	58	34.48	0
13	51N	170E	6– 3	66	31.82	25.6	70	37.14	3.8
14	52N	170E	5–25	77	35.06	30.6	107	39.25	8.5
15	52N	170E	6– 1	46	28.26	20.9	43	34.88	0
16	52N	170E	5–25	76	30.26	23.8	104	40.38	11.0
17	51N	171E	6–25	33	33.33	28.2	33	36.36	2.1
18	51N	171E	6–28	33	21.21	10.8	35	42.86	16.4
19	50N	171E	6–10	127	37.01	33.4	194	39.69	9.5
20	50N	171E	5–25	75	44.00	43.4	104	46.15	23.7
21	50N	171E	5–25	76	52.63	55.8	108	62.96	60.7
22	50N	174E	5–31	81	48.15	49.4	115	57.39	48.4
23	50N	174E	5–31	64	65.62	74.4	118	64.41	63.9
24	51N	176E	6– 5	37	56.76	61.7	37	59.46	53.0
25	50N	176E	6– 6	75	25.33	16.7	82	31.71	0
26	51N	176E	6– 6	91	83.52	100.0	110	69.09	74.2
27	50N	177E	6– 6	66	33.33	28.2	74	39.19	8.3
28	51N	177E	6– 6	91	80.22	95.4	111	74.77	86.7
29	51N	177E	6– 6	67	67.16	76.6	109	60.55	55.4
30	50N	177E	6– 6	85	72.94	84.9	116	68.10	72.0
31	50N	180	6– 2	122	42.62	41.5	200	51.00	34.4
32	51N	179W	6– 1	74	79.73	94.6	106	69.81	75.8
33	51N	178W	6– 1	81	69.14	79.5	110	64.55	64.2
34	54N	177W	6–16	54	79.63	94.5	65	87.69	100.0
35	51N	176W	6–31	77	70.13	80.9	108	67.59	70.9
36	51N	176W	6–11	47	72.34	84.1	39	53.85	40.6
37	53N	176W	6–19	30	73.33	85.5	33	66.67	68.9
38	51N	175W	5–31	75	78.67	93.1	103	73.79	84.5
39	53N	167W	7–12	27	57.14	62.3	42	71.43	79.3

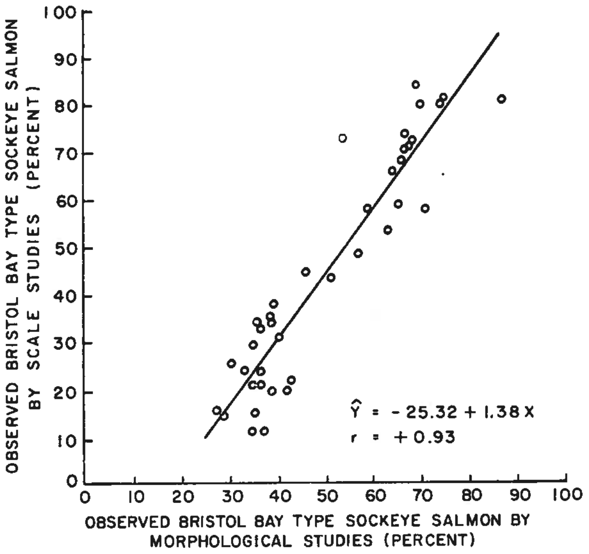

FIGURE 19. Relationship between observed percentage of Bristol Bay type sockeye salmon obtained from scale and morphological studies of samples collected at sea in 1962.

