Identification of Arctic char stocks in the Cambridge Bay Area, Nunavut Territory, and evidence of stock mixing during overwintering

by

Allan H. Kristofferson

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy

Department of Zoology
University of Manitoba
Winnipeg, Manitoba

November, 2002

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

I examined samples of anadromous Arctic char spawners from twelve locations in the Cambridge Bay area, Nunavut Territory, for evidence of stock structuring. These samples could be distinguished from one another on the basis of differences in morphological characters, using discriminant function analysis. Significant differences in the means of morphometric characters (ANOVA, minimum $p < 0.05$) were evident for most pair-wise comparisons. The morphometric characters that contributed the most to the discrimination were orbital length, maxillary width, and head depth. Discrimination among samples was less effective using meristic counts, but many significant differences were observed in pair-wise comparisons, and results paralleled those from the morphometric analysis. The meristic counts that contributed most to the discrimination were anal fin ray count, pyloric caeca count, and upper gill raker count. There was evidence of reproductive isolation among these spawning aggregations, based on significant differences ($p < 0.05$, $p < 0.001$) in allele frequencies for Malic Enzyme between some samples of spawners. I present clear evidence of homing to natal spawning grounds based on significant differences among samples (ANOVA, minimum $p < 0.05$) in mean strontium (Sr) concentrations (micro-PIXE) in the early growth regions of otoliths of spawners. The consistency of the Sr concentrations among all age groups within each sample of spawners is evidence of philopatry. I conclude that anadromous Arctic char in the study area home to a high degree and have formed discrete stocks, both within and between river systems. Samples of nonspawning Arctic char captured in autumn upstream migrations as they returned to fresh water showed considerable heterogeneity in morphometric characters (cluster analysis and discriminant function analysis) and otolith Sr concentrations in the early growth regions. This is evidence that these upstream migrations are composed of an admixture of stocks. Nonsatisfaction of Castle-Hardy-Weinberg equilibrium (Malic Enzyme, heterozygote deficiency) in one sample provides additional evidence of mixing of stocks during this overwintering migration.The Arctic char is very important to the economy of the Inuit of the study area and is harvested regularly.Threats to the genetic diversity of this species, contained within the aggregate of these discrete stocks, include habitat destruction and harvest. In order to preserve the genetic diversity of individual stocks, an effective management strategy must be developed and implemented. I present an "Adaptive Management" approach for future consideration. This approach utilizes the traditional ecological knowledge of the resource users, in particular the location of spawning grounds, and couples it with the biological complexities of this species. Harvest plans need to be developed, based on this information, so that individual stocks can be harvested at a level that will not adversely affect the genetic diversity of the species.

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ACKNOWLEDGEMENTS

A great many people have provided me with the support needed to carry out this study. I would like to begin by thanking the Inuit of Cambridge Bay for very willingly sharing their knowledge of Arctic char with me, particularly the locations of spawners. Without this information, the study would not have been possible. Individuals include Bill Lyall, David Kaomayok, the Ohokannoak family, and Moses Koihok.

I thank my supervisor, Dr. Kenneth Stewart, for his guidance, advice, stimulation, wisdom, humour and patience throughout the rather long gestation period of this work. He was always there when I needed him. I thank my advisory committee members, Dr. Drew Bodaly, Dr. Fikret Berkes and Dr. Mark Abrahams for their advice, constructive criticisms and reviews of this work . I also thank Dr. Geoffrey Power for acting as external examiner.

The Department of Fisheries and Oceans has supported this project from the beginning. From that organization I would like to thank Robert Moshenko and Roger Peet and Drs. Burt Ayles and Redmond Clarke for providing me with the opportunity to pursue this endeavour, and to Larry de March for continued support. Gary Carder and Dale McGowan provided essential support in the field and the lab and to them I will be forever grateful. I thank John Babaluk for introducing me to the world of micro-PIXE and for that he has my everlasting gratitude. Others who helped with field and laboratory work include George Low, Burt Hunt, Lianne Postma, Jennifer Brown Gladden, Theresa Carmichael, Fred Hnytka, Len Andrusiak, Jim Johnson, Rick Wastle and the students. Dr. Ray Hesslein and Dr. Pat Ramlal helped with the stable isotope analysis. Dan Topolniski, Peter Thompson, Patt Hall, Judy Freeman and Don Dowler provided plenty of encouragement when needed. Ron Hempel and Chelsey Booth provided key support with figures and typing.

Margaret Koshinsky and Ron Bretecher from North/South did an excellent job with the morphology. Dr. Norman Halden and Sergio Mejia from the Department of Geological Sciences, University of Manitoba, and Dr. Ian Campbell and Bill Teesdale from the Department of Physics, University of Guelph , provided key support for the micro-PIXE analysis, and I thank all of them.

I would like to extend a special thanks to Dr. Lionel Johnson for many stimulating discussions about Arctic char and to Dr. Casimir Lindsey, a former mentor, for his faith in my ability.

Finally, I would like to thank my wife Arleen for putting up with me for all these years and believing in me when I most needed it. Without her support I could not have done this.

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INTRODUCTION

The Arctic Char

The Arctic char, *Salvelinus alpinus* (Linnaeus), is the most northerly-distributed freshwater fish. Worldwide, it has a circumpolar distribution, including northern North America and northern Eurasia, especially in the Scandinavian countries and parts of the Alps. It also occurs in Iceland, Greenland and the many interspersed Arctic islands. In North America it is found in Newfoundland, Labrador, north along the Ungava Peninsula to Hudson Bay, the Arctic Archipelago, and west to the Mackenzie River (Fig. 1). A few relict lacustrine populations occur west of the Mackenzie along the Yukon north slope (Reist 1997) as well as in Quebec and the Canadian Maritime Provinces, Maine and New Hampshire (McPhail and Lindsey 1970; Scott and Crossman 1973). In the extreme northern areas of its range, no other freshwater fishes are present (Johnson 1980).

Across its range, the Arctic char exhibits extreme variability in meristics, morphometry and coloration. Initially, several of these variants were named as distinct species (Johnson 1980; Nyman 1989). Current taxonomic information indicates that the Arctic char examined in this study are all members of a single species, *Salvelinus alpinus* (Reist 1989, 1997).

Arctic char occur as anadromous or nonanadromous forms throughout the species range (Johnson 1980). Nonmigratory freshwater char occur both in lakes separated from the sea by impassable barriers and in many lakes and rivers with access to the sea where they live sympatrically with the anadromous form. By definition, *anadromous* refers to migratory fishes that spend most of their lives in the sea, returning to freshwater to spawn

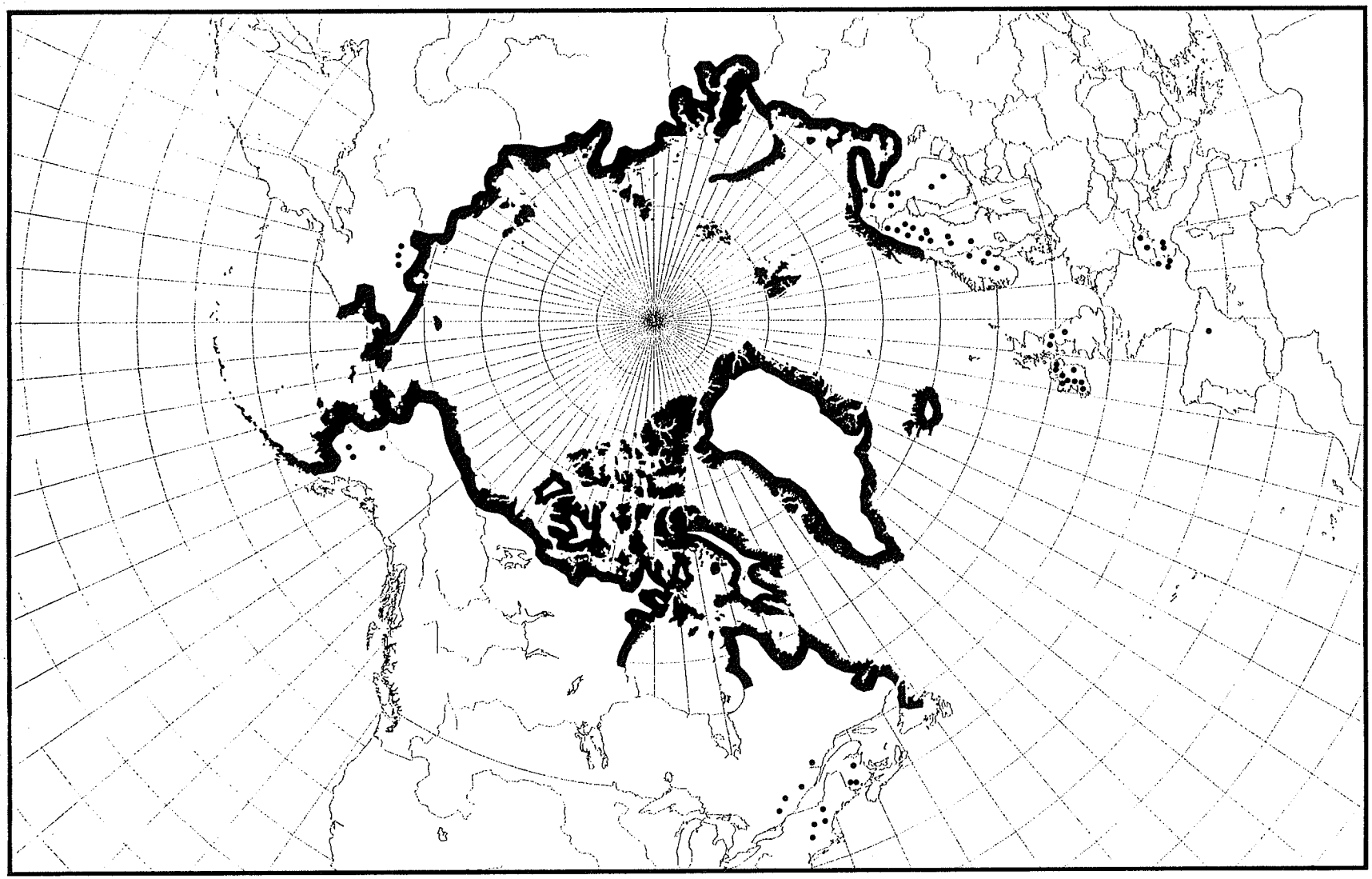

Figure 1. Distribution of Arctic char in North America and worldwide, after Scott and Crossman (1973) and Johnson (1980).

(Myers 1949, cited in McDowall 1987). In the case of the Arctic char, the migration to sea and back is primarily a feeding migration, and takes place on an annual basis once salinity tolerance has been attained. The term *amphidromous* refers to migratory fishes whose migration from freshwater to sea, or vice versa, is not for the purpose of breeding (Myers 1949). Perhaps this term better describes the searun form of Arctic char. However, there are instances where upstream migrations of Arctic char do include spawners. To avoid confusion in this study, Arctic char that migrate to sea to feed and return in fall to fresh water to overwinter are referred to as *anadromous*. Those that live sympatrically with the anadromous char but do not go to sea are referred to as *nonanadromous*. Arctic char isolated from the sea are referred to as *landlocked.*

Life History

The life history of Arctic char in Canada has been described in detail by Sprules (1952), Grainger (1953), Andrews and Lear (1956), McPhail and Lindsey (1970), Scott and Crossman (1973), Moore and Moore (1974), Moore (1975a, 1975b), Johnson (1980), Dempson and Green (1985), Cunjak et al. (1986), Dutil (1986) and Johnson (1989). All forms spawn in freshwater in the fall (usually September or October) over a gravel substrate. Lakes are utilized in the central Canadian Arctic and the Arctic islands because most rivers freeze completely in winter (Johnson 1980). In other areas, spawning occurs in rivers, often because suitable lakes are not available. The males are the first to arrive on the spawning grounds and most establish territories that they defend. Arriving females are then "courted" by the males. The female digs a redd, 2-3 m in diameter, in water 3-6 m deep, into which the eggs are deposited once spawning takes place. The males'

territorial behaviour diminishes after the last female leaves the spawning grounds although some continue to fight occasionally for several months after spawning is complete (Johnson 1980). The eggs incubate under the ice for a period of about six months. After hatching in spring, the young char spend their early life entirely in fresh water.

Arctic char are carnivorous, the young feeding on amphipods and insect larvae, and the adults on small fish and bottom organisms, including gastropods and chironomid larvae. When they reach a size of about 150-200 mm (4 or 5 years in most systems) they make their first migration to the sea. They then continue to make an annual migration to sea until they reach sexual maturity (Johnson 1980). Feeding in the sea is along nearshore areas and char may migrate 50-100 km from the home stream during the summer (Moore 1975b; Sekerak et al. 1976; Johnson 1980). This migratory strategy allows char access to the much greater food resources of the marine environment, which results in a considerable increase in growth rate compared with nonanadromous Arctic char (Moore and Moore 1974). Depending upon geographic location and local environmental conditions, these summer feeding forays into the sea may last from 5 to 8 weeks (Johnson 1980; Dempson and Kristofferson 1987). In the fall, all Arctic char return to freshwater to overwinter, to escape freezing in the sea (Johnson 1980).

Once they reach sexual maturity, at a size generally exceeding 450 mm in length, the char are ready to spawn. In the study area, the absence of mature char in the fall upstream migration is an indication that they do not, for the most part, make the annual feeding migration to the sea the summer prior to spawning in the fall (Sprules 1952; Grainger 1953; Johnson 1980). In fact, mature char can be captured on the spawning

grounds in freshwater in mid-summer. They are easily recognized as spawners by their bright red coloration. After spawning, these char remain in fresh water for another winter, entering the sea again to feed the following summer. At this point, they are often very emaciated, having lost up to 30-40% of their body weight as a consequence of spawning and missing a summer of feeding in the sea (Dutil 1986).

Arctic char are iteroparous. That is, they are capable of spawning more than once. However, annual spawning has not been observed in stocks in the Canadian Arctic. Spawning is energy-dependent and may occur at intervals of two to four years. Therefore, some char may spawn only once or twice in their lifetime (Sprules 1952; Johnson 1980).

During nonspawning years, there is evidence that Arctic char may not return to the "home" stream to overwinter. Armstrong and Morrow (1980) suggested that nonspawning anadromous Dolly Varden char (*S. malma*) entered freshwater more or less indiscriminately in order to overwinter, and returned to the "parent stream" when ready to spawn.

Anadromous Arctic char from the Canadian Central Arctic have been tagged on the spawning grounds and recaptured as nonspawners in winter in other freshwater systems (Kristofferson unpublished). Johnson (1980) observed more returning nonspawners to Nauyuk Lake in fall than were counted migrating downstream the previous spring. Therefore, interchange of anadromous Arctic char between freshwater systems is known to occur, but the extent of and reasons for this behaviour have yet to be determined.

Little information is available on the degree of homing of anadromous Arctic char to natal spawning grounds. Studies by Alm (1951) in Lake Vattern, Sweden, Frost

(1963), LeCren and Kipling (1963), and Kipling and LeCren (1984) in Windermere, England, and McCleave et al. (1977) in Floods Pond, Maine, provide evidence of very strong homing behaviour by landlocked Arctic char spawners. As Johnson (1980) points out, it is unlikely that these nonmigratory populations of Arctic char evolved this homing behaviour after their isolation at the end of the Pleistocene epoch. Most likely, homing was inherited from anadromous ancestors, but proof of homing of anadromous spawners to natal sites has not been established.

Humans and Arctic char

The Arctic char has been a critically important element in the subsistence economy of Inuit in Canada's Nunavut Territory (Balikci 1980) and continues to be so today. In areas where an apparent abundance of Arctic char exists, small commercial fisheries have developed that supply local and sometimes export markets (Kristofferson et al. 1984). There is also a growing interest in sport fishing for Arctic char. However, the low fecundity, slow growth rate and infrequent spawning events make the Arctic char particularly vulnerable to overexploitation (Scott and Crossman 1973). Oil and gas exploration and other developments in the Canadian Arctic pose a threat to Arctic char habitat as well.

The Stock

The term "stock" has had many applications in fisheries science. It has been used to describe a unit of population of lower category than that recognized by taxonomists (Cushing 1981). From a management perspective, a stock has been characterized by

homogeneity of natural production parameters such as growth, recruitment and death rates, and may include a portion of a population or more than one population (Tyler and Gallucci 1980). An international symposium was held in 1980 (Stock Concept International Symposium [STOCS] convened at Alliston, Ontario, September 29-October 9, 1980) in an attempt to formalize the stock concept. Included in the proceedings Booke (1981) provided both a general and a precise definition of a fish stock. His general definition is a species group, or population, of fish that maintains and sustains itself in a definable area. This is essentially the "population" or "deme" of Mayr (1963). His precise definition of stock (genotypic) is a population of fish maintaining and sustaining Castle-Hardy-Weinberg equilibrium. Essentially it describes a stock as a population that has a degree of genetic uniqueness (Larkin 1972), hence a degree of reproductive isolation. The term "stock", as it is used in this study, follows Booke (1981).

Two behavioral characteristics are fundamental to the formation and maintenance of discrete stocks of fish. These include homing of spawners to natal spawning sites and imprinting during early life history stages to the natal site. This results in some degree of reproductive isolation that manifests itself as genotypic-phenotypic differences, which may be adaptive to the local environment (Horrall 1981).

Booke (1981) maintains that if genotypic stock characterization is not possible, a phenotypic stock should be recognized. His definition of a phenotypic stock is a group, or population, of fish maintaining characteristics, which are expressed in one or more ways depending on the type of environment. A phenotypic stock is recognized by any definable character difference, whether largely genetically controlled or affected in its expression by the environment.

Stocks, then, are the groupings within which genetic adaptation to local conditions may develop. They are the proving ground for new genes and gene combinations. Within each stock is a range of individual genetic variation and among all stocks is a range of group variation. Collectively, the extent of the genetic diversity of a species is contained within the aggregate of these local stocks. Human-induced threats to genetic variation generally include harvest and habitat destruction. Therefore, it is important to be able to identify genetically unique local populations or stocks in order to protect them from irreversible reduction due to excessive harvest and loss of habitat (Dizon et al. 1991).

Study Objectives

In this study, I have attempted to demonstrate whether distinct stocks of Arctic char exist within and between several river systems in the Cambridge Bay area, Nunavut Territory, in Canada's Central Arctic. This includes an examination of some fundamental life history characteristics such as homing to natal spawning grounds and migrations to and from the sea for the purpose of feeding. Toward that end I have compared samples of spawners both within and among several river systems using morphology, meristic counts, trace element analysis of otoliths, protein electrophoresis, mitochondrial DNA analysis and stable isotope analysis. The first hypothesis to be tested is:

Ho: Arctic char from the various locations sampled in the study area comprise a panmictic population.

Ha: Arctic char from the various locations sampled in the study area are comprised of discrete populations.

Char that are not spawning in a given year may overwinter in a river system other than their natal river system. Therefore, I have also gathered these data from samples of nonspawners from these systems taken during fall upstream migrations in order to determine whether these migrations are comprised of char from more than one stock. Therefore, the second hypothesis to be tested is:

Ho: The upstream migration of Arctic char in river systems within the study area is comprised of individuals from a discrete homogeneous population.

Ha: The upstream migration of Arctic char in river systems within the study area is comprised of a mixture of individuals from more than one discrete population.

In the Canadian Arctic, the entire Arctic char resource is encompassed within two settled land claim areas. In the west is the Inuvialuit Settlement Region, and in the central and eastern areas, the newly created territory of Nunavut, which includes the study area. The Federal Government has entered into legislated comanagement of fish resources with both of these groups. Comanagement provides fishers with an opportunity to play a participatory role in the management of this important resource as well as to contribute their traditional knowledge to the management process. This traditional knowledge was vital to this study, in particular in the identification of spawning areas. There is a pressing need to develop a more effective management approach to the utilization of the Arctic char resource in order to preserve the genetic diversity of the species. Therefore, an additional objective of this study is to outline how this new management relationship can provide a more effective means of managing this important resource in light of the results of this study.

MATERIALS AND METHODS

The Study Area

Geography and Geology

The study area is centred around the community of Cambridge Bay (69° 07′ N, 105° 03′ W) on the south shore of Victoria Island. (Fig.2). Victoria Island is the second largest island in the Canadian Arctic Archipelago and is part of the Arctic Lowlands physiographic region. The southeastern portion, including the study area, is part of the Victoria Lowland (Bostock 1970, 1972). The surface topography of the study area is relatively flat with the exception of eskers, moraines and drumlins. It is dotted with many small lakes and seasonal streams and also some lakes of considerable size (Johnson 1962). The surface is primarily covered by unconsolidated glacial drift. Vegetation is predominantly sedges, grasses and mosses with lichens appearing on rock outcrops (Peterson et al. 1981). The underlying geology consists of Paleozoic limestones, sandstones, dolomites and shales (Thorsteinsson and Tozer 1962, 1970; Fyles 1963; Douglas 1971, 1973; Campbell 1981).

Most of Victoria Island, including the study area, was covered by the Laurentide Ice Sheet. The glaciers are believed to have melted between 8 500 and 12 500 years ago, based on radiocarbon dates of marine bivalve shells found at elevations above 80 m asl (Fyles 1963; Prest et al. 1972; Prest 1973). Much of the southeast corner of the island including almost all of the study area was inundated by sea water following glacial retreat (Wilson et al. 1958). Over time, the land rose, apparently at a uniform rate, based on the

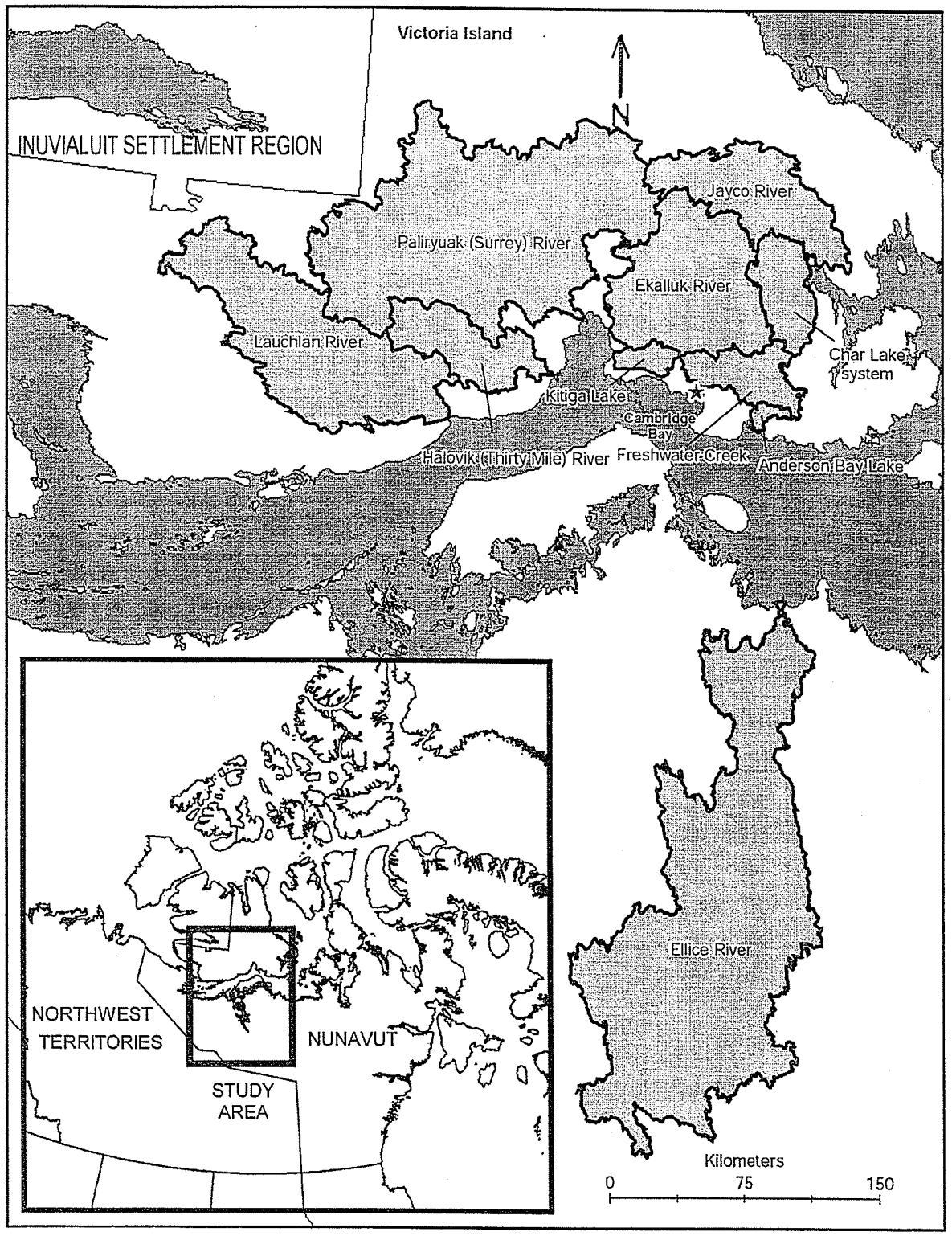

Figure 2. Map of the study area showing locations of river systems sampled.

spacing between strand lines (Johnson 1962). The rate of elevation has been estimated at between 1.96 m and 1.16 m per 100 years. The explorer Collinson surveyed Cambridge Bay Harbour in 1853 and charted a reef 61 cm below sea level in an unambiguous location. Washburn (1947, cited in Johnson 1962) observed that the shoal was 33 cm above sea level at the highest high tide in 1947. This change in elevation of the shoal suggests that the area near Cambridge Bay has risen from the sea within the last 1 300 years (Johnson 1962).

The Community of Cambridge Bay

The Inuit name for the community of Cambridge Bay is "Ikaluktutiak" which means fair fishing place (Abrahamson 1964). Inuit were known to congregate here in autumn to fish for the abundant Arctic char that made their way up Freshwater Creek to overwinter in the Greiner Lake system. The first permanent contact with people of European origin from Southern Canada began in 1921 when the Hudson's Bay Company established a trading post there. Over the years various missions and a Royal Canadian Mounted Police post were established as well, but Inuit continued to live off the land. In 1946-47 United States and Canadian military interests constructed a Long-Range Navigation (L.O.R.A.N.) beacon. This offered some wage employment to local Inuit who then began living in the settlement. More job opportunities occurred as a result of the construction of a Distant Early Warning (DEW) site in 1955-56. This was followed in later years by the location of various government agencies in the community (Abrahamson 1964). Today the community consists of over 1100 inhabitants, most of whom are Inuit (NWT Data Book 1991) and commercial fishing plays an important role in the local economy.

The Fishery

Fishing for food was and still is a very important activity for the Inuit of Cambridge Bay. Commercial fishing by gillnet began in 1960 when approximately 2000 kg of Arctic char and some lake char (*Salvelinus namaycush*) were taken from nearby Freshwater Creek. However, this fishery was in direct competition with the food fishery and, after a few years, it was clear that the Arctic char stock was suffering from overexploitation. The commercial fishery was relocated to Wellington Bay, at the mouth of the Ferguson River in 1962 (Abrahamson 1964; Barlishen and Webber 1973). The Ferguson River is now known as the Ekalluk River. Ferguson Lake, upstream on the Ekalluk River, was also fished in both summer and winter. As the fishery developed, other sites were established. These included the Halovik (Thirty Mile) River, the Paliryuak (Surrey) River, the Lauchlan River (Byron Bay), all of which flow into Wellington Bay (Fig. 2), and the Jayco River, emptying into Albert Edward Bay. Two rivers on the mainland, the Ellice and the Perry, were also fished (Barlishen and Webber 1973). Arctic char was and still is the target species of the fishery.

Fishing with gillnets (139 mm mesh, stretched measure) takes place at the mouths of the various rivers. The catch is dressed on site and flown by float-equipped aircraft to the processing facility where it is cleaned and fast-frozen and then delivered to market (Kristofferson and Carder 1980; Kristofferson et al. 1984). The first processing facility was located at the mouth of the Ekalluk River but was subsequently moved to Cambridge Bay in 1972 (Barlishen and Webber 1973). In the early years, fishing took place both in spring and in fall. This was done because the processing facility had a limited capacity and the allowable harvest was too much to process at one time. Today, most commercial

fishing for Arctic char in the Cambridge Bay area targets the fall upstream run, all of which can be processed in a larger facility.

A traditional Inuit method of harvesting Arctic char employed a stone weir or "saputit" installed across a river to trap upstream migrants which were then speared in the shallow enclosures (Balikci 1980). The Department of Fisheries and Oceans used a modern version of the weir to enumerate the upstream migration of Arctic char for population studies. This weir, made of vertically arranged conduit pipe, was also evaluated as a commercial harvesting gear (Kristofferson et al. 1986). Although gillnets are still the mainstay fishing gear, conduit-pipe weirs are used at two locations.

Sampling Locations and Sample Collection

I had very little information about the location of the spawning grounds of Arctic char in the study area at the outset of this study. During discussions with Inuit fishers of Cambridge Bay, I explained the need to sample spawners in order to gain a better understanding of their biology, which in turn, would contribute to better management of the resource for present and future generations. After some discussion, they agreed to assist me. Using their traditional ecological knowledge of the area, they identified the spawning locations on a map, and in some cases, led me directly to them. I was therefore able to collect myself or obtain from others samples of spawners at seventeen different sites in nine different river systems on Victoria Island. Most of the spawners were captured by gillnet (139 mm mesh, stretched measure, 47-50 m long and 2-3 m deep) in upstream lakes between mid-August and early September, because most Arctic char do not go to sea the summer before spawning. They were easily recognized as spawners by

external examination based on their bright orange-red spawning colouration. Samples from four locations were captured through the ice in December. Nonspawners were collected in the mouths of rivers as they made their way in from the sea during late August to early September. Most were taken with gillnets (139 mm mesh, stretched measure) by myself and in some cases by the commercial gillnet fishery. Some were taken in a weir used by the commercial fishery. Samples were also taken in a seine net and counting weir at Freshwater Creek by Department of Fisheries and Oceans (DFO) staff. The latter captured all size ranges present in the run. Details of the collection of spawners is provided in Table 1 and of nonspawners in Table 2. The coordinates for river systems sampled identify the river mouth. Following is a brief description of each of the river systems and the sampling activity that took place there:

EKALLUK RIVER (69° 23′ N, 106° 18′ W)

The Ekalluk River drains an area of approximately 5 835 km^2 (Fig. 3). Its headwaters begin about 200 km from the sea, at an elevation of 185 m above sea level. It begins by draining a myriad of small tundra potholes in a southward flow, consolidating into a main branch about 185 km from its outlet. At this point it widens to almost 0.5 km, forming a narrow lake that stretches for about 12 km in a southeasterly direction (69° 57′ N, 105° 07′ W). Local residents report that Arctic char spawners have been taken in this section of the river (D. Hamilton pers. comm.). The river narrows once again, flowing for about 10 km in an easterly direction into a large unnamed lake (69° 46′ N, 104° 30′

Table 1. A summary of the sampling details for the collection of Arctic char spawners.

LOCATION		DATE	GEAR	N
(Ekalluk River System)				
Lady Pelly Lake	69° 22′ N, 105° 03′ W	Dec. 1987	Gillnet	51
Wishbone Lake	69° 34′ N, 104° 10′ W	Aug. 16 1994	Gillnet	60
Ferguson Lake	69° 24′ N, 106° 13′ W	Sept. 3 1996	Gillnet	43
Paliryuak River	69° 40′ N, 106° 40′ W	Dec. 1987	Gillnet	5
Halovik River	69° 16′ N, 108° 00′ W	Dec. 1987	Gillnet	30*
	69° 17′ N, 108° 03′ W	Aug. 24 1993	Gillnet	20
	69° 14′ N, 108° 20′ W	Aug. 22-27 1993	Gillnet	32
Lauchlan River	69° 04′ N, 109° 14′ W	Dec. 1987	Gillnet	34†
	69° 03′ N, 109° 06′ W	Aug. 28 1993	Gillnet	2
Char Lake	69° 37′ N, 103° 35′ W	Aug. 18-23 1991	Gillnet	36
	69° 36′ N, 103° 34′ W	Aug. 19 1991	Gillnet	10
Fish Trap Lake	69° 39′ N, 103° 34′ W	Aug. 18-19 1991	Gillnet	11
Kitiga Lake	69° 14′ N, 105° 37′ W	Sept. 1994	Gillnet	23
Anderson Bay L.	Gillnet Location Unknown	Sept. 1993	Gillnet	31
	68° 54′ N, 104° 16′ W	Aug. 17 1994	Gillnet	28
(Freshwater Creek System)				
Mount Pelly L.	69° 12′ N, 104° 44′ W	Aug. 30 1991	Gillnet	1
Mount Pelly L.	69° 12′ N, 104° 44′ W	Aug. 25-28 1992	Gillnet	44
Mount Pelly L.	69° 12′ N, 104° 43′ W	Aug. 25-26 1993	Gillnet	11

* Only 13 whole specimens. Tissue samples from remaining 17 specimens.
† Only 4 whole specimens. Tissue samples from remaining 30 specimens.

Table 2. A summary of the sampling details for the collection of nonspawning Arctic char.

LOCATION		DATE	GEAR	N
Ekalluk River	69° 23′ N, 106° 18′ W	Sept. 9 1988	Gillnet	51
Ekalluk River	69° 23′ N, 106° 18′ W	Aug. 16-22 1990	Gillnet	50*
Ekalluk River	69° 23′ N, 106° 18′ W	Aug. 24-25 1991	Gillnet	50
Ekalluk River	69° 23′ N, 106° 18′ W	Aug. 27-28 1992	Gillnet	51
Ekalluk River	69° 23′ N, 106° 18′ W	Aug. 28 1993	Gillnet	50
Ekalluk River	69° 23′ N, 106° 18′ W	Aug. 27 1994	Gillnet	49
Paliryuak River	69° 27′ N, 106° 40′ W	Jul. 17-19 1992	Gillnet	52*
Halovik River	69° 09′ N, 107° 06′ W	Aug. 21-22 1992	Gillnet	52
Lauchlan River	68° 57′ N, 108° 32′ W	Aug. 21 1992	Gillnet	57
Lauchlan River	68° 57′ N, 108° 32′ W	July 17 1996	Gillnet	50*
Freshwater Ck.	69° 08′ N, 104° 58′ W	Aug. 20 – Sept. 10 1988	Weir	125
Freshwater Ck.	69° 08′ N, 104° 58′ W	Aug. 14 – Sept. 12 1991	Weir	87
Freshwater Ck.	69° 08′ N, 104° 58′ W	Aug. 23 – Sept. 7 1994	Weir	100
Ellice River	68° 03′ N, 104° 00′ W	Aug. 24-27 1990	Gillnet	50*
Jayco River	69° 44′ N, 103° 16′ W	Aug. 31 – Sept. 10 1990	Weir	49*

* Samples taken from commercial fishery

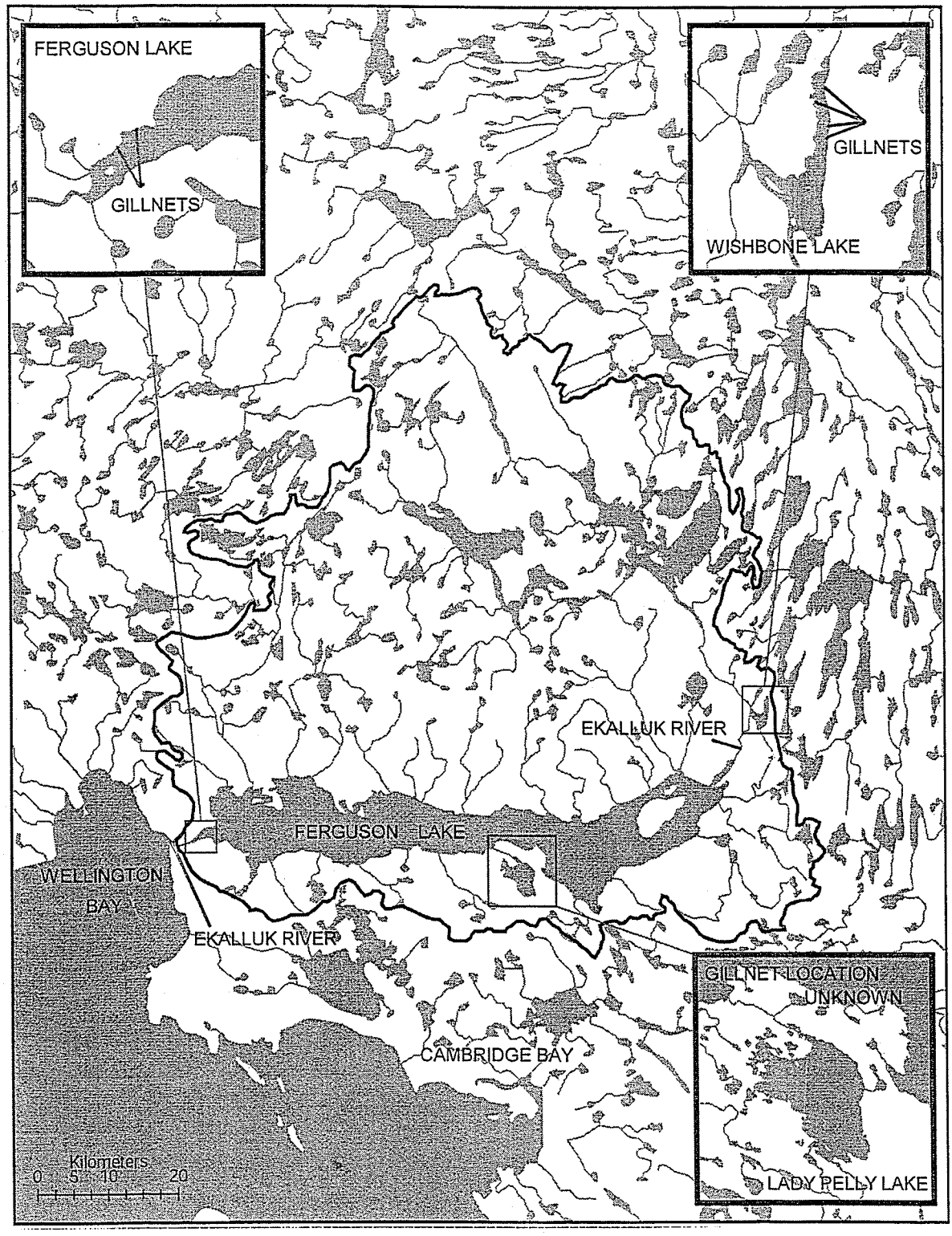

Figure 3. Map of the Ekalluk River drainage basin showing sampling locations of Arctic char spawners at Lady Pelly Lake in 1987, Wishbone Lake in 1994 and Ferguson Lake in 1996. Upstream migrants were sampled at the mouth of the Ekalluk River (1988, 1990, 1991, 1992, 1993, 1994) where it empties into Wellington Bay.

W). The upper reaches of this lake are also reported to be an Arctic char spawning ground. Downstream of this lake, the river continues to flow in a southeasterly direction for another 20 km where it meets a small irregular-shaped lake on its east bank (69° 34′ N, 104° 10′ W). I call this unnamed lake Wishbone Lake due to its shape. Wishbone Lake is one of three locations on the Ekalluk River system where Arctic char spawners were captured for this study. The sample from Wishbone Lake was taken on August 16, 1994 from four gillnets set the previous day at the location shown in Fig. 3. The gillnets were set on the surface perpendicular to shore with one end fastened to the shore. At least 11 spawners were captured in each net with the most northerly net taking 26 for a total of 60 fish. This capture site is 98 km upstream from the sea.

Downstream of Wishbone Lake, the river continues in a southwesterly direction for about 11 km and drains into the east end of Ferguson Lake. Ferguson Lake is the largest lake on Victoria Island at 740 km^2 in surface area. It is 75 km long in an east-west direction and is 15 km wide at its widest point. Its elevation above sea level is about 11 m. Approximately 30 km west of the inlet to Ferguson Lake, on its south shore, is an esker elevation known as Mount Lady Pelly. A relatively large lake, 7 km long and 4 km wide, is situated on the southwest side of this esker (69° 22′ N, 105° 03′ W). This lake drains into Ferguson Lake by a very narrow stream over a length of about 2.5 km. This stream is very shallow and is likely passable to Arctic char only during the spring high water period. I call this unnamed lake Lady Pelly Lake and it is the second location on the Ekalluk River system where I obtained Arctic char spawners. This sample of 51 Arctic

char was taken from this lake in December 1987 by gillnet at an unspecified location. This lake is 54 km upstream from the sea.

Ferguson Lake narrows considerably near its outlet at its west end. I obtained the third sample of Arctic char spawners from Ferguson Lake on September 3, 1996 at a location about 0.5 km from the Lake's outlet (69° 24′ N, 106° 13′ W). This sample of 43 Arctic char was taken from two gillnets set on the north shore on September 2. Each net was fastened to shore and set perpendicular to the shoreline. At this location, the lake is about 0.5 km wide. The Ekalluk River then drains Ferguson Lake into the Arctic Ocean over a short fast run of about 4 km. This capture location is about 4.5 km upstream from the sea.

I obtained samples of nonspawning Arctic char from the upstream run in freshwater at a location about 0.5 km from the mouth of the Ekalluk River (69° 23′ N, 106° 18′ W) on September 9, 1988. Samples were taken from the commercial gillnet fishery from August 16-22, 1990. Samples were taken on August 24-25, 1991, August 27-28, 1992, August 28, 1993 and August 27, 1994 at the same location by myself or by other DFO staff using gillnets.

PALIRYUAK (SURREY) RIVER (69° 27′ N, 106° 40′ W)

This river drains an area of 14 913 km^2 into Wellington Bay from the northwest (Fig. 4). Although it drains a series of relatively large lakes, including Washburn Lake with a surface area of 292 km^2, and has a substantial flow even in late summer, it does not appear to be used as an overwintering system for anadromous Arctic char. There is little

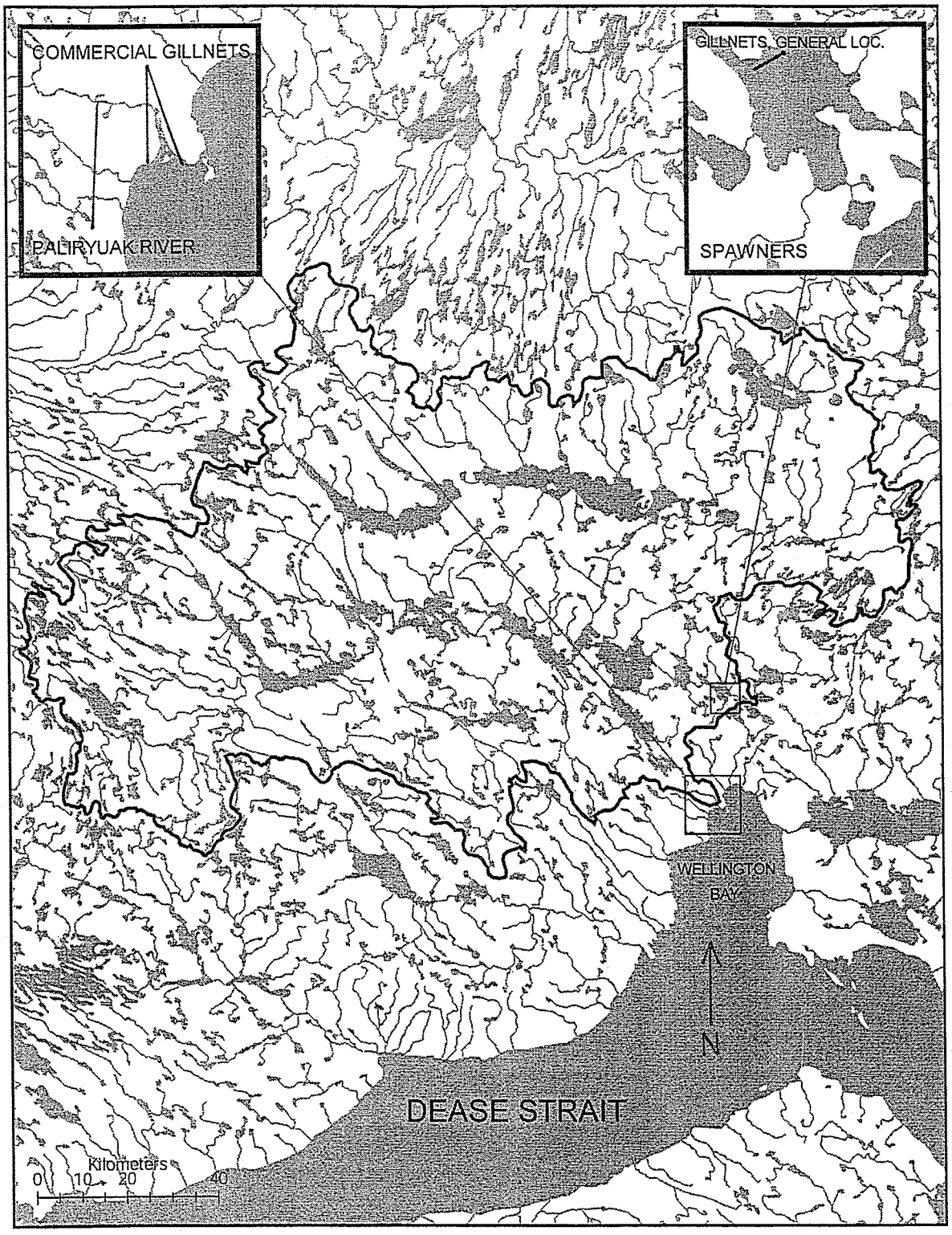

Figure 4. Map of the Paliryuak River drainage basin showing sampling locations of Arctic char spawners in 1987 and the 1992 commercial gillnet fishery.

evidence of old camp sites near the mouth and local knowledge (Abrahamson 1964) and an unsuccessful attempt to enumerate an upstream run here by DFO staff in 1983 has led to this conclusion. However, the site is used for commercial fishing, particularly in the spring (Kristofferson and Carder 1980). Gillnets are set mostly in brackish water near the mouth of the river (69° 27′ N, 106° 40′ W) and likely intercept itinerant char as they move along the coast feeding in summer. I obtained a sample of nonspawning Arctic char from this commercial fishery on July 17-19, 1992 to compare with samples of nonspawners from other locations. A small number (N=5) of spawners was obtained opportunistically from an upstream lake (69° 40′ N, 106° 40′ W) in December 1987.