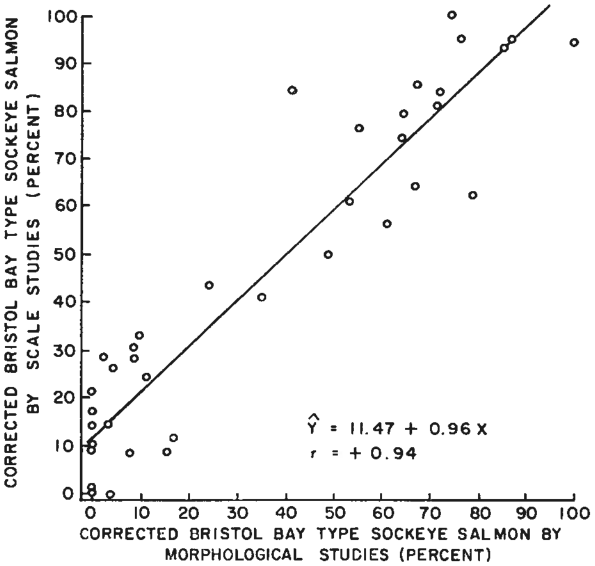

FIGURE 20. Relationship between corrected percentage of Bristol Bay type sockeye salmon obtained from scale and morphological studies of samples collected at sea in 1962.

that Asian type sockeye salmon predominated eastward to 171°E and Bristol Bay type sockeye salmon predominated westward to 174°E.

Results from scales showed, in general, a higher proportion of Bristol Bay type fish for the corrected values. The higher corrected values for Bristol Bay are reflected in the lower errors of classification for the Asian samples by the scale method (Fig. 21). For instance, for an observed value of 40 percent Bristol Bay type fish and a sample size of 90, the corrected value for morphology is 10 percent, whereas the corrected value for scales is 37 percent.

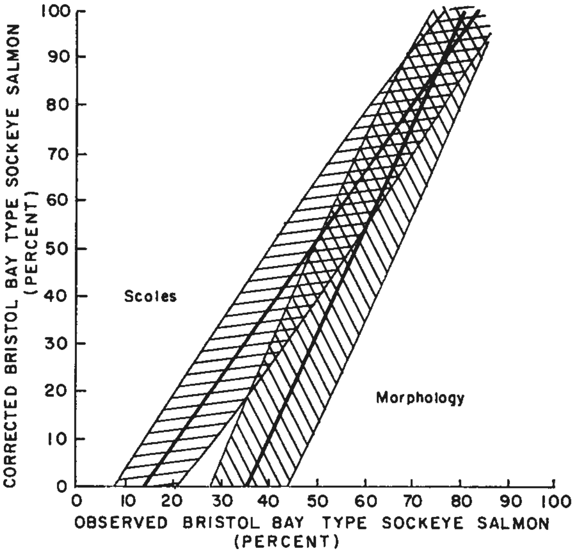

FIGURE 21. Relationship between observed and corrected proportions of Bristol Bay type sockeye salmon and their 90 percent confidence limits for scale and morphological studies (sample size=90).

SUMMARY AND CONCLUSIONS

A method was investigated to determine from three scale characters the continental origin of mature sockeye salmon caught from 1956 through 1962 in the Aleutian area of the high seas. To develop the method, samples from Bristol Bay river systems were used to represent the North American continent; oceanic samples from close to the east and west coasts of Kamchatka were used to represent the Asian continent (except for 1959 when a river sample was available).

Techniques of scale sampling, preparation, and data collection are described. Variability not associated with real continental differences did not invalidate the method. Tests showed that scale readers, selection of radius, fishing gear within age groups, sampling date within season and river system, sex, and plus growth did not add significant variability to the continental differences, whereas differences in year class and age did. The difference between Asian and Bristol Bay sockeye salmon was large enough, however, to offset the effects of year class and age.

A linear discriminant function was computed from inshore data collected each year from 1956 through 1962 and from 1956–62 data pooled. Also, a quadratic discriminant function was computed from the 1957 data and from the 1956–62 pooled data. All of the linear and quadratic discriminant functions effectively separated Asian and Bristol Bay sockeye salmon collected in each of the seven years. Differences among the linear functions were nil or very small. The small differences between the linear and quadratic functions confirmed Isaacson's (1954) conclusion that for large sample sizes the consequences of not satisfying the assumption of common variance-covariance matrices in the use of the linear function is not very serious. The 1956–62 pooled-years quadratic function was selected as the best for our use because: (1) the variance-covariance matrices of the scale characters differed within continents, and (2) on the average, that function was the best for classifying Bristol Bay sockeye salmon. The function is:

$$L=0.0053X^2-0.0159Y^2+0.0276Z^2+0.0002XY+0.0006XZ+0.0366YZ-0.8824X-0.2146Y-2.1620Z+63.7242$$

where

L=the discriminant score (which determines continent of origin)

X=the circulus count in the first half of the first ocean zone (X10)

Y=the measured distance between circuli 1 and 6 of the first ocean zone (in mm)

Z=the measured distance between circuli 13 and 18 of the first ocean zone (in mm).

The selection of one function which can be used for data from all years has two advantages: (1) it eliminates the need for the computation of a new function each year, and (2) consequently, samples collected from the high seas can be classified in a relatively short time. Results from the use of linear and quadratic functions computed from data collected in 1957 were similar to those obtained from the pooled-years functions in each year except 1962; for 1962, the pooled-years functions were superior to the 1957 functions. For the pooled-years quadratic function, errors of classification for Bristol Bay sockeye salmon collected in 1956–62 ranged from 12 to 26 percent (average, 19 percent); those for Asian sockeye salmon ranged from 14 to 37 percent (average, 27 percent).

Analysis of samples collected at sea in 1962 showed that mature Asian sockeye salmon predominated in the western North Pacific Ocean and that Bristol Bay sockeye salmon predominated in the eastern North Pacific Ocean. Mature Bristol Bay sockeye salmon occurred as far west as 173°E and predominated from 175°W to 173°E. Substantial proportions of mature Asian sockeye salmon occurred as far east as 180° and these fish predominated from 162° to 171°E. Intermingling evidently was greatest between 173°E and 180°.

As compared with morphological characters, scales were equally good for classifying Bristol Bay sockeye salmon and five percent better for classifying Asian sockeye salmon. The correlation between the results obtained from scale and morphological methods was high; thus both methods were about equally effective.

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APPENDIX TABLES

Appendix Table 1. Continued.

f. Between year classes

River	Date	Age	Sample size
Ugashik	7- -57	1.3*	63
	7- -58	1.3*	31
Ugashik	7- -56	1.2*	84
	7- -57		30
	7- -60		162
Kvichak	7- -56	1.2*	89
	7- -59		29
	7- -60		153
Wood	7- -56	1.2*	85
	7- -58		105
	7- -59		78
	7- -60		75
Naknek	7- -56	1.3*	32
	7- -57		35
Wood	7- -56	1.3*	33
	7- -57		40
Ugashik	7- -58	2.2	59
	7- -59		49
Kvichak	7- -58	2.2	149
	7- -59		216
Egegik	7-17-56	2.2	99
	7- 7-58		84
	7- 7-59		57
	7-11-60		35
Egegik	7-13-57	2.3	87
	7- 7-58		46
	7- 7-59		32

g. Between freshwater ages

River	Date	Age	Sample size
Naknek	7- 8-56	1.3*	32
	7- -57	2.3*	138

h. Between ocean ages

River	Date	Age	Sample size
Ugashik	7-23-56	1.2*	84
	7-19-57	1.3*	63
Kvichak	7-13-56	1.2*	89
	7- 9 & 10-57	1.3*	95
Wood	7-11-56	1.2*	85
	7-17-57	1.3*	40
Egegik	7- 7-58	2.2	83
	7- 7-59	2.3	32
Ugashik	7-16-58	2.2	59
	7-11-59	2.3	71

APPENDIX TABLE 1. Samples used for tests of extraneous variability. (Asterisk after age designation indicates plus growth.)

a. Between readers

River / boat	Date	Age	Sample size
Karluk	6-24-59	Mixed	30
Kvichak	7- 9-59	„	30
Ugashik	7-11-59	„	30
Ozernaya	9- 1-59	„	30
Wakashio Maru	7- -59	„	60[1]

[1] Two samples of 30 scales.