HALOVIK (THIRTY MILE) RIVER (69° 09′ N, 107° 06′ W)

The Halovik River flows into Wellington Bay from the west-northwest (Fig. 5) and drains an area of 2 450 km^2. It has its headwaters approximately 110 km upstream at an elevation of about 185 m above sea level. Approximately 42 km upstream from the mouth it drains an irregular-shaped lake that is 7 km at its longest and 6 km at its widest point. I captured 20 Arctic char spawners in two gillnets set off a point (69° 17′ N, 108° 03′ W) in the middle of this lake on August 24, 1993. During the same sampling period, I obtained an additional 32 spawners on August 22, 25, 26 and 27 a further 7 km upstream from this lake. These spawners were captured in a series of narrow bays (69° 14′ N, 108° 20′ W) that formed the outlet of a larger lake to the west. This lake is about 20 km long. In total, 52 spawners were captured from these locations. Upstream, for an additional 30 km, the Halovik River drains a myriad of small tundra potholes at its higher elevation. A

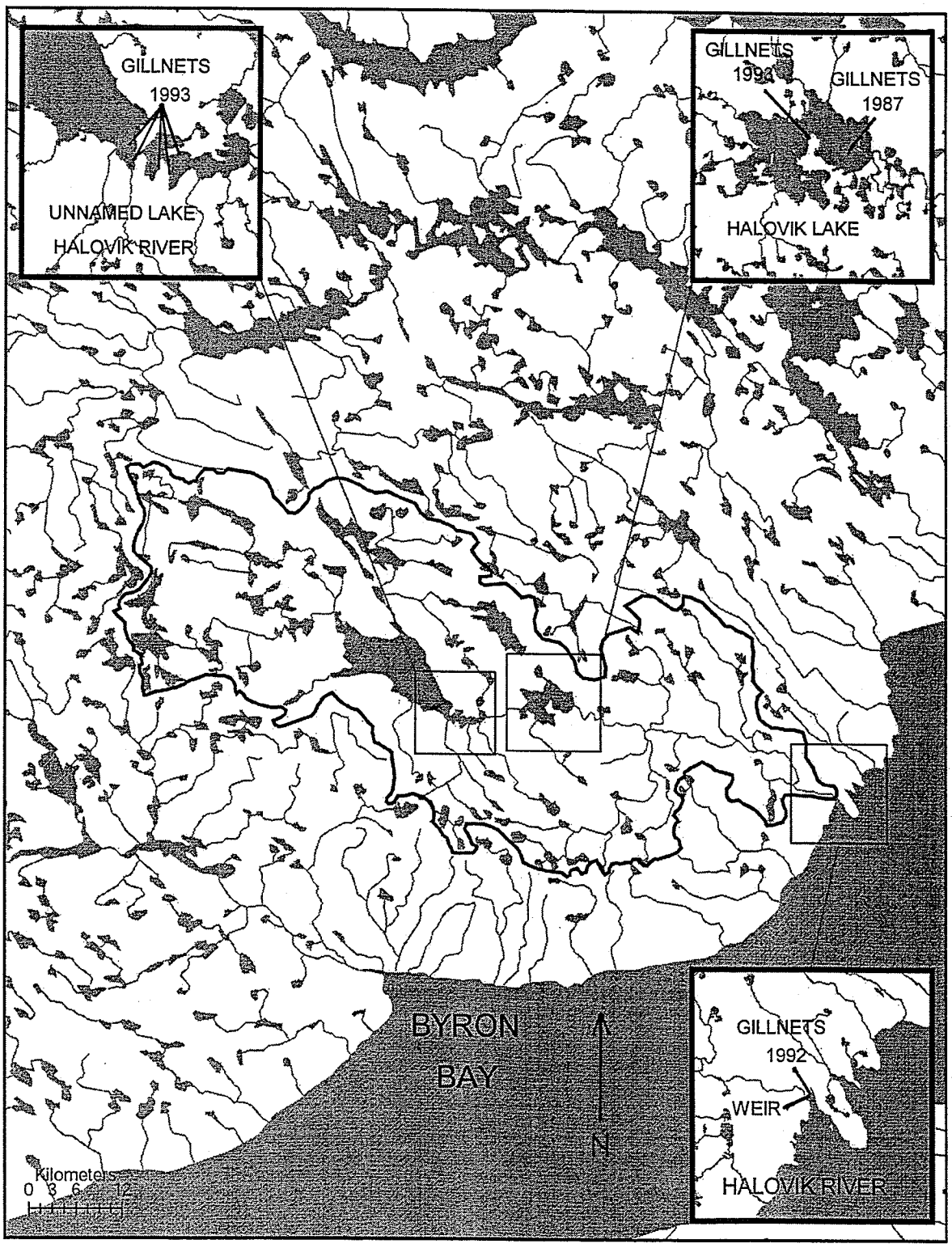

Figure 5. Map of the Halovik River drainage basin showing sampling locations of Arctic char spawners at Halovik Lake 1987 and 1993, the weir site, and the sampling location of the 1992 upstream migration.

sample of 30 Arctic char, reported to be spawners, was taken opportunistically at 69° 16 N, 108° 00′ W, in December 1987. Of these, only 13 were whole specimens which were incorporated into my morphological analysis. Only the tails of the remaining 17 char were kept so tissue samples from these fish were used in the electrophoretic analysis.

The commercial fishery is located at the mouth of the Halovik River (69° 09′ N, 107° 06′ W). In the past, gillnets were used during the spring and some were set in brackish water off the mouth of the river. Today, a weir is used about 1 km upstream in freshwater and the catch is taken in fall from the upstream run. I captured 52 nonspawning Arctic char with gillnets set in freshwater near the mouth of this river on August 21,22, 1992 as the upstream run returned from the sea.

LAUCHLAN RIVER (BYRON BAY) (68° 57′ N, 108° 32′ W)

The Lauchlan River drains an area of 7 935 km^2 and has its headwaters at an elevation of 235 m above sea level, approximately 190 km northeast of its outlet into Dease Strait (Fig. 6). A sample of 34 Arctic char, reported to be spawners, was obtained opportunistically in December 1987 from a lake 35 km upstream from the mouth at 69° 04′ N, 109° 14′ W. Of these, only 4 whole specimens were kept along with the tails from the remaining 30 fish. Therefore, only tissue samples were available from the latter 30 specimens. Two spawners were obtained from a lake (69° 03′ N, 109° 06′ W) approximately 30 km upstream of the mouth on August 28, 1993. I captured 57 nonspawners by gillnet as the upstream run entered the mouth of the river on August 21,

Figure 6. Map of the Lauchlan River drainage basin showing sampling location of Arctic char spawners in 1987, and the sampling location at the 1992 and the 1996 commercial gillnet fisheries.

1992 and a sample of 50 nonspawners was obtained from the commercial gillnet fishery which was located near the mouth of the river in July 17, 1996.

JAYCO RIVER (69° 42′ N, 103° 17′ W)

The mouth of this river is located 100 km northeast of Cambridge Bay and empties into Albert Edward Bay (Fig. 7). Its headwaters lie about 120 km to the northwest of its outlet at an elevation of 140 m above sea level and it drains an area of 3 733 km^2. There is a large lake, called Jayco Lake, 5 km upstream from the mouth of the river (69° 48′ N, 103° 10′ W). This lake is 21 km at its longest stretch and 11 km at its widest point. Anadromous Arctic char migrate up this short stretch of the Jayco River into this lake in autumn to overwinter. The commercial fishery is located at the outlet of this lake at 69° 44′ N, 103° 16′ W and a weir is used for the harvest.

Although I did not obtain spawners from the Jayco River system, I did capture spawners from an adjacent system which empties into Albert Edward Bay at 69° 42′ N, 103° 27′ W (Fig. 8). This system drains an area of about 1 632 km^2. Local residents believe that Arctic char from the Jayco River system will overwinter in this system during low water years when the lower Jayco River becomes very shallow. The first lake on this system that I sampled, known locally as Fish Trap Lake, is a small lake about 0.5 km long and 1 km wide located 10 km upstream from the sea. I captured a total of 11 Arctic char spawners from this lake from two overnight sets lifted on August 18 and 19, 1991. The two gillnets were set perpendicular to shore on either side of the inlet at 69°

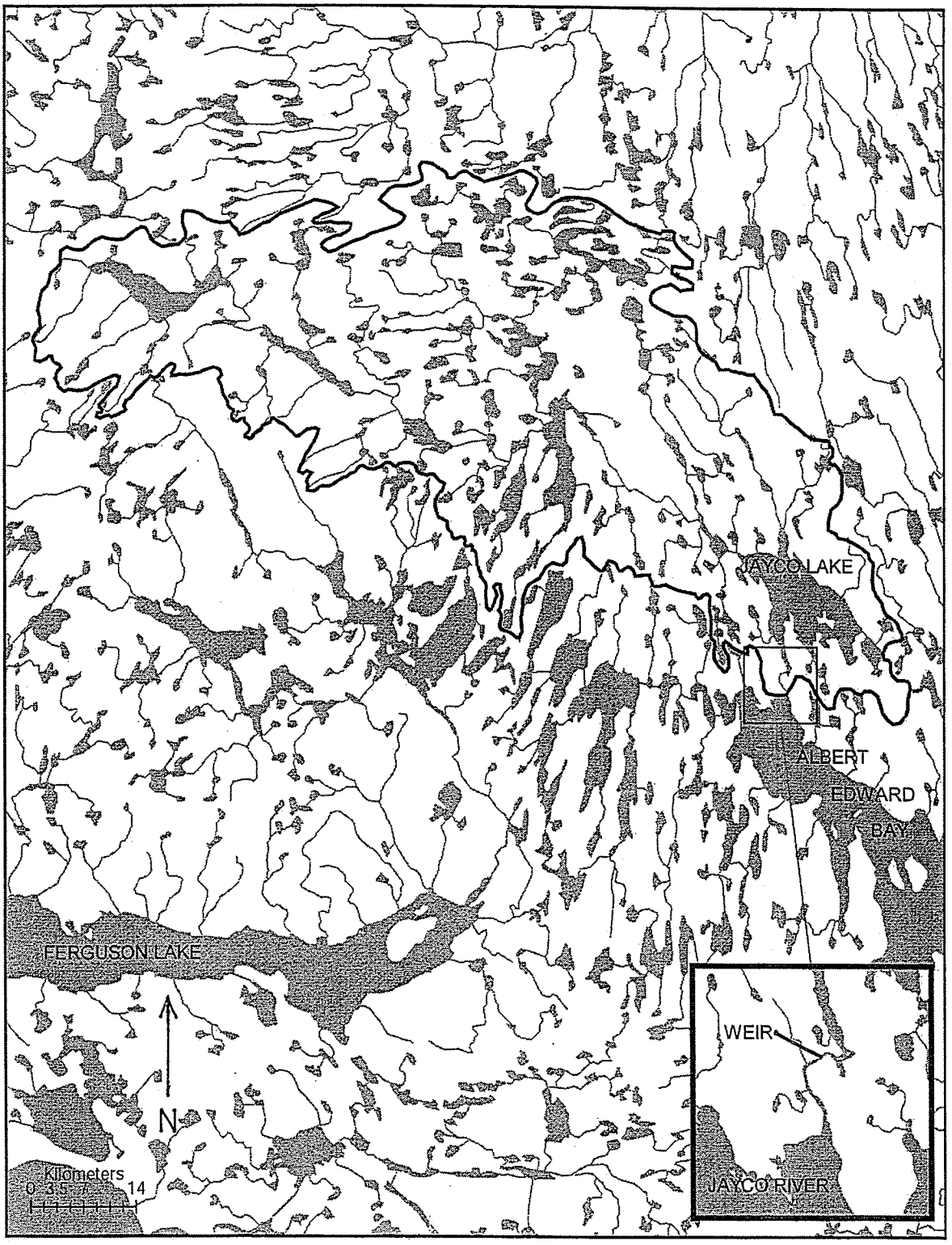

Figure 7. Map of the Jayco River drainage basin showing sampling location of the 1990 upstream migration of Arctic char at the weir.

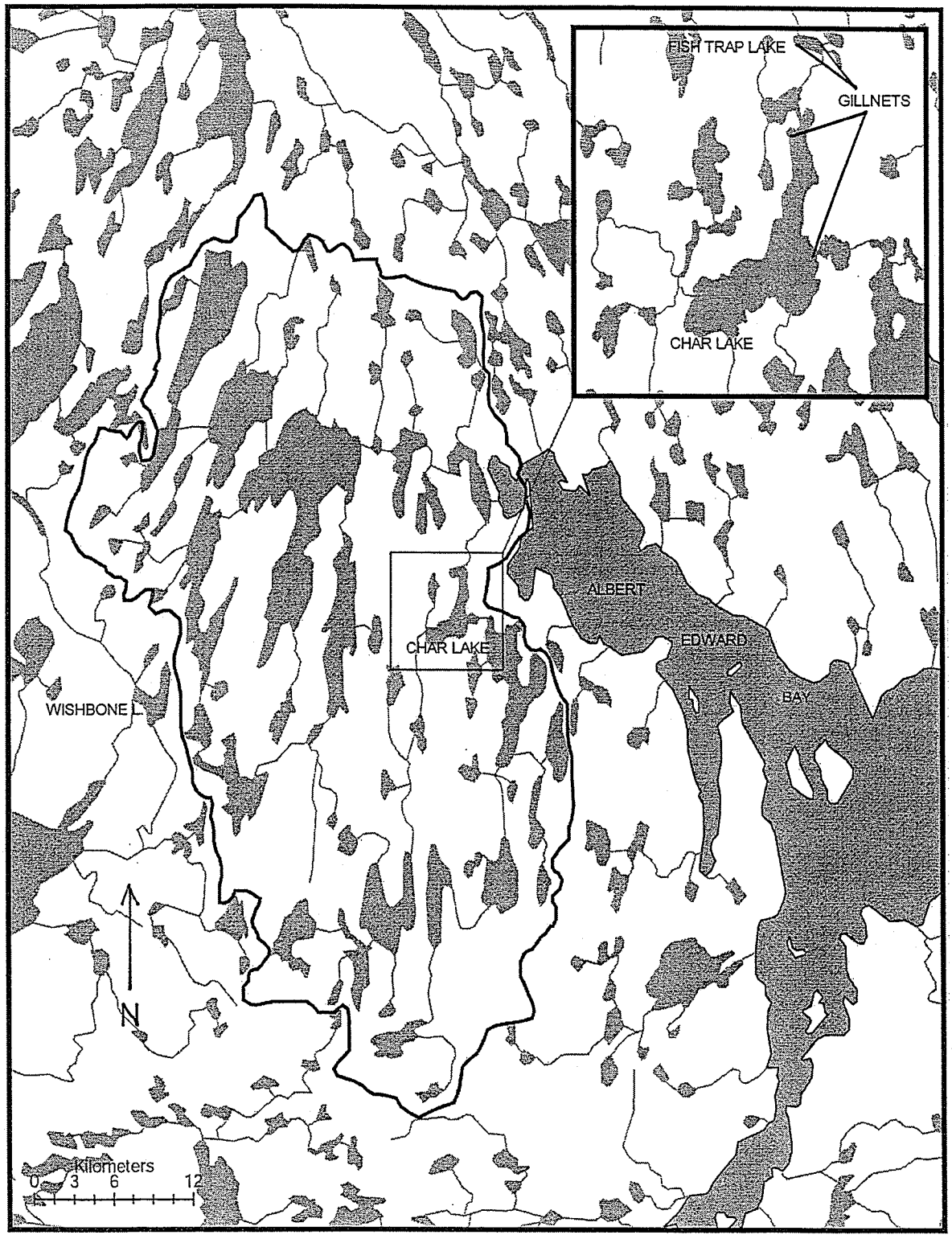

Figure 8. Map of the drainage basin showing sampling locations of Arctic char spawners at Char and Fish Trap lakes in 1991.

39′ N, 103° 34′ W. I also captured spawners from the next lake 1 km upstream on this system. This lake, located at (69° 36′ N, 103° 35′ W), is known locally as Char Lake. One net was set perpendicular to shore on the west side of the lake at (69° 37′ N, 103° 35′ W) just south of Arctic Outpost Camp and the other was set perpendicular to the east shore at (69° 36′ N, 103° 34′ W). The nets were set overnight and lifted the following day. A total of 46 spawners were captured on August 18, 19 and 23, 1991 from this lake.

ELLICE RIVER (68° 03′ N, 104° 00′ W)

The Ellice River is located on the mainland south of Victoria Island (Fig. 9), and drains an area of about 20 627 km^2. Its headwaters begin over 250 km to the south of its outlet to the sea. There is a fork in the river about 28 km upstream of its mouth and a set of rapids on the main stem is likely impassable to upstream migrating Arctic char. The west channel follows a zigzag pattern for about 40 km where it serves as the outlet of Brichta Lake (67° 45′ N, 104° 52′ W). It is not known whether anadromous Arctic char overwinter in this lake. The lower reaches of the Ellice River are influenced by tidal surges. A water sample taken at a location 5 km from the mouth contained brackish water. The commercial fishery takes place in the mouth of the river and a short distance upstream. I obtained a sample of 50 nonspawning Arctic char from this commercial gillnet fishery during the period of August 24-27, 1990.

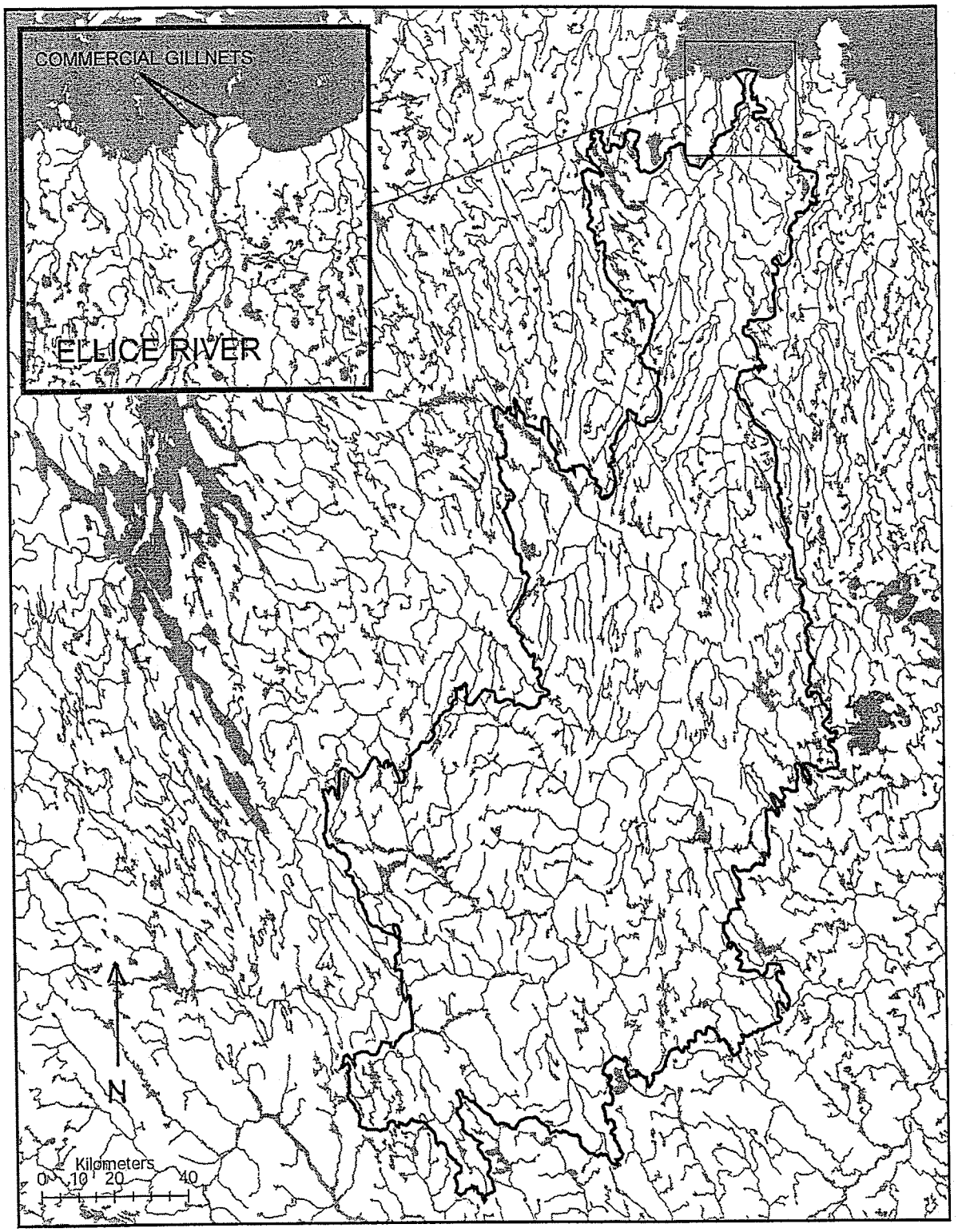

Figure 9. Map of the Ellice River drainage basin showing sampling location of Arctic char at the 1990 commercial gillnet fishery.

KITIGA LAKE (69° 14′ N, 105° 37′ W)

This lake, located 22 km northeast of Cambridge Bay (Fig. 10), was set aside by local Inuit residents for subsistence fishing only. It drains an area of about 445 km^2. This relatively large lake is divided into two basins that are connected by a narrow channel. Situated at an elevation of 40 m above sea level, it drains to the west into Wellington Bay through a narrow (3-4 m wide) outlet over a distance of 15 km. I obtained a sample of spawning Arctic char from this lake from a local resident of Cambridge Bay who used gillnets set in the general vicinity of 69° 14′ N, 105° 37′ W in September 1994.

FRESHWATER CREEK (69° 07′ N, 105° 01′ W)

Freshwater Creek is located 2 km east of the community of Cambridge Bay (Fig. 11). Although it was the site of the first commercial fishery in this area, today fishing at this location is for food and recreation only. The drainage basin covers an area of about 1 532 km^2. Greiner Lake (69° 12′ N, 104° 44′ W), the largest lake in this system, is 47 km^2 in surface area. At an elevation of 15 m above sea level, it is the last in a series of lakes on this system that extend to the east and south east for over 60 km. Headwaters are about 60 m above sea level.

Residents of Cambridge Bay concluded that the anadromous Arctic char stock in this system was depleted and asked DFO to help with its rehabilitation. A restricted angling harvest and voluntarily reduction in the harvest of the food fishery was put into effect to reduce fishing pressure in this area. In addition, DFO staff enumerated upstream migrations of anadromous Arctic char in this system on four occasions using a weir. The

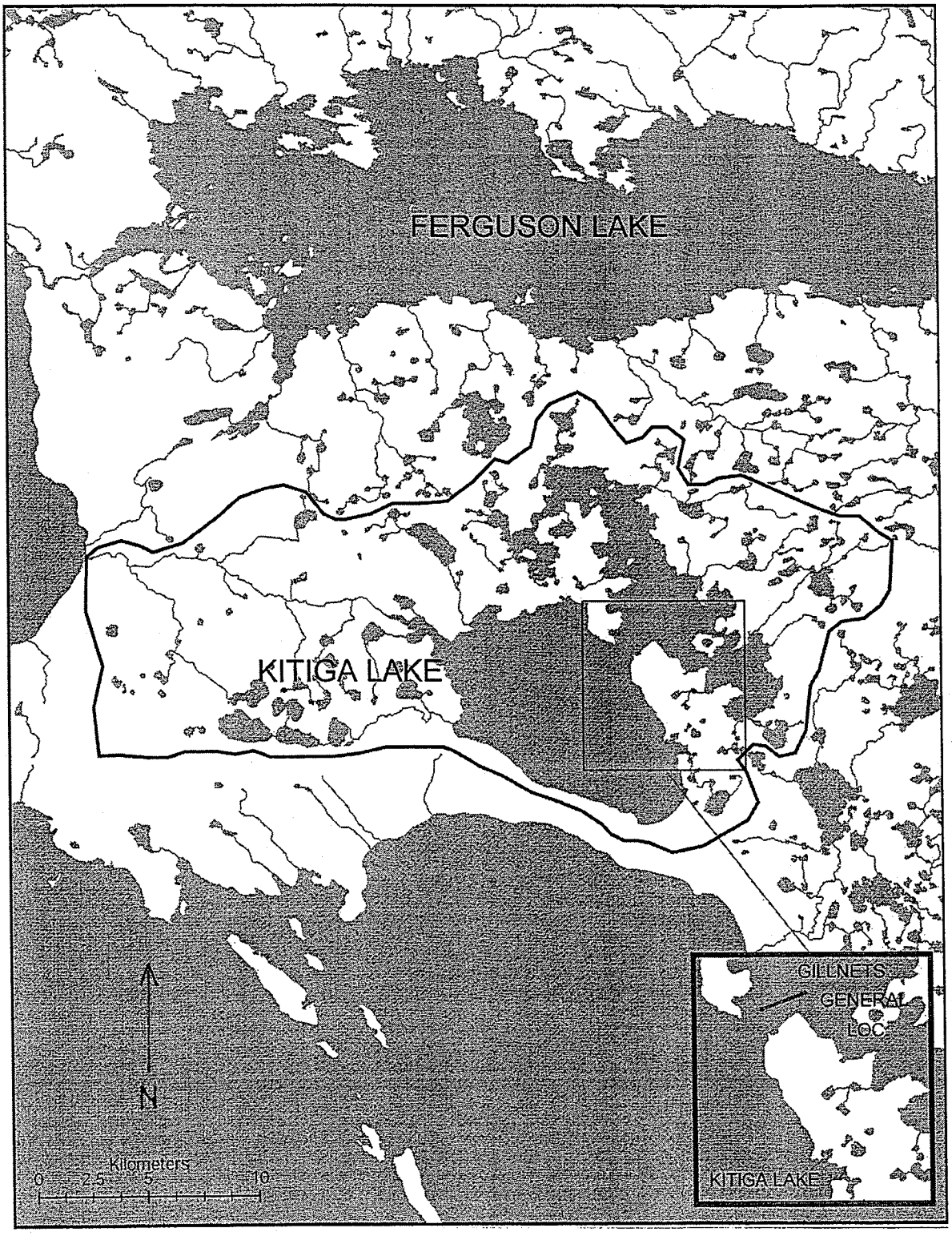

Figure 10. Map of the Kitiga Lake drainage basin showing sampling location of Arctic char spawners in 1994.

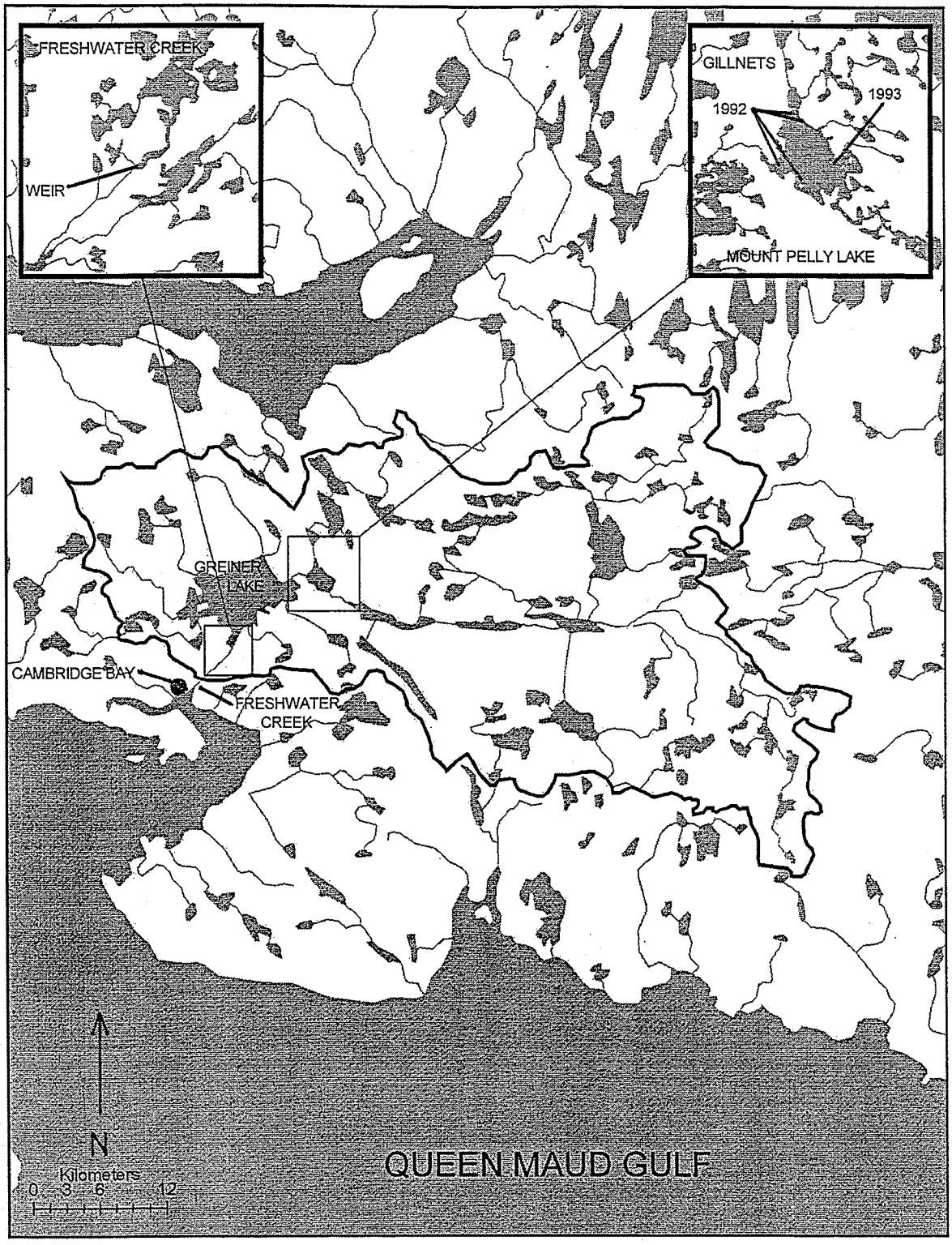

Figure 11. Map of the Freshwater Creek drainage basin showing sampling locations of Arctic char spawners at Mount Pelly Lake 1992 and 1993, and the weir site where the upstream migration was sampled in 1988, 1991 and 1994.

weir was located at 69° 08′ N, 104° 58′ W, near the outlet of Greiner Lake (Fig. 11). I was able to obtain samples of nonspawning anadromous Arctic char from the weir during the period August 20- September 10, 1988. I also obtained samples taken in the weir over the period of August 14-September 12, 1991 and August 23-September 7, 1994. I captured spawners by gillnet from a small lake (69° 12′ N, 104° 44′ W) 2 km upstream of Greiner Lake (Fig. 11) over a three-year period (1991-93). I call this small lake Mount Pelly Lake because it is located at the northwest slope of Mount Pelly, the highest geographic feature (203 m) in the area. The 1991 sample of one char was taken in early September. The 1992 sample was taken on August 25-28 and the 1993 sample was taken on August 25 and 26. Nets were set perpendicular to shore and left in overnight.

ANDERSON BAY LAKE (68° 56′ N, 104° 14′ W)

This unnamed lake is located 40 km southeast of Cambridge Bay on the east side of Anderson Bay (Fig. 12). I call this lake Anderson Bay Lake and I was able to obtain a sample of Arctic char spawners from this lake taken by a local resident using gillnets in September 1993. The exact location of the set is unknown. I captured a sample of 28 spawners in two gillnets on August 17, 1994 at 68° 54′ N, 104° 16′ W. The lake is 7 km long and 4 km wide at its widest point. Its drainage area, about 189 km^2, does not appear to extend much beyond 18 km of its shoreline. It drains into the sea through a very short (1 km) and very shallow outlet. It appears that Arctic char could be prevented from entering this lake from the sea during low water years.

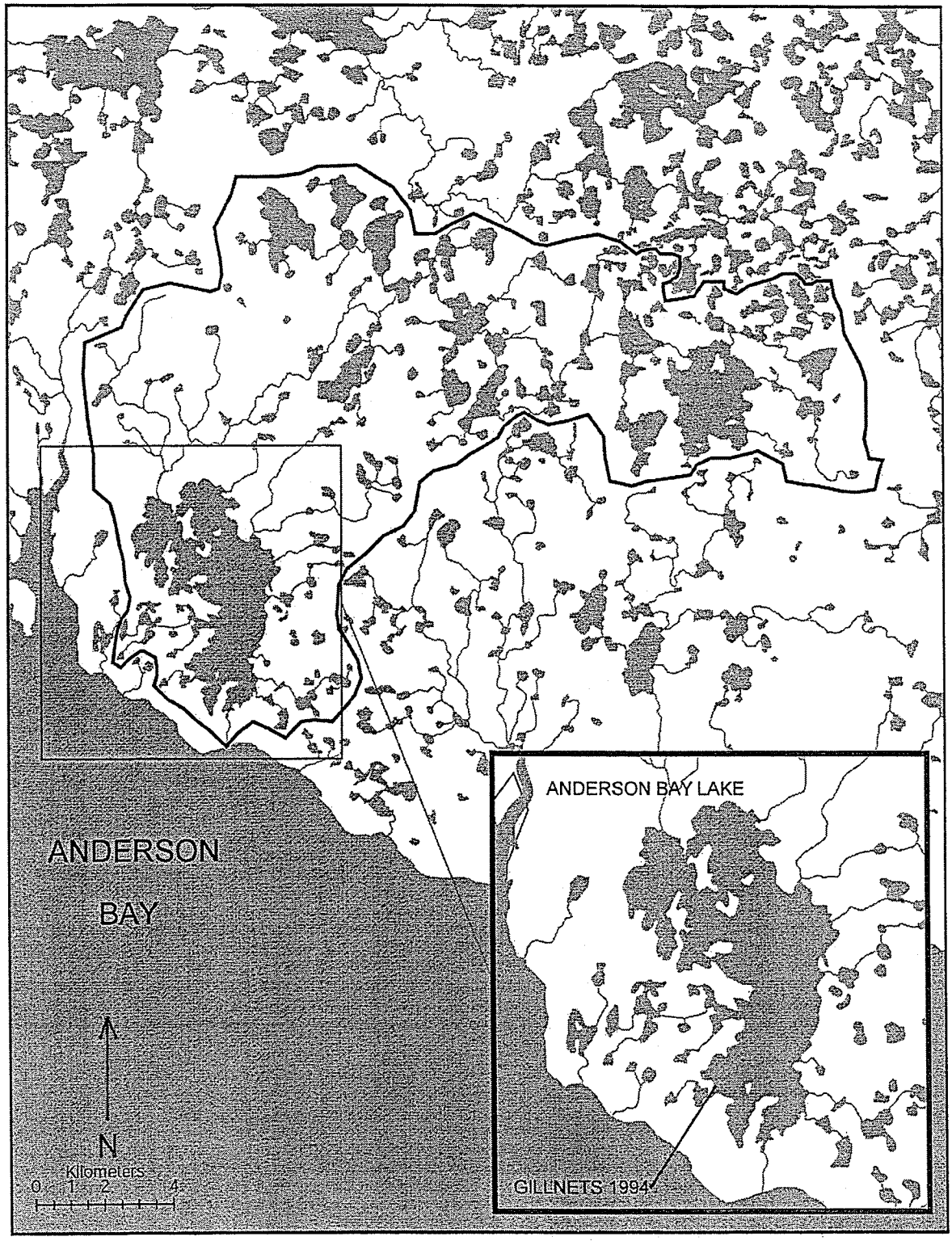

Figure 12. Map of the Anderson Bay Lake drainage basin showing sampling location of Arctic char spawners at Anderson Bay Lake in 1994. The 1993 sample location is not shown.

Biological Variables Examined

Five biological variables were measured on each whole specimen. They are listed below with their codes and include:

Weight (WT): measured in grams to the nearest gram.

Sex (SEX): determined by gross examination of the gonads (Males = 1, Females = 2).

Maturity (MAT): coded by developmental stage of gonads as follows:

Maturity State	Female Code	Male Code
Immature (Virgin)	1	6
Mature (Spawner)	2	7
Ripe and Running	3	8
Spent	4	9
Post Spawner (Prev. Year)	5	10
Unknown (Virgin)	0	
Unknown (Non-virgin)	11	

Gonad Weight (GWT): measured in grams to the nearest gram.

Age (AGE): estimated by examination of a cross section of the sagittal otolith under magnification (X 4) and counting the annuli according to Nordeng (1961).

Morphometric Measurements

Twenty-one morphometric measurements were taken on whole specimens following Reist et al. (1995). All measurements were taken on the left side of the fish

except if the fish was damaged and the right side had to be used (infrequent). Gill raker and gill arch measurements were taken from the first right gill arch. The measurements are described below and illustrated in Fig. 13:

a) measurements taken parallel to the long axis of the body:

Standard length (STL): measured from the tip of the snout to the caudal flexure, the latter being the base of the caudal fin rays indicated by a crease when the tail is flexed.

Fork length (FRL): tip of the snout to the fork of the tail, to the nearest 1.0 mm.

Preorbital length (POL): tip of snout posterior to the anterior fleshy margin of the orbit.

Orbital length (OOL): anterior fleshy margin of the orbit to posterior fleshy margin of the orbit.

Postorbital length (PSL): posterior fleshy margin of the orbit to the end projection of the bony operculum.

Trunk length (TTL): posterior end of bony operculum to the origin of the dorsal fin.

Dorsal length (DOL): origin of the dorsal fin posterior to the end of the fin ray base.

Lumbar length (LUL): end of dorsal fin to the origin of the anal fin.

Anal length (ANL): origin of anal fin posterior to the end of the fin ray base.

Caudal peduncle length (CPL): end of the anal fin posterior to the caudal flexure.

b) measurements taken parallel to the dorsoventral body axis:

Head depth (HDD): vertical depth through the centre of the pupil perpendicular to the long axis of the body.

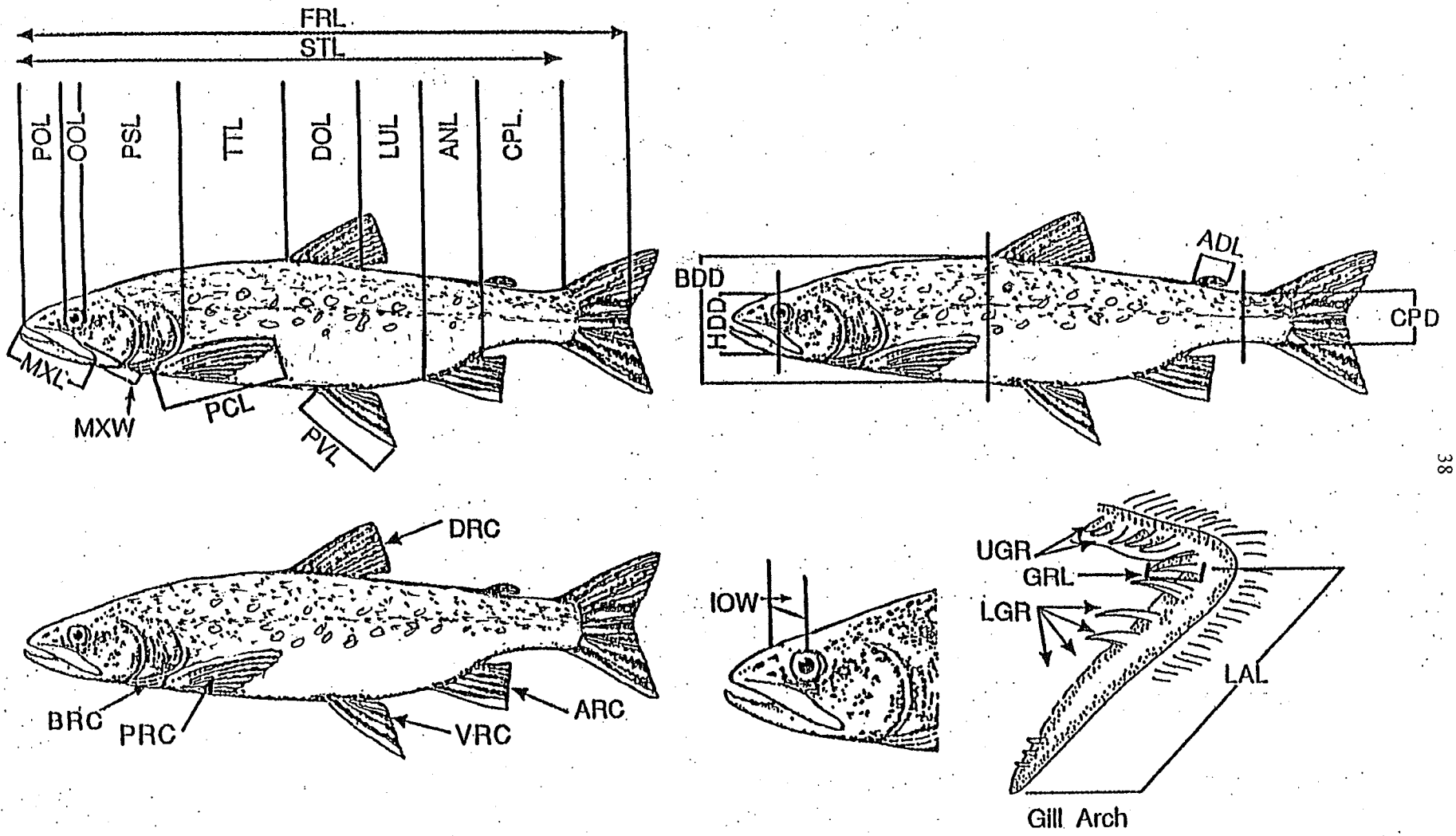

Figure 13. The morphological variables examined in this study. A description of each measurement and acronym is provided in the text. (by permission of Dr. J.D. Reist)

Body depth (BDD): vertical depth from dorsal origin to ventral surface of the body, perpendicular to the long axis of the body.

Caudal peduncle depth (CPD): the shortest vertical depth from dorsal to ventral surface of the caudal peduncle.

c) measurements parallel to the lateral body axis:

Interorbital width (IOW): measured on the dorsal surface of the head; it is the distance between the orbits.

d) measurements following the axis of the body part:

Maxillary length (MXL): anterior most to posterior most point of the maxillary.

Maxillary width (MXW): widest depth of the maxillary (bony structure only) perpendicular to the length of the maxillary.

Pectoral fin length (PCL): anterior most part of the first fin ray to the end of the fin.

Pelvic fin length (PVL): anterior most part of the first fin ray to the end of the fin.

Adipose fin length (ADL): measured from the point where the skin and scales meet at the anterior end of the fin posterior to the end of the fin.

Middle gill raker length (GRL): on the first right side gill arch, the base of the middle gill raker to its tip.

Lower gill raker arch length (LAL): on the lower arch of the first right side gill arch, base of the middle gill raker to the base of the last gill raker.

Meristic Counts

Eight meristic counts were made on whole specimens following Reist et al. (1995). They are described as follows:

Dorsal fin ray count (DRC): first unbranched ray forming the leading edge of the fin back to the last ray; rays arising from a common base are counted as one.

Anal fin ray count (ARC): first unbranched ray forming the leading edge of the fin back to the last ray; rays arising from a common base are counted as one.

Pectoral fin ray count (PCR): ray forming the leading edge of the fin back to the final ray.

Pelvic fin ray count (VRC): ray forming the leading edge of the fin back to the final ray.

Branchiostegal ray count (BRC): total number of branchiostegal rays.

Upper gill raker count (UGR): on the right first gill arch, topmost to and including the one immediately above the middle gill raker. Every raker is counted including bony rudiments that can be felt with a probe.

Lower gill raker count (LGR): on the right first gill arch, middle gill raker to the bottom most raker including bony rudiments that can be felt with a probe.

Pyloric caeca count (PYL): total number of pyloric caeca.

Genetic Analyses

Electrophoresis

All specimens of Arctic char collected were frozen less than one day after capture and shipped to the Freshwater Institute in Winnipeg by air freight. They were then stored at –35° C until examined. The fish were thawed to take morphological measurements and

during this process, tissue samples were extracted and immediately refrozen until enzyme extraction took place. Extracts from liver and white muscle were prepared by macerating one gram of tissue in a ratio of 1:3 with 0.25 M sucrose (Reist 1989), with coenzyme NADP used with the white muscle. Samples were spun at 14 000 rpm for 10 minutes at 4° C to remove cell debris. The supernatants were withdrawn and stored at –20° C until used. The micro-starch gel electrophoresis technique of Tsuyuki et al. (1966) was carried out on the following six enzyme systems:

Phosphoglucomutase (PGM) Enzyme Commission (E.C.) No. 2.7.5.1

Malic Enzyme (ME) E.C. 1.1.1.40

Esterase (EST) E.C. 3.1.1.1

Isocitrate dehydrogenase (IDH) E.C. 1.1.1.42

Superoxide dismutase (SOD) E.C. 1.15.1.1

Phosphoglucose isomerase (PGI) E.C. 5.3.1.9

Details are provided in Table 3. Samples from five spawning aggregations and nine nonspawning aggregations were examined.

Mitochondrial DNA (mtDNA)

Total genomic DNA extraction was carried out on white muscle tissue from samples taken from the Ekalluk, Halovik and Ellice rivers, and Anderson Bay. The extraction method followed Sambrook et al. (1989) with some modification (Maiers et al. 1998). The tissue was homogenized and digested with proteinase K, followed by phenol-chloroform extraction and DNA precipitation. Amplification of the mtDNA control

Table 3. Summary of starch gel electrophoresis protocols used on Arctic char samples.

Enzyme	Tissue	pH	Buffer	Voltage	Duration
GPI-3	white muscle	8.0	0.002 M citric acid	160 v	2.0 h
ME	white muscle	6.1	0.002 M citric acid	210 v	2.5 h
EST	liver	6.1	0.002 M citric acid	210 v	2.5 h
IDH	liver	6.1	0.002 M citric acid	210 v	2.5 h
SOD	liver	6.1	0.002 M citric acid	200 v	2.0 h
PGM	white muscle	6.1	0.002 M citric acid	210 v	2.5 h

Enzyme	pH	Buffer	Additives	Duration
GPI-3	8.0	0.1 M TRIS (HCl)	NBT,PMS, $MgCl_2 \cdot 4H_2O$ fructose-6-phosphate glucose-6-phosphate dehyd.	1-2 h
ME	8.0	0.15 M Bicine	2.0 M malic acid, $MgCl_2$, NADP, NBT, PMS	1.5 h
EST	6.5	0.05 M phosphate	α naphthyl acetate. Acetone, Fast Blue RR	1 h
IDH	8.5	0.15 M Bicine	sodium isocitrate, $MgCl_2 \cdot 4H_2O$, NADP, NBT,PMS	0.5-1.5 h
SOD	9.0	0.15 M Diethanolamine	NBT, PMS (expose to bright light)	2.0 h
PGM	8.0	0.15 M Tricine	$MgCl_2 \cdot 4H_2O$, glucose-1-phosphate glucose-6-phosphate dehyd. NADP, NBT, PMS	0.5 h

NADP = Nicotinamide Adenine Dinucleotide Phosphate
NBT = Nitroblue Tetrazolium chloride monohydrate
PMS= Phenazine Methosulfate

region was carried out using HN20 and LN20 primers using the polymerase chain reaction (PCR) as described by Brown Gladden et al. (1995). The amplified mtDNA was then purified using a PCR purification kit (Quiagin Inc.). The mtDNA samples were then sent to the National Research Council, University of Saskatchewan, Saskatoon, SK, and processed using an Applied Biosystems Prism 377 automated sequencer and the d Rhodamine dye terminator sequencing chemistry. The resulting sequences were aligned and examined for sequence variation using the MacVector program (IBI)(Brown Gladden et al. 1995).

Stable Isotope Analysis

Stable isotope analysis was carried out on white muscle samples of Arctic char from four nonspawning aggregations (Ekalluk, Jayco, Ellice and Halovik rivers) and one sample of spawners (Char lake) in order to examine food sources and trophic levels utilized by these char. The stable isotopes of carbon (^{13}C) and nitrogen (^{15}N) were examined from a single aliquot of about 15 mg of dried white muscle. The stable isotope of sulfur (^{34}S) required approximately 1 g of dry tissue. The samples for sulfur analysis were converted to sulfate by nitric acid digestion, nitrate fusion and precipitation with barium chloride, followed by thermal decomposition to sulfur dioxide. Nitrogen and carbon samples were combusted to nitrogen gas and carbon dioxide by a modified Dumas method, and then cryogenically separated and trapped. The preparation is described in detail by Hesslein et al. (1989).

The isotopic determinations were performed on a dual-inlet ratio mass spectrometer (VG Micromass 602E). The carbon was standardized to PDB and the

nitrogen was standardized against air. Standards used for sulfur were traceable to Canyon Diablo Troilite (CDT).

Micro-PIXE Analysis of Otolith Strontium Concentrations

The proton microbeam (**P**roton **I**nduced **X**-ray **E**mission or PIXE) (Fig. 14) functions by exciting a sample with a beam of protons, usually accelerated to an energy equivalent to 2 to 3 MeV but sometimes up to 5 MeV. Interaction with atoms on selected areas of the surface of samples causes the emission of X-rays with wave lengths characteristic of each element present and allows for the identification of elements present in the sample. The X-ray intensity allows for the quantification of each element present. The beam can be focussed down to a minimum diameter of about 1μm for microanalysis. Detection limits from excited areas down to 5-10 μm are in the ppm range. This technique can detect Sr at very low levels (0.5-1.0 ppm) compared with other element assay techniques (Campana et al. 1997).

Sagittal otoliths of the Arctic char samples were removed in the laboratory when the specimens were thawed for processing. The otoliths were cleaned and placed in envelopes for dry storage. The proton microprobe methodology followed Halden et al. (1995). In preparation for the proton microprobe analysis, the otoliths were mounted in epoxy resin in a lucite-disc probe mount (25.4mm diameter). The surface of the otolith and disc was then ground to expose a dorso-ventral cross section through the nucleus of the otolith. The ground surface was then polished and carbon coated. Just prior to carbon coating, an optical image of each otolith cross section was recorded in glancing reflected

Scanning Proton Microprobe (SPM)

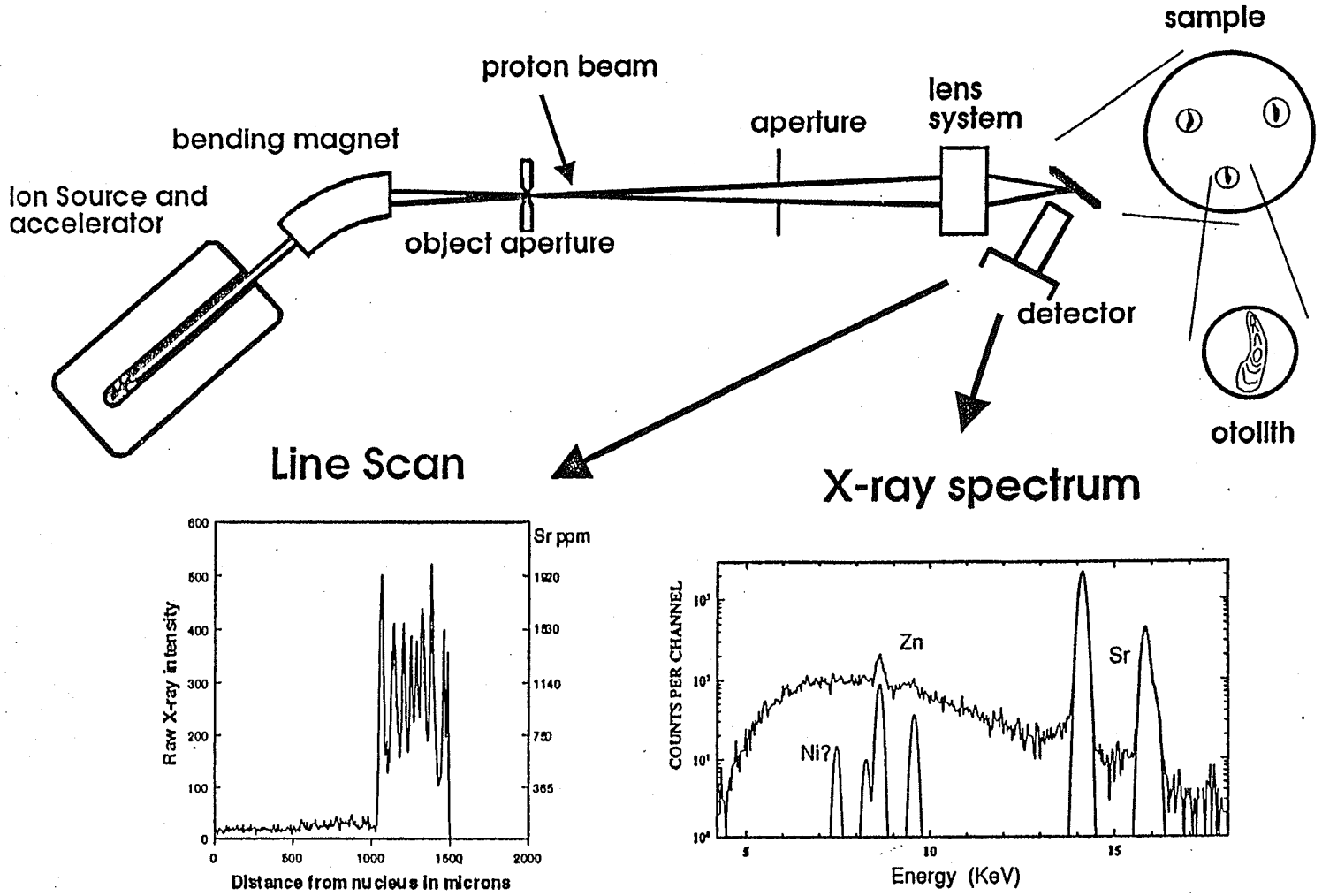

Figure 14. Diagram of Scanning Proton Microprobe used in micro-PIXE analysis. (by permission of Mr. J. Babaluk)

light. This image provided good resolution of the otolith nucleus and annual growth zones. A minimum thickness of 60 μm of otolith material was retained to stop the proton beam from exiting the mounting medium.

One-dimensional line scans were obtained by rastering the proton beam. X-ray intensities and corresponding X-Y coordinates were recorded to computer disc in list mode. The X-ray maps comprised 256 × 256 pixels covering an area of 400 × 400 μm. Line scans were created by focussing the proton beam at the nucleus of the otolith. The probe was pre-programmed to conduct a line scan from the central core to the edge. This provided a measure of the strontium concentration across the otolith from core to edge. A relatively low and constant Sr concentration across the otolith from core to edge is consistent with a nonanadromous life history where the char is exposed to a relatively constant Sr concentration in the water over the course of its life. A low Sr concentration in the core and early life of the char followed by a marked increase in Sr near the edge, showing a "spiked" pattern, is consistent with the life history of an anadromous Arctic char (Halden et al. 1996). The marked increase in Sr in the outer edge of the otolith is reflective of the much higher Sr concentrations in in seawater (8 ppm) compared with freshwater (0.1 ppm) (Rosenthal et al. 1970) and is believed to be accumulated during the chars' seawater feeding forays. Proof of anadromy is very important because the spawners captured in this study were taken in fresh water. Therefore, as many spawners as possible were examined in this way to determine their life history type. Also, mean Sr concentration in the otolith primordium was determined by taking an average Sr

concentration over the first 100 μm of the line scan (27 data points) in all cases where spawners were examined in this manner.

Point analysis was carried out on specimens of nonspawners because this method was less costly than line scans. In this case, anadromy was known because the char were captured returning from the sea. The probe was directed at three random locations within the nucleus of each otolith examined. These points provided an absolute determination of Sr concentration for the very early life history of the char (Halden et al. 1995). The three point values were averaged for each specimen examined in this manner.

Water samples were taken in acid washed bottles from the surface waters of Kitiga, Ferguson, Anderson Bay, Halovik, Char, Mount Pelly, Jayco, Lady Pelly and Wishbone lakes, and Freshwater Creek and Ellice River in August 1995. Water samples were taken with a Kemmerer sampler from a depth of about 2 m from Mount Pelly, Lady Pelly, Wishbone, and Jayco lakes in late August-early September 1996. A surface, mid-water and bottom water sample was taken in this manner from Ferguson Lake on September 2, 1996. All samples were stored in acid washed bottles, kept refrigerated and examined in the laboratory at the Freshwater Institute for elemental composition by atomic absorption spectrometry. Mean Sr concentrations in the otolith nucleus were then compared with Sr concentrations in the water to determine if there was a correlation between environmental and otolith Sr concentrations.

Data Analysis

All graphic displays and statistical analyses were carried out using the statistical software package Statistica (Version 5.5) by StatSoft Inc., Tulsa Oklahoma.

When studying population affinities it is necessary to separate nongeographic intraspecific variation from geographic variation. This nongeographic variation consists of intralocality variation, sexual dimorphism and ontogenetic variation (including allometry). Intralocality variation in single characters can be examined by the normal univariate statistics. Sexual dimorphism can be dealt with by keeping sexes separate and analyzing each separately. Allometric variation can be dealt with by various techniques (Thorpe 1976).

All morphometric data were transformed ($\log_{10}$) and regressed against standard length to determine the effect of size on each body measurement. Data from males and females were compared for each variable for evidence of sexual dimorphism (ANCOVA on $\log_{10}$ variable vs $\log_{10}$ standard length). These data were then subjected to an allometric adjustment to a standard size (539 mm, the grand mean of the standard length of all samples) to remove the effects of size differences between samples following Reist (1985). The common within-groups slope was used for the adjustment (Thorpe 1975, 1976) because of the possibility of within-groups heterogeneity (Reist 1986). The common within-groups slope was calculated only from the samples of spawners because group identity of these samples was known and the slopes had biological significance. Samples of nonspawners were not included in the calculation of this slope because of the possibility that these samples were comprised of an admixture of more than one stock. However, the samples of spawners were taken from across the study area and were thus

assumed to be representative of nonspawners as well as spawners. The slope was calculated from the analysis of covariance program available in the ANOVA/MANOVA Statistica module. The adjustment for size was then carried out using the following allometric formulae from Thorpe (1975):

$$\hat{\hat{Y}}_i = 10^{\hat{Y}i}$$

where

$$\hat{Y}_i = \log Y_i - b\,(\log X_i - \log \bar{\bar{X}})$$

and $\hat{\hat{Y}}_i$ is the adjusted character value of the *i*th specimen; $\hat{Y}_i$ is the logarithm of the adjusted character value of the *i*th specimen; Y_i is the original unadjusted character value of the *i*th specimen; X_i is the standard length of the *i*th specimen; $\bar{\bar{X}}$ is the grand mean of the standard length across all specimens.The allometric coefficient b is the common within-groups slope.

The data from spawners were compared for morphometric and meristic differences using forward stepwise Discriminant Function Analysis (DFA). Discriminant Function Analysis was used because it requires some knowledge of group membership and spawning aggregations were considered as representing homogeneous groups. Missing data were substituted by the overall means for the respective variables. The DFA was run separately on the morphometric data and the meristic data because the former are continuous variables and the latter are discrete variables. The DFA provides a distance matrix based on the Mahalanobis D^2 statistic. I used this distance matrix to provide an indication of the degree of morphological difference/similarity among the samples when all were compared simultaneously.

The Mahalanobis D^2 statistic is a similarity coefficient (Mahalanobis 1936, cited in Thorpe 1976) that is most popular as a mutivariate distance measure for continuous variables (Gould and Johnston 1972). It considers differences in means, variance and covariance of characters among groups. The information in a matrix of distance coefficients can be presented as a hierarchical diagram clustering the phenetically nearest neighbours and joining larger clusters at appropriate levels of mutual similarity (Gould and Johnston 1972).

The morphological data for nonspawners was examined using Cluster Analysis because group membership does not need to be known. This method allows examination of a potential mixed sample to determine whether group structure exists within the sample. I used Cluster Analysis only as a first step to examine whether there was evidence of group structure because Cluster Analysis is useful for hypothesis generation (Anderberg 1973). Validation of clusters may be carried out in statistical or nonstatistical ways (Legendre and Legendre 1998). Where possible, I validated putative groups using morphological and genetic data.

Amalgamation was by Unweighted Pair Group Method using arithmetic Averages (UPGMA). Euclidean distance, the geometric distance in multidimensional space, was used as a distance measure. All data were standardized to a mean of 0 and a standard deviation of 1. Missing data were substituted by the means for the respective dimensions. Output was a Vertical Hierarchical Tree Plot with specimen identification numbers on the horizontal axis.

Data from the electrophoretic analysis were tested for Castle-Hardy-Weinberg equilibrium within samples (chi-square goodness-of-fit) and gene frequencies were compared between samples by chi-square contingency analysis.

The mtDNA sequences were compared following alignment with the MacVector program. The identity of two sequences is the percentage of shared bases and deletions, and insertions are scored as a single change, regardless of length following Hoelzel and Bancroft (1992).

The $\delta^{15}N$ values were plotted against the $\delta^{13}C$ and $\delta^{34}S$ values from the stable isotope analysis following Hesslein et al. (1991) to examine food source and trophic level of the samples tested.

Strontium concentrations in the nucleus of otoliths from spawners were compared between locations by analysis of variance (ANOVA). Water Sr concentrations were compared with mean otolith Sr concentrations of spawners by location using correlation analysis.

RESULTS

Comparison of Spawning Samples

Discriminant Function Analysis (DFA)

Sexual dimorphism was evident in seventeen of the nineteen morphometric variables used in this analysis (difference in means, $p < 0.05$). The two variables that did not exhibit evidence of sexual dimorphism were orbital length (OOL) and dorsal length (DOL). Sex ratios varied amongst most of the samples of spawners compared (Table 4).

Table 4. Sex ratio of Arctic char spawners by location.

Location	Males	Females
Wishbone L.	25	35
Lady Pelly L.	39	12
Ferguson L.	32	13
Halovik L. 87	9	4
Halovik L. 93	21	31
Kitiga L.	14	9
Mount Pelly L. 92	27	17
Mount Pelly L. 93	6	5
Anderson Bay L. 93	25	6
Anderson Bay L. 94	19	9
Fish Trap L.	8	3
Char L.	20	26
Totals	245	170

Therefore, the DFA was carried out separately on males and females, and then with the sexes combined. Results did not differ among these three data sets, and most of the variables that contributed to discrimination were the same in each case, regardless of sex. That is, differences between groups were greater than differences between sexes. The

DFA using sexes combined is presented here to include the larger sample sizes. An example of the DFA by sex is included in Appendix I.

In order to examine whether stock structuring was evident within a river system, I compared three samples of spawners from the lakes that were tributary to the Ekalluk River system. The plot of canonical scores from the discriminant function analysis of morphometric measurements made on Arctic char spawners from Ferguson, Lady Pelly and Wishbone lakes shows that the three groups can be readily distinguished from one another (Fig. 15). Root 1 shows the scores from the first discriminant (canonical) function for each individual specimen examined. This function contributes most to overall discriminatory power. Root 2 shows the scores from the second discriminant (canonical) function, which is independent (orthogonal) of the first function. It contributes less to overall discriminatory power. The results of the DFA are summarized in Table 5. All Chi-square tests with successive roots removed (0,1) were significant ($p< 0.001$). The variables that contributed the most to the discrimination included orbital length (OOL), maxillary width (MXW), and lower gill arch length (LAL) in that order. Arctic char from Ferguson Lake have small orbits and those from Lady Pelly Lake have large orbits compared with char from Wishbone Lake (Fig. 16a). Char from Wishbone Lake have a narrow maxillary width compared with those from Lady Pelly and Ferguson lakes (Fig. 16b). Char from Lady Pelly Lake appear to have a shorter lower gill arch length compared with those from the other two lakes (Fig. 16c). Orbital length is shown plotted against maxillary width for each group (Fig. 17).

It is evident from the above comparison that I was not able to obtain samples of spawners from all locations simultaneously. However, each sample was comprised of

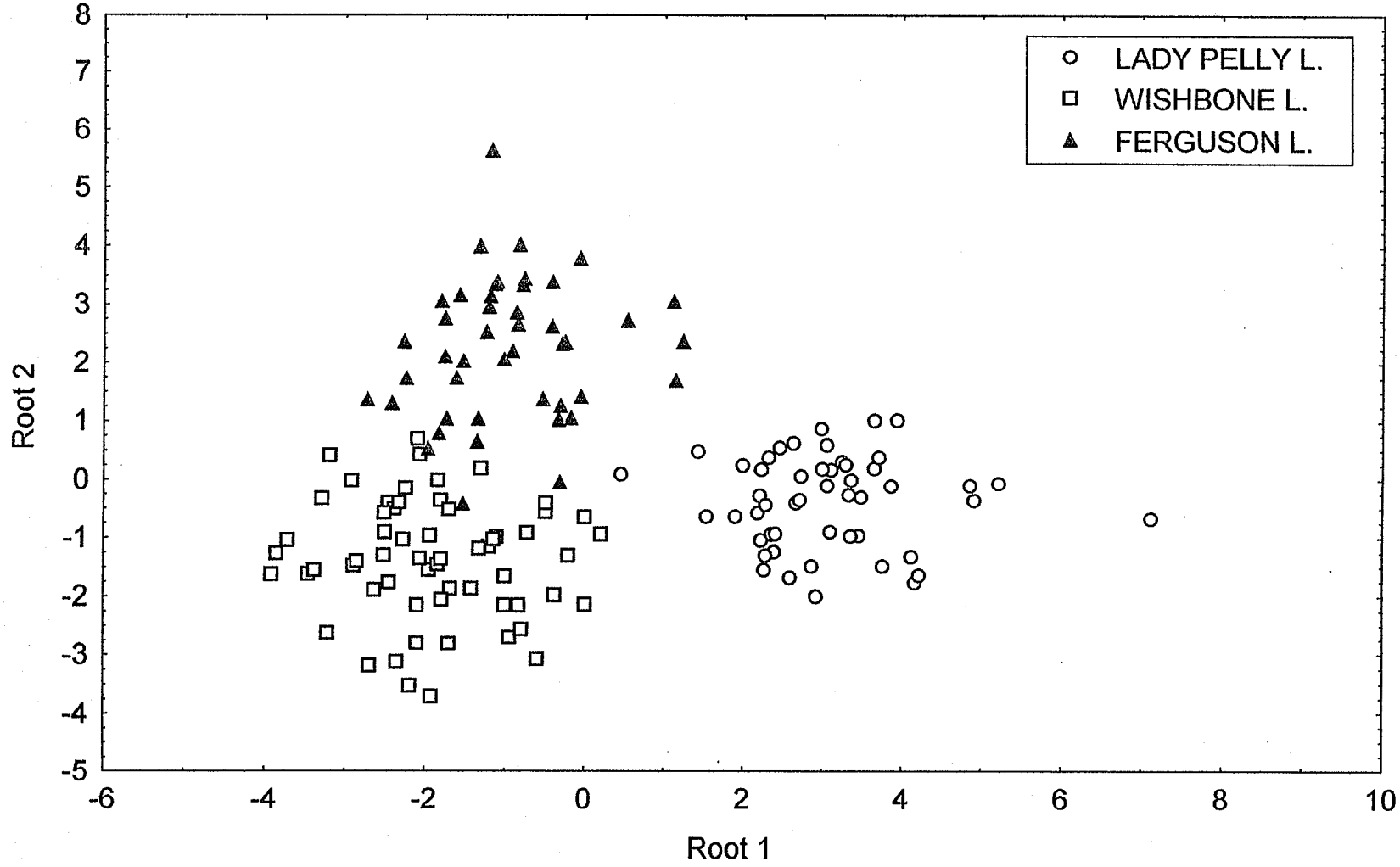

Figure 15. Discriminant function analysis of morphometric measurements of Arctic char spawners from Ferguson, Lady Pelly and Wishbone lakes in the Ekalluk River system.

Table 5. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Lady Pelly, Wishbone and Ferguson lakes.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 10, N of vars in model: 10; Grouping: GROUP (3 grps) Wilks' Lambda: .05260 approx. F (20,288)=48.387 p<0.0000					
N=156	Wilks' Lambda	Partial Lambda	F-remove (2,144)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGOOL	.120252	.437416	92.60309	.000000	.912921	.087079
LOGMXW	.087560	.600733	47.85351	.000000	.826654	.173346
LOGLAL	.066569	.790158	19.12098	.000000	.684814	.315186
LOGCPL	.063632	.826638	15.09979	.000001	.738955	.261045
LOGANL	.062205	.845594	13.14729	.000006	.622359	.377641
LOGBDD	.055754	.943432	4.31707	.015107	.723560	.276440
LOGTTL	.063625	.826727	15.09040	.000001	.495119	.504882
LOGDOL	.063537	.827868	14.97037	.000001	.585916	.414084
LOGLUL	.063557	.827611	14.99738	.000001	.520184	.479816
LOGPSL	.056282	.934589	5.03925	.007668	.566694	.433306

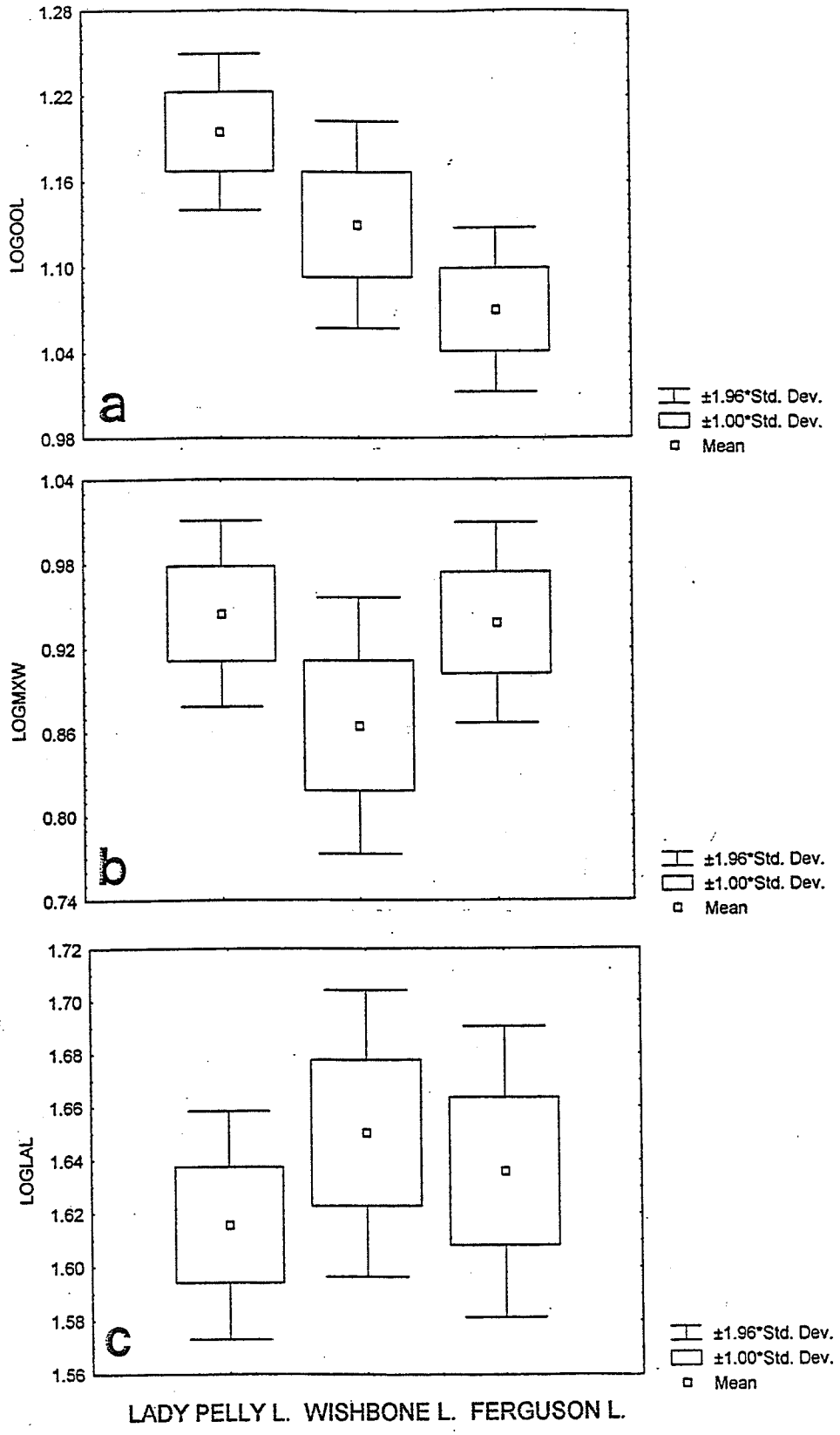

Figure 16. A comparison of mean log (a) orbital length (OOL), (b) maxillary width (MXW), and (c) lower gill arch length (LAL) among samples of Arctic char spawners from Lady Pelly, Wishbone and Ferguson lakes.

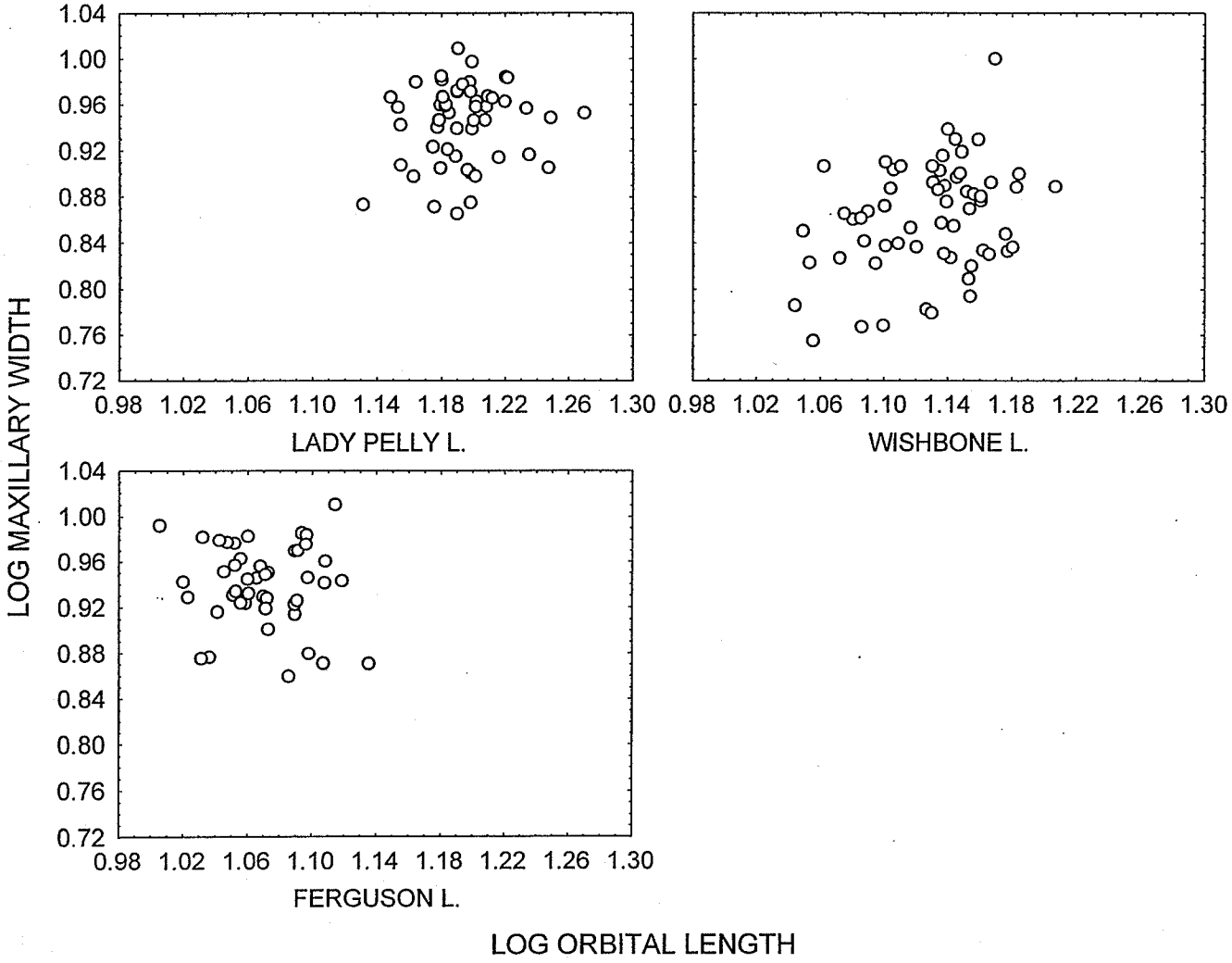

Figure 17. A plot of log orbital length (OOL) against log maxillary width (MXW) for Arctic char spawners from Lady Pelly, Wishbone and Ferguson lakes.

multiple year classes of Arctic char. Values of morphological characters consistent across all year classes within each sample provide evidence that the morphological differences observed among samples were not a product of year-to-year variations based on samples taken in different years (Fig. 18). Additionally, due to the range of year classes present in most samples, the same year classes were present in a number of samples although the samples were taken in different years.

In order to examine whether stock structuring was evident among river sysems, I compared samples of spawners from a number of geographically adjacent river systems. The DFA on morphometric measurements of Arctic char spawners from the three river systems draining into Wellington Bay shows that group separation is evident among spawners from Ferguson Lake, Halovik Lake and Kitiga Lake (Fig. 19). All Chi-square tests with successive roots removed (0,1) were significant ($p< 0.001$). Variables contributing most to the discrimination included caudal peduncle length (CPL), maxillary width (MXW), head depth (HDD) and orbital length (OOL) (Table 6). All Chi-square tests with successive roots removed (0,1,2) were significant ($p < 0.001$). A relatively small orbit (Fig. 20a) characterizes Ferguson Lake spawners. Kitiga Lake spawners appear to have a narrow maxillary width (Fig. 20b) and smaller head depth (not shown) relative to those from Ferguson Lake and Halovik Lake. Halovik Lake (1993) spawners appear to have a longer caudal peduncle (Fig. 20c) than the others. Differences in mean maxillary width (Fig.20b) and caudal peduncle length (Fig. 20c) are evident between the Halovik Lake 1987 and 1993 samples. Orbital length is shown plotted against maxillary width for each group (Fig. 21). A wide range in orbital length is evident for the Halovik Lake 1993 spawners (Figs. 20a, 21).

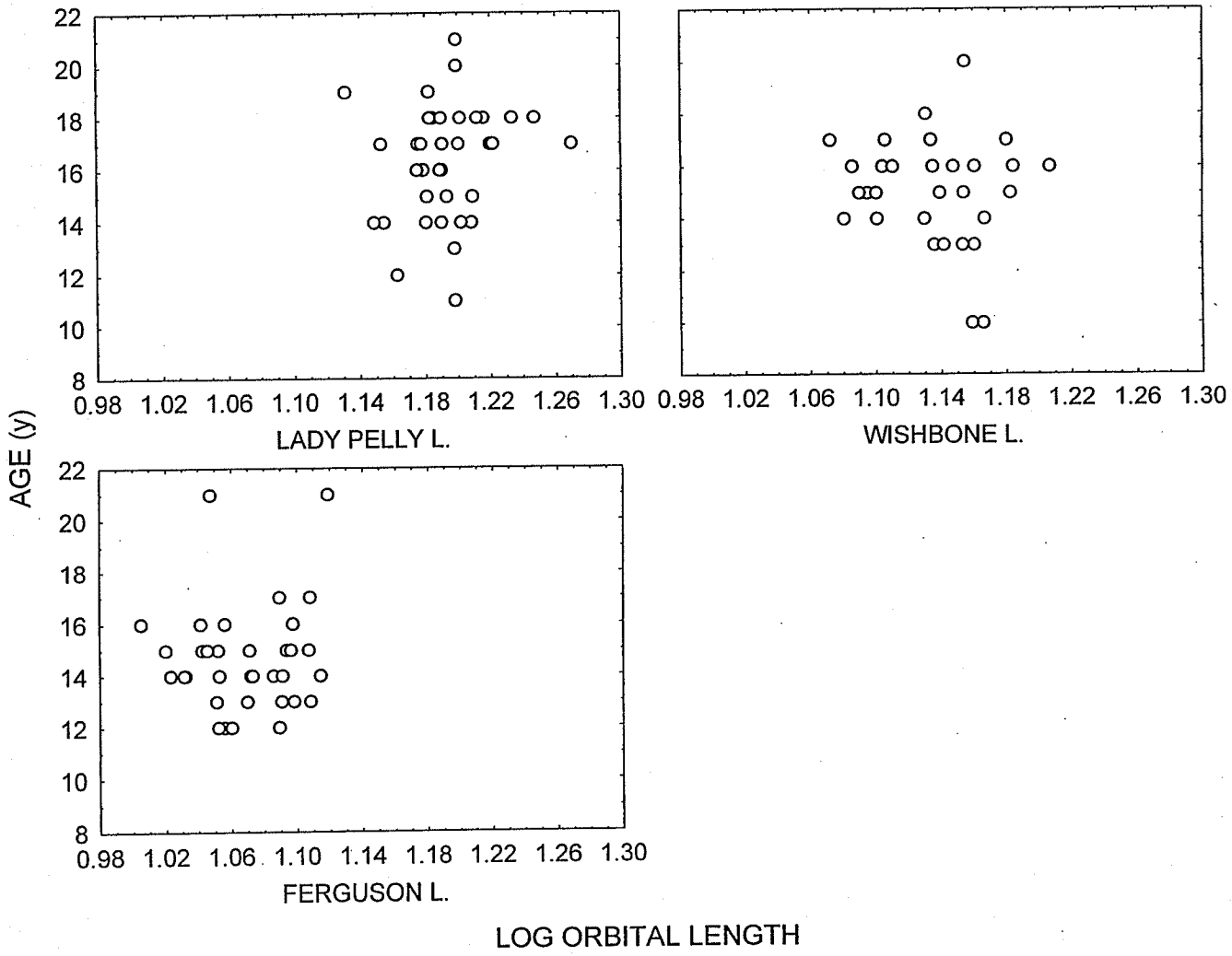

Figure 18. A plot of log orbital length (OOL) against age for Arctic char spawners from Lady Pelly, Wishbone and Ferguson lakes.

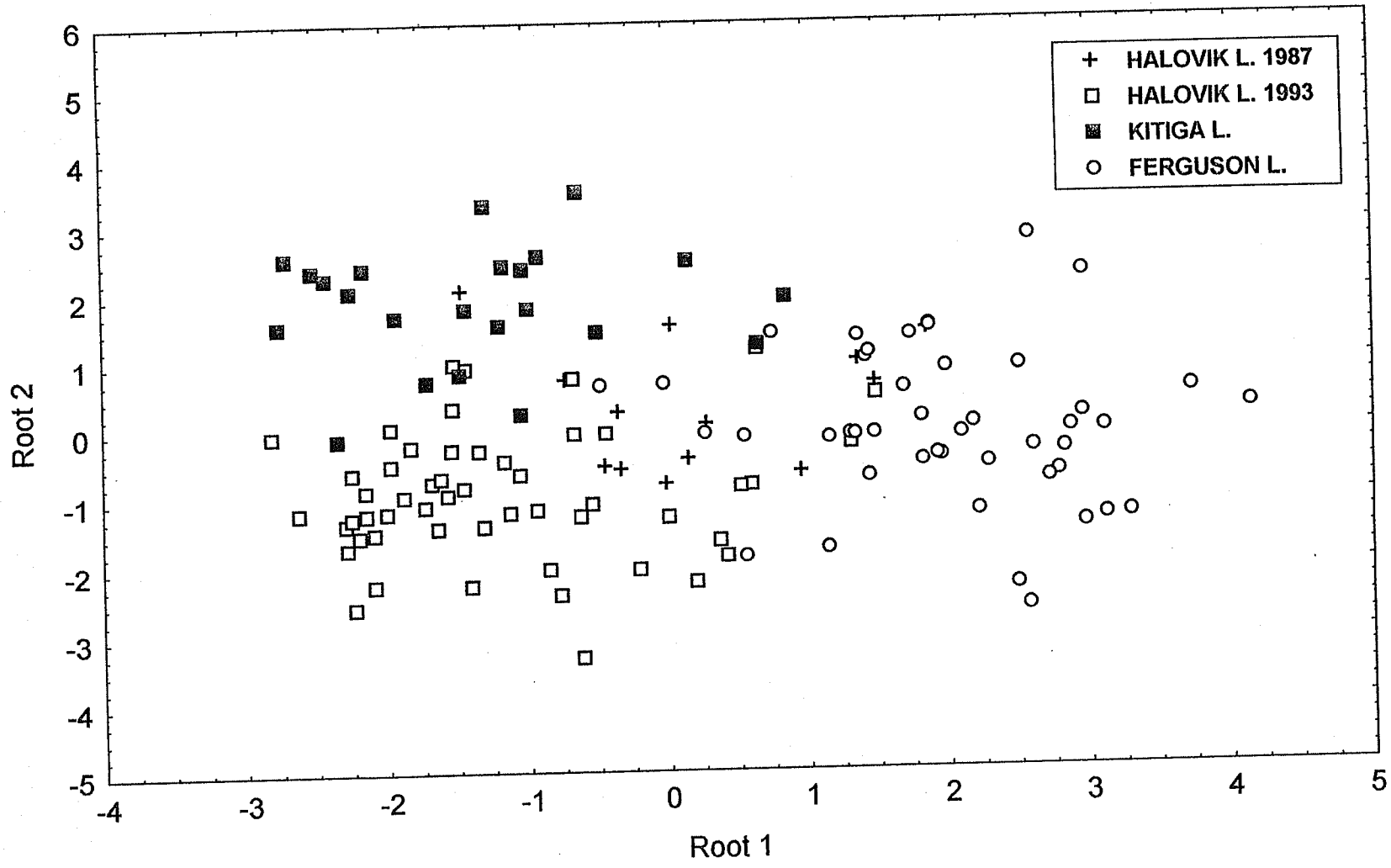

Figure 19. Discriminant function analysis of morphometric measurements of Arctic char spawners from Halovik Lake 1987, Halovik Lake 1993, Kitiga Lake and Ferguson Lake.

Table 6. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Halovik Lake 1987, Halovik Lake 1993, Kitiga Lake and Ferguson Lake.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 10, N of vars in model: 10; Grouping: GROUP (4 grps) Wilks' Lambda: .08017 approx. F (30,352)=16.028 p<0.0000					
N=133	Wilks' Lambda	Partial Lambda	F-remove (3,120)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGBDD	.094732	.846329	7.26292	.000162	.504615	.495385
LOGMXW	.107888	.743130	13.82637	.000000	.843681	.156319
LOGCPL	.112357	.713573	16.05596	.000000	.738734	.261266
LOGOOL	.097308	.823924	8.54818	.000034	.902334	.097666
LOGLAL	.093472	.857738	6.63426	.000348	.698275	.301725
LOGHDD	.098135	.816986	8.96042	.000021	.508966	.491034
LOGGRL	.093702	.855637	6.74881	.000303	.844967	.155033
LOGLUL	.093384	.858551	6.59011	.000368	.706497	.293503
LOGPSL	.089114	.899687	4.45992	.005241	.664646	.335354
LOGCPD	.088328	.907692	4.06781	.008604	.531740	.468260

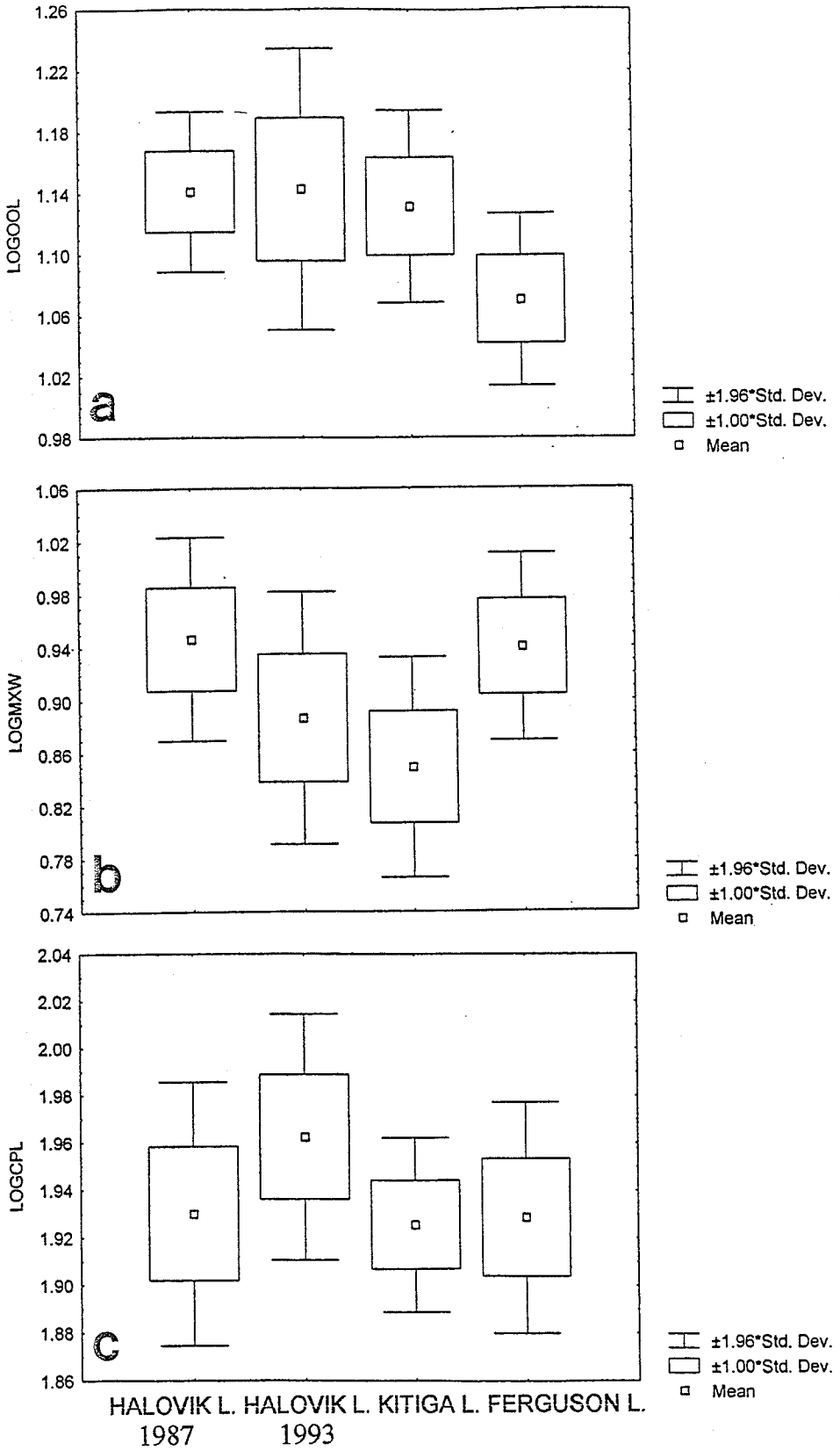

Figure 20. A comparison of mean log (a) orbital length (OOL), (b) maxillary width (MXW), and (c) caudal peduncle length (CPL) among samples of Arctic char spawners from Halovik Lake 1987, Halovik Lake 1993, Kitiga Lake and Ferguson Lake.