b. Between sampling dates

River	Age	Sampling dates Date	No.
Naknek	2.3*	7- 5-57	47
		7-12-57	34
Kvichak	1.3*	7- 9-57	50
		7-10-57	45
Kvichak	2.2	7-10-58	36
		7-16-58	38
		7-24-58	75
Kvichak	2.3	7-10-58	58
		7-16-58	33
		7-24-58	40
Kvichak	2.2	7- 9-59	126
		7-14-59	51
		7-26-59	39
Kvichak	1.2	7- 2-60	42
		7- 8-60	60
		7-21-60	30
Kvichak	1.2*	7- 2-60	56
		7- 8-60	45
		7-21-60	52

c. Fishing gear

River	Date	Age	Sample size
Naknek	7- 8-56	1.3*	32
Egegik	7-17-56	2.2	99
Ugashik	7-23-56	1.2*	84
Kvichak	7-13-56	1.3*	89
Naknek	7- 3-57	2.3*	35
Naknek	7- 5-57	2.3*	47
Naknek	7-12-57	2.3*	34
Naknek	7-25-57	2.3	57
Egegik	7-13-57	1.3*	87
Kvichak	7- 9-57	1.3*	50
Kvichak	7-10-57	1.3*	45
Wood	7-17-57	2.2	40
Naknek	7- 9-58	2.2	31
Kvichak	7-26-59	1.2*	29
Wood	6-29-59		78

d. Between sexes

River	Date	Age	Sample size by sex Male	Female
Wood	7-11-56	1.2*	34	51
Kvichak	7-13-56	1.2*	43	46
Ugashik	7-23-56	1.2*	42	42
Egegik	7- 7-58	2.2	32	52
Kvichak	7-24-58	2.2	37	38

e. Between presence or absence of plus growth

River	Date	Age	Sample size
Kvichak	7- 9-59	2.2	126
		2.2*	46
Ugashik	7-11-59	2.2	49
		2.2*	30
Kvichak	7- 2 & 8-10-60	1.2	132
		1.2*	153
Egegik	7-11-60	1.2	46
		1.2*	48

Continued . . .

Appendix Table 2. Analysis of variance tests of readers for three scale characters of sockeye salmon.

Source of variation	Degrees of freedom	Sums of squares	Mean squares
a. *Circulus count in the first half of the first ocean zone*			
Areas	5	222.67	44.53
Scales within area	174	697.71	4.01
Readers	2	14.88	7.44
Areas × readers	10	12.38	1.24
Scales within area × readers	348	139.23	0.40
Replicates	540	241.88	0.45
Total	1,079	1,328.74	
b. *Distance between circuli 1 and 6 of the first ocean zone*			
Areas	5	2,417.14	483.43
Scales within area	174	6,992.22	40.19
Readers	2	71.74	35.87
Areas × readers	10	25.08	2.51
Scales within area × readers	348	892.15	2.56
Replicates	540	1,000.00	1.85
Total	1,079	11,398.33	
c. *Distance between circuli 13 and 18 of the first ocean zone*			
Areas	5	405.75	81.15
Scales within area	174	5,016.62	28.83
Readers	2	458.63	229.32
Areas × readers	10	25.79	2.58
Scales within area × readers	348	783.56	2.25
Replicates	540	1,043.00	1.93
Total	1,079	7,733.35	

Appendix Table 3. Components of variance for three scale characters of sockeye salmon to determine the effects of different readers.

	Scale character		
Source of variation	Circulus count in the first half of the first ocean zone	Distance between circuli 1 and 6 of the first ocean zone	Distance between circuli 13 and 18 of the first ocean zone
Areas	0.2205	2.4628	0.2888
Scales within area	0.6016	6.2703	4.4299
Reader	0.0172	0.0927	0.6298
Reader × Areas	0.0140	0	0.0055
Reader × Scales within area	0	0.3559	0.1601
Error	0.4479	1.8519	1.9315
Reader + Reader × Scales within area	0.0172	0.4486	0.7899

Appendix Table 4. Between-scale variances (within area) for three scale characters of sockeye salmon to determine the value of duplicate readings.