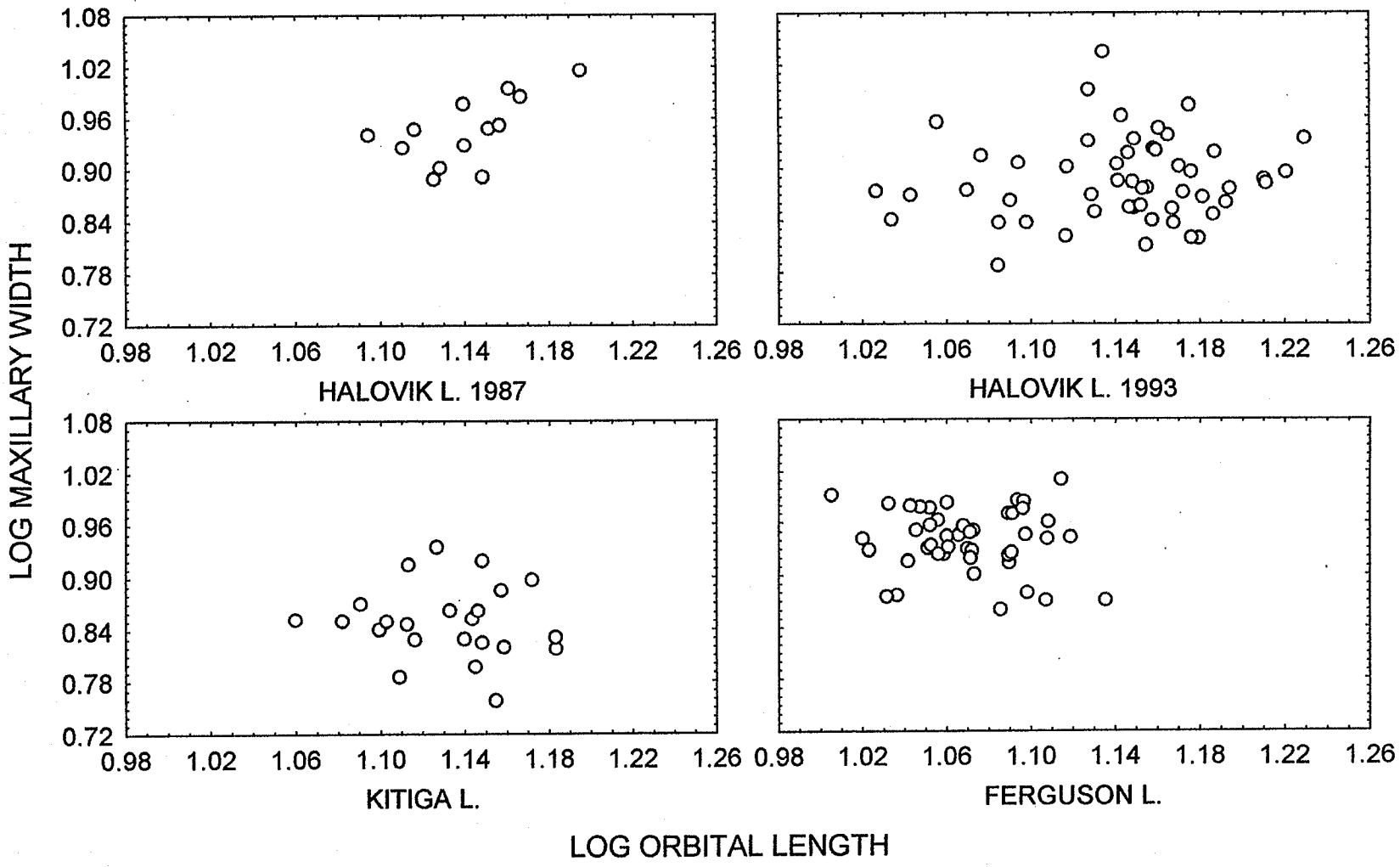

Figure 21. A plot of log orbital length (OOL) against log maxillary width (MXW) for Arctic char spawners from Halovik Lake 1987, Halovik Lake 1993, Kitiga Lake and Ferguson Lake.

Segregation is apparent in the morphological comparison among Arctic char spawners from Kitiga Lake, Freshwater Creek (Mount Pelly Lake 1992) and Anderson Bay Lake (1994), (Fig. 22). The morphometric variable that contributed most to this discrimination was gill raker length (GRL) followed by dorsal length (DOL), trunk length (TTL) and pectoral fin length (PCL) (Table 7). All Chi-square tests with successive roots removed (0,1) were significant ($p < 0.001$). Spawners from Mount Pelly Lake 1992 were characterized by relatively short pectoral fins (Fig.23a), long dorsal length (Fig. 23b) and long gill raker length (Fig 23c) compared with those from the other two locations. Spawners from Kitiga Lake had short dorsal length (Fig. 23b) and gill raker length (Fig. 23c) while those from Anderson Bay Lake (1994) had intermediate values for these variables but a short trunk length (TTL) (not shown) compared with the other two groups. A plot of dorsal length against gill raker length is shown in Fig. 24.

The results of the DFA between Mount Pelly Lake 1992 and 1993 and Anderson Bay Lake 1993 and 1994 shows that group structure is evident between Anderson Bay Lake 1993, Anderson Bay Lake 1994, and the two Mount Pelly Lake samples (Fig. 25). Discrimination between the two Mount Pelly Lake samples is not evident here. Chi-square tests with successive roots removed (0,1) were significant ($p < 0.001$). The variable head depth (HDD) appears to have contributed most to this discrimination (Table 8). Body depth (BDD), orbital length (OOL) and pectoral fin length (PCL) also contributed. Both samples from Mount Pelly Lake, 1992 and 1993, had similar small mean head depth while those from Anderson Bay Lake 1993 a larger mean head depth than those from Anderson Bay Lake 1994 (Fig. 26a.). Both samples from Mount Pelly Lake had similar body depth while those from Anderson Bay Lake 1993 had the smallest body depth

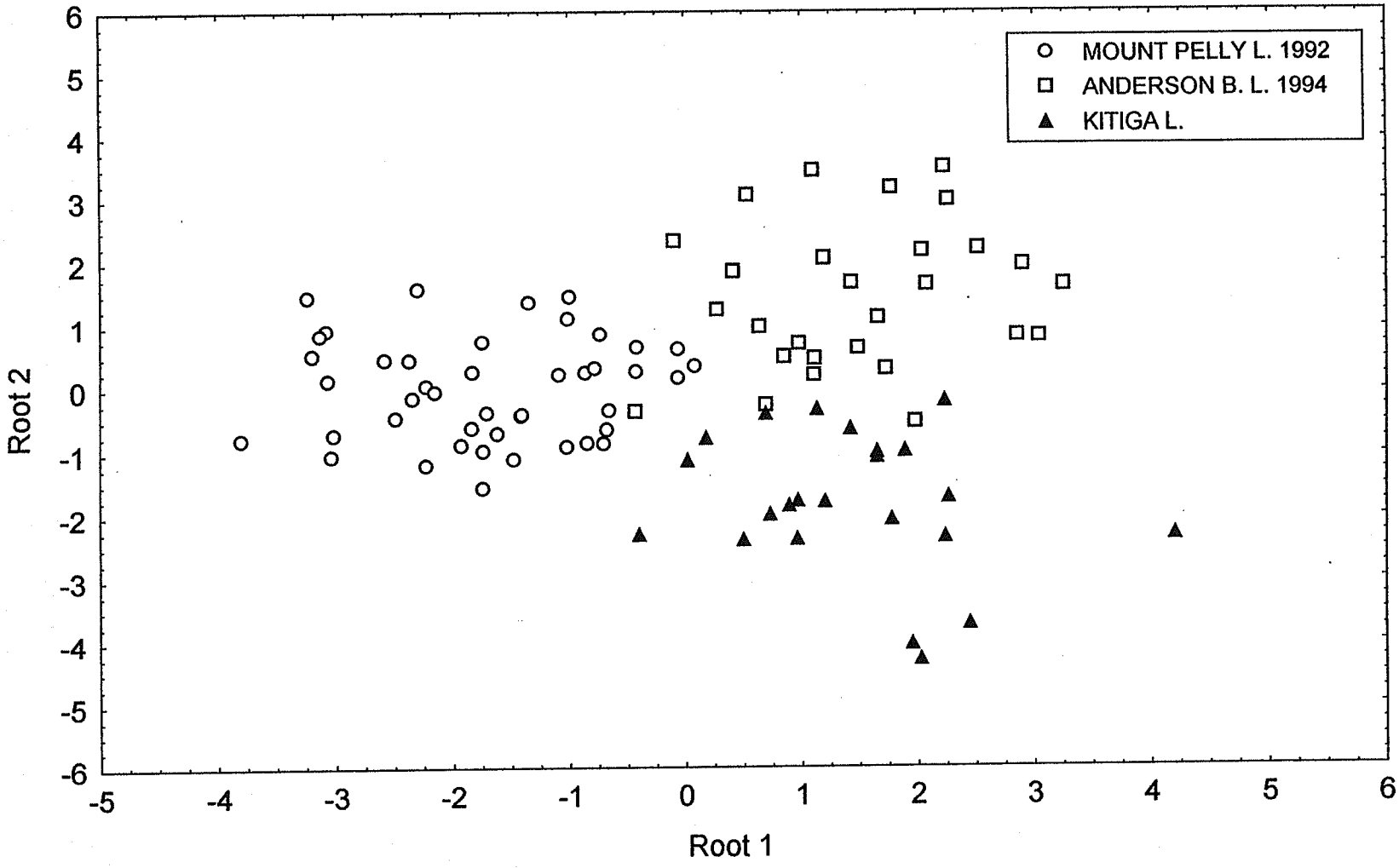

Figure 22. Discriminant function analysis of morphometric measurements of Arctic char spawners from Kitiga Lake, Mount Pelly Lake 1992 and Anderson Bay Lake 1994.

Table 7. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Kitiga Lake, Freshwater Creek (Mount Pelly Lake) 1992, and Anderson Bay Lake 1994.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 11, N of vars in model: 11; Grouping: GROUP (3 grps) Wilks' Lambda: .11374 approx. F (22,164)=14.649 p< .0000					
N=95	Wilks' Lambda	Partial Lambda	F-remove (2,82)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGPCL	.147285	.772276	12.08986	.000025	.386343	.613657
LOGGRL	.167249	.680091	19.28601	.000000	.756364	.243636
LOGOOL	.120664	.942653	2.49425	.088804	.769982	.230018
LOGDOL	.157225	.723451	15.67278	.000002	.400657	.599343
LOGTTL	.153175	.742580	14.21288	.000005	.413160	.586840
LOGPOL	.134273	.847117	7.39946	.001111	.396806	.603194
LOGLAL	.137353	.828118	8.50986	.000438	.611376	.388624
LOGPVL	.127262	.893781	4.87254	.010011	.323210	.676790
LOGHDD	.129458	.878624	5.66389	.004965	.365848	.634152
LOGCPD	.138186	.823124	8.81023	.000342	.467316	.532684
LOGBDD	.128049	.888289	5.15617	.007775	.441453	.558547

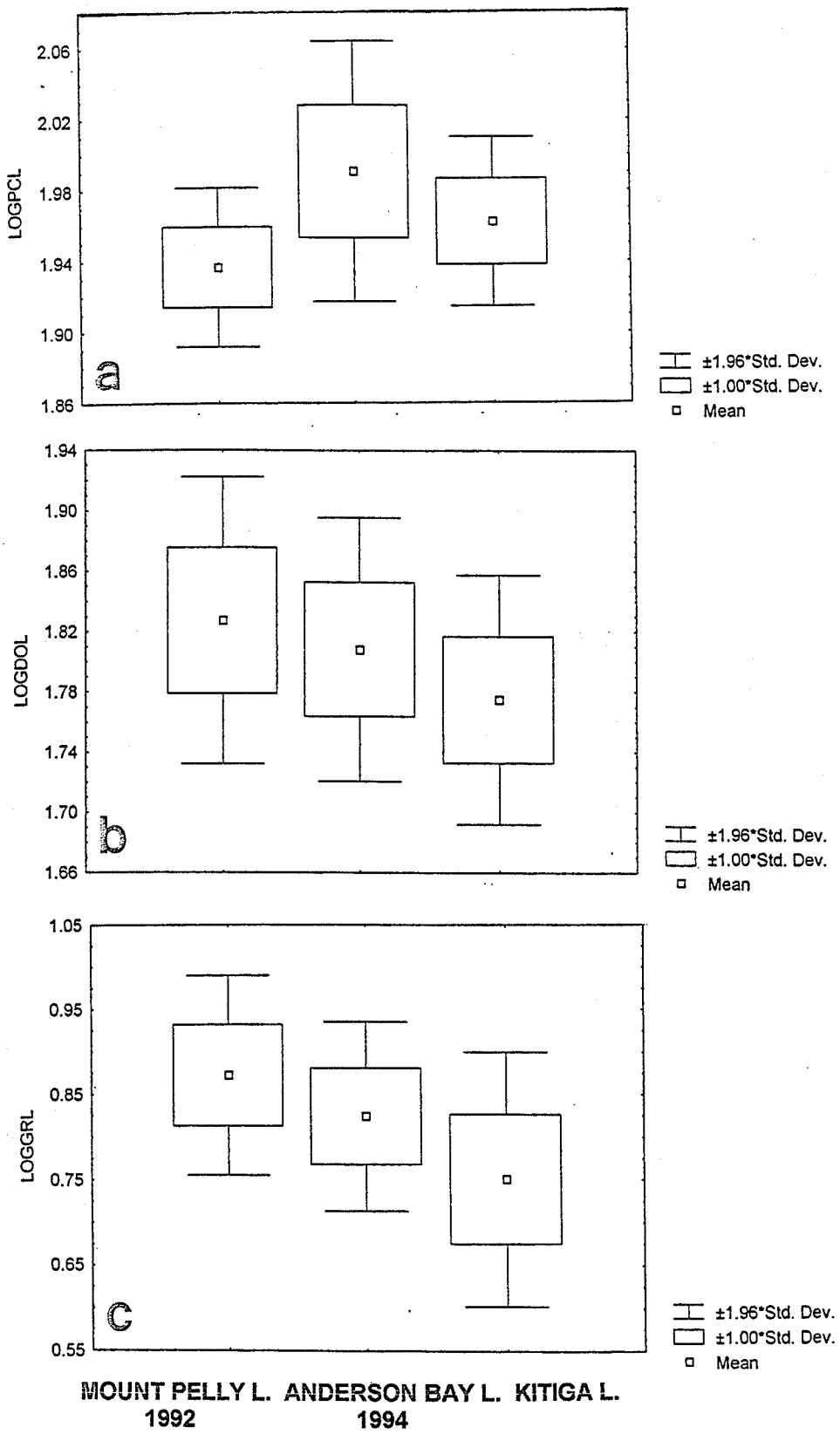

Figure 23. A comparison of mean log (a) pectoral fin length (PCL), (b) dorsal length (DOL), and (c) gill raker length (GRL) among samples of Arctic char spawners from Kitiga Lake, Mount Pelly Lake 1992 and Anderson Bay Lake 1994.

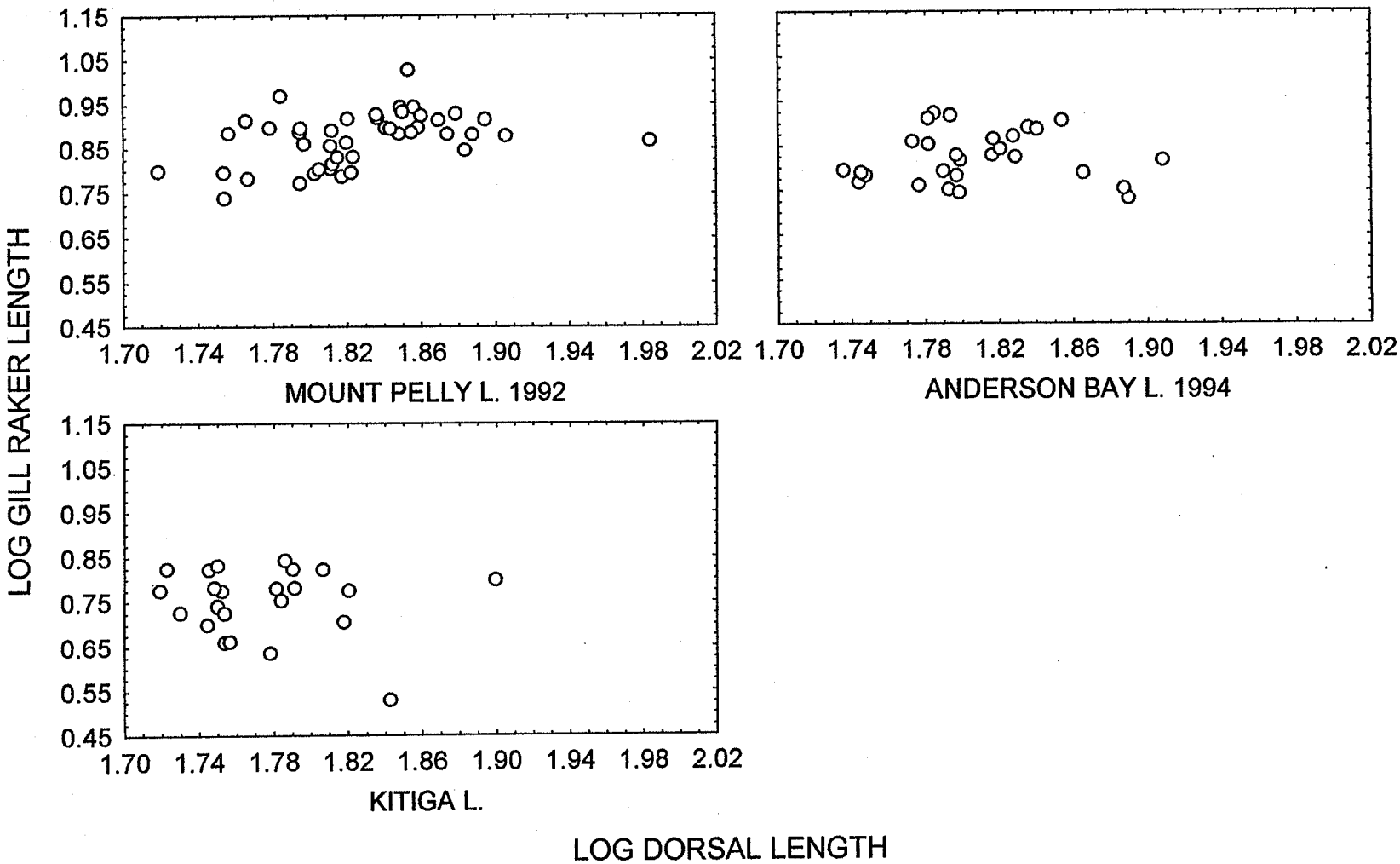

Figure 24. A plot of log dorsal length (DOL) against log gill raker length (GRL) for Arctic char spawners from Kitiga Lake, Mount Pelly Lake 1992 and Anderson Bay Lake 1994.

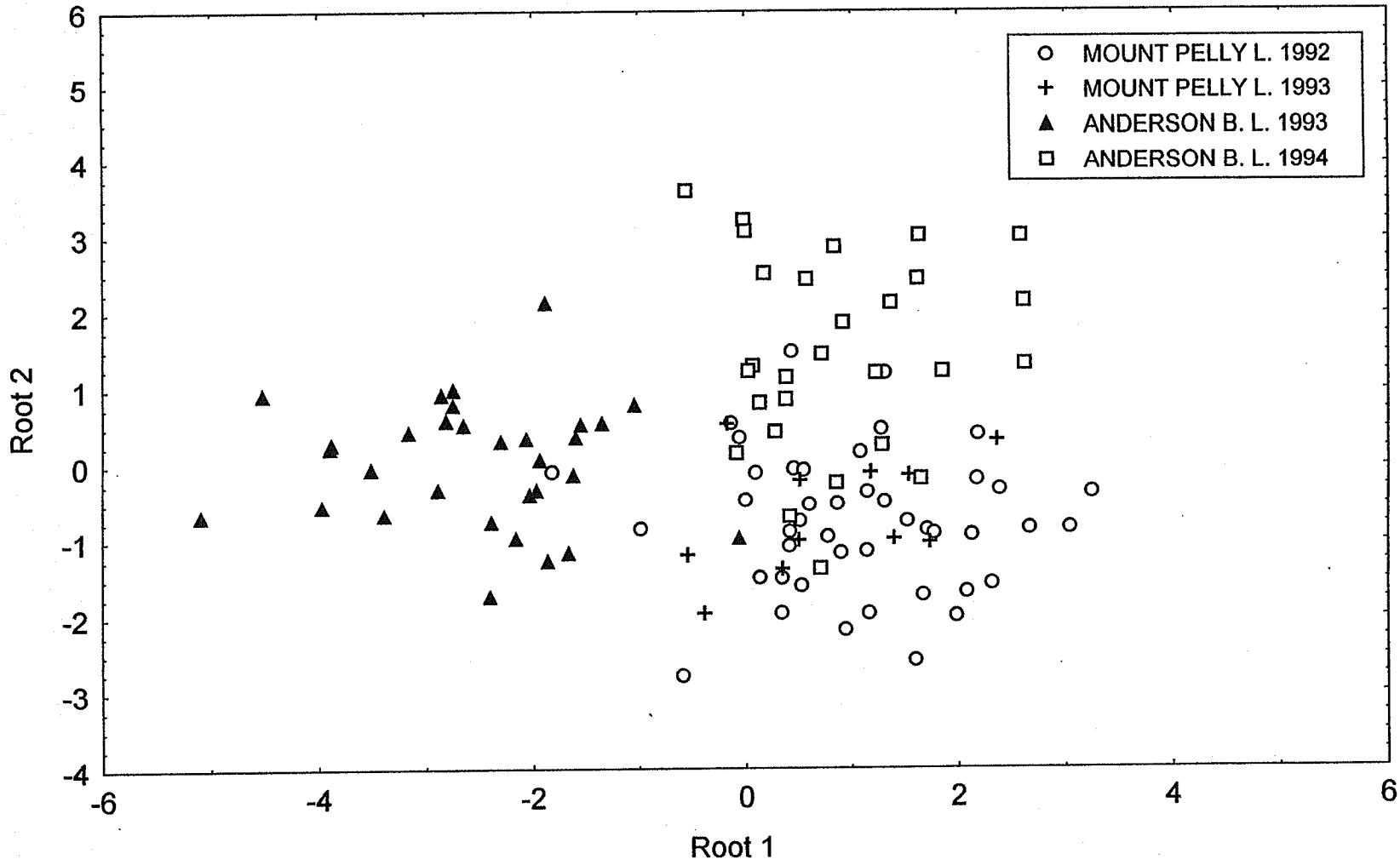

Figure 25. Discriminant function analysis of morphometric measurements of Arctic char spawners from Mount Pelly Lake 1992 and 1993 and Anderson Bay Lake 1993 and 1994.

Table 8. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Mount Pelly Lake 1992 and 1993, and Anderson Bay Lake 1993 and 1994.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 6, N of vars in model: 6; Grouping: GROUP (4 grps) Wilks' Lambda: .11277 approx. F (18,297)=19.224 p<0.0000					
N=114	Wilks' Lambda	Partial Lambda	F-remove (3,105)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGHDD	.270609	.416709	48.99155	.000000	.476449	.523551
LOGBDD	.169419	.665597	17.58437	.000000	.460297	.539703
LOGOOL	.152101	.741382	12.20914	.000001	.946073	.053927
LOGPCL	.145105	.777127	10.03767	.000007	.829760	.170240
LOGMXW	.135987	.829233	7.20769	.000191	.877326	.122674
LOGCPD	.133208	.846534	6.34507	.000538	.458759	.541241

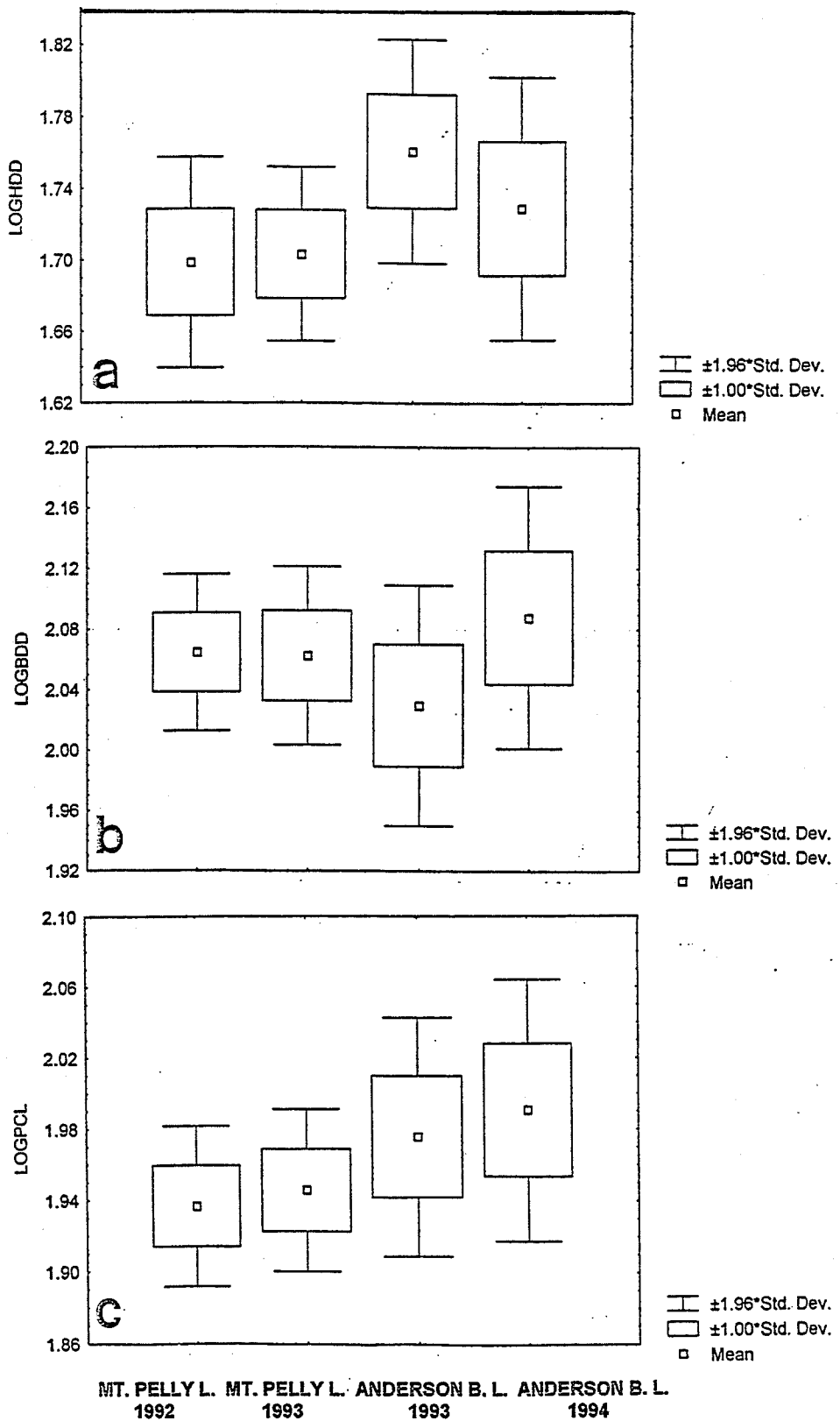

Figure 26. A comparison of mean log (a) head depth (HDD), (b) body depth (BDD), and (c) pectoral fin length (PCL) among samples of Arctic char spawners from Mount Pelly Lake 1992 and 1993 and Anderson Bay Lake 1993 and 1994.

of all groups and those from Anderson Bay Lake had the largest body depth of all groups (Fig. 26b). Both Mount Pelly Lake samples had short pectoral fins while those from Anderson Bay Lake 1994 had the longest pectoral fins of all four samples (Fig. 26c). Orbital length contributed to discrimination in root 3 (not shown) with samples from Mount Pelly Lake 1993 having the smallest mean orbital length of all four groups. The relationships of the variables head depth and body depth for these groups is shown in Fig. 27.

The Anderson Bay Lake 1993 sample appears to be the most distinct when compared with Anderson Bay Lake 1994 and Char and Fish Trap lakes (Fig. 28). Chi-square tests with successive roots removed (0,1) were significant ($p < 0.001$). The variable that contributed most to this discrimination was body depth (BDD) followed by head depth (HDD) and orbital length (OOL) (Table 9). The Anderson Bay 1993 spawners had the smallest mean body depth (Fig. 29a) and largest mean head depth (Fig. 29b), compared with the samples from the other three locations. The discriminating character of the Anderson Bay 1994 sample was the large mean body depth (Fig.29a). The Char Lake and Fish Trap samples were similar with respect to body depth and head depth but the Fish Trap Lake sample had the smallest mean orbital length although the range of the values of this variable was wide (Fig. 29c). The relationship of the variables body depth and head depth for these groups is shown in Fig. 30.

A discriminant function analysis of all twelve samples of spawners from across the study area was carried out to identify similarities/differences among the groups. All Chi-square values with successive roots removed (0, 1-6) were significant at $p < 0.001$, and root 7 removed at $p = 0.01$. The summary of the DFA (Table 10) indicated that

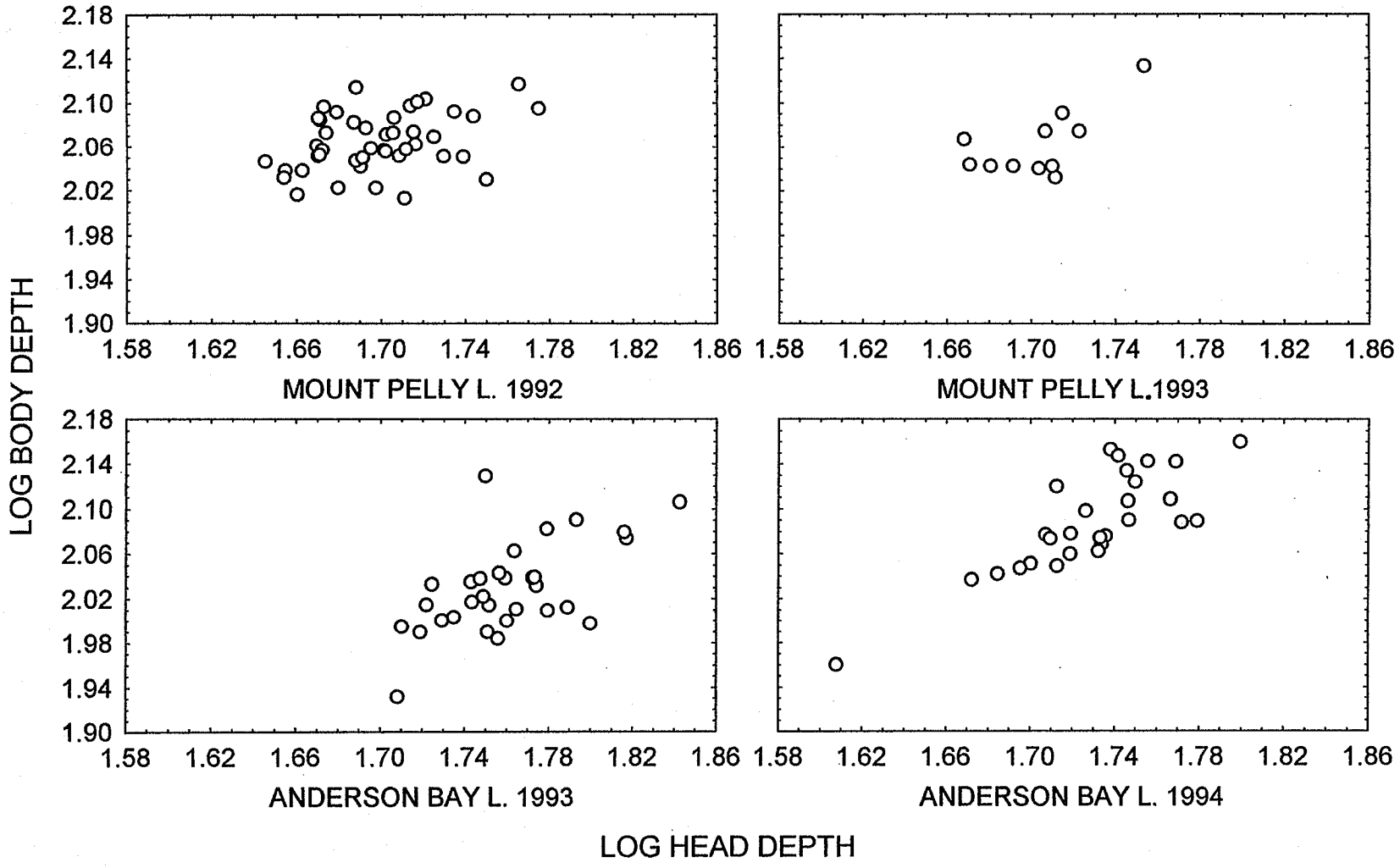

Figure 27. A plot of log head depth (HDD) against log body depth (BDD) for Arctic char spawners from Mount Pelly Lake 1992 and 1993, and Anderson Bay Lake 1993 and 1994.

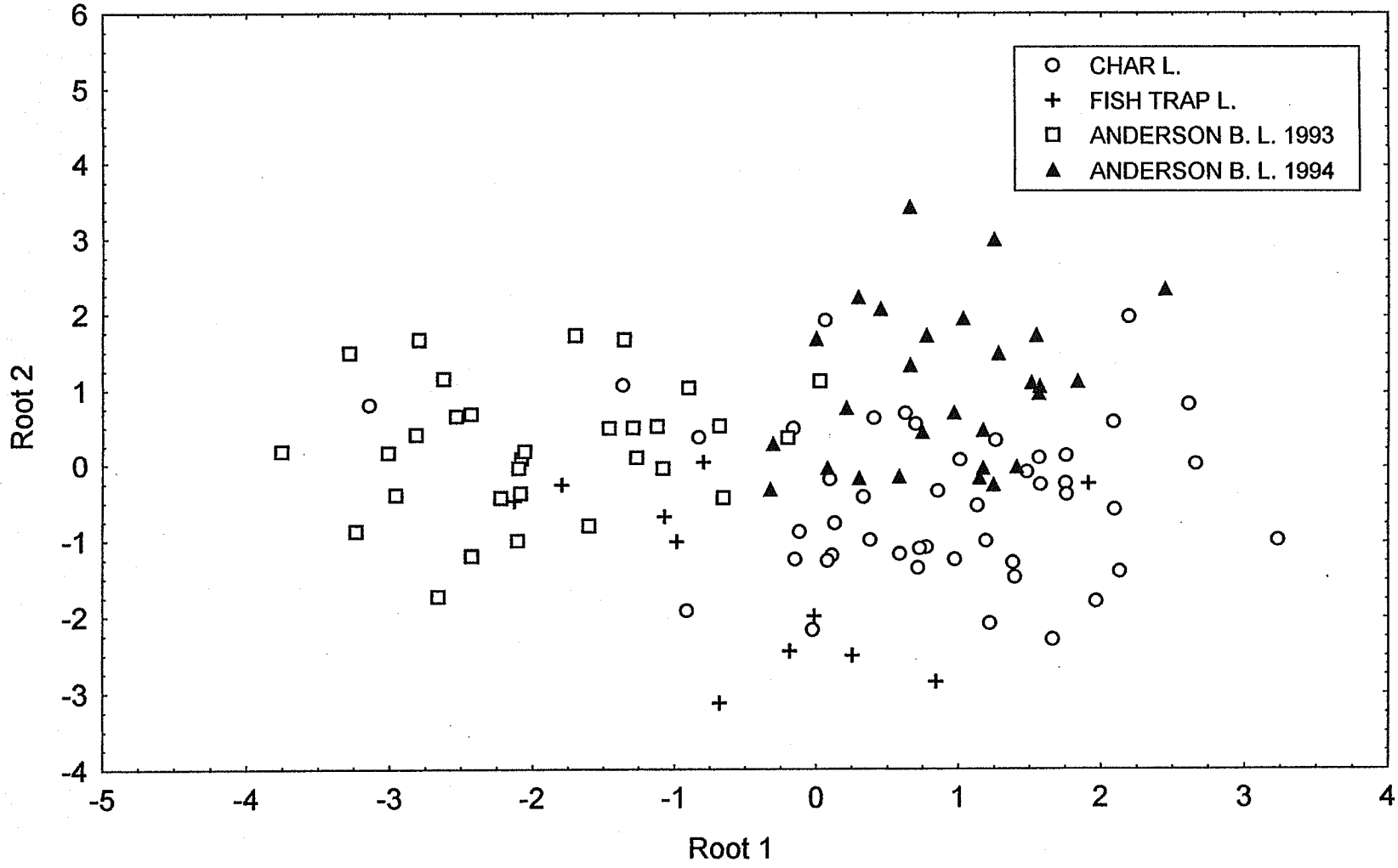

Figure 28. Discriminant function analysis of morphometric measurements of Arctic char spawners from Anderson Bay Lake 1993 and 1994, Char Lake and Fish Trap Lake.

Table 9. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Anderson Bay Lake 1993 and 1994, Char Lake and Fish Trap Lake.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 7, N of vars in model: 7; Grouping: GROUP (4 grps) Wilks' Lambda: .20956 approx. F (21,304)=10.502 p< .0000					
N=116	Wilks' Lambda	Partial Lambda	F-remove (3,106)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGHDD	.274357	.763804	10.92632	.000003	.613808	.386192
LOGBDD	.307136	.682287	16.45326	.000000	.396022	.603978
LOGOOL	.267586	.783132	9.78467	.000009	.862523	.137477
LOGMXW	.250176	.837630	6.84917	.000291	.824653	.175347
LOGTTL	.249540	.839767	6.74183	.000331	.767518	.232482
LOGADL	.239667	.874361	5.07713	.002526	.887057	.112943
LOGCPD	.237578	.882047	4.72500	.003909	.362534	.637466

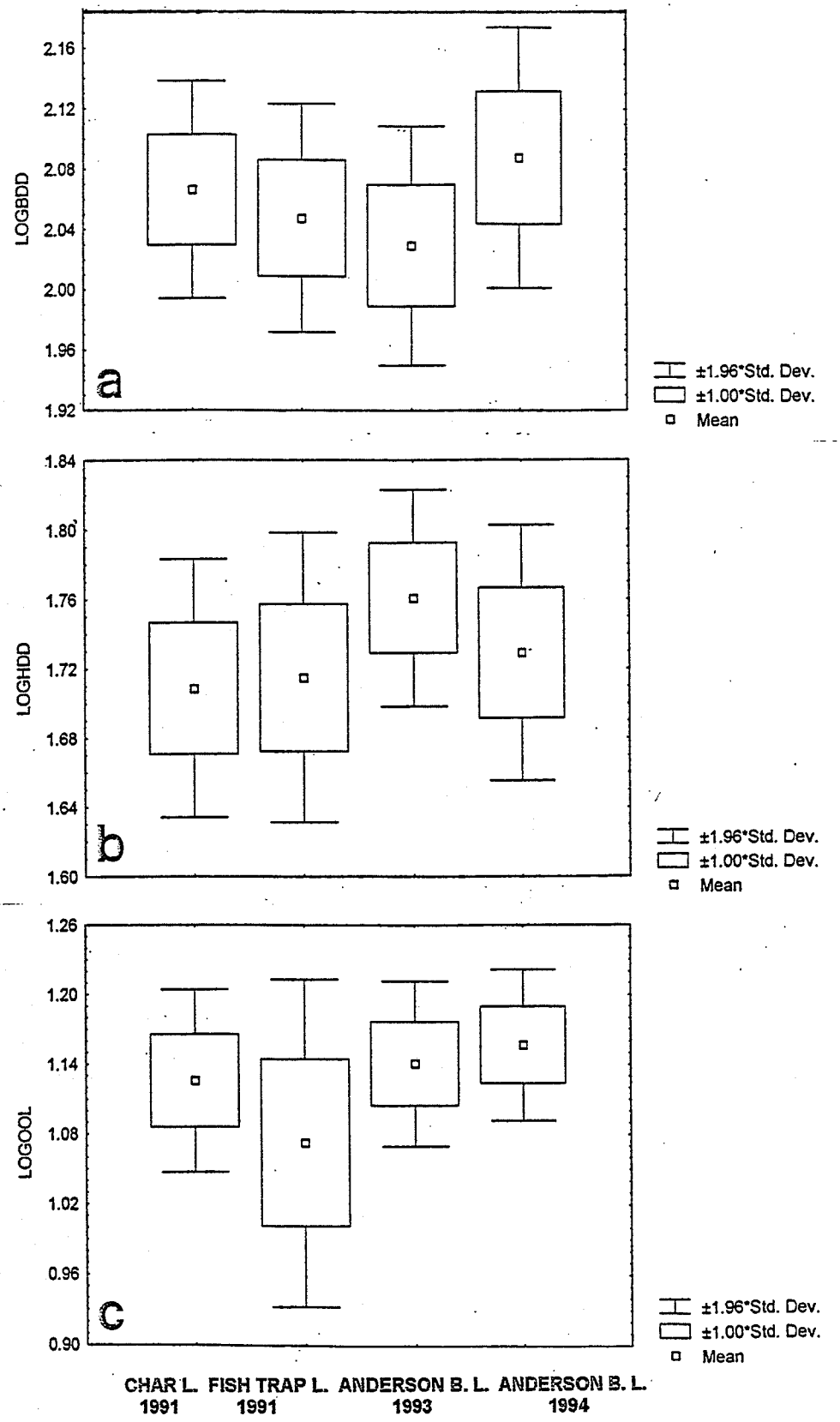

Figure 29. A comparison of mean log(a) body depth (BDD), (b) head depth (HDD), and (c) orbital length (OOL) among samples of Arctic char spawners from Anderson Bay Lake 1993 and 1994, Char Lake and Fish Trap Lake.