Source	Circulus count in the first half of the first ocean zone	Distance between circuli 1 and 6 of the first ocean zone	Distance between circuli 13 and 18 of the first ocean zone
1 reader[1]; 1 reading	1.05	8.48	6.52
2 readers[2]; 1 reading	0.90	7.42	5.79
1 reader[3]; 2 readings	0.83	7.56	5.56

[1] $V = \alpha^2_{S(A)} + \alpha^2_{R\times S(A)} + \alpha^2_E$

[2] $V = \alpha^2_{S(A)} + \frac{1}{2}(\alpha^2_R + \alpha^2_{R\times S(A)} + \alpha^2_E)$

[3] $V = \alpha^2_{S(A)} + \alpha^2_{R\times S(A)} + \frac{1}{2}\alpha^2_E$

where: $\alpha^2_{S(A)}$ = scales-within-area variance
$\alpha^2_{R\times S(A)}$ = readers, scales-within-area variance
α^2_E = error variance

Appendix Table 5. Summary of one-way analysis of variance tests between sampling dates for three scale characters of sockeye salmon.

River	Degrees of freedom	*F*-values for: Circulus count in the first half of the first ocean zone	*F*-values for: Distance between circuli 1 and 6 of the first ocean zone	*F*-values for: Distance between circuli 13 and 18 of the first ocean zone
Naknek	(1,79)	0.32	0.51	1.18
Kvichak	(1,93)	0.18	0.52	0.69
Kvichak	(2,146)	1.13	1.49	3.23*
Kvichak	(2,128)	0.25	0.20	0.80
Kvichak	(2,213)	0.36	0.22	0.77
Kvichak	(2,129)	2.69	0.86	2.71
Kvichak	(2,150)	0.65	1.10	1.00

* $P<0.05$.

Appendix Table 6. Tests for common correlation coefficients (r) and average correlation ($\bar{r}$) between scale characters and body length for 15 samples of sockeye salmon collected in Bristol Bay, 1956–59.

Scale character	Test for common r[1]	$\bar{r}$	$\bar{r}^2$
		Fraction	*Percent*
Circulus count in the first half of the first ocean zone	N S	+0.06	0.36
Distance between circuli 1 and 6 of the first ocean zone	N S	+0.04	0.16
Distance between circuli 13 and 18 of the first ocean zone	N S	+0.05	0.25

[1] NS=Not significant.

Appendix Table 7. Summary of analysis of variance[1] tests between sexes for three scale characters of sockeye salmon.

River	Degrees of freedom		*F*-values for: Circulus count in the first half of the first ocean zone		Distance between circuli 1 and 6 of the first ocean zone		Distance between circuli 13 and 18 of the first ocean zone	
	Interaction	Sexes	Interaction	Sexes	Interaction	Sexes	Interaction	Sexes
Wood Kvichak Ugashik	(2,252)	(1,252)	2.04	0	0.58	2.41	1.57	0.27
Egegik Kvichak	(1,155)	(1,155)	0.05	0.41	0.36	1.24	0.09	1.44

[1] Approximate R×C method described by Snedecor (1956) was used because the sample sizes were not equal.

Appendix Table 8. Summary of analysis of variance[1] between presence or absence of plus growth for three scale characters of sockeye salmon.

River	Degrees of freedom		*F*-values for: Circulus count in the first half of the first ocean zone		Distance between circuli 1 and 6 of the first ocean zone		Distance between circuli 13 and 18 of the first ocean zone	
	Interaction	Plus growth	Interaction	Plus growth	Interaction	Plus growth	Interaction	Plus growth
Kvichak Ugashik Wood	(2,247)	(1,247)	1.17	0.10	0	1.36	0.59	0.21
Kvichak Egegik	(1,375)	(1,375)	0.05	0.12	1.08	0.57	0.03	1.56

[1] Approximate R×C method described by Snedecor (1956) was used because the sample sizes were not equal.

Appendix Table 9. Summary of one-way analysis of variance tests between year classes for three scale characters of sockeye salmon.

River	Degreess of freedom	*F*-values for: Circulus count in the first half of the first ocean zone	Distance between circuli 1 and 6 of the first ocean zone	Distance between circuli 13 and 18 of the first ocean zone
Ugashik	(1,92)	5.49*	1.77	9.62**
Ugashik	(2,273)	3.24	18.01**	4.25*
Kvichak	(2,268)	4.90*	16.64**	1.44
Wood	(3,339)	4.40*	28.52**	4.55*
Naknek	(1,65)	16.18**	8.46*	7.86**
Wood	(1,71)	12.86**	0.05	3.21
Ugashik	(1,106)	0.11	16.24**	2.53
Kvichak	(1,363)	6.30*	2.36	5.06*
Egegik	(3,271)	3.93*	24.51**	6.51*
Egegik	(2,162)	0.83	17.73**	1.87

* $P<0.05$.
** $P<0.01$.

Appendix Table 10. Summary of one-way analysis of variance test between freshwater ages for three scale characters of sockeye salmon.

		F-values for:		
River	Degrees of freedom	Circulus count in the first half of the first ocean zone	Distance between circuli 1 and 6 of the first ocean zone	Distance between circuli 13 and 18 of the first ocean zone
Naknek	(1,169)	21.18**	24.27**	4.31*

* P<0.05.
** P<0.01.

Appendix Table 11. Summary of analysis of variance tests[1] between ocean ages for three scale characters of sockeye salmon.

			F-values for:					
	Degrees of freedom		Circulus count in the first half of the first ocean zone		Distance between circuli 1 and 6 of the first ocean zone		Distance between circuli 13 and 18 of the first ocean zone	
River	Interaction	Ocean ages	Interaction	Ocean ages	Interaction	Ocean ages	Interaction	Ocean ages
Ugashik Kvichak	(2,450)	(1,450)	0.28	1.15	0.85	7.61	1.09	1.83
Wood Egegik Ugashik	(1,241)	(1,241)	6.33*	—	4.18*	—	1.35	2.30

* P<0.05.
** P<0.01.

[1] Approximate R×C method described by Snedecor (1956) was used because the samples sizes were not equal.

APPENDIX TABLE 12. Percentage errors in classification of sockeye salmon from Bristol Bay and Asia, 1956–62.

							Misclassification by:			
							Linear function		Quadratic function	
Area	Subarea	Date	Sample size	Function	Escapement (millions of fish)	Relative abundance	Observed value	Weighted value	Observed value	Weighted value
A. 1956										
Bristol Bay	Naknek R.	7- 8-56	32	1957	1.773	.1313	31.3	4.1097	31.3	4.1097
				1956–62			40.6	5.3308	37.5	4.9238
	Egegik R.	7-17-56	100	1957	1.104	.0817	2.1	0.1716	3.0	0.2451
				1956–62			6.0	0.4902	6.0	0.4902
	Ugashik R.	7-23-56	91	1957	0.425	.0315	15.5	0.4883	16.5	0.5198
				1956–62			20.9	0.6584	18.7	0.5891
	Kvichak R.	7-13-56	93	1957	9.444	.6995	11.5	8.0443	9.7	6.7852
				1956–62			9.7	6.7852	8.6	6.0157
	Wood R.	7-11-56	120	1957	0.756	.0560	18.6	1.0416	16.7	0.9352
				1956–62			13.3	0.7448	11.7	0.6552
SW Kamchatka	51°N 154°E	7-13-56	55	1957	—	—	27.8	—	27.3	—
				1956–62			27.3	—	27.2	—
	52°N 154°E	7- 6-56	160	1957	—	—	28.8	—	30.0	—
				1956–62			32.5	—	32.5	—
	52°N 154°E	6-21-56	119	1957	—	—	37.0	—	42.0	—
				1956–62			47.9	—	48.7	—
	52°N 154°E	6-28-56	164	1957	—	—	25.5	—	29.3	—
				1956–62			37.2	—	36.6	—
Bristol Bay	Pooled	1956	436	1957	13.502	1.000	—	13.8555	—	12.6740
				1956–62			—	14.0094	—	12.5950
SW Kamchatka	Pooled	1956	498	1957	—	—	29.7750	—	32.1500	—
				1956–62			36.2250	—	36.2500	—
B. 1957										
Bristol Bay	Naknek R.	7-3, 25-57	173	1957	0.635	.1409	4.6	0.6481	4.6	0.6481
				1956–62			10.4	1.4654	9.8	1.3808
	Egegik R.	7-13-57	88	1957	0.391	.0868	3.3	0.2864	3.4	0.2951
				1956–62			9.1	0.7899	5.7	0.4948
	Ugashik R.	7-19-57	93	1957	0.215	.0477	10.8	0.5152	9.7	0.4627
				1956–62			11.8	0.5629	9.7	0.4627
	Kvichak R.	7-9, 10-57	97	1957	2.965	.6580	14.4	9.4752	12.4	8.1592
				1956–62			17.5	11.5150	13.4	8.8172
	Wood R.	7-17-57	40	1957	0.300	.0666	7.5	0.4995	5.0	0.3330
				1956–62			5.0	0.3330	7.5	0.4995
SW Kamchatka	51°N 154°E	7-14-57	162	1957	—	—	13.6	—	14.8	—
				1956–62			13.0	—	15.4	—
	51°N 154°E	7- 4-57	171	1957	—	—	19.9	—	22.8	—
				1956–62			24.0	—	24.6	—
	52°N 154°E	6-24-57	154	1957	—	—	21.4	—	23.4	—
				1956–62			24.0	—	24.0	—
Bristol Bay	Pooled	1957	491	1957	4.506	1.0000	—	11.4244	—	9.8981
				1956–62			—	14.6662	—	11.6550
SW Kamchatka	Pooled	1957	487	1957	—	—	18.3000	—	20.3333	—
				1956–62			20.3333	—	21.3333	—