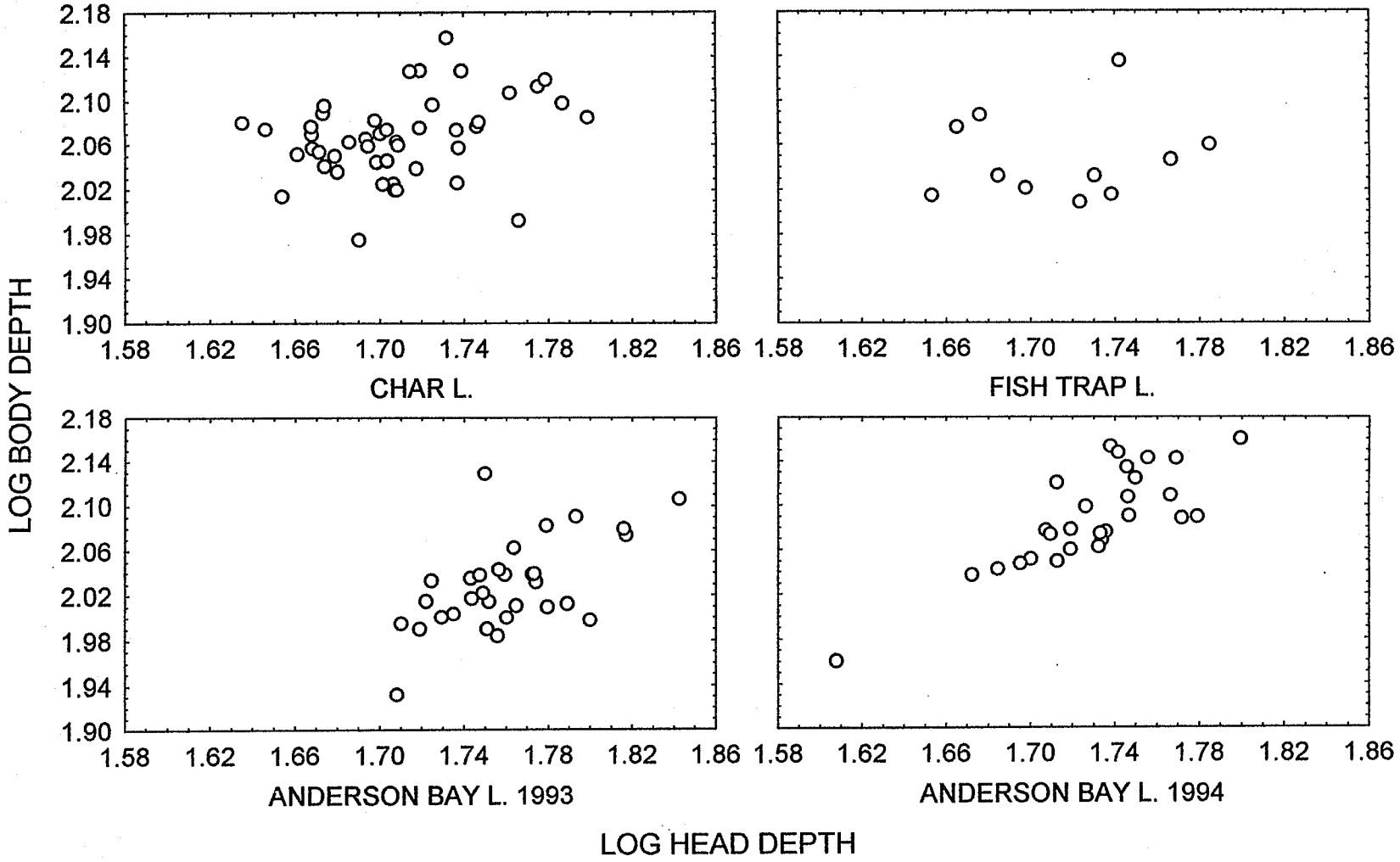

Figure 30. A plot of log head depth (HDD) against log body depth (BDD) for Arctic char spawners from Anderson Bay Lake 1993 and 1994, Char Lake and Fish Trap Lake.

Table 10. Summary of the discriminant function analysis of morphometric measurements of Arctic char from the twelve samples of spawners examined across the study area.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 12, N of vars in model: 12; Grouping: GROUP (12 grps) Wilks' Lambda: .02989 approx. F (132,3225)=13.085 p<0.0000					
N=415	Wilks' Lambda	Partial Lambda	F-remove 11,392	p-level	Toler.	1-Toler. (R-Sqr.)
LOGMXW	.047991	.622860	21.57775	0.000000	.874414	.125586
LOGOOL	.051260	.583136	25.47518	0.000000	.914888	.085112
LOGCPL	.039549	.755825	11.51259	.000000	.806292	.193708
LOGBDD	.040865	.731483	13.08160	.000000	.520781	.479219
LOGLAL	.037399	.799260	8.95031	.000000	.661933	.338067
LOGHDD	.042494	.703432	15.02431	.000000	.531124	.468876
LOGGRL	.038763	.771138	10.57634	.000000	.903172	.096828
LOGCPD	.036827	.811692	8.26744	.000000	.535946	.464054
LOGPCL	.035631	.838933	6.84186	.000000	.776585	.223415
LOGANL	.035109	.851405	6.21961	.000000	.744690	.255310
LOGIOW	.033954	.880360	4.84294	.000001	.584199	.415801
LOGLUL	.033524	.891655	4.33019	.000004	.736441	.263559

orbital length (OOL) contributed most to the overall discrimination of groups, followed by maxillary width (MXW) and head depth (HDD) in that order. Spawners from Lady Pelly Lake had the largest mean orbital length of all groups (Fig. 31a), while those from Ferguson Lake, Mount Pelly Lake 1993 and Fish Trap Lake had the smallest mean orbital length. Analysis of variance (ANOVA) revealed significant differences ($p < 0.01$) in mean orbital length between some groups. A Least Significant Difference (LSD) test provided probabilities for differences between all pairs of means (Table 11).

Spawners from Lady Pelly, Ferguson and Halovik (1987) lakes had the greatest maxillary width of all groups (Fig. 31b) while those from Mount Pelly Lake 1993 and Anderson Bay Lake 1993 had the smallest maxillary width. Significant differences (ANOVA, $p < 0.01$) in mean maxillary width existed between some groups across the study area (Table 12).

Spawners from Lady Pelly Lake and Anderson Bay Lake 1993 had the greatest head depth of all groups (Fig. 31c), while those from Kitiga Lake, Mount Pelly Lake 1992 and 1993 had the smallest head depth. Significant differences in mean head depth (ANCOVA, $p < 0.01$) existed between some groups (Table 13) across the study area.

The dendrogram (Fig. 32), based on Squared Mahalanobis Distances (D^2) calculated from the discriminant function analysis of all twelve samples of spawners from across the study area (Table 14), reveals similarities among them. The samples from Char Lake and Wishbone Lake appear to be the most similar to one another. The samples from Anderson Bay Lake 1993 and Ferguson Lake are distant from the first eight groups. Halovik Lake 1987 and Lady Pelly Lake samples, although distant from one another, appear to form a group of their own, quite distant from all other groups.

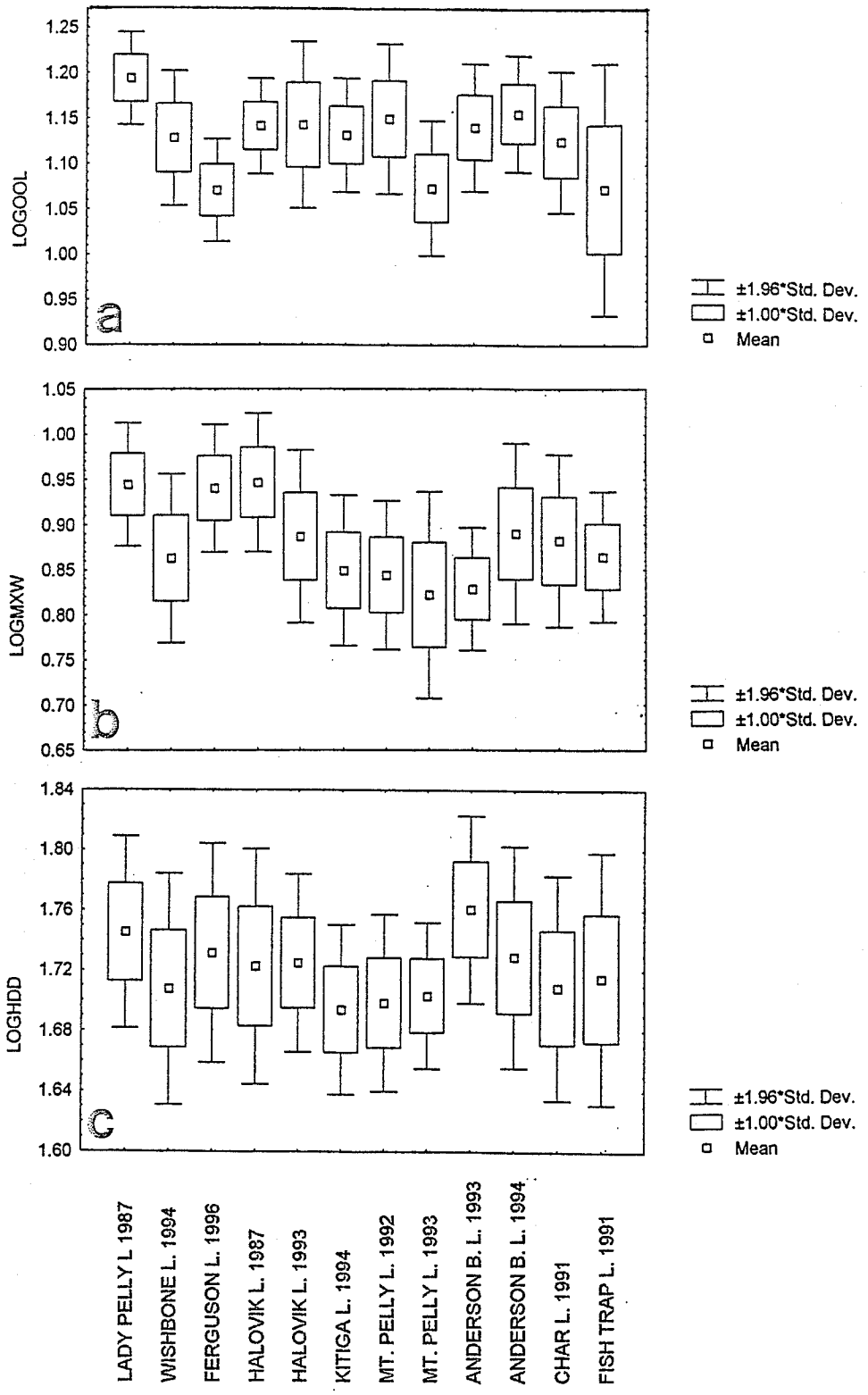

Figure 31. A comparison of mean log (a) orbital length (OOL), (b) maxillary width (MXW), and (c) head depth (HDD) among the twelve samples of Arctic char spawners examined across the study area.

Table 11. A comparison of all pairs of means for the morphometric measurement log orbital length (OOL) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable LOGOOL Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} 1.193761	{2} 1.127801	{3} 1.070281	{4} 1.141002	{5} 1.142525	{6} 1.131470
LADY PELLY L. [1]		.000000*	0.000000*	.000010*	.000000*	.000000*
WISHBONE L. [2]	.000000*		.000000*	.256471	.041352*	.693813
FERGUSON L. [3]	0.000000*	.000000*		.000000*	.000000*	.000000*
HALOVIK L. 87 [4]	.000010*	.256471	.000000*		.897167	.469822
HALOVIK L. 93 [5]	.000000*	.041352*	.000000*	.897167		.245687
KITIGA L. [6]	.000000*	.693813	.000000*	.469822	.245687	
MT. PELLY L. 92 [7]	.000000*	.004299*	.000000*	.481694	.374252	.066562
MT. PELLY L. 93 [8]	.000000*	.000015*	.815046	.000017*	.000000*	.000036*
ANDERS. B. L. 93 [9]	.000000*	.121813	.000000*	.988658	.843583	.371276
ANDERS. B. L. 94 [10]	.000044*	.000900*	.000000*	.213784	.107795	.017917*
CHAR L. [11]	.000000*	.805337	.000000*	.208165	.031799*	.570635
FISH TRAP L. [12]	.000000*	.000015*	.820907	.000017*	.000000*	.000035*

STAT. GENERAL MANOVA	LSD test; variable LOGOOL Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} 1.149444	{8} 1.073270	{9} 1.140824	{10} 1.156872	{11} 1.125965	{12} 1.073174
LADY PELLY L. [1]	.000000*	.000000*	.000000*	.000044*	.000000*	.000000*
WISHBONE L. [2]	.004299*	.000015*	.121813	.000900*	.805337	.000015*
FERGUSON L. [3]	.000000*	.815046	.000000*	.000000*	.000000*	.820907
HALOVIK L. 87 [4]	.481694	.000017*	.988658	.213784	.208165	.000017*
HALOVIK L. 93 [5]	.374252	.000000*	.843583	.107795	.031799*	.000000*
KITIGA L. [6]	.066562	.000036*	.371276	.017917*	.570635	.000035*
MT. PELLY L. 92 [7]		.000000*	.333577	.418935	.003559*	.000000*
MT. PELLY L. 93 [8]	.000000*		.000001*	.000000*	.000043*	.995252
ANDERS. B. L. 93 [9]	.333577	.000001*		.105811	.092989	.000001*
ANDERS. B. L. 94 [10]	.418935	.000000*	.105811		.000753*	.000000*
CHAR L. [11]	.003559*	.000043*	.092989	.000753*		.000042*
FISH TRAP L. [12]	.000000*	.995252	.000001*	.000000*	.000042*	

Table 12. A comparison of all pairs of means for the morphometric measurement log maxillary width (MXW) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable LOGMXW Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} .9441499	{2} .8626874	{3} .9400857	{4} .9465106	{5} .8866708	{6} .8491483
LADY PELLY L. [1]		.000000*	.648941	.861795	.000000*	.000000*
WISHBONE L. [2]	.000000*		.000000*	.000000*	.003910*	.206353
FERGUSON L. [3]	.648941	.000000*		.640178	.000000*	.000000*
HALOVIK L. 87 [4]	.861795	.000000*	.640178		.000012*	.000000*
HALOVIK L. 93 [5]	.000000*	.003910*	.000000*	.000012*		.000653*
KITIGA L. [6]	.000000*	.206353	.000000*	.000000*	.000653*	
MT. PELLY L. 92 [7]	.000000*	.032450*	.000000*	.000000*	.000003*	.653531
MT. PELLY L. 93 [8]	.000000*	.004748*	.000000*	.000000*	.000010*	.091086
ANDERS. B. L. 93 [9]	.000000*	.000467*	.000000*	.000000*	.000000*	.088500
ANDERS. B. L. 94 [10]	.000000*	.006473*	.000003*	.000132*	.744052	.000951*
CHAR L. [11]	.000000*	.024912*	.000000*	.000003*	.591604	.003438*
FISH TRAP L. [12]	.000000*	.913944	.000000*	.000006*	.121937	.345998

STAT. GENERAL MANOVA	LSD test; variable LOGMXW Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} .8441069	{8} .8220657	{9} .8286521	{10} .8900113	{11} .8819304	{12} .8642344
LADY PELLY L. [1]	.000000*	.000000*	.000000*	.000000*	.000000*	.000000*
WISHBONE L. [2]	.032450*	.004748*	.000467*	.006473*	.024912*	.913944
FERGUSON L. [3]	.000000*	.000000*	.000000*	.000003*	.000000*	.000000*
HALOVIK L. 87 [4]	.000000*	.000000*	.000000*	.000132*	.000003*	.000006*
HALOVIK L. 93 [5]	.000003*	.000010*	.000000*	.744052	.591604	.121937
KITIGA L. [6]	.653531	.091086	.088500	.000951*	.003438*	.345998
MT. PELLY L. 92 [7]		.134645	.131559	.000017*	.000048*	.171797
MT. PELLY L. 93 [8]	.134645		.667234	.000015*	.000052*	.023901*
ANDERS. B. L. 93 [9]	.131559	.667234		.000000*	.000000*	.020596*
ANDERS. B. L. 94 [10]	.000017*	.000015*	.000000*		.440019	.097536
CHAR L. [11]	.000048*	.000052*	.000000*	.440019		.227453
FISH TRAP L. [12]	.171797	.023901*	.020596*	.097536	.227453	

Table 13. A comparison of all pairs of means for the morphometric measurement log head depth (HDD) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable LOGHDD Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} 1.745176	{2} 1.707508	{3} 1.731475	{4} 1.722535	{5} 1.724842	{6} 1.693907
LADY PELLY L. [1]		.000000*	.053730	.035952*	.003060*	.000000*
WISHBONE L. [2]	.000000*		.000499*	.156811	.008559*	.110021
FERGUSON L. [3]	.053730	.000499*		.412739	.347399	.000029*
HALOVIK L. 87 [4]	.035952*	.156811	.412739		.829950	.017652*
HALOVIK L. 93 [5]	.003060*	.008559*	.347399	.829950		.000404*
KITIGA L. [6]	.000000*	.110021	.000029*	.017652*	.000404*	
MT. PELLY L. 92 [7]	.000000*	.187421	.000009*	.028021*	.000225*	.611756
MT. PELLY L. 93 [8]	.000300*	.703917	.015592*	.173404	.060249	.465074
ANDERS. B. L. 93 [9]	.049352*	.000000*	.000334*	.000923*	.000007*	.000000*
ANDERS. B. L. 94 [10]	.048764*	.006777*	.773783	.573762	.602117	.000346*
CHAR L. [11]	.000000*	.865642	.001797*	.202710	.021433*	.096091
FISH TRAP L. [12]	.008559*	.523419	.152057	.584006	.380877	.101190

STAT. GENERAL MANOVA	LSD test; variable LOGHDD Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} 1.698433	{8} 1.703189	{9} 1.760723	{10} 1.729077	{11} 1.708657	{12} 1.714761
LADY PELLY L. [1]	.000000*	.000300*	.049352*	.048764*	.000000*	.008559*
WISHBONE L. [2]	.187421	.703917	.000000*	.006777*	.865642	.523419
FERGUSON L. [3]	.000009*	.015592*	.000334*	.773783	.001797*	.152057
HALOVIK L. 87 [4]	.028021*	.173404	.000923*	.573762	.202710	.584006
HALOVIK L. 93 [5]	.000225*	.060249	.000007*	.602117	.021433*	.380877
KITIGA L. [6]	.611756	.465074	.000000*	.000346*	.096091	.101190
MT. PELLY L. 92 [7]		.683890	.000000*	.000285*	.162212	.162624
MT. PELLY L. 93 [8]	.683890		.000003*	.036257*	.638250	.433633
ANDERS. B. L. 93 [9]	.000000*	.000003*		.000507*	.000000*	.000179*
ANDERS. B. L. 94 [10]	.000285*	.036257*	.000507*		.014300*	.245980
CHAR L. [11]	.162212	.638250	.000000*	.014300*		.599705
FISH TRAP L. [12]	.162624	.433633	.000179*	.245980	.599705	

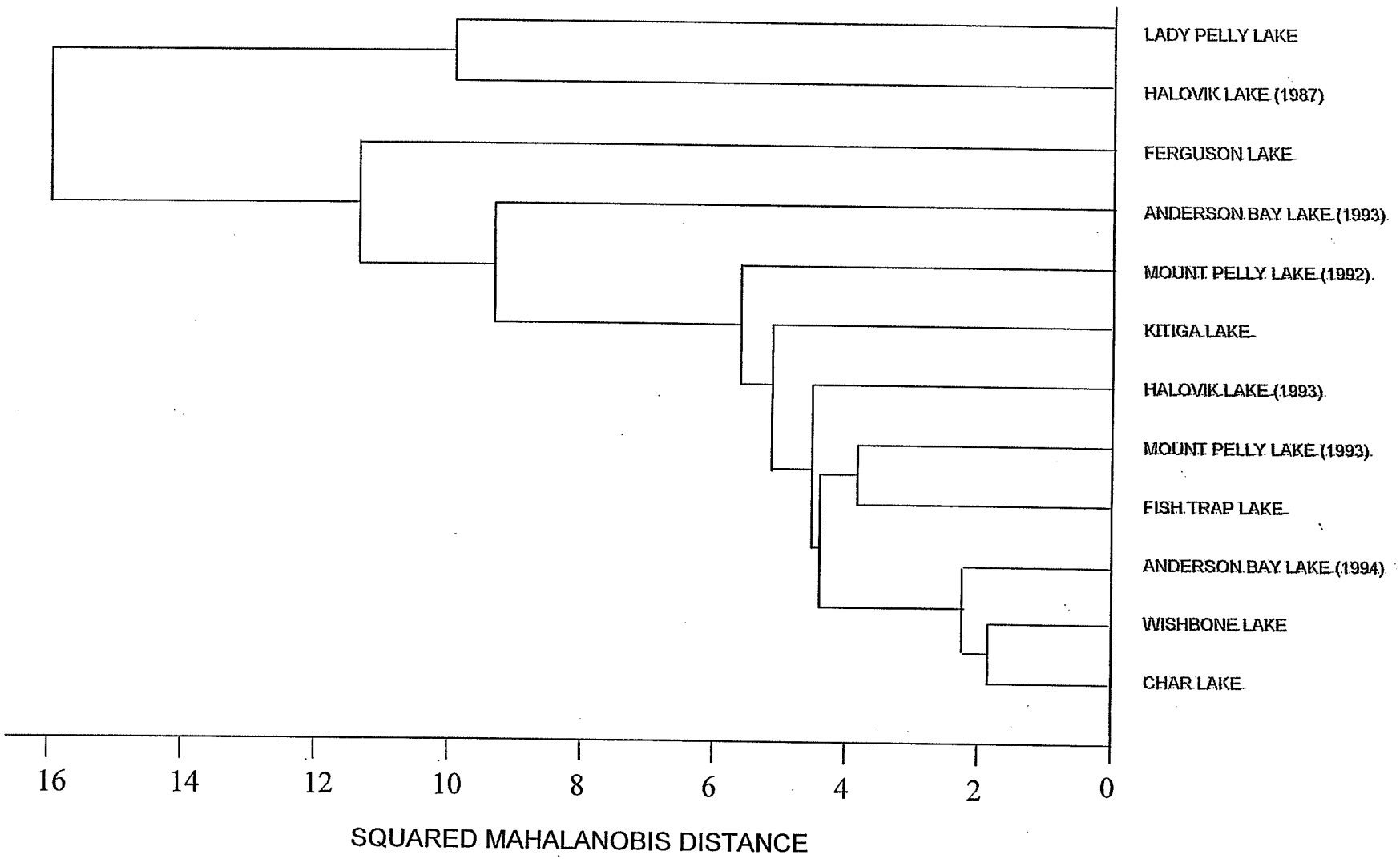

Figure 32. A dendrogram of Squared Mahalanobis Distances showing morphological relationships among the samples of Arctic char spawners examined.

Table 14. A comparison of Squared Mahalanobis Distances among the twelve samples of Arctic char spawners examined across the study area.

STAT. DISCRIM. ANALYSIS	Squared Mahalanobis Distances								
GROUP	LADY PELLY L	WISHBONE L	FERGUSON L	HALOVIK L 93	HALOVIK L 87	KITIGA L	MT PELLY L 92	MT PELLY L 93	ANDER.B L 93
LADY PELLY L	0.00000	16.69256	17.28539	14.22091	10.05363	23.27652	16.65691	25.35519	19.97432
WISHBONE L	16.69256	0.00000	11.49273	2.88604	15.84033	4.77493	5.57417	5.59719	9.60125
FERGUSON L	17.28539	11.49273	0.00000	12.32170	15.88546	18.06606	18.01483	13.00419	27.09344
HALOVIK L 93	14.22091	2.88604	12.32170	0.00000	11.29992	7.77827	7.36378	11.55359	11.10287
HALOVIK L 87	10.05363	15.84033	15.88546	11.29992	0.00000	17.72115	20.15940	20.83342	18.18811
KITIGA L	23.27652	4.77493	18.06606	7.77827	17.72115	0.00000	11.47294	10.24306	14.59668
MT PELLY L 92	16.65691	5.57417	18.01483	7.36378	20.15940	11.47294	0.00000	7.03996	12.16521
MT PELLY L 93	25.35519	5.59719	13.00419	11.55359	20.83342	10.24306	7.03996	0.00000	10.50451
ANDER.B L 93	19.97432	9.60125	27.09344	11.10287	18.18811	14.59668	12.16521	10.50451	0.00000
ANDER.B L 94	15.45816	3.07086	16.61037	7.05201	20.64503	11.67989	6.38341	9.82706	9.51104
CHAR L	14.03767	1.83869	12.22598	4.41722	14.79436	9.80712	5.15338	6.36813	9.27134
FISH TRAP L	23.56573	4.30436	10.93082	5.71799	14.80188	8.67531	8.79704	3.86582	10.07770

STAT. DISCRIM. ANALYSIS	Squared Mahalanobis Distances		
GROUP	ANDER.B L 94	CHAR L	FISH TRAP L
LADY PELLY L	15.45816	14.03767	23.56573
WISHBONE L	3.07086	1.83869	4.30436
FERGUSON L	16.61037	12.22598	10.93082
HALOVIK L 93	7.05201	4.41722	5.71799
HALOVIK L 87	20.64503	14.79436	14.80188
KITIGA L	11.67989	9.80712	8.67531
MT PELLY L 92	6.38341	5.15338	8.79704
MT PELLY L 93	9.82706	6.36813	3.86582
ANDER.B L 93	9.51104	9.27134	10.07770
ANDER.B L 94	0.00000	2.15584	9.28261
CHAR L	2.15584	0.00000	4.37555
FISH TRAP L	9.28261	4.37555	0.00000

Examinations of Upstream Migrations

Cluster Analysis

Cluster analysis was performed on samples of Arctic char from thirteen upstream migrations (Table 15). Samples from two commercial fisheries were also examined in this way. The latter samples were taken from gillnets set along shore in July and captured char as they moved along shore feeding.

Cluster analysis begins by linking the most similar specimens and proceeds in a stepwise fashion, linking the next most similar cases until all specimens have been linked. Linkage distance (Euclidean in this case) provides a measure of similarity/dissimilarity of specimens and groups of specimens. The shorter the linkage distance, the more similar are the specimens and the greater the linkage distance between groups of specimens, the greater the dissimilarity of those groups. None of the specimens were identical with respect to morphometric measurements so all were considered as individuals in the first step. As the steps proceed, individuals that are similar to one another are grouped together and so on. All samples will contain a certain amount of intra-group variation and this will be reflected in various clusters formed during the analysis.

I was interested in examining these samples for evidence of group structure similar to that seen in the discriminant function analysis of spawners. Therefore, in order to establish a linkage distance that reflected inter-group rather than intra-group variation, I examined two known groups of spawners by this method. I used the samples of spawners from Lady Pelly Lake and Ferguson Lake that were clearly different from one another with respect to morphometric measurements (Fig. 15). The cluster analysis of these two groups (Fig.33) shows the separation of an apparent outlier (A) from the main

Table 15. Location and year of upstream migration of Arctic char examined by cluster analysis.

Location	Year
Ekalluk River	1988
Ekalluk River	1990
Ekalluk River	1991
Ekalluk River	1992
Ekalluk River	1993
Ekalluk River	1994
Halovik River	1992
Lauchlan River	1992
Lauchlan River	1996*
Paliryuak River	1992*
Freshwater Creek	1988
Freshwater Creek	1991
Freshwater Creek	1994
Jayco River	1990
Ellice River	1990

*Commercial fishery along shore

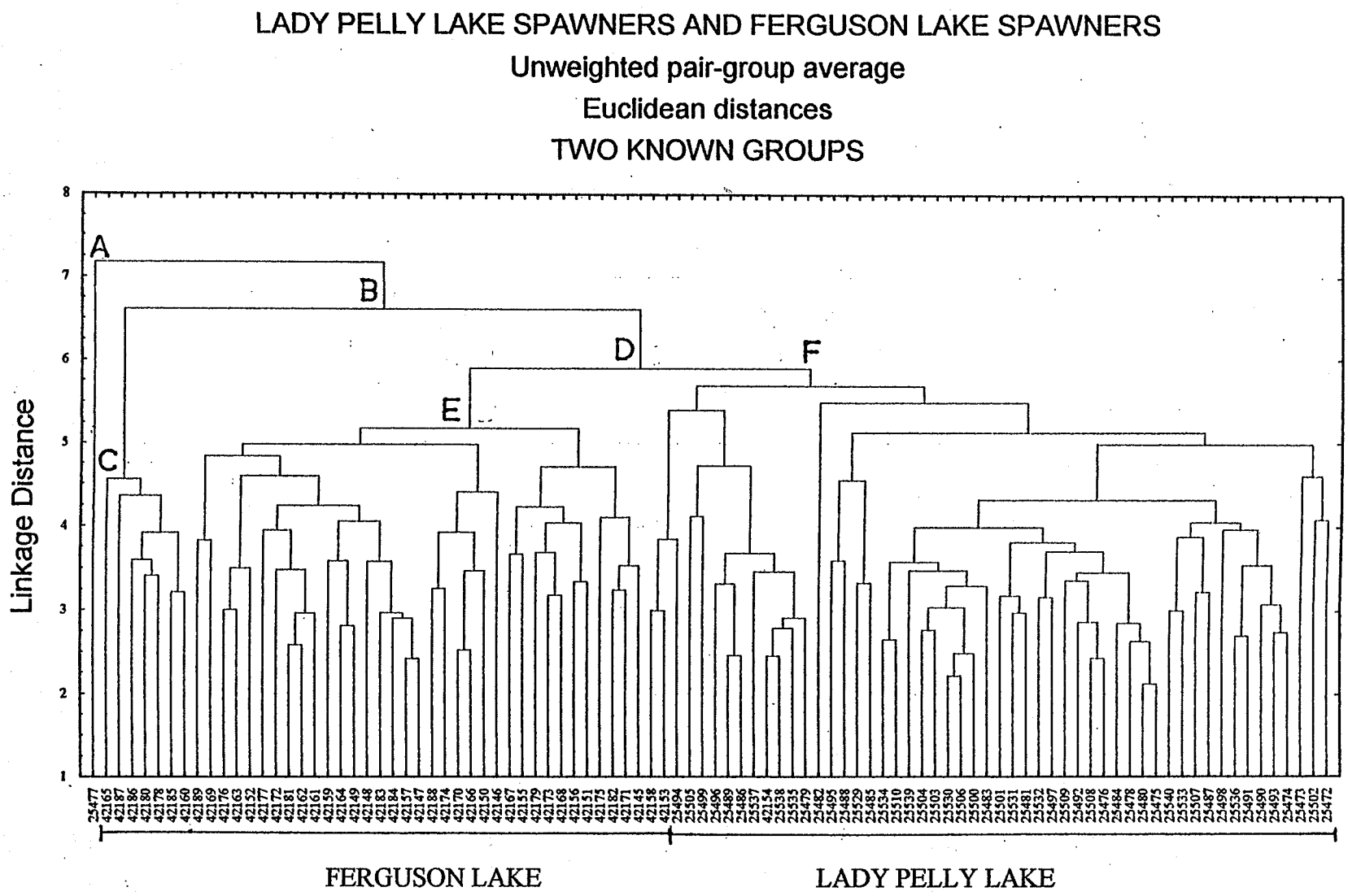

Figure 33. Cluster analysis of morphometric measurements from two known groups of spawners (Ferguson Lake and Lady Pelly Lake). Sample identification numbers along abscissa.

group (B) at a distance of about 7.2. Group B appears to separate into Groups C and D at a distance of about 6.6. Group D separates into groups E and F at a distance of about 5.8. Group E comprises most of the specimens from Ferguson Lake and Group F comprises all but 2 of the specimens from Lady Pelly Lake. I repeated this comparison with nine other pairs of known spawners from across the study area. Group separation was reached at an Euclidean distance of between 5 and 6 in all cases. I then used this range as a decision-making guide to decide whether group separation in samples of upstream migrants was likely due to inter- or intra-group variation.

The cluster analysis of the 1988 upstream migration of Arctic char in the Ekalluk River reveals a distinct separation of two specimens at cluster A from the remainder of the cluster B at a distance greater than 8 (Fig. 34). Cluster B separates into Cluster C and D at a distance of about 6.5. Cluster D separates into Clusters E and F at a distance of about 5.7. A further separation of cluster E into clusters G and H occurs at a distance of about 5.5. A conservative interpretation is to consider that Group D represents group structure. Cluster D comprises the majority of the sample. On this basis, a DFA with this sample as one group, and the samples of Ekalluk River spawners from Lady Pelly, Ferguson and Wishbone lakes was carried out (Fig. 35). The 1988 upstream migrants appear as a separate group. Chi-square tests with successive roots removed (0,1,2) were significant ($p < 0.001$). Variables contributing most to the discrimination were orbital length (OOL), gill raker length (GRL) and maxillary width (MXW) in that order (Table 16). The Ekalluk River 1988 nonspawners appear to have longer gill rakers (Fig 36a) and a shorter maxillary width (Fig 36b) than the three groups of spawners. They appear to

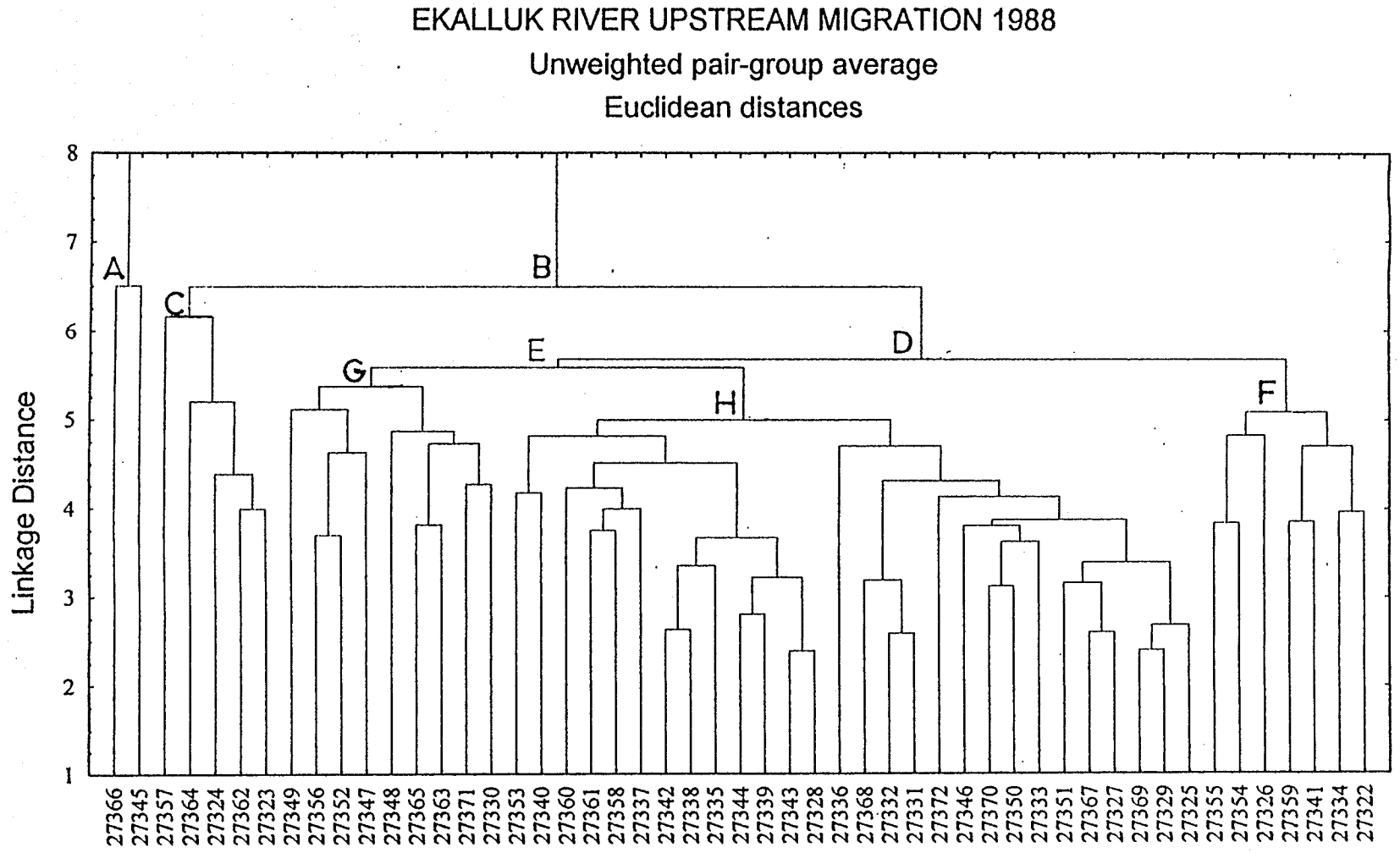

Figure 34. Cluster analysis of morphometric measurements of Arctic char in the 1988 upstream migration in the Ekalluk River. Cluster D is considered to represent a group in this analysis but clusters F, G and H could possibly represent separate groups as well. Sample identification number along abcissa.

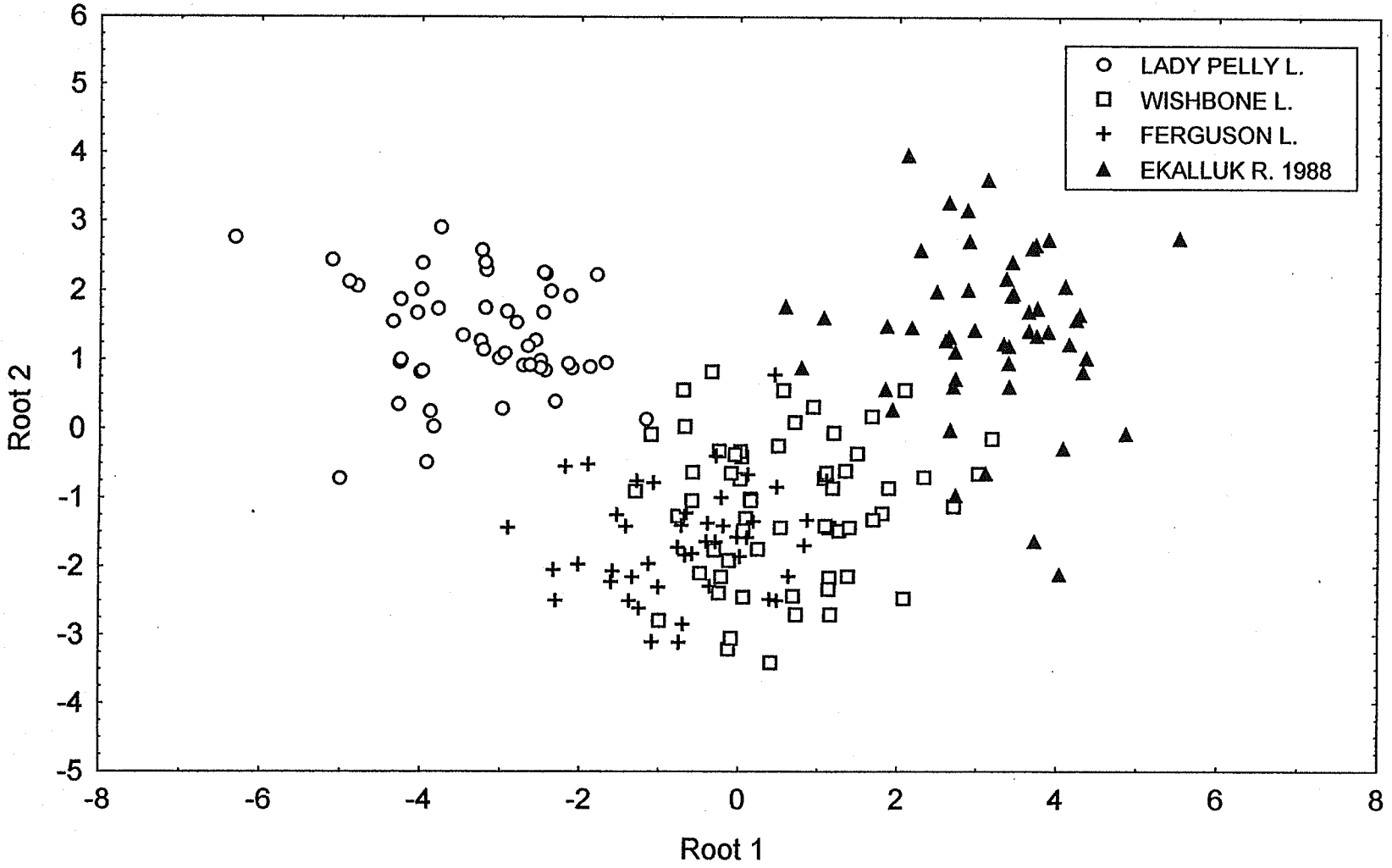

Figure 35. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1988 upstream migration in the Ekalluk River.

Table 16. Summary of the discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and a sample of nonspawning Arctic char from the 1988 upstream migration in the Ekalluk River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 13, N of vars in model: 13; Grouping: GROUP (4 grps) Wilks' Lambda: .02217 approx. F (39,566)=38.040 p<0.0000					
N=207	Wilks' Lambda	Partial Lambda	F-remove (3,191)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGMXW	.033339	.664900	32.08704	.000000	.837098	.162902
LOGOOL	.039466	.561682	49.68328	.000000	.857997	.142003
LOGGRL	.034502	.642489	35.42709	.000000	.893044	.106956
LOGPCL	.026281	.843482	11.81407	.000000	.699757	.300243
LOGLAL	.026196	.846221	11.56979	.000001	.718523	.281477
LOGCPL	.026345	.841433	11.99791	.000000	.784229	.215771
LOGBDD	.026521	.835828	12.50528	.000000	.625622	.374378
LOGCPD	.026862	.825234	13.48313	.000000	.506588	.493412
LOGANL	.025617	.865338	9.90771	.000004	.679336	.320664
LOGLUL	.026231	.845076	11.67169	.000000	.657879	.342121
LOGTTL	.025943	.854445	10.84560	.000001	.614433	.385567
LOGDOL	.025302	.876110	9.00303	.000013	.678028	.321972
LOGIOW	.024209	.915648	5.86511	.000750	.574546	.425454

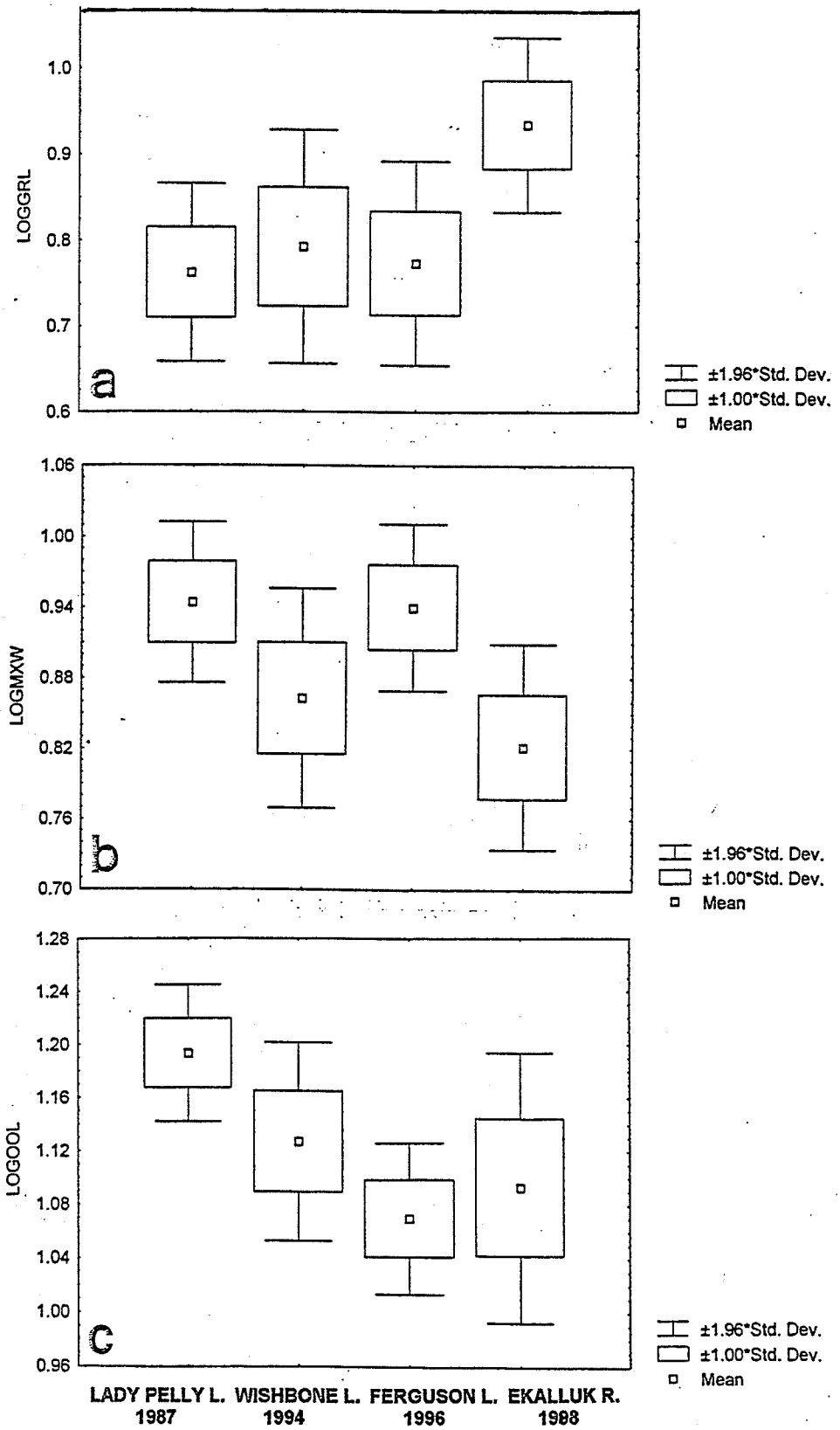

Figure 36. A comparison of mean log (a) gill raker length (GRL), (b) maxillary width (MXW), and (c) orbital length (OOL) among samples from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1988 upstream migration in the Ekalluk River.

have a small orbital length, similar to the spawners from Ferguson Lake (Fig 36c). A comparison of maxillary width and gill raker length between samples is shown in Fig. 37.

The sample from the 1990 Ekalluk River upstream migration appears to be comprised of one main group (Fig. 38), cluster G, separated from a number of individuals at a distance of about 5.7. Further separation at a distance less than this could represent intra- rather than inter-group variation. Cluster G comprises the majority of specimens in the sample therefore it was included in a DFA with the three groups of Ekalluk River spawners (Fig. 39). The Ekalluk River 1990 upstream migrants appear to be most similar to the spawners from Wishbone Lake.

The cluster analysis of the sample from the 1991 Ekalluk River upstream migration reveals a number of possible outliers and one main group separated at a distance of about 5.8 (Fig. 40). Group F comprises the majority of specimens in the sample. It was therefore compared with the samples from the Ekalluk River spawning aggregations from Ferguson, Lady Pelly and Wishbone lakes by DFA (Fig. 41). The 1991 Ekalluk River upstream migrants appear to be similar to the Wishbone Lake spawners.

Cluster analysis of the sample from the 1992 Ekalluk River upstream migration appears to be quite heterogeneous and separates into six clusters at a distance of 5.2 or greater (Fig. 42). Cluster J appears to be the main cluster with clusters C, F, I, H and B as outliers. Cluster separation at a distance less than this is likely to represent intra-group variation. Therefore, I did not consider cluster separation at a distance less than this as representative of group structure for that reason. This sample was then compared with the three Ekalluk River spawning aggregations that were taken in Lady Pelly, Wishbone and

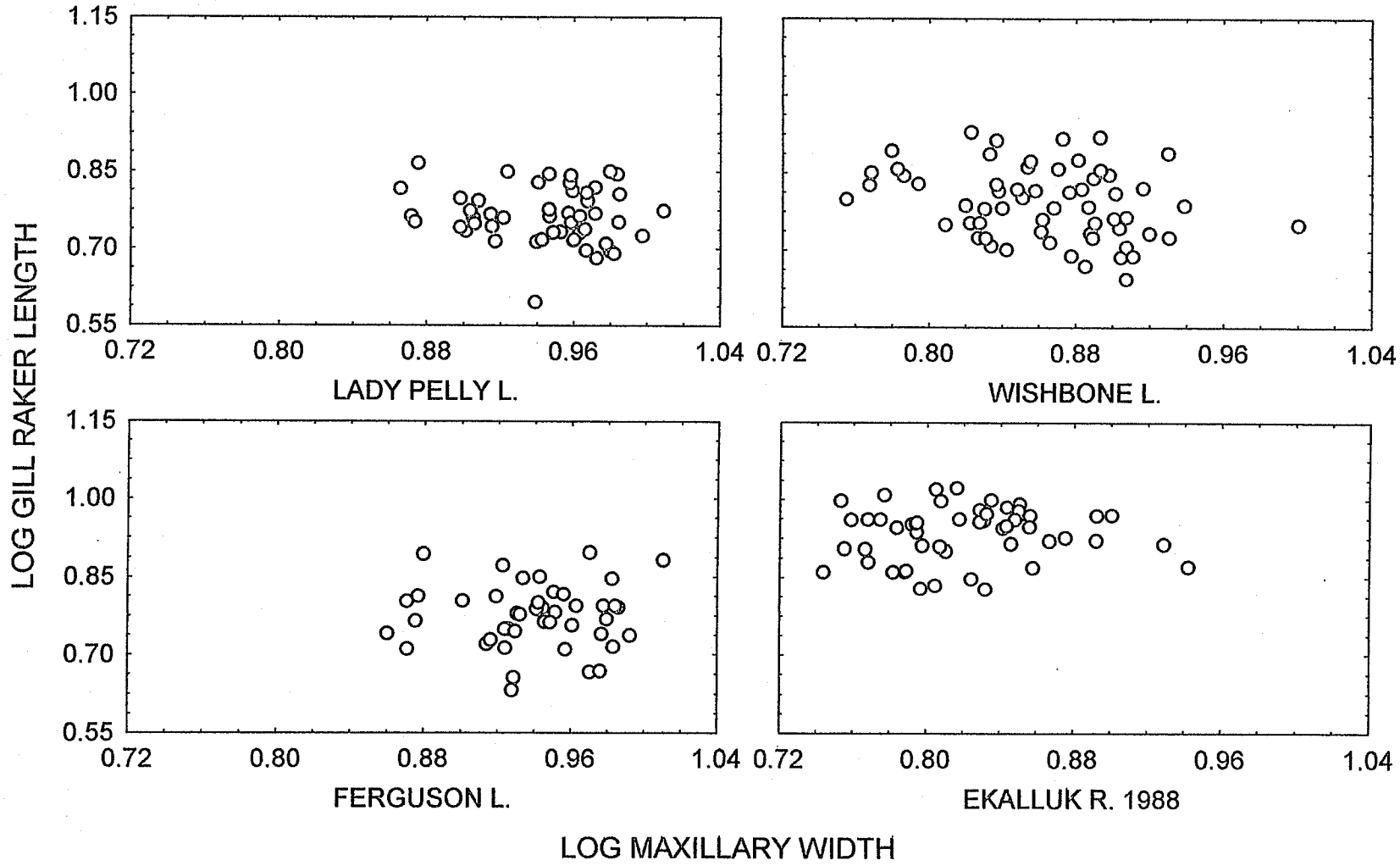

Figure 37. A plot of log maxillary width (MXW) against log gill raker length (GRL) for Arctic char spawners from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1988 upstream migration in the Ekalluk River.

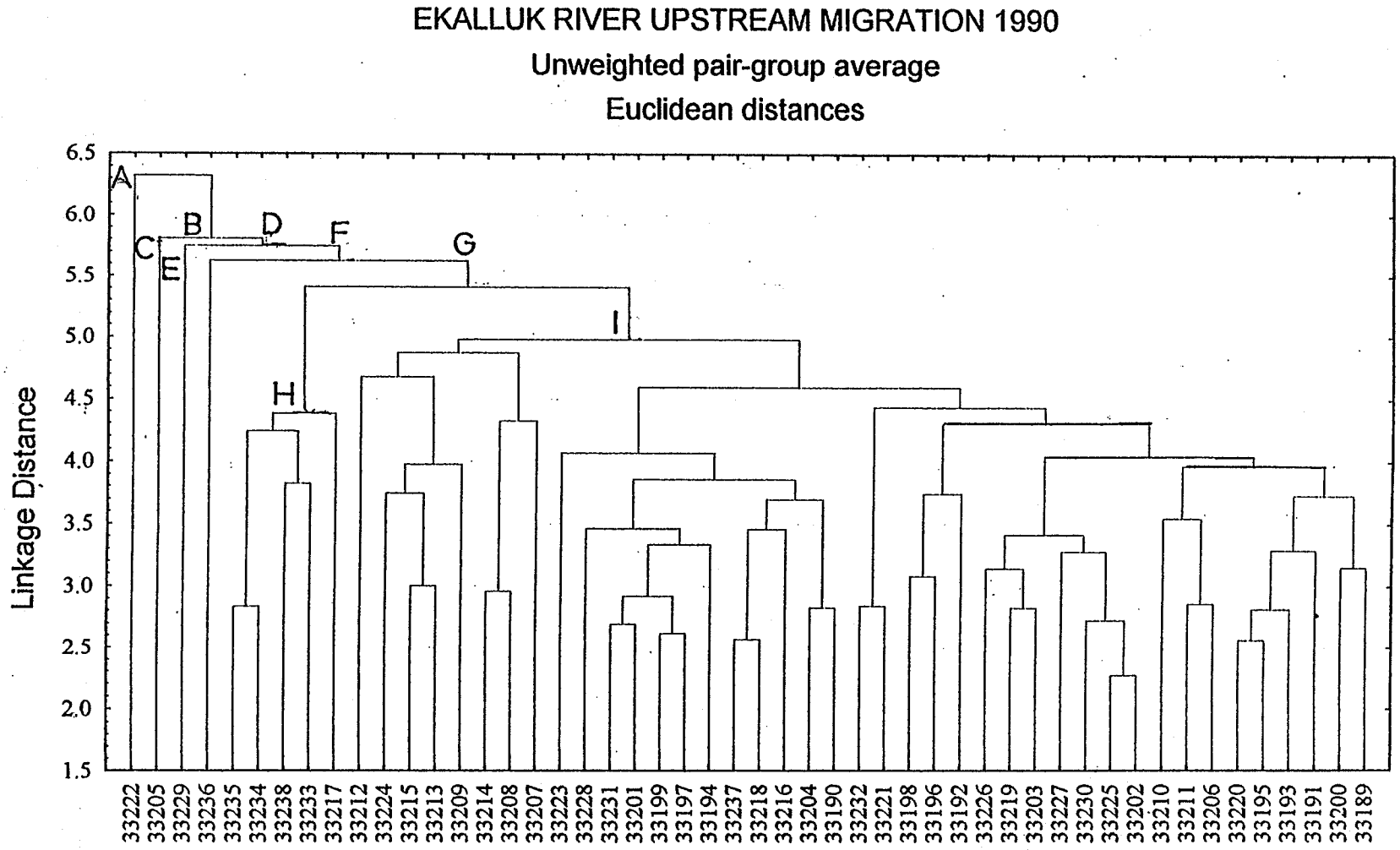

Figure 38. Cluster analysis of morphometric measurements of Arctic char from the 1990 upstream migration in the Ekalluk River. Cluster G is considered to represent a group in this analysis. Sample identification number along abscissa.

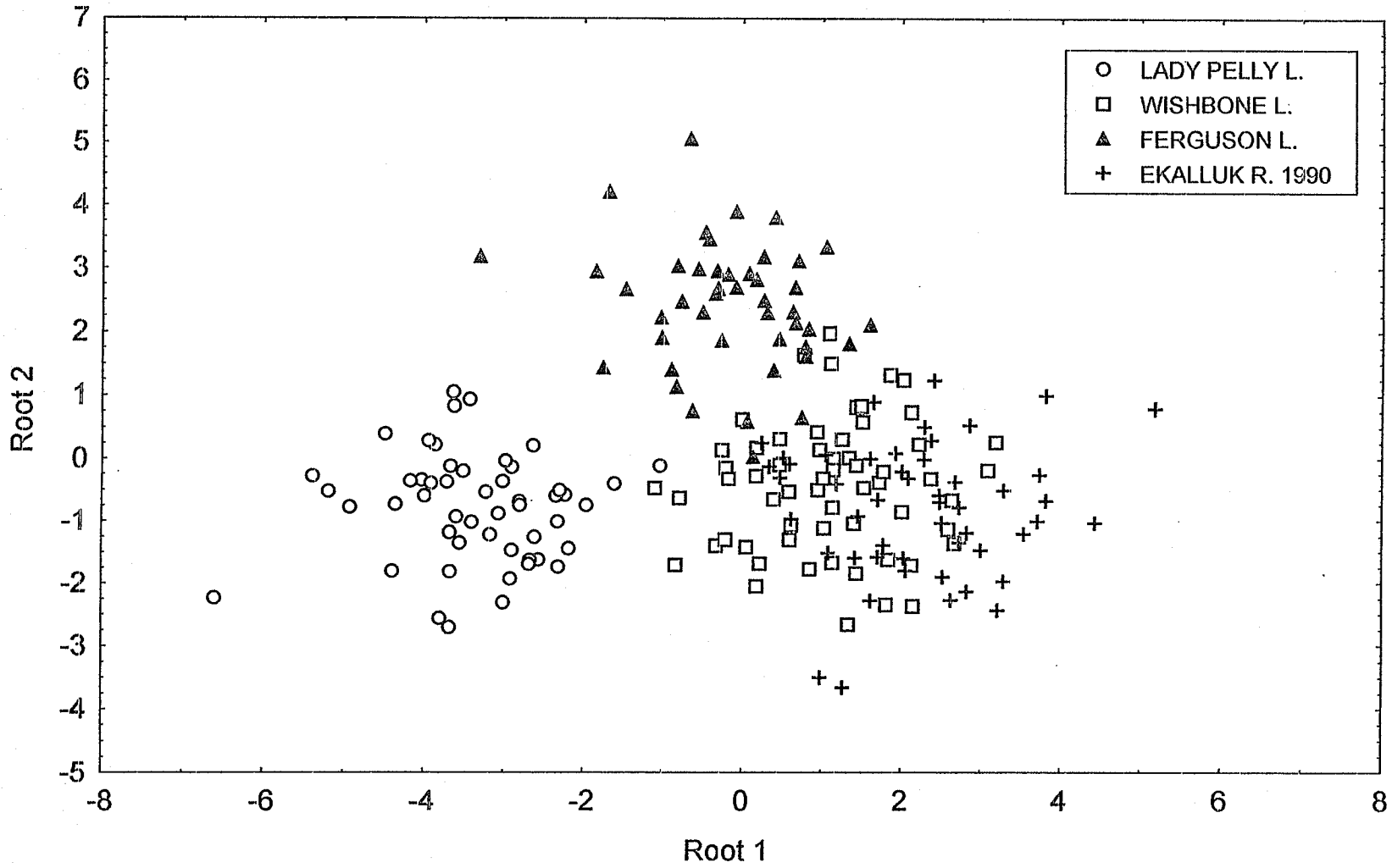

Figure 39. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1990 upstream migration in the Ekalluk River.

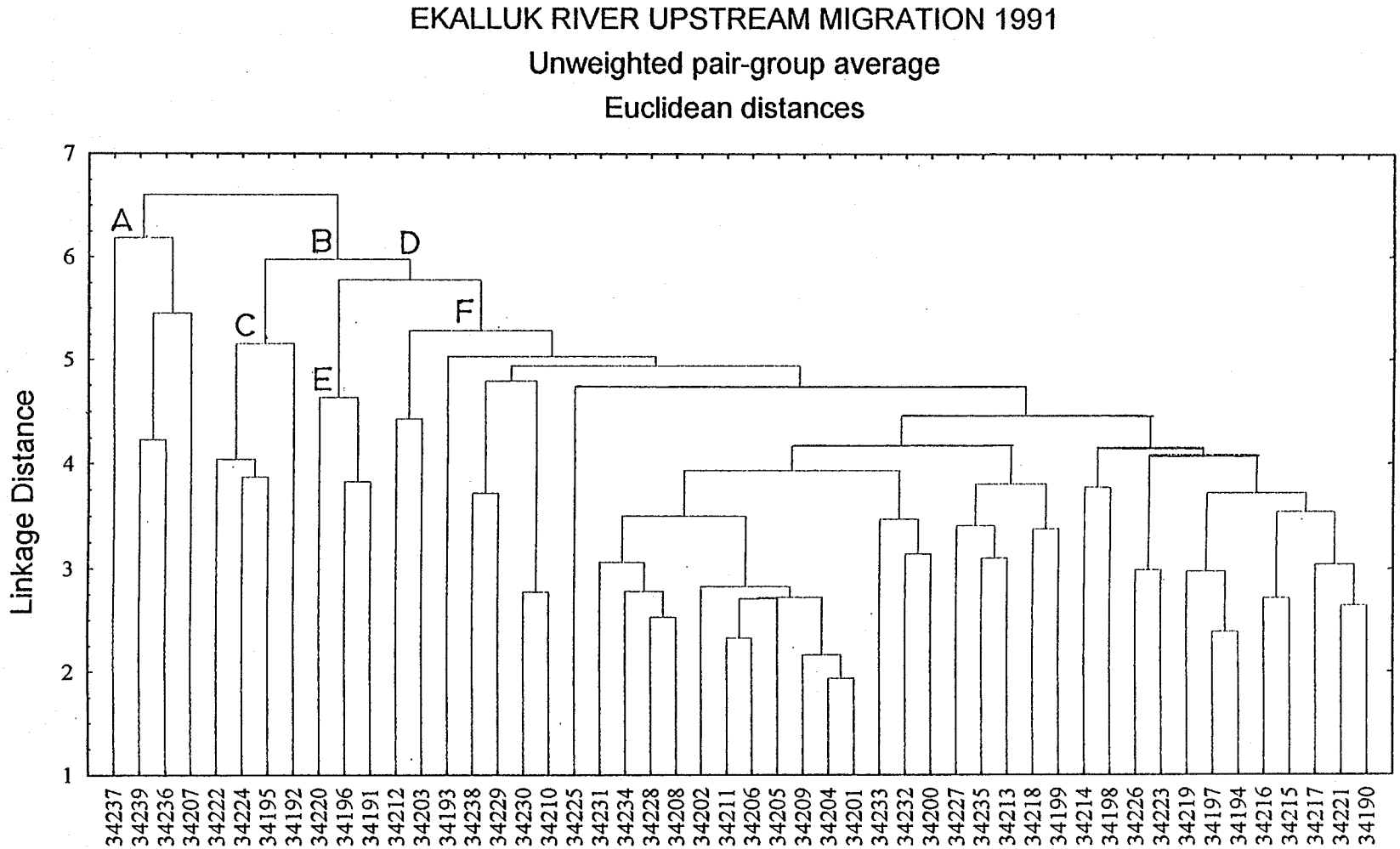

Figure 40. Cluster analysis of morphometric measurements of Arctic char from the 1991 upstream migration in the Ekalluk River. Cluster F is considered to represent a group in this analysis. Sample identification number along abscissa.

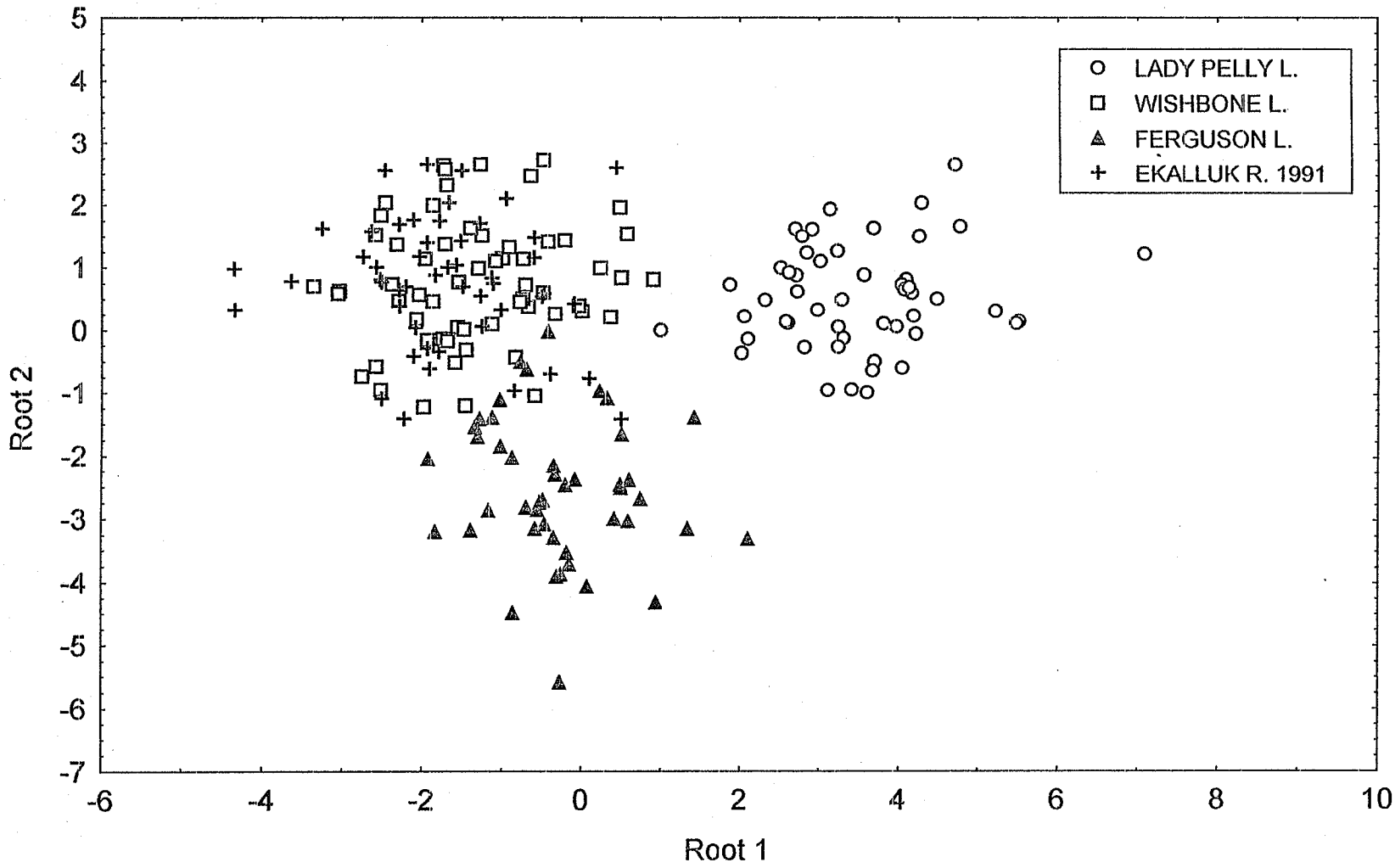

Figure 41. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1991 upstream migration in the Ekalluk River.

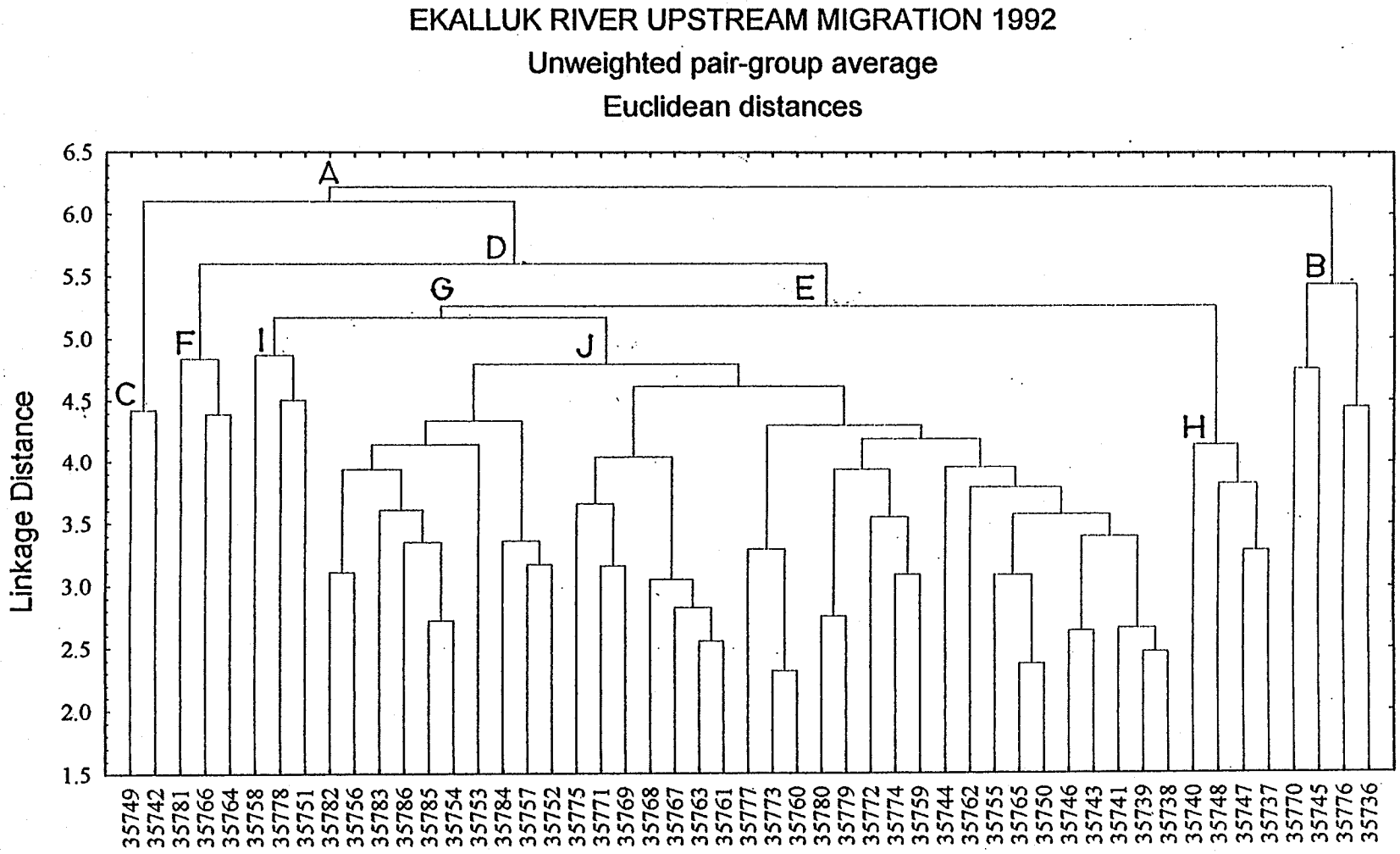

Figure 42. Cluster analysis of morphometric measurements of Arctic char from the 1992 upstream migration in the Ekalluk River. Cluster J is considered to represent a group in this analysis. Sample identification number along abscissa.

Ferguson lakes by DFA (Fig. 43). It appears to be most similar to the sample from Wishbone Lake, but group centroids differ.

Cluster analysis of the sample from the Ekalluk River 1993 upstream migration reveals a number of individuals or pairs that separate from a main group at a distance of about 5.8 (Fig. 44). Cluster A, C and E appear to be distinct from cluster F, which comprises the majority of the sample. This sample was then compared with the spawners from Lady Pelly, Ferguson and Wishbone lakes by DFA (Fig. 45). The results indicate that the Ekalluk River 1993 sample is most similar in morphology to that from Wishbone Lake, although a small number of specimens appear to resemble those from Ferguson Lake.

The sample from the 1994 upstream migration in the Ekalluk River appears to be comprised of one main group and a number of outliers as shown by the cluster analysis (Fig. 46). Cluster F separates from clusters A, C, and E at distances greater than 6.5. Further separation of cluster F takes place at a distance of about 5.3. This distance is close to the lower level observed in the separation of groups of known spawners, therefore, cluster F was considered to be representative of group structure. It comprises most of the sample and was compared with the spawning aggregations from Lady Pelly, Ferguson and Wishbone lakes by DFA (Fig. 47). In the discriminant function analysis, the sample from the 1994 Ekalluk River upstream migration appears to be a distinct group, but appears to be most similar to the sample from Wishbone Lake. A summary of the DFA analysis is presented in Table 17. All Chi-square values for successive roots removed (0,1,2) were significant ($p < 0.001$). Morphometric measurements that

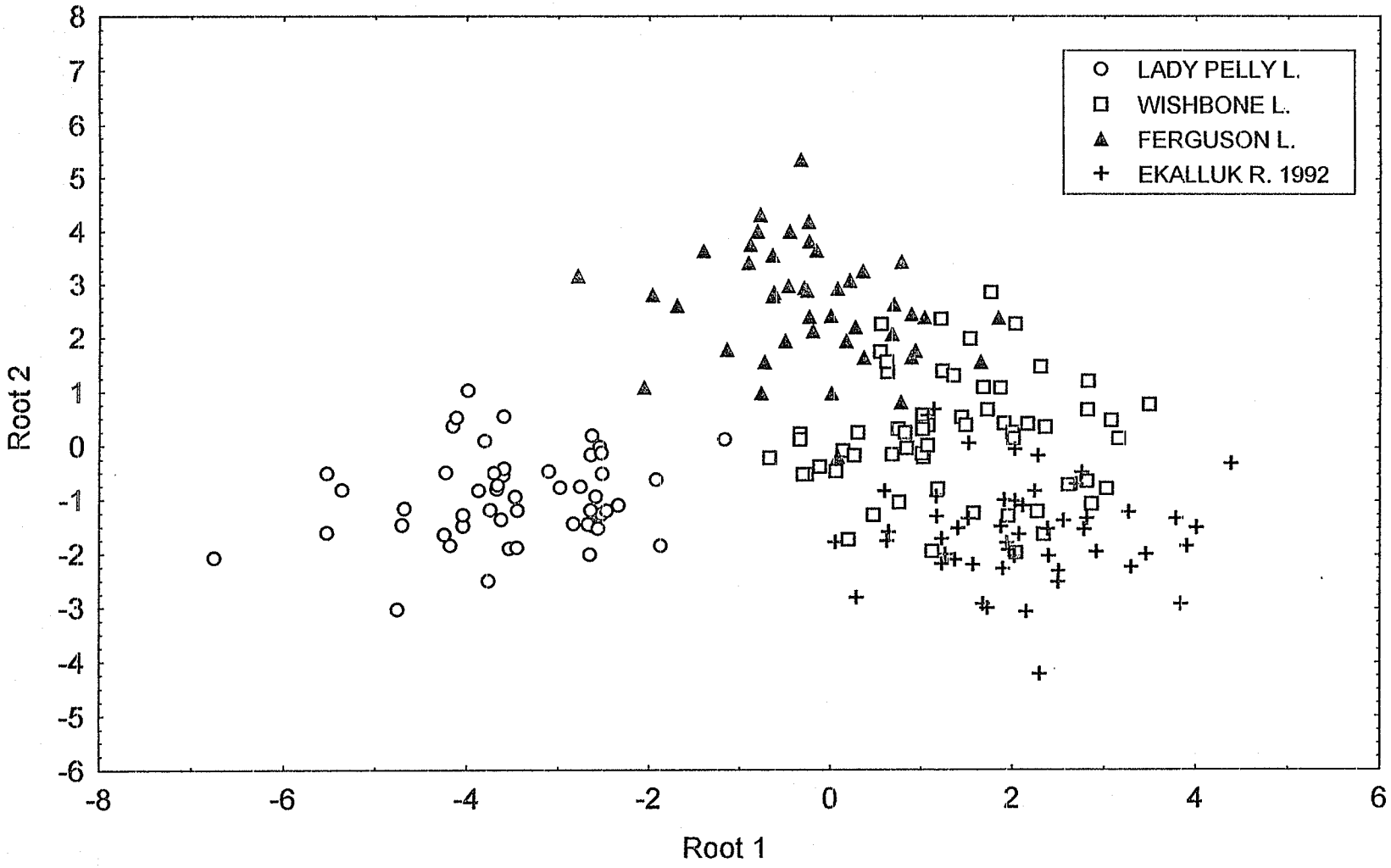

Figure 43. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1992 upstream migration in the Ekalluk River.

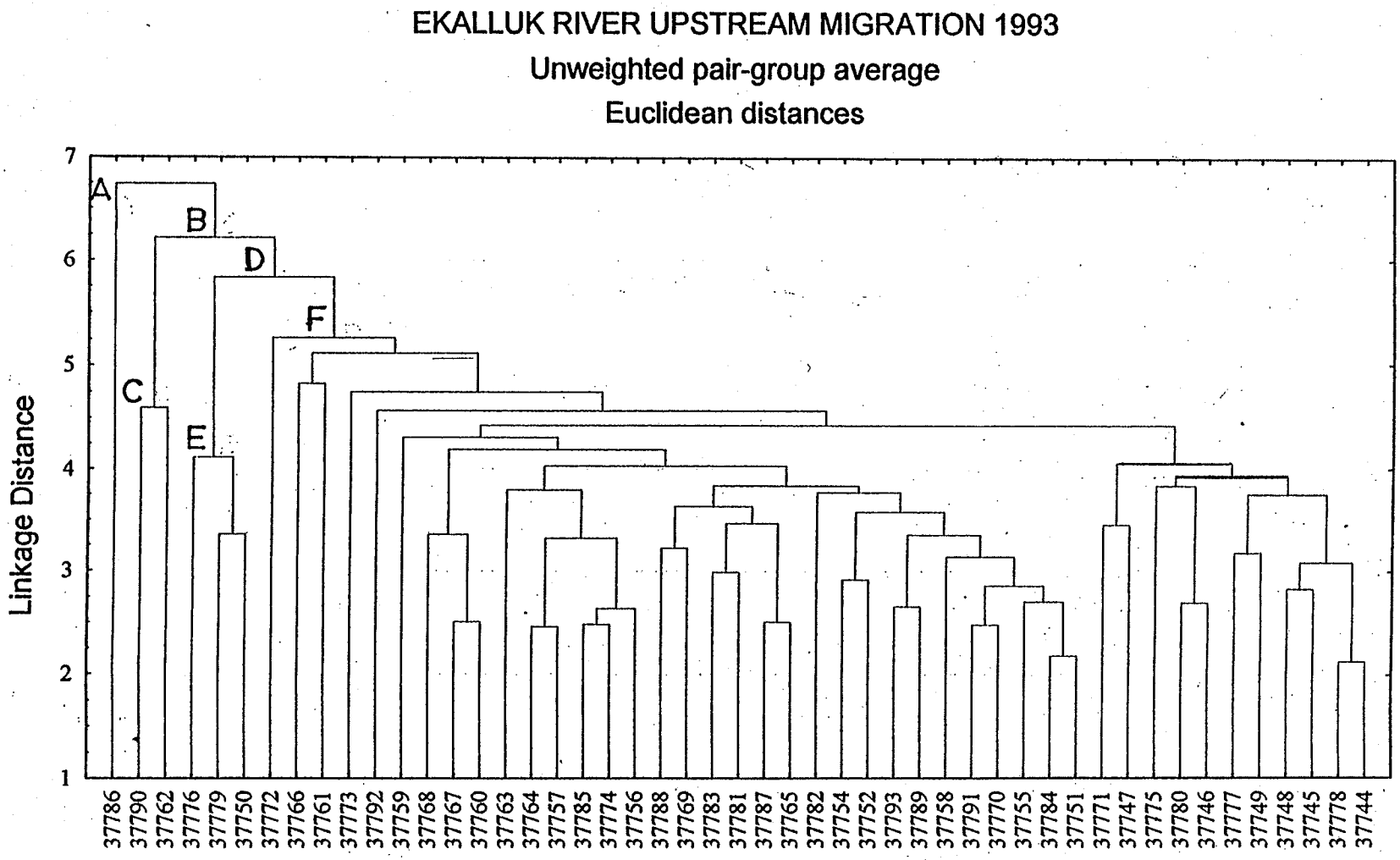

Figure 44. Cluster analysis of morphometric measurements of Arctic char in the 1993 upstream migration in the Ekalluk River. Cluster F is considered to represent a group in this analysis. Sample identification number along abscissa.

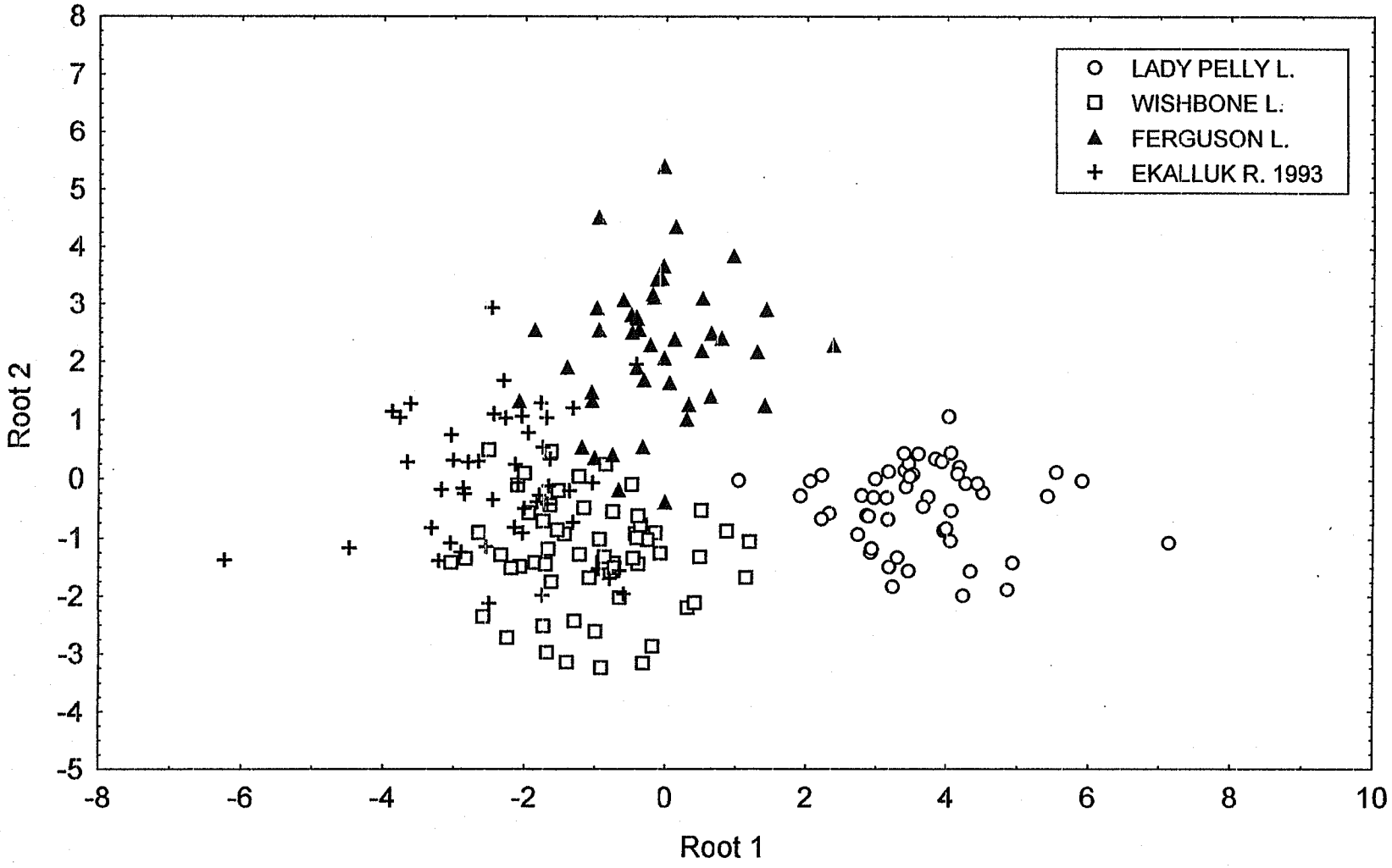

Figure 45. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1993 upstream migration in the Ekalluk River.

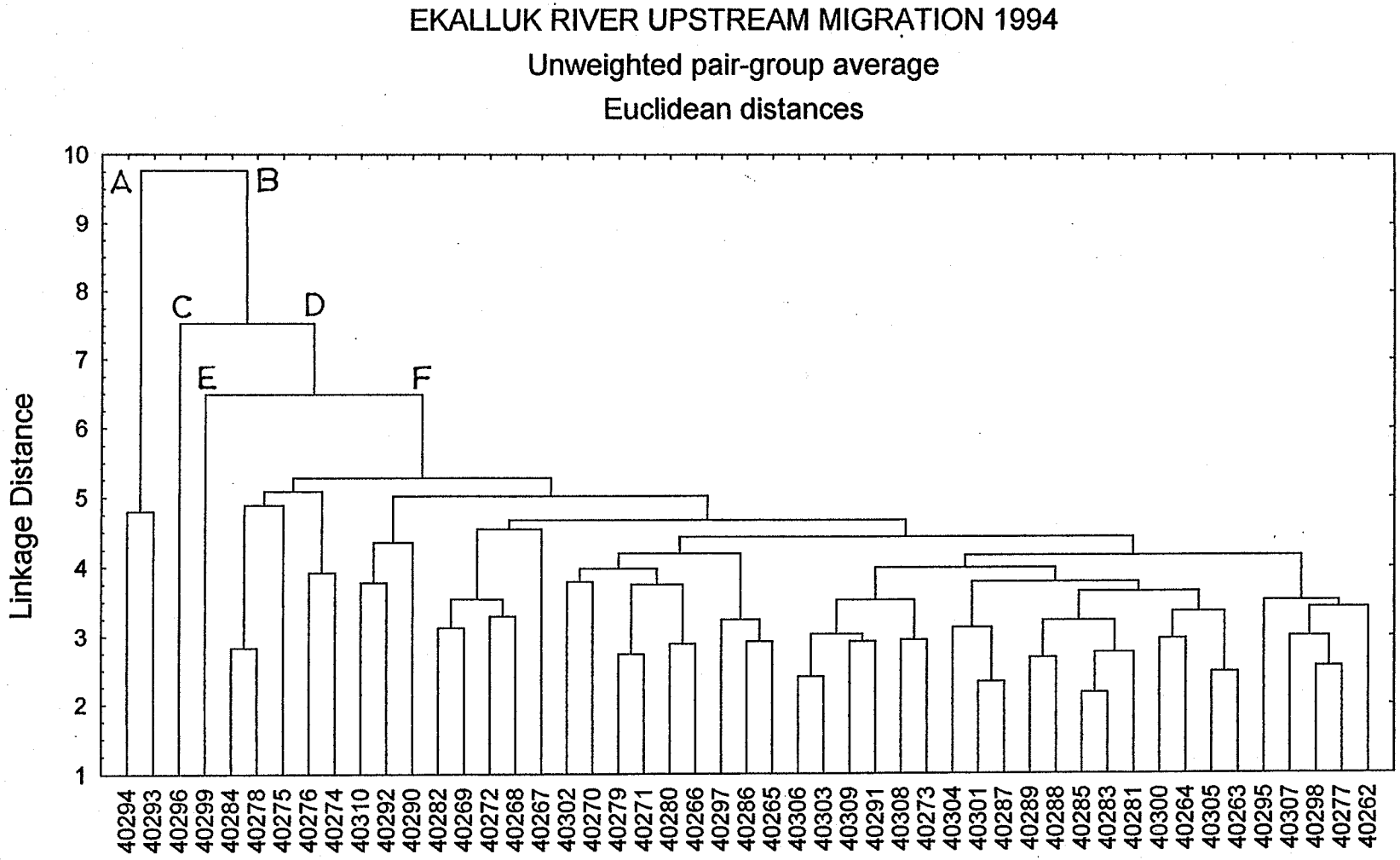

Figure 46. Cluster analysis of morphometric measurements of Arctic char from the 1994 upstream migration in the Ekalluk River. Cluster F is considered to represent a group in this analysis. Sample identification number along abscissa.

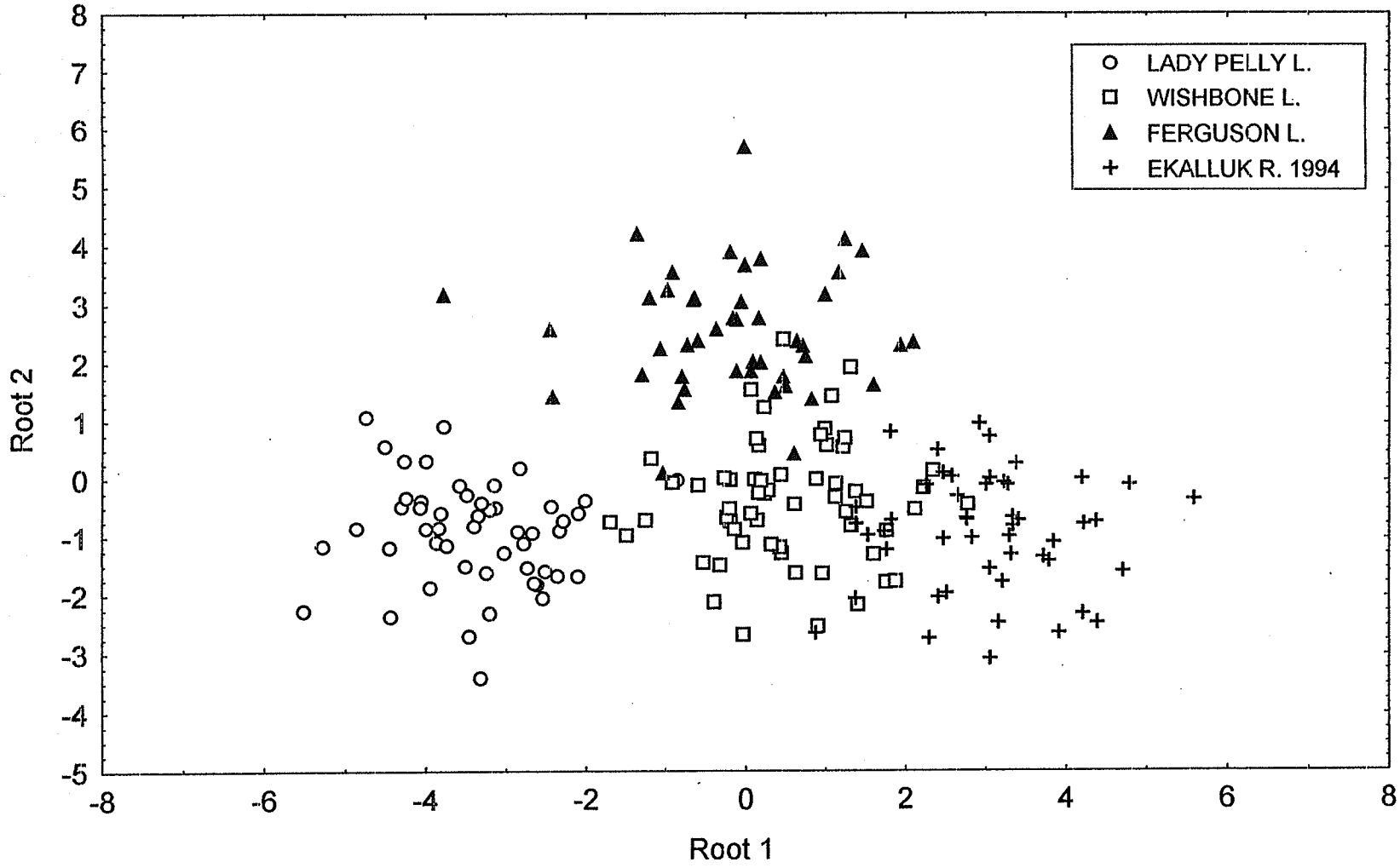

Figure 47. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1994 upstream migration in the Ekalluk River.