Continued . . .

Appendix Table 12. Continued.

							Misclassification by:			
							Linear function		Quadratic function	
Area	Subarea	Date	Sample size	Function	Escapement (millions of fish)	Relative abundance	Observed value	Weighted value	Observed value	Weighted value
G. 1962										
Bristol Bay	Naknek R.	7- 5-62	159	1957	0.718	.1297	7.9	1.0246	7.5	0.9728
				1956-62			8.2	1.0635	7.5	0.9728
	Egegik R.	7-11-62	163	1957	1.027	.1856	10.3	1.9117	14.7	2.7283
				1956-62			9.2	1.7075	13.5	2.5056
	Ugashik R.	7-18-62	165	1957	0.255	.0461	23.2	1.0695	27.9	1.2862
				1956-62			23.0	1.0603	26.7	1.2309
	Kvichak R.	7-7, 12-62	312	1957	2.580	.4663	12.1	5.6422	13.8	6.4349
				1956-62			12.5	5.8288	13.5	6.2951
	Wood R.	7- 4-62	163	1957	0.863	.1560	40.0	6.2400	36.8	5.7408
				1956-62			38.0	5.9280	33.7	5.2572
	Branch R.	7- 9-62	36	1957	0.090	.0163	11.8	0.1923	13.9	0.2266
				1956-62			11.1	0.1809	16.7	0.2722
SE Kamchatka	50°N 163°E	7-11-62	35	1957	—	—	28.6	—	22.9	—
				1956-62			14.3	—	17.1	—
	50°N 164°E	7-11-62	31	1957	—	—	25.8	—	23.5	—
				1956-62			12.9	—	19.4	—
	50°N 164°E	7-13-62	29	1957	—	—	27.6	—	24.1	—
				1956-62			10.3	—	17.2	—
	51°N 164°E	7- 9-62	42	1957	—	—	14.3	—	14.3	—
				1956-62			4.8	—	7.1	—
	51°N 164°E	7- 9-62	49	1957	—	—	18.4	—	12.2	—
				1956-62			6.1	—	6.1	—
	51°N 163°E	7-13-62	32	1957	—	—	15.6	—	15.2	—
				1956-62			12.1	—	15.2	—
Bristol Bay	Pooled	1962	998	1957	—	1.0000	—	16.0803	—	17.3896
				1956-62			—	15.7690	—	16.5338
SE Kamchatka	Pooled	1962	218	1957	5.533	—	21.7167	—	18.7000	—
				1956-62			10.0833	—	13.6833	—

APPENDIX TABLE 13. Computation of the 1956–62 quadratic discriminant function.