Table 17. Summary of the discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and a sample of nonspawning Arctic char from the 1994 upstream migration in the Ekalluk River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 10, N of vars in model: 10; Grouping: GROUP (4 grps) Wilks' Lambda: .02682 approx. F (30,564)=45.719 p<0.0000					
N=205	Wilks' Lambda	Partial Lambda	F-remove (3,192)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGOOL	.058040	.462130	74.48921	0.000000	.855914	.144086
LOGMXW	.042318	.633828	36.97374	.000000	.762773	.237227
LOGPCL	.036465	.735566	23.00782	.000000	.657311	.342689
LOGLAL	.036808	.728708	23.82664	.000000	.581636	.418364
LOGBDD	.037585	.713650	25.67982	.000000	.533042	.466958
LOGANL	.030846	.869561	9.60038	.000006	.774761	.225239
LOGHDD	.030026	.893298	7.64465	.000075	.549400	.450600
LOGCPL	.029049	.923349	5.31289	.001540	.901973	.098027
LOGIOW	.029772	.900936	7.03726	.000163	.473174	.526826
LOGMXL	.029372	.913186	6.08427	.000563	.401267	.598733

contributed to this discrimination of the four groups were orbital length (OOL), maxillary width (MXW), and pectoral fin length (PCL) in that order. The sample from the Ekalluk River 1994 upstream migration had relatively short pectoral fin length (Fig. 48a) and narrow maxillary width (Fig. 48b) compared with the spawning aggregations. They had a small orbital length (Fig. 48c), similar to those in the sample of spawners from Ferguson Lake. The relationship of maxillary width and pectoral fin length for each group is shown in Fig. 49.

A discriminant function analysis of the three spawning aggregations from the Ekalluk River (Lady Pelly, Wishbone, Ferguson lakes) and the two distinct groups of upstream migrants observed in the 1988 and 1994 samples reveals discrimination among all five groups (Fig. 50). The summary of this DFA is presented in Table 18. All Chi-square values with successive roots removed (0,1,2,3) were significant ($p < 0.001$). The variables that contributed most to this discrimination were orbital length (OOL), gill raker length (GRL) and maxillary width (MXW) in that order. The samples from the 1988 and 1994 upstream migrations had a small orbital length similar to the Ferguson Lake sample (Fig. 51a). The sample from the Ekalluk River 1988 upstream migration was distinguished from the other four samples by a relatively long gill raker length (Fig. 51b). The samples from the 1988 and 1994 upstream migrations had a narrow maxillary width, similar to those from Wishbone Lake (Fig. 51c). The relationship between maxillary width and gill raker length for these five groups is shown in Fig. 52.

A discriminant function analysis including the six Ekalluk River upstream runs, the three spawning aggregations from the Ekalluk River system (Ferguson, Lady Pelly,

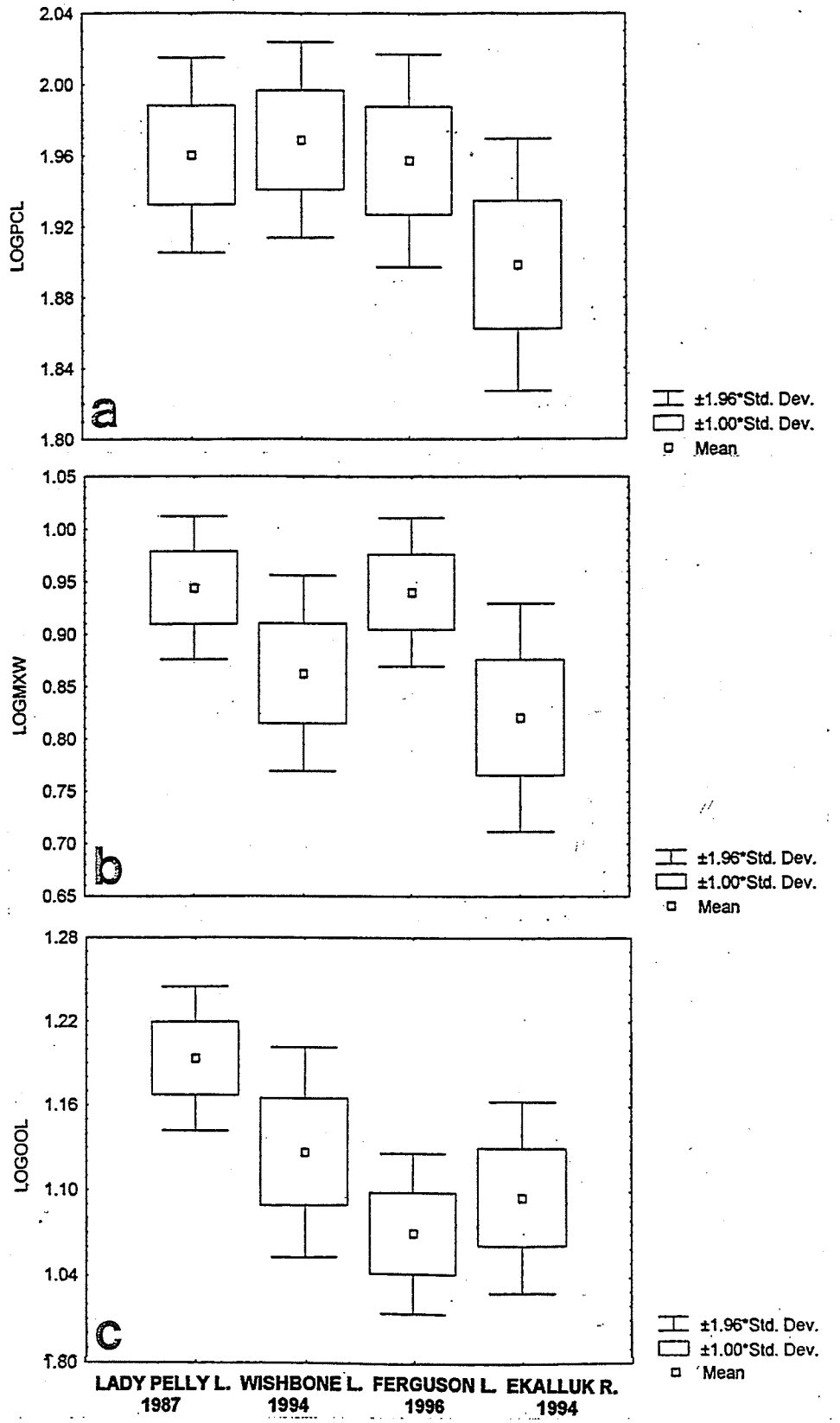

Figure 48. A comparison of mean log (a) pectoral fin length (PCL), (b) maxillary width (MXW), and (c) orbital length (OOL) among samples from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1994 upstream migration in the Ekalluk River.

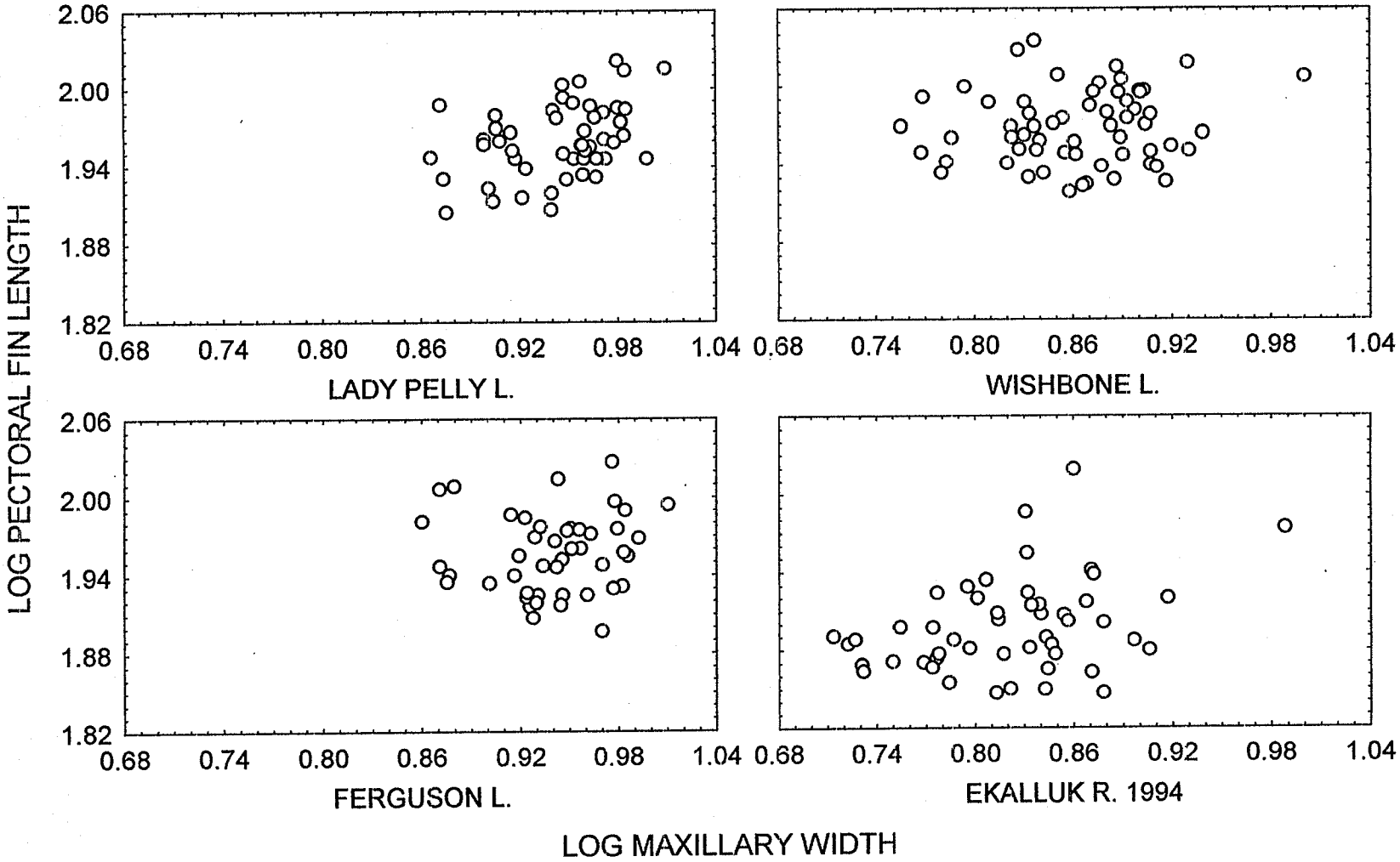

Figure 49. A plot of log maxillary width (MXW) against log pectoral fin length (PCL) for Arctic char spawners from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the sample of nonspawning Arctic char from the 1994 upstream migration in the Ekalluk River.

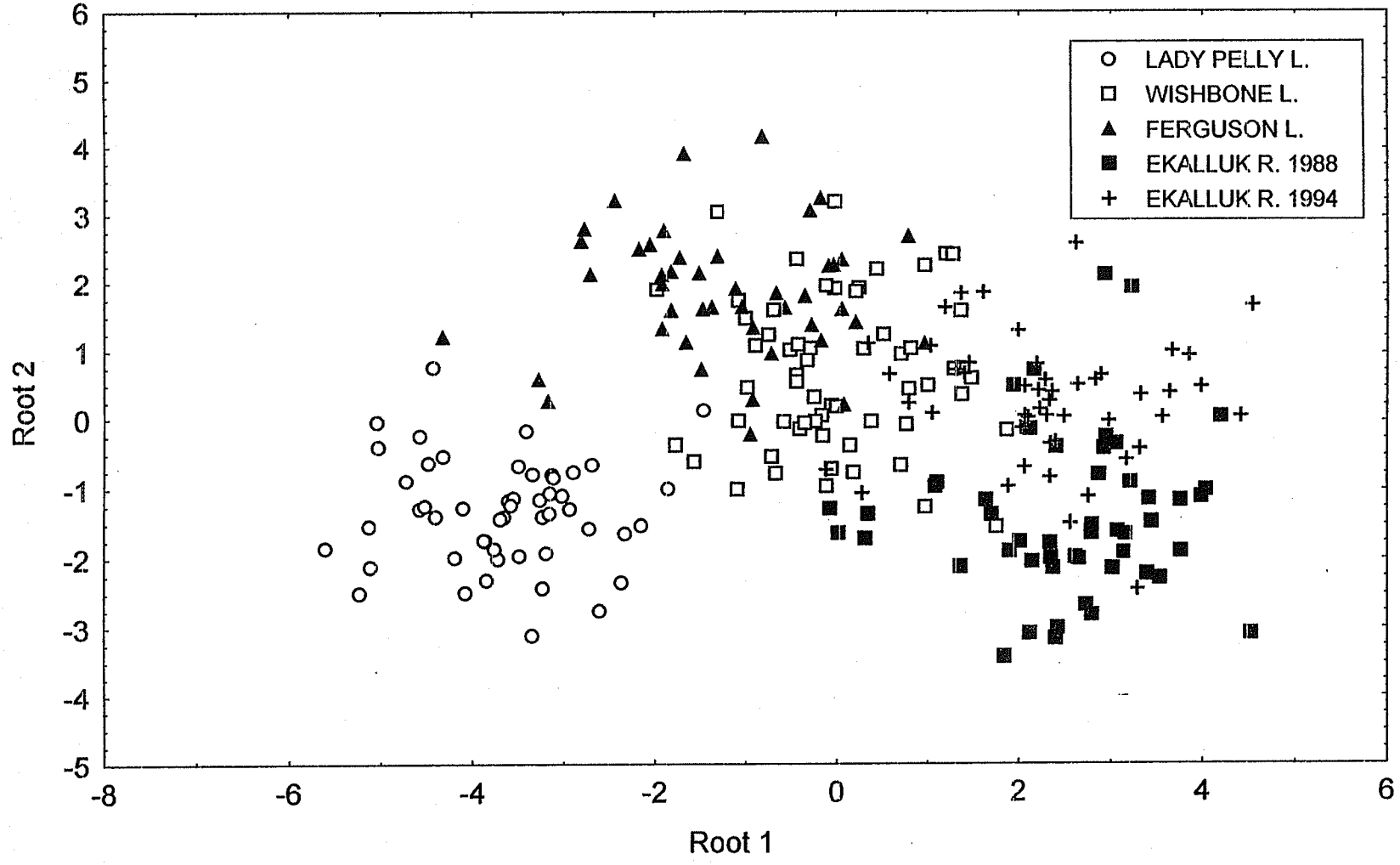

Figure 50. Discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the samples of nonspawning Arctic char from the 1988 and 1994 upstream migrations in the Ekalluk River.

Table 18. Summary of the discriminant function analysis of morphometric measurements of Arctic char from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and samples of nonspawning Arctic char from the 1988 and 1994 upstream migrations in the Ekalluk River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 13, N of vars in model: 13; Grouping: GROUP (5 grps) Wilks' Lambda: .01838 approx. F (52,927)=32.229 p<0.0000					
N=256	Wilks' Lambda	Partial Lambda	F-remove (4,239)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGMXW	.025401	.723549	22.82907	.000000	.800304	.199696
LOGOOL	.033110	.555080	47.89217	.000000	.859152	.140848
LOGGRL	.032230	.570242	45.03006	.000000	.907920	.092080
LOGPCL	.022420	.819748	13.13823	.000000	.598497	.401503
LOGANL	.021905	.839023	11.46380	.000000	.750394	.249606
LOGLAL	.023251	.790452	15.83962	.000000	.607490	.392510
LOGBDD	.023479	.782756	16.58281	.000000	.589561	.410439
LOGHDD	.021026	.874101	8.60595	.000002	.536418	.463582
LOGCPD	.020740	.886138	7.67744	.000008	.504907	.495093
LOGMXL	.020217	.909072	5.97636	.000134	.415318	.584682
LOGIOW	.020471	.897796	6.80189	.000034	.491466	.508534
LOGLUL	.019956	.920958	5.12811	.000557	.793672	.206328
LOGCPL	.019793	.928553	4.59743	.001356	.866918	.133082

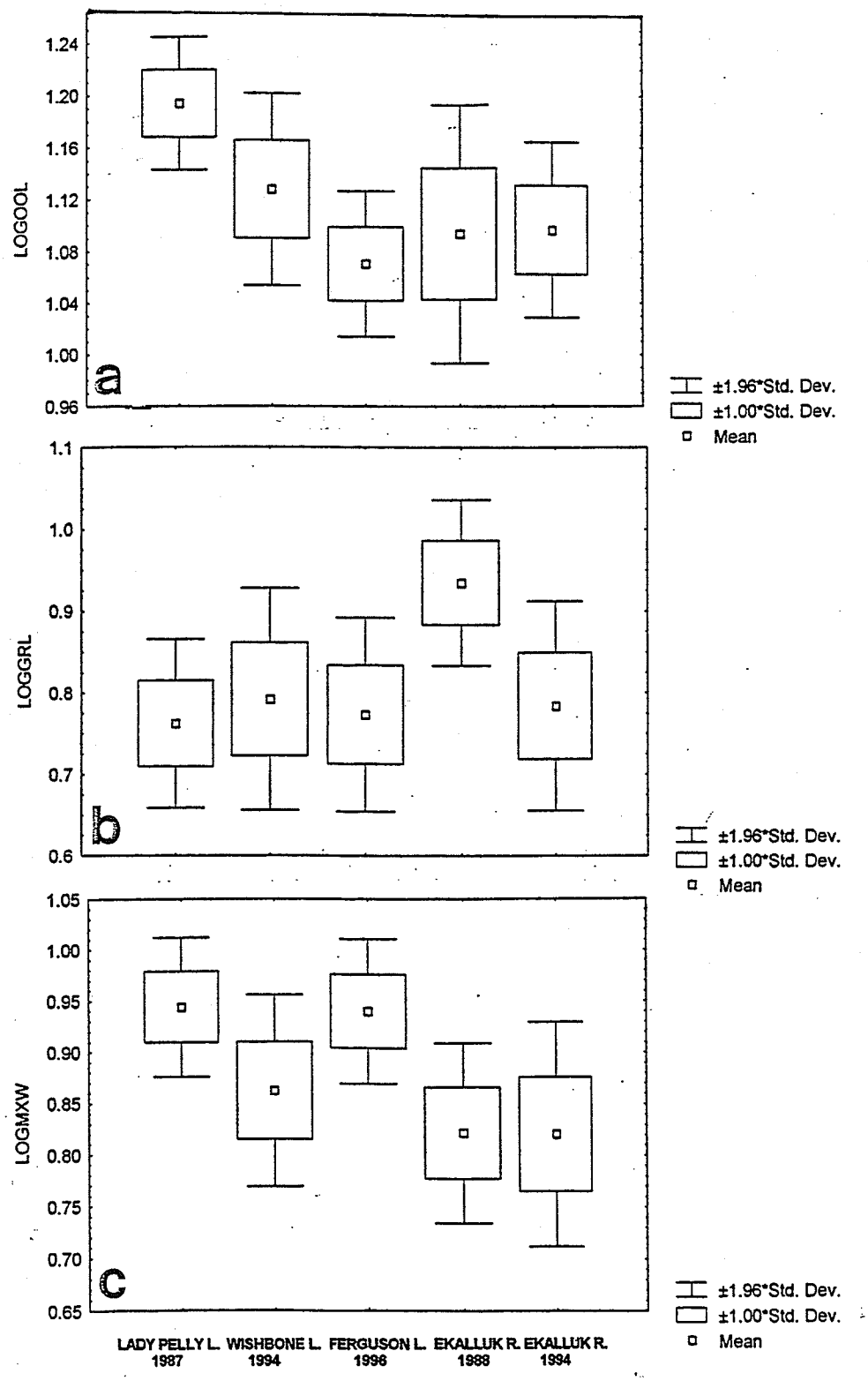

Figure 51. A comparison of mean log (a) orbital length (OOL), (b) gill raker length (GRL), and (c) maxillary width (MXW) among samples from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the samples of nonspawning Arctic char from the 1988 and 1994 upstream migration in the Ekalluk River.

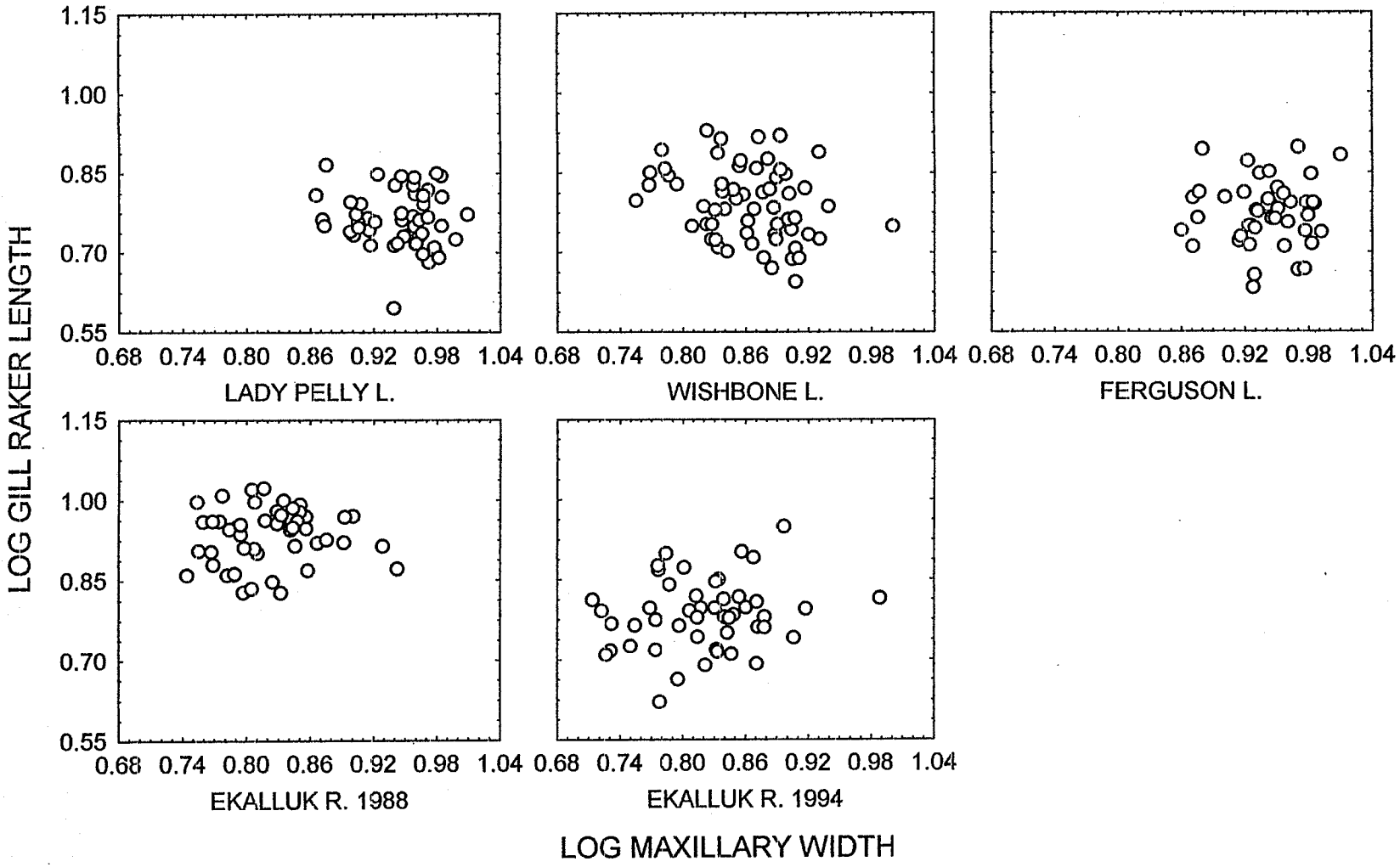

Figure 52. A plot of log maxillary width (MXW) against log gill raker length (GRL) for Arctic char spawners from three spawning aggregations in the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes) and the samples of nonspawning Arctic char from the 1988 and 1994 upstream migration in the Ekalluk River.

Wishbone lakes), and the other spawners from the Wellington Bay area (Halovik Lake 1987, Halovik Lake 1993 and Kitiga Lake) was carried out. A comparison of Squared Mahalanobis Distances indicates that all six samples of Ekalluk River upstream migrations are more similar to the samples of Ekalluk River spawners than to those from the other samples of spawners (Table 19). The Ekalluk River 1990, 1991 and 1993 samples appear to be most similar to the Wishbone Lake spawners while the Ekalluk River 1988, 1992 and 1994 samples are more distant. There was a similarity between the Ekalluk River 1991 and 1993 samples of upstream migrants and spawners from Halovik Lake 1993.

A cluster analysis of the upstream migration of Arctic char in the Halovik River in 1992 suggests that it was comprised almost entirely of one cluster (Fig 53). Outlier A separates from the remainder of the specimens at a distance of about 10.8. The pair represented by cluster C separate from cluster D at a distance of about 5.8. Further separation of cluster D occurs below 5.5, which could represent intra- rather than inter-group variation. Therefore, cluster D was considered as representative of group structure.

This sample was compared with the samples of spawners from Halovik Lake 1987 and 1993 by DFA (Fig. 54). The three samples appear to be distinct from one another in terms of morphometric measurements. A summary of the DFA is shown in Table 20. The variables that contributed most to the discrimination were body depth (BDD), caudal peduncle depth (CPD) and maxillary width (MXW), in that order. All Chi-square values with successive roots removed (0,1) were significant ($p < 0.001$). Halovik River 1987 spawners were characterized by small body depth (Fig. 55a), relative to the 1993 spawners and the 1992 upstream migrants. The Halovik River 1993 spawners

Table 19. A comparison of Squared Mahalanobis Distances among samples of Arctic char spawners from the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes), Halovik Lake 1987 and 1993, and Kitiga Lake, and the six samples of nonspawning Arctic char from the upstream migrations in the Ekalluk River (1988, 1990, 1991, 1992, 1993 and 1994).

	STAT. DISCRIM. ANALYSIS	Squared Mahalanobis Distances					
	GROUP	LADY PELLY L	WISHBONE L	FERGUSON L	HALOVIK L 87	HALOVIK L 93	KITIGA L
SPAWNERS	LADY PELLY L	0.00000	17.61093	18.74642	11.03262	13.01005	23.01470
	WISHBONE L	17.61093	0.00000	11.21963	16.26840	2.98881	4.82983
	FERGUSON L	18.74642	11.21963	0.00000	17.65114	12.21518	17.72591
	HALOVIK L 87	11.03262	16.26840	17.65114	0.00000	10.49247	17.77559
	HALOVIK L 93	13.01005	2.98881	12.21518	10.49247	0.00000	7.67038
	KITIGA L	23.01470	4.82983	17.72591	17.77559	7.67038	0.00000
NONSPAWNERS	EKALLUK R 88	33.36045	15.95907	24.21993	34.55931	19.17118	28.67112
	EKALLUK R 90	25.61927	8.59169	14.09122	26.34739	11.26628	16.56207
	EKALLUK R 91	22.48420	5.75210	12.79076	20.89145	7.49061	14.19243
	EKALLUK R 92	26.12351	10.29441	21.31739	22.83909	11.79131	16.69717
	EKALLUK R 93	29.46458	8.03519	15.43286	25.51837	9.03257	16.94164
	EKALLUK R 94	33.58931	10.29136	20.87114	31.72584	15.01415	15.65920

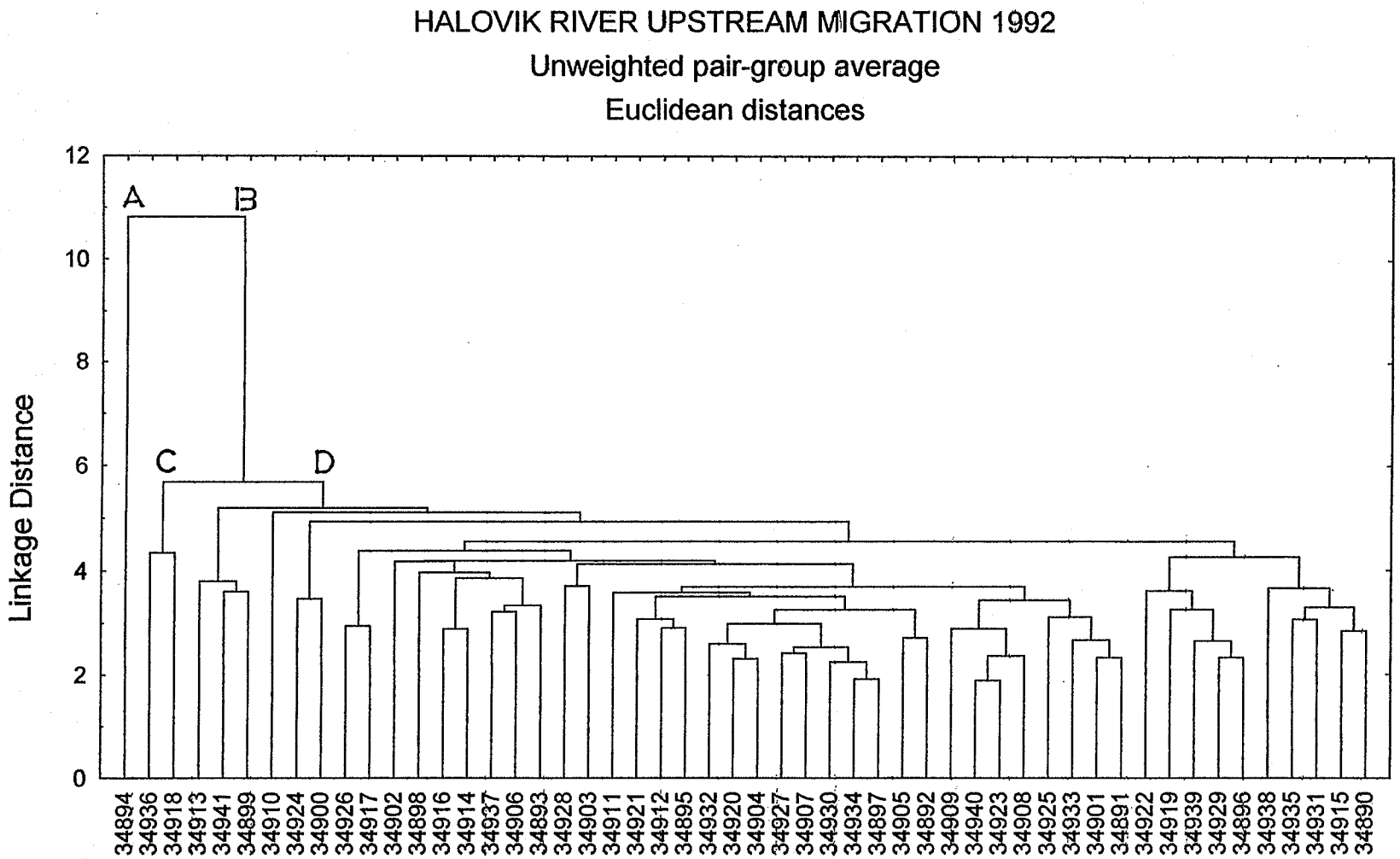

Figure 53. Cluster analysis of morphometric measurements of Arctic char from the 1992 upstream migration in the Halovik River. Cluster D is considered to represent a group in this analysis. Sample identification number along abscissa.

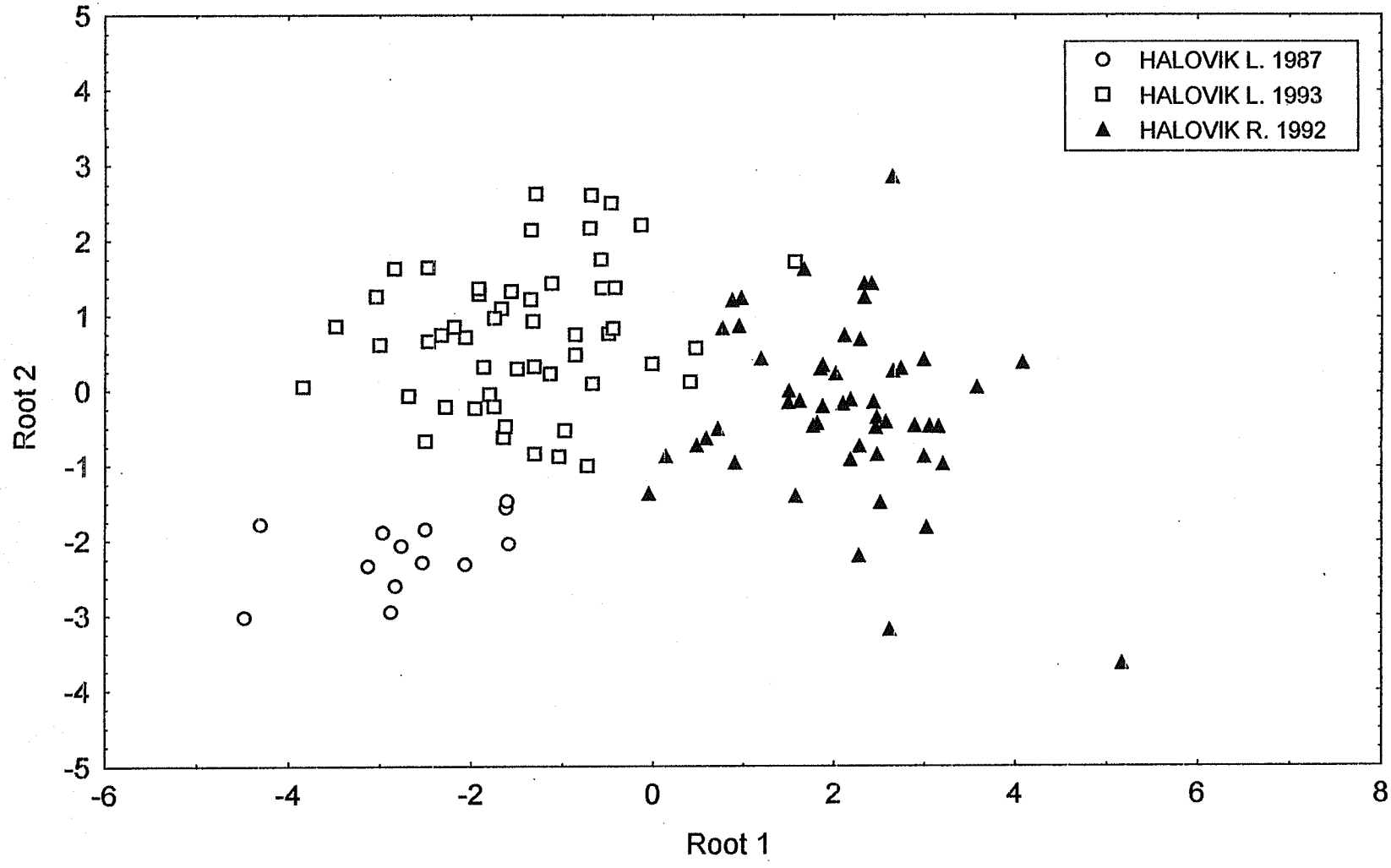

Figure 54. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in Halovik Lake 1987 and Halovik Lake 1993 and a sample of nonspawning Arctic char from the 1992 upstream migration in the Halovik River.

Table 20. Summary of the discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in Halovik Lake 1987 and 1993, and a sample of nonspawning Arctic char from the 1992 upstream migration in the Halovik River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 5, N of vars in model: 5; Grouping: GROUP (3 grps) Wilks' Lambda: .11644 approx. F (10,220)=42.471 p<0.0000					
N=117	Wilks' Lambda	Partial Lambda	F-remove (2,110)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGMXW	.147970	.786932	14.89170	.000002	.828675	.171325
LOGBDD	.218290	.533430	48.10629	.000000	.600826	.399174
LOGCPD	.160535	.725341	20.82635	.000000	.559036	.440964
LOGCPL	.146957	.792359	14.41296	.000003	.957707	.042293
LOGHDD	.125150	.930422	4.11297	.018941	.661850	.338150

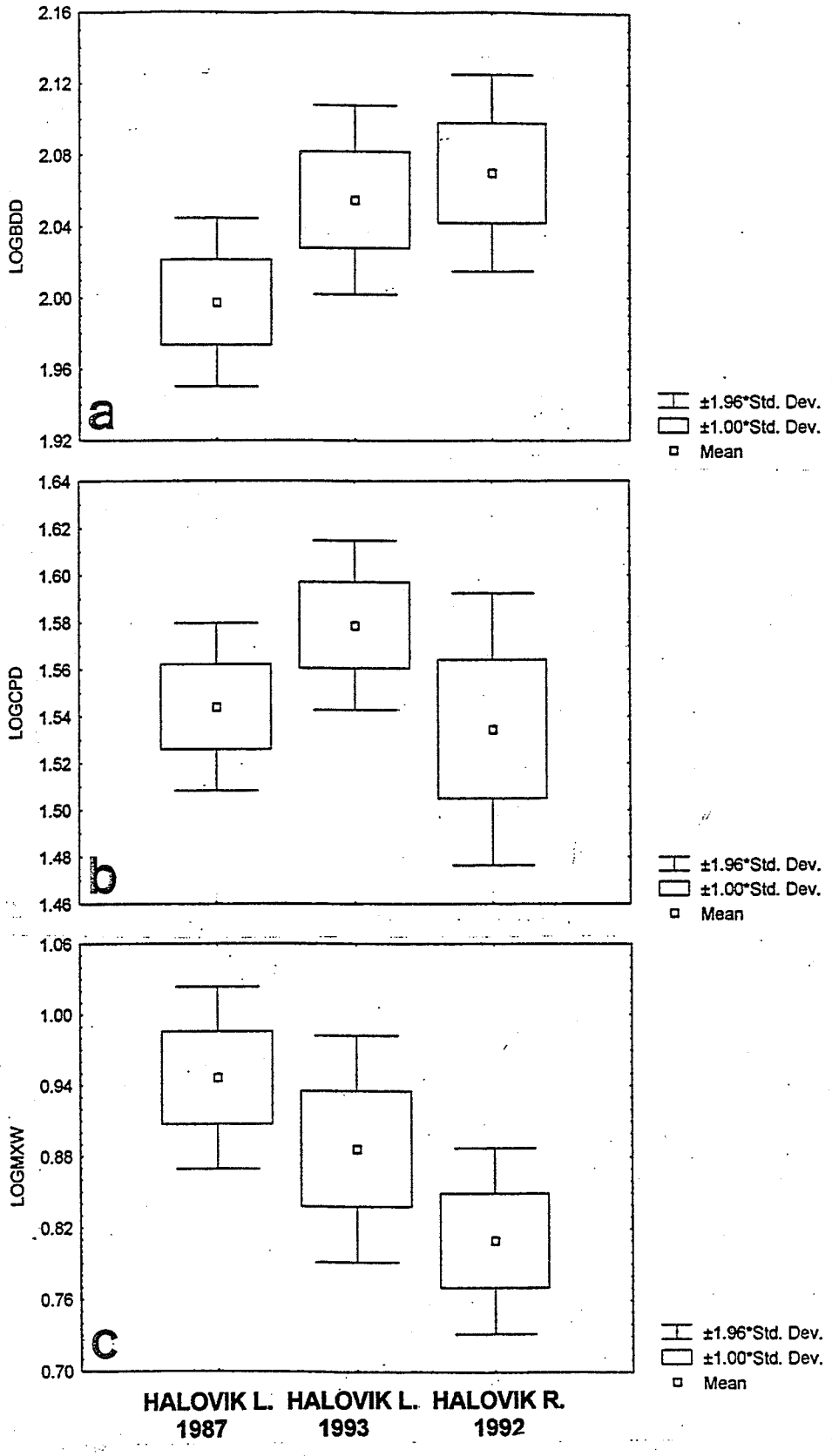

Figure 55. A comparison of mean log (a) body depth (BDD), (b) caudal peduncle depth (CPD), and (c) maxillary width (MXW) among samples of Arctic char spawners from Halovik Lake 1987 and Halovik Lake 1993 and a sample of nonspawning Arctic char from the 1992 upstream migration in the Halovik River.

had a greater caudal peduncle depth (Fig. 55b) relative to the other two samples. The 1992 upstream migrants had a narrow maxillary width (Fig. 55c) relative to the two samples of spawners. The relationship between body depth and maxillary width for each group is shown in Fig. 56.

The cluster analysis of the sample from the 1992 upstream migration of Arctic char into the Lauchlan River suggests that it was comprised almost entirely of one group, based on morphology (Fig. 57). With the exception of one outlier, A, that separated from cluster B at a distance of about 13.4, the rest of cluster B shows separation at a distance of 4.6 or less. Therefore, cluster B was considered to have comprised a single group. There were no spawners from this system with which to compare this sample.

The cluster analysis of the sample of Arctic char from the commercial gillnet fishery at the Lauchlan River in July 1996 (Fig. 58) suggests that it was comprised primarily of one group, based on morphology. Specimens A, C, and F separate from cluster E at a distance of about 5.3 or greater. Further separation within cluster E occurs at a distance of about 5 or less. Therefore, cluster E is considered representative of a group.

The sample of Arctic char taken in the commercial gillnet fishery at Paliryuak River in July 1992 appears to be comprised of one main group and a number of outliers (Fig. 59). Cluster L comprises about 70 percent of the sample. The other specimens separate from this group at a distance of about 5.3 or greater. Further separation of cluster L into two groups occurs at a distance of about 5.1. However, this separation could represent intra- rather than inter-group separation. There were no samples of spawners from this system with which to compare this sample.

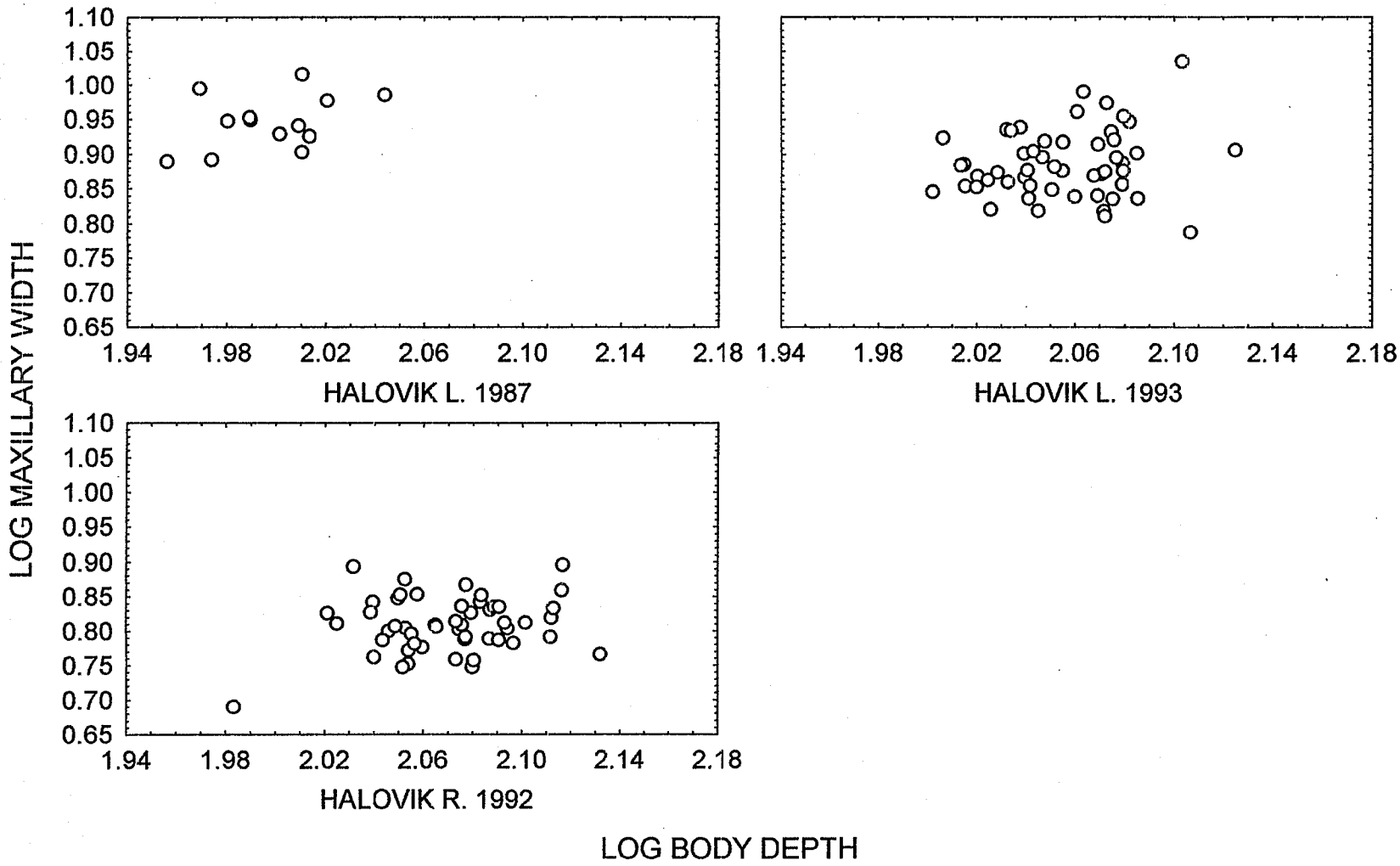

Figure 56. A plot of log body depth (BDD) against log maxillary width (MXW) for Arctic char spawners from Halovik Lake 1987 and Halovik Lake 1993 and a sample of nonspawning Arctic char from the 1992 upstream migration in the Halovik River.