Scale character	Mean scale characters for:	
	Asia	Bristol Bay
X = circulus count in the first half of the first ocean zone (× 10)	$m_x = 106.4046$	$M_x = 91.1553$
Y = measured distance between circuli 1 and 6 of the first ocean zone (in mm)	$m_y = 30.1440$	$M_y = 32.7896$
Z = measured distance between circuli 13 and 18 of the first ocean zone (in mm)	$m_z = 25.7970$	$M_z = 22.9521$

Bristol Bay Variance—Covariance Matrix

	x	*y*	*z*	
x	89.195	−12.921	10.520	
y	—	9.035	−0.076	$=V$
z	—	—	6.781	

Asian Variance—Covariance Matrix

	x	*y*	*z*	
x	158.877	−17.634	21.508	
y	—	8.929	0.044	$=v$
z	—	—	9.896	

Bristol Bay Inverse Variance—Covariance Matrix

	x	*y*	*z*	
x	0.018272	0.025894	−0.028056	
y	0.025894	0.147388	−0.038520	$=I$
z	−0.028056	−0.038520	0.190565	

Asian Inverse Variance—Covariance Matrix

	x	*y*	*z*	
x	0.012999	0.025813	−0.028368	
y	0.025813	0.163252	−0.056827	$=i$
z	−0.028368	−0.056827	0.162958	

Continued . . .

$$\alpha_{xx} = I_{xx}-i_{xx} = 0.0053$$

$$\alpha_{yy} = I_{yy}-i_{yy} = -0.0159$$

$$\alpha_{zz} = I_{zz}-i_{zz} = 0.0276$$

$$\alpha_{xy} = I_{xy}-i_{xy} = 0.0001$$

$$\alpha_{xz} = I_{xz}-i_{xz} = 0.0003$$

$$\alpha_{yz} = I_{yz}-i_{yz} = 0.0183$$

$$\alpha_{x} = i_{xx}m_x+i_{xy}m_y+i_{xz}m_z-I_{xx}M_x-I_{xy}M_y-I_{xz}M_z=-0.4412$$

$$\alpha_{y} = i_{xy}m_x+i_{yy}m_y+i_{yz}m_z-I_{xy}M_x-I_{yy}M_y-I_{yz}M_z=-0.1073$$

$$\alpha_{z} = i_{xz}m_x+i_{yz}m_y+i_{zz}m_z-I_{xz}M_x-I_{yz}M_y-I_{zz}M_z=-1.0810$$

$$\begin{aligned}\alpha = {} & I_{xx}M_x^2+2I_{xy}M_xM_y+2I_{xz}M_xM_z+I_{yy}M_y^2+2I_{yz}M_yM_z+I_{zz}M_z^2-i_{xx}m_x^2-2i_{xy}m_xm_y \\ & -2i_{xz}m_xm_z-i_{yy}m_y^2-2i_{yz}m_ym_z-i_{zz}m_z^2-\ln(w/W) = 64.6632-0.9390 = 63.7242\end{aligned}$$

and:

$$w = v_{xx}v_{yy}v_{zz}-v_{xy}^2-v_{xz}^2-v_{yz}^2 = 13265.0376$$

$$W = V_{xx}V_{yy}V_{zz}-V_{xy}^2-V_{xz}^2-V_{yz}^2 = 5187.0224$$

$$^{*}L = \alpha_{xx}X^2+\alpha_{yy}Y^2+\alpha_{zz}Z^2+2\alpha_{xy}XY+2\alpha_{xz}XZ+2\alpha_{yz}YZ+2\alpha_xX+2\alpha_yY+2\alpha_zZ+\alpha$$

$$\begin{aligned}L = {} & 0.0053X^2-0.0159Y^2+0.0276Z^2+0.0002XY+0.0006XZ+0.0366YZ-0.8824X-0.2146Y \\ & -2.1620Z+63.7242\end{aligned}$$

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* Smith (1947) used the equation:

$$L = I_{xx}(X-M_x)^2-i_{xx}(X-m_x)^2+\ldots+2I_{xy}(x-M_x)(y-M_y)-2i_{xy}(x-m_x)(y-m_y)+\ldots$$

for solving a quadratic discriminant for any number of variables. Use of our equation (Smith's two-variable equation expanded for three variables) gave the same results.