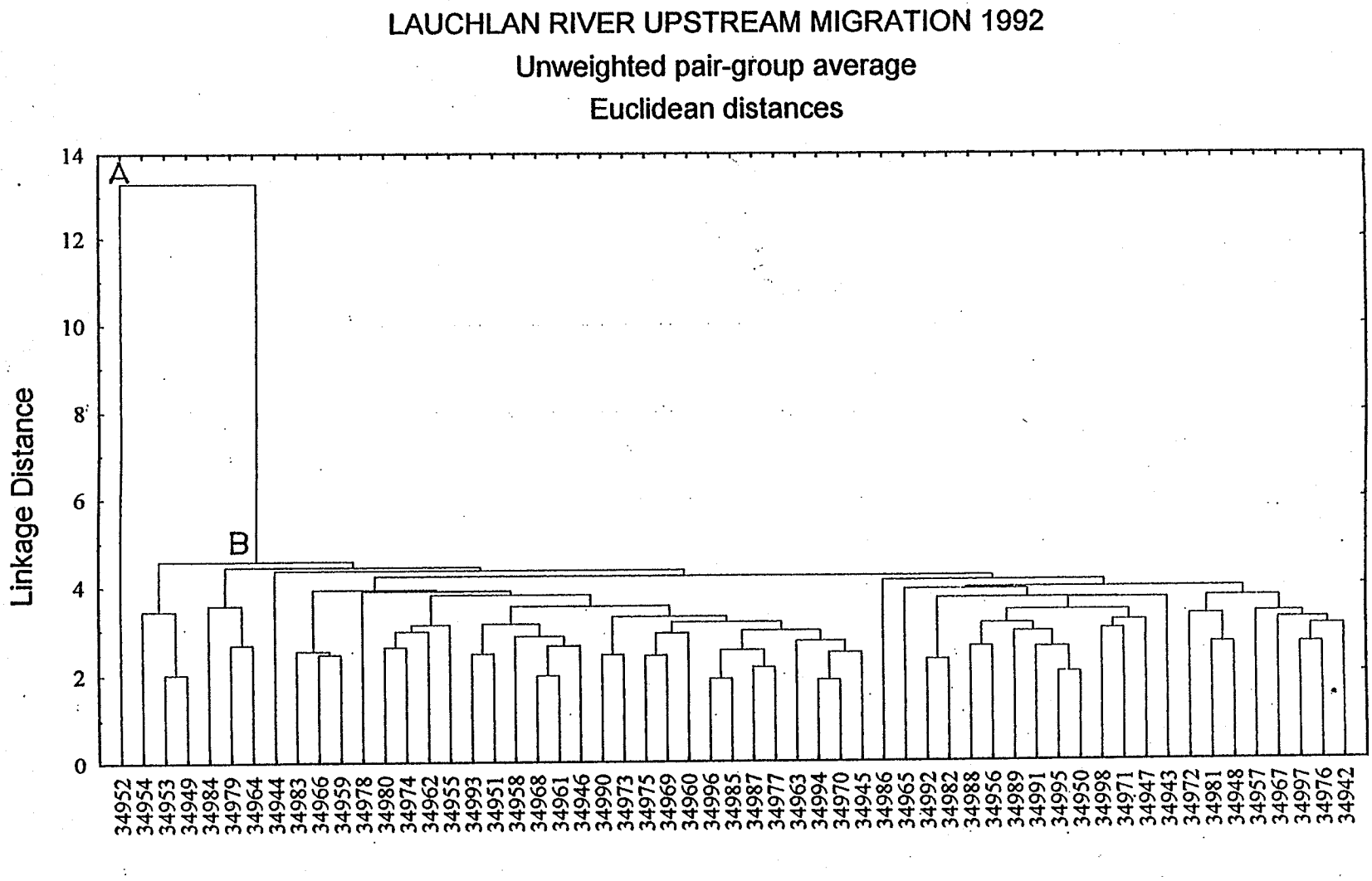

Figure 57. Cluster analysis of morphometric measurements of Arctic char from the 1992 upstream migration in the Lauchlan River. Cluster B is considered to represent a group in this analysis. Sample identification number along abscissa.

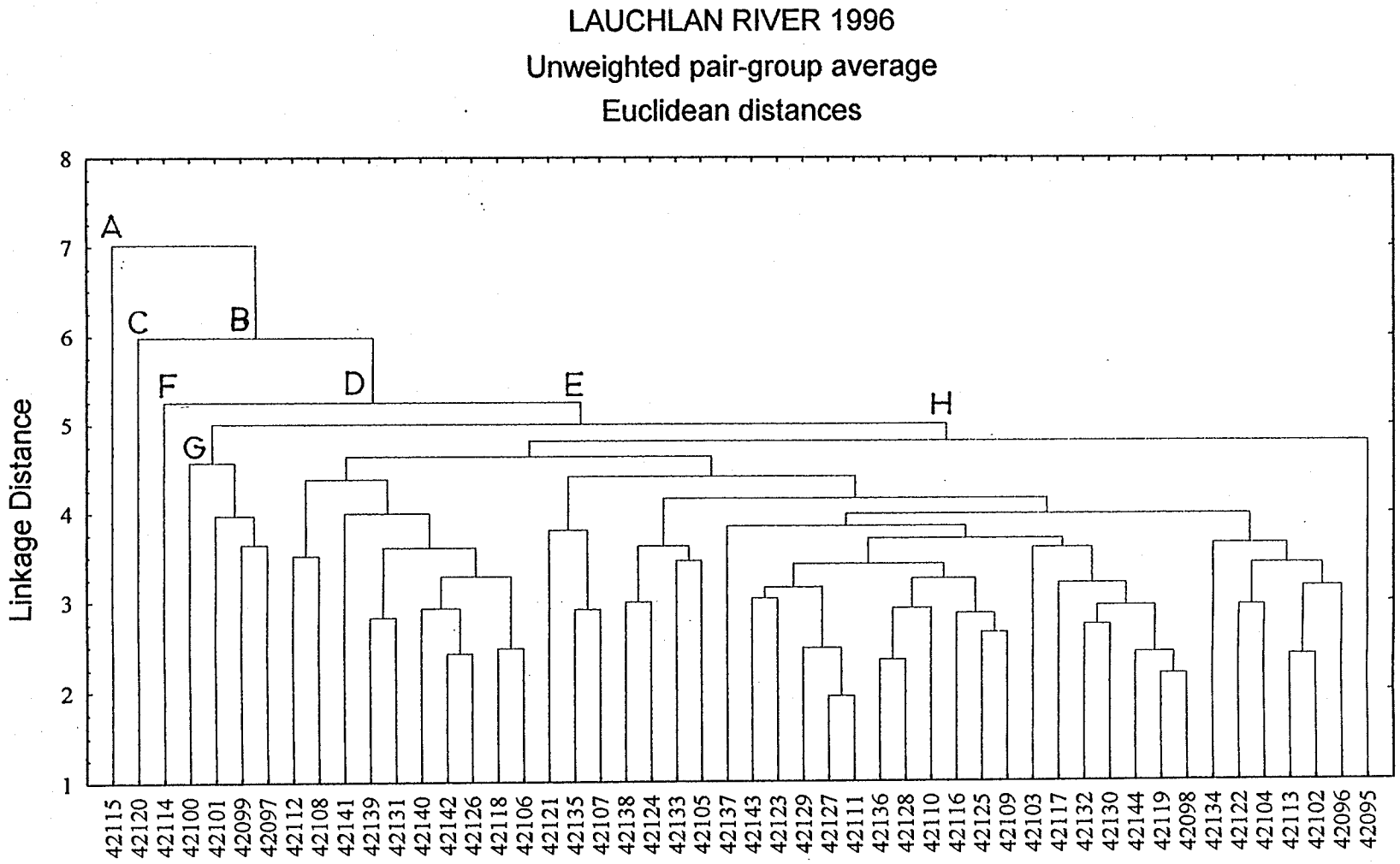

Figure 58. Cluster analysis of morphometric measurements of Arctic char from the commercial gillnet fishery at the Lauchlan River in July 1996. Cluster E could represent a group. Sample identification number along abscissa.

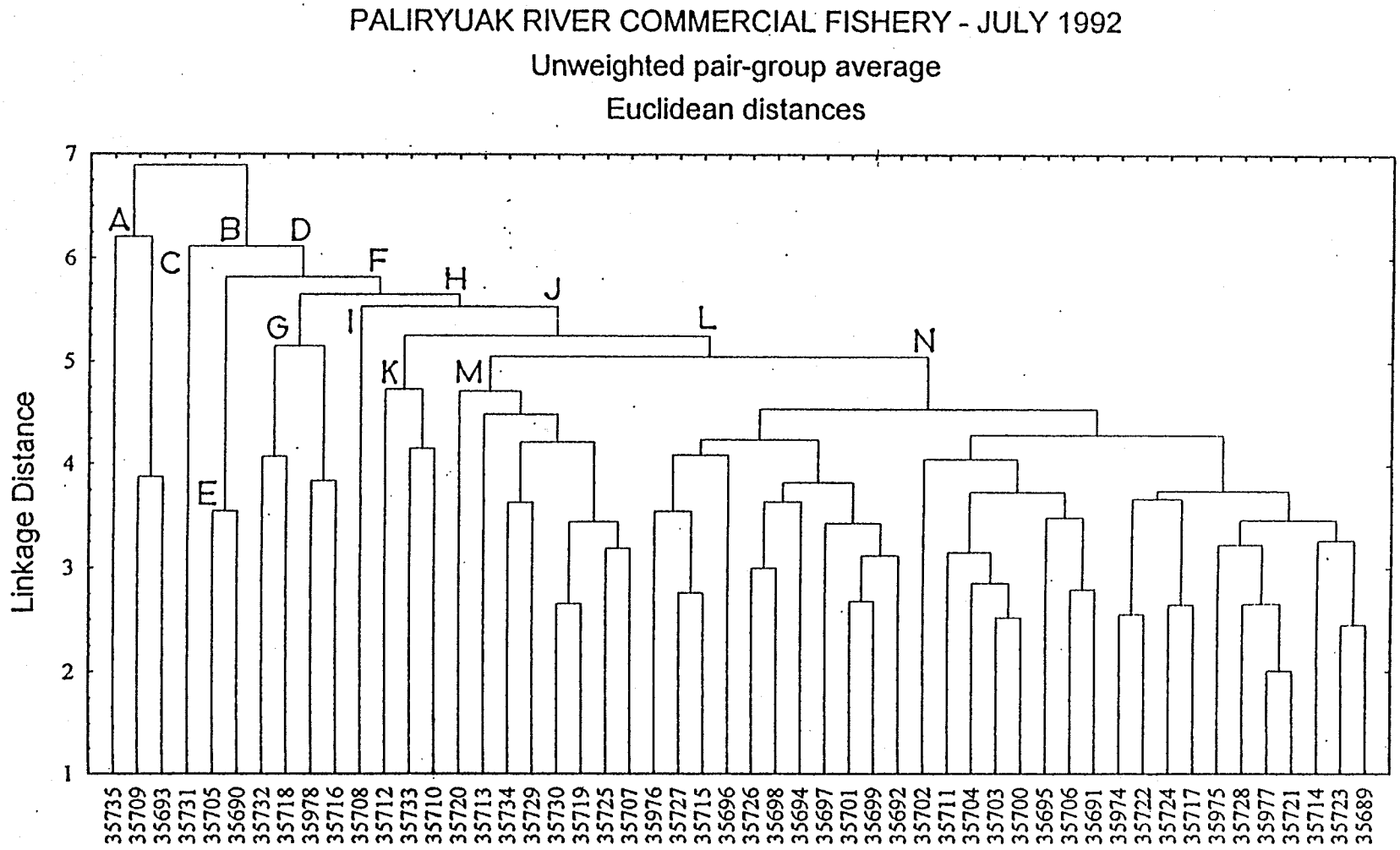

Figure 59. Cluster analysis of morphometric measurements of Arctic char from the commercial gillnet fishery at Paliryuak River in July 1992. Cluster N could represent a group. Sample identification number along abscissa.

A discriminant function analysis comparing the samples of nonspawners from Paliryuak River 1992, Halovik River 1992, Lauchlan River 1992 and Lauchlan River 1996 with the samples of spawners from the Ekalluk River system (Ferguson, Wishbone, Lady Pelly lakes) and spawners from Halovik Lake 1987, Halovik Lake 1993 and Kitiga Lake was carried out. The Squared Mahalanobis Distances (Table 21) suggest that the Halovik River 1992 and Lauchlan River 1992 nonspawners were most similar to the Wishbone Lake spawners. The Paliryuak River 1992 nonspawners appear to be similar to the Wishbone Lake, Halovik Lake 1993 and Kitiga Lake spawners. The Lauchlan River 1996 nonspawners do not show the same degree of similarity with any of the samples of spawners as the previous three samples did.

There appears to be considerable heterogeneity in structure within the sample from the upstream migration of Arctic char into Freshwater Creek in 1988 (Fig. 60). Clusters E, G, J, M, N, O, P, D and B separate at a distance of about 5.5 or greater. Cluster O comprises the majority of the sample. This sample was compared to the samples of spawners taken from the Freshwater Creek system (Mount Pelly Lake) in 1992 and 1993 by discriminant function analysis (Fig. 61). Only a few specimens appeared to be similar morphologically to the samples of spawners. Individual clusters were compared by DFA with the two samples of spawners (Fig. 62 a,b,c,d). Only a few specimens from Cluster O (Fig. 62c) appeared to be similar to the 1992 and 1993 samples of spawners.

The cluster analysis of the upstream migration of Arctic char into Freshwater Creek in 1991 (Fig. 63) reveals three possible clusters based on morphology. Clusters C and D separate from one another at a distance of about 6.1 and cluster D separates into

Table 21. A comparison of Squared Mahalanobis Distances among samples of Arctic char spawners from the Ekalluk River system (Lady Pelly, Wishbone and Ferguson lakes), Halovik Lake 1987 and 1993, and Kitiga Lake, and the samples of nonspawning Arctic char that were taken at Paliryuak River 1992, Halovik River 1992, Lauchlan River 1992 and Lauchlan River 1996.

	STAT. DISCRIM. ANALYSIS	Squared Mahalanobis Distances					
	GROUP	LADY PELLY L	WISHBONE L	FERGUSON L	HALOVIK L 93	KITIGA L	HALOVIK L 87
SPAWNERS	LADY PELLY L	0.00000	21.37011	18.86604	18.17392	27.36102	10.56732
	WISHBONE L	21.37011	0.00000	13.47847	3.78007	4.87487	18.69973
	FERGUSON L	18.86604	13.47847	0.00000	14.02393	19.25016	18.17439
	HALOVIK L 93	18.17392	3.78007	14.02393	0.00000	8.02772	12.99648
	KITIGA L	27.36102	4.87487	19.25016	8.02772	0.00000	19.78512
	HALOVIK L 87	10.56732	18.69973	18.17439	12.99648	19.78512	0.00000
NON SPAWNERS	HALOVIK R 92	31.57986	8.24780	21.79531	13.25572	14.02908	28.63830
	LAUCHL R 92	30.93624	9.75078	19.55601	14.80345	15.92375	28.13617
	PALIRYU R 92	28.07032	5.88160	20.24806	6.28965	7.79344	18.27318
	LAUCHL R 96	38.12983	16.76287	18.47163	17.05565	15.73171	14.86516

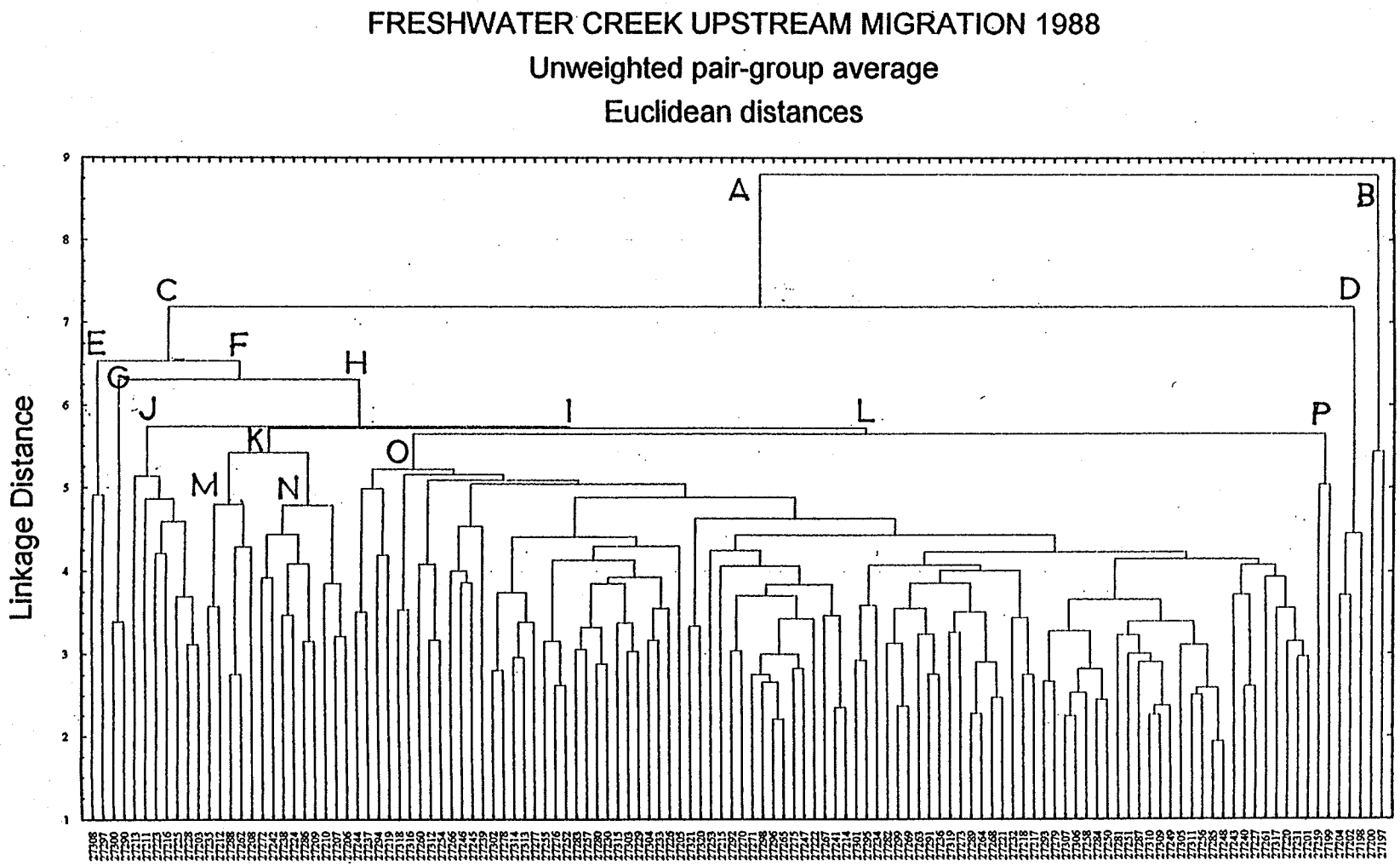

Figure 60. Cluster analysis of morphometric measurements of Arctic char from the 1988 upstream migration into Freshwater Creek 1988. Cluster O could represent a group. Sample identification number along abscissa.

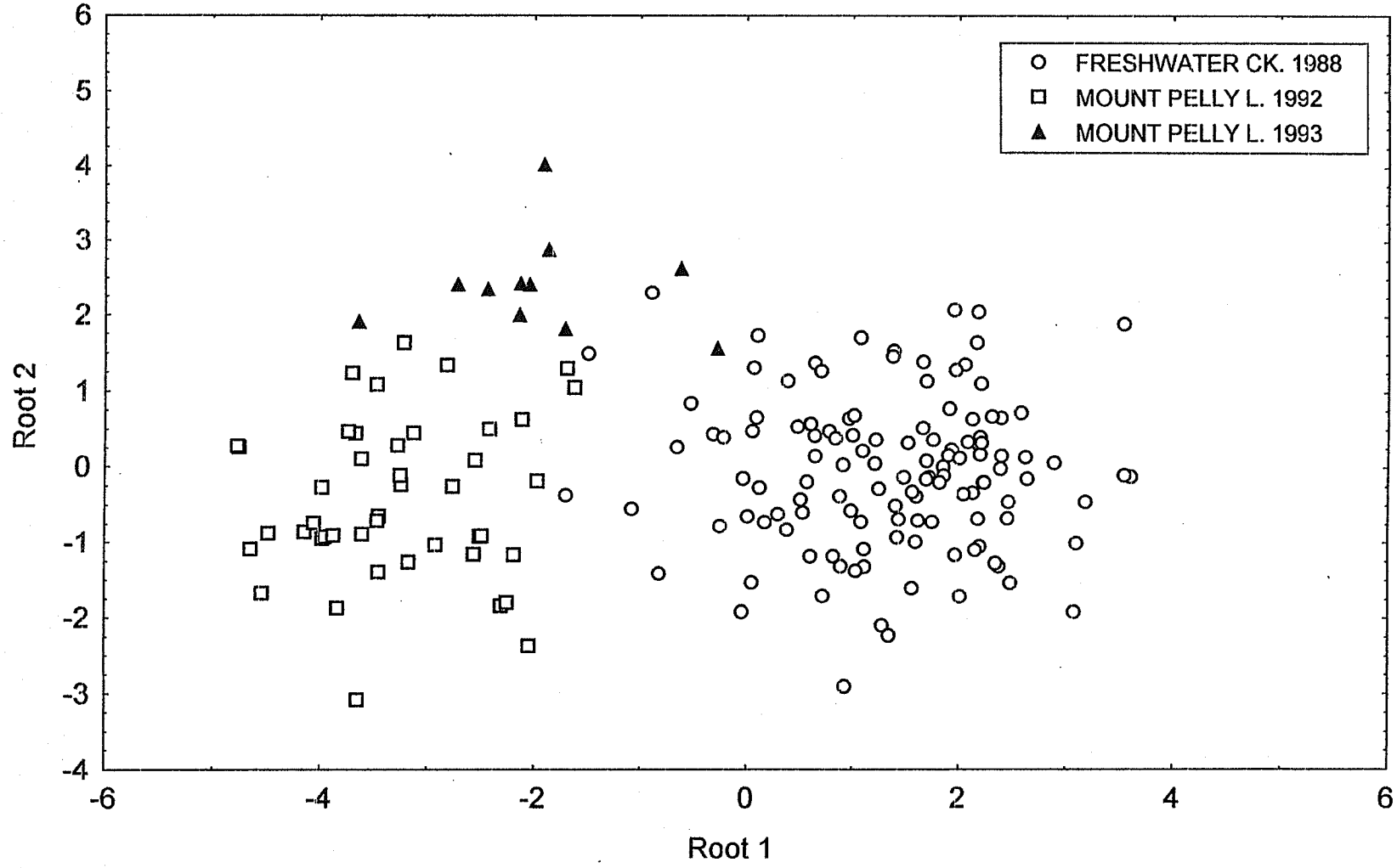

Figure 61. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in the Freshwater Ceek system (Mount Pelly Lake 1992 and 1993) and a sample of nonspawning Arctic char from the 1988 upstream migration in Freshwater Creek.

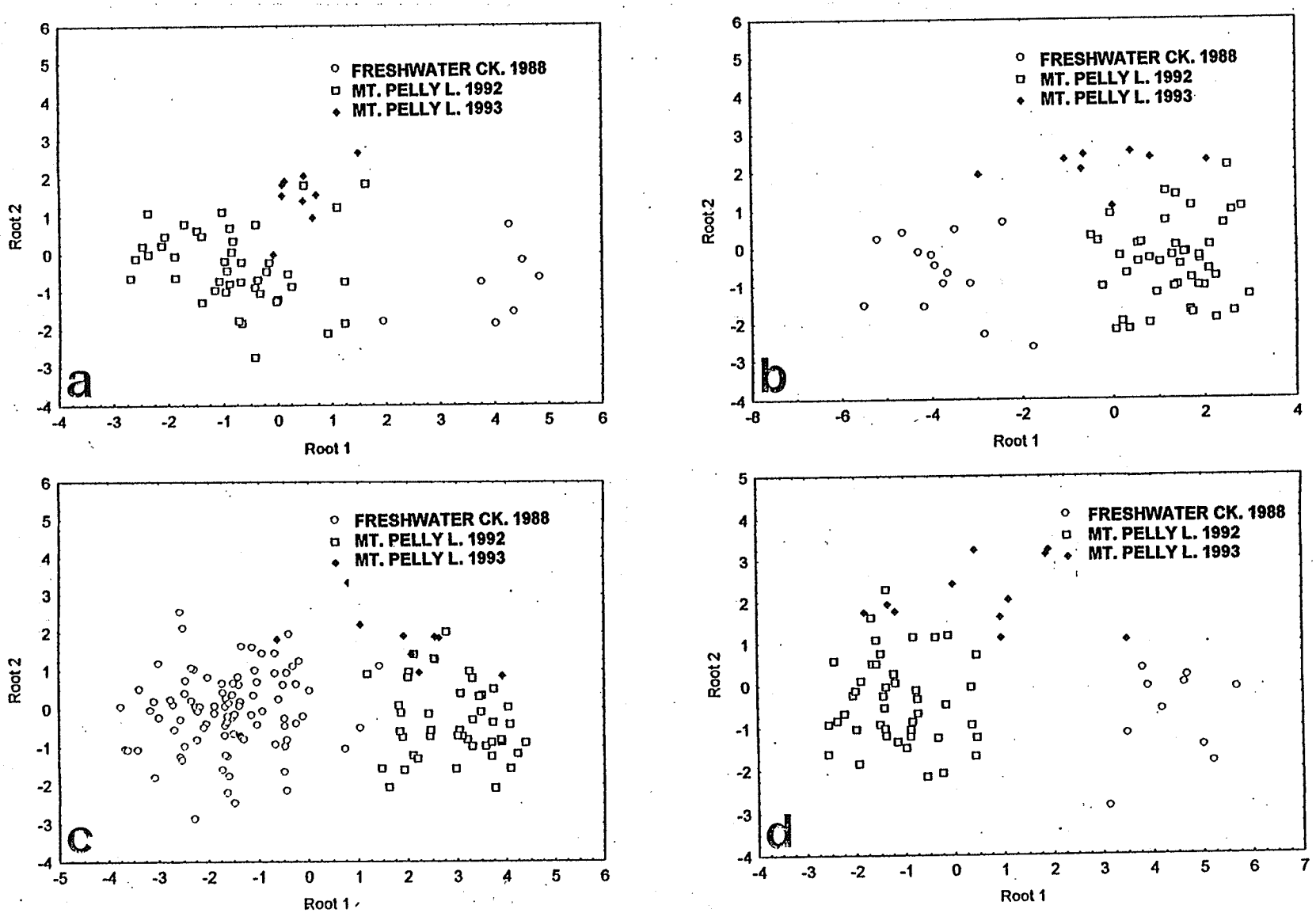

Figure 62. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in the Freshwater Creek system (Mount Pelly Lake 1992 and 1993) and different clusters (Fig. 60) of the 1988 upstream migration. The comparisons are: (a) Cluster J, (b) Cluster K, (c) Cluster N, and (d) Clusters E, G, O, D and B.

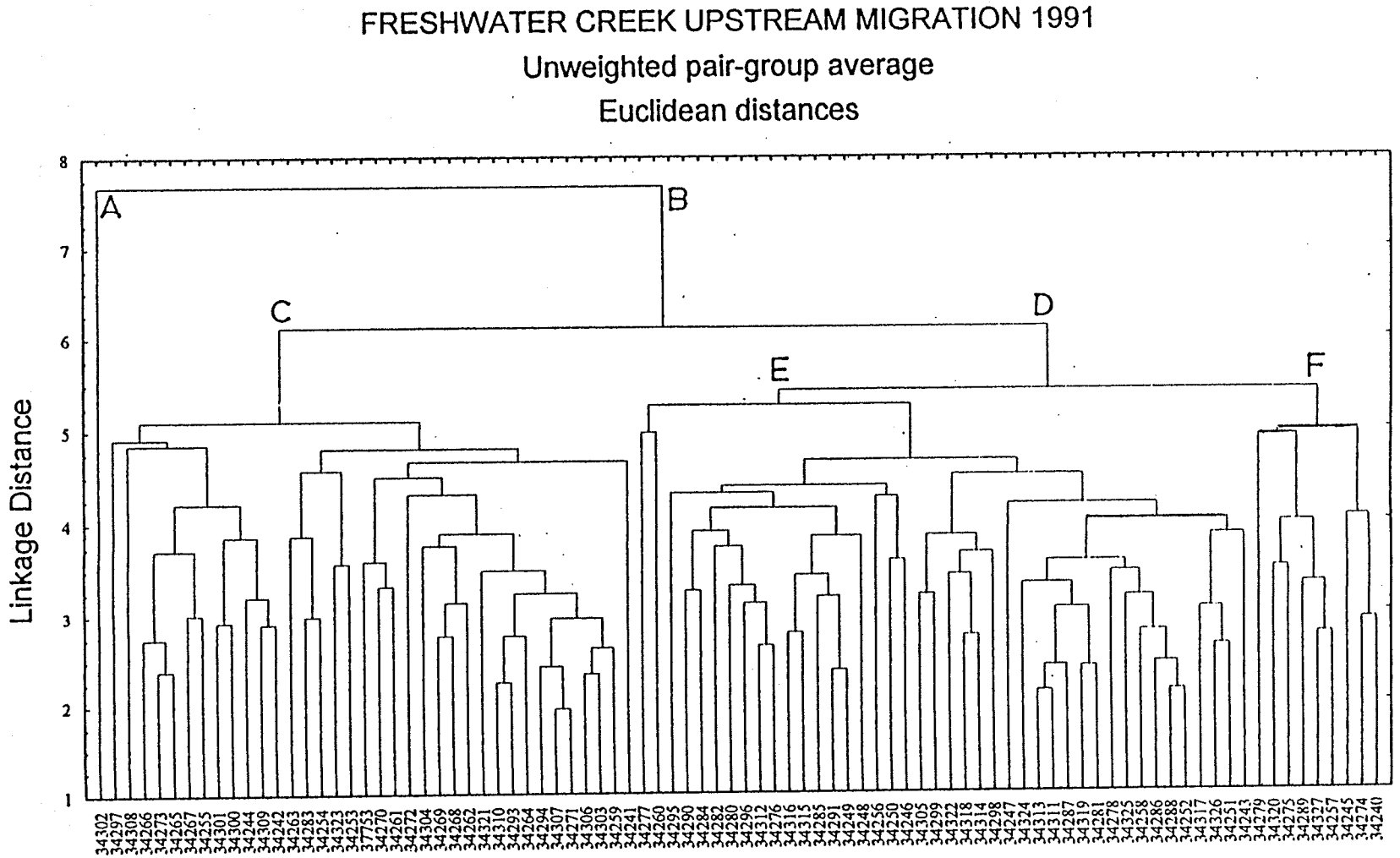

Figure 63. Cluster analysis of morphometric measurements of Arctic char from the 1991 upstream migration into Freshwater Creek. Clusters C, E and F could represent different groups. Sample identification number along abscissa.

clusters E and F at a distance of about 5.5. On this basis I considered clusters C, E, and F as having group structure. A discriminant function analysis comparing each of these groups with the two samples of spawners (Mount Pelly Lake) taken in 1992 and 1993 revealed no similarity between cluster C and the spawners (Fig. 64a) but some similarity with cluster D and the spawners (Fig. 64b). Cluster D was further divided into clusters E and F. Cluster E showed no similarity in morphology with the two samples of spawners (Fig. 64c) but cluster F appeared to be indistinguishable from the spawners (Fig. 64d), particularly those from 1993.

The cluster analysis of the upstream migration of Arctic char into Freshwater Creek in 1994 reveals the presence of two possible groups and a number of apparent outliers (Fig. 65). Separation of clusters M and N from the remainder of the specimens occurs at a distance of about 5.5 and they separate from one another at a distance of 5.4. The discrimnant function analysis comparing this entire sample with the samples from the spawners taken from Mount Pelly Lake in 1992 and 1993 showed that the groups appeared to differ (Fig. 66).

The cluster analysis of the sample of Arctic char taken in the upstream migration into Jayco River in 1990 reveals the presence of one main group and a few outliers (Fig. 67). Cluster D separates from the outliers at a distance of about 5.3. No samples of spawners were available from this system with which to compare this group. However, the mouth of the Jayco River is only 8 km from the mouth of the river system that drains Char and Fish Trap lakes (Fig. 7,8). Local residents of Cambridge Bay suspect that Jayco Lake Arctic char may overwinter and spawn in this system. Therefore, a discriminant function analysis of the samples of spawners from Char and Fish Trap lakes and the

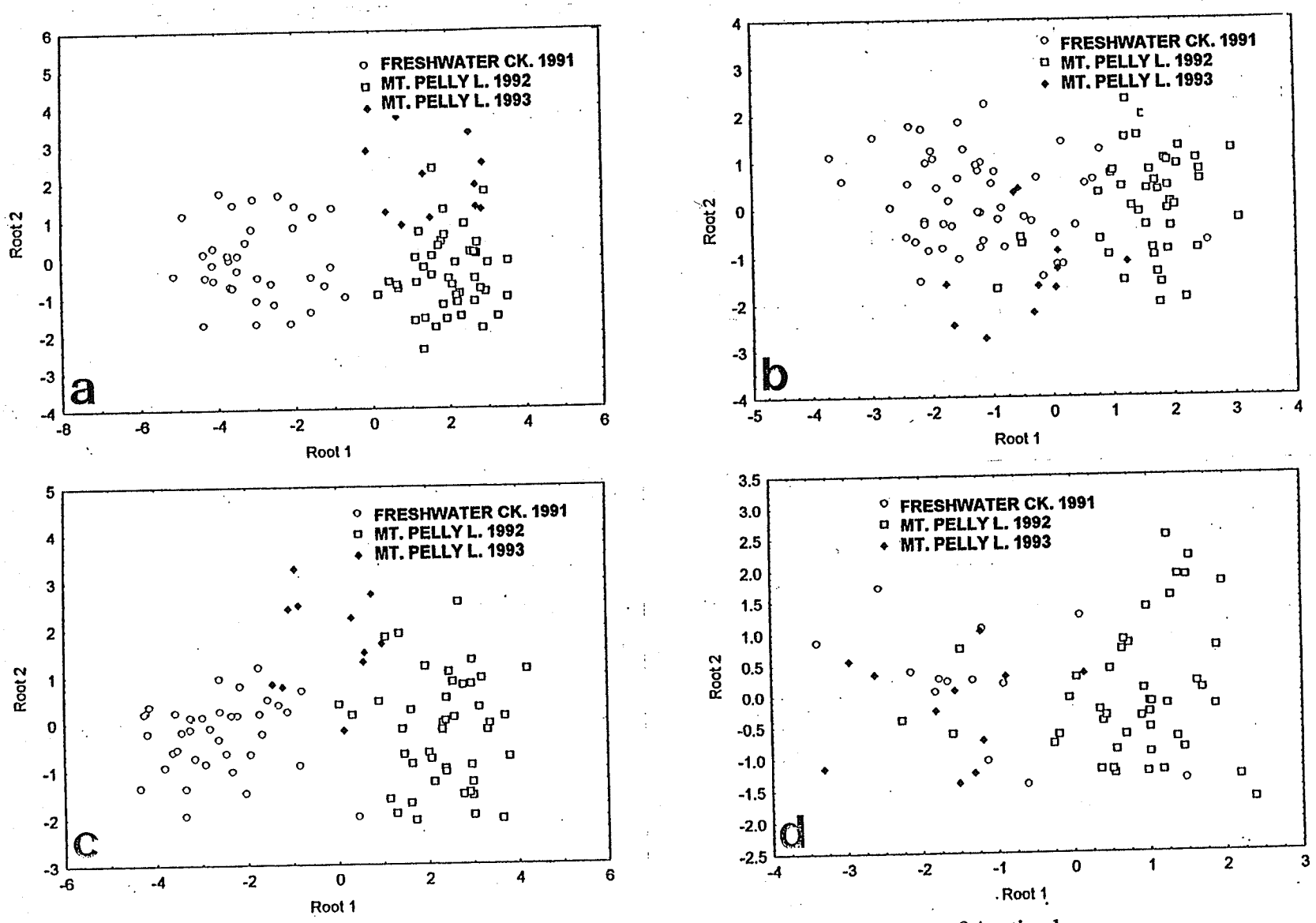

Figure 64. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in the Freshwater Creek system (Mount Pelly Lake 1992 and 1993) and different clusters (Fig. 63) of the 1991 upstream migration. The comparisons are: (a) Cluster C, (b) Cluster D, (c) Cluster E, and (d) Cluster F.

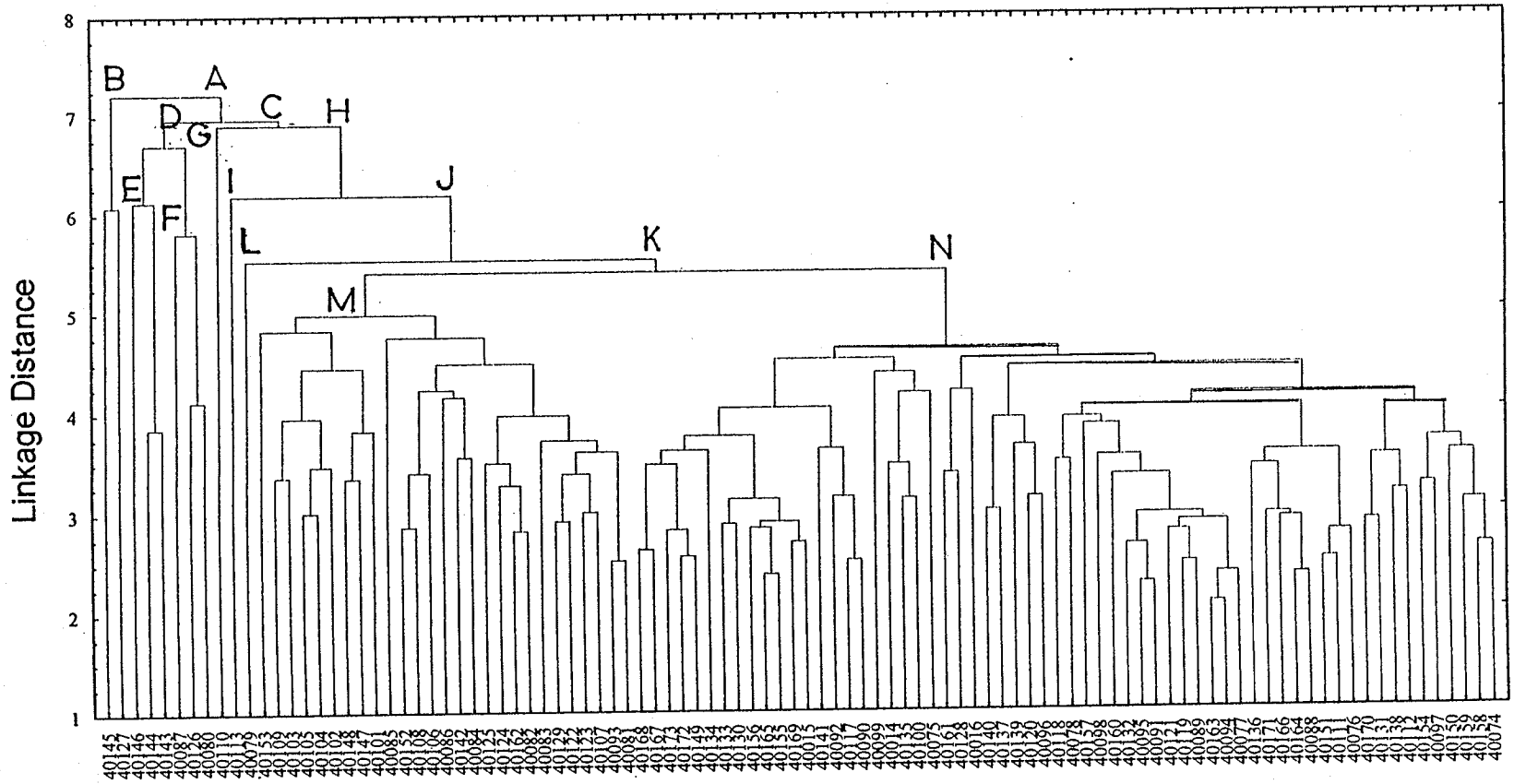

Figure 65. Cluster analysis of morphometric measurements of Arctic char from the upstream migration into Freshwater Creek 1994. Clusters M and N could represent different groups. Sample identification number along abscissa.

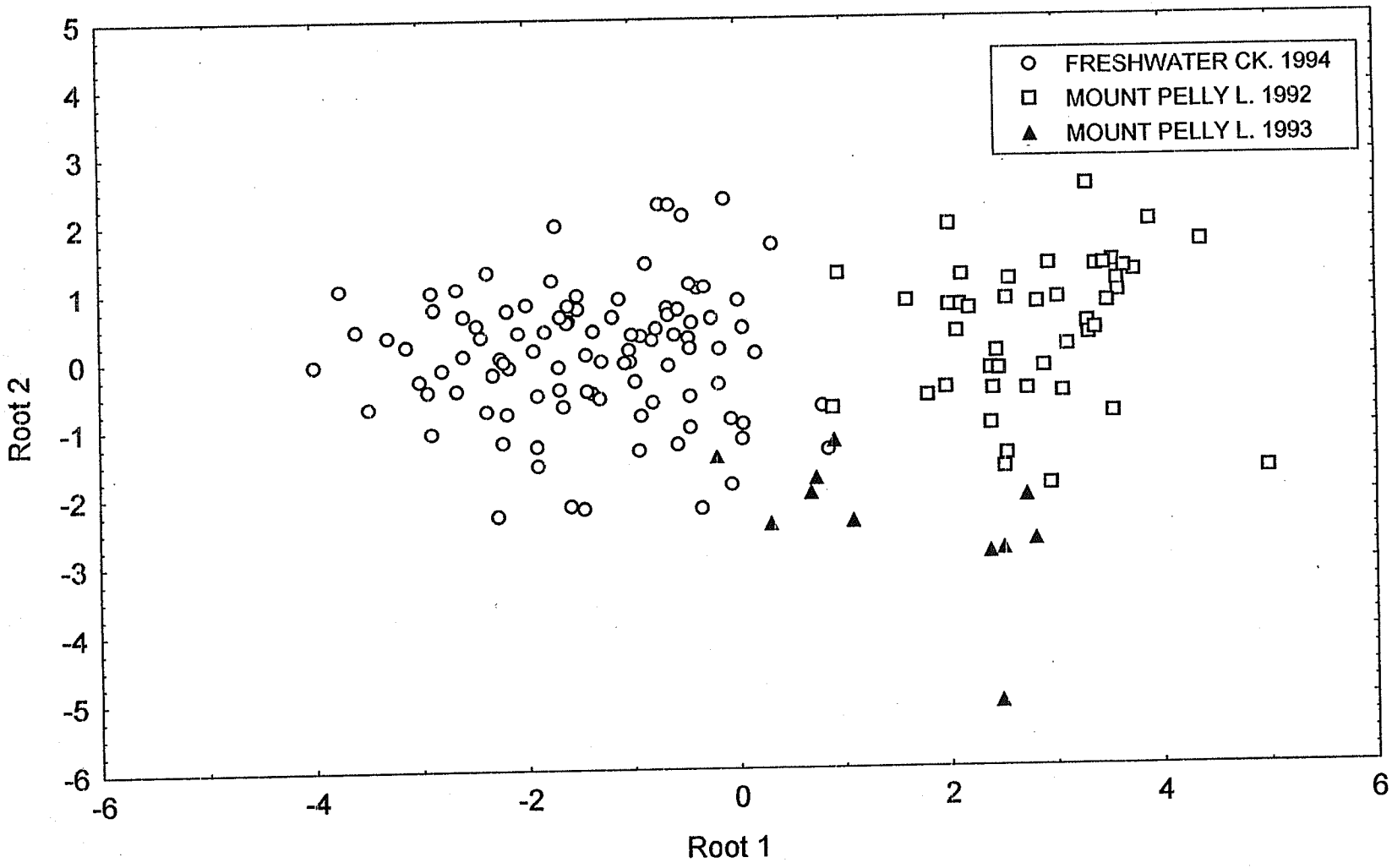

Figure 66. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in the Freshwater Creek system (Mount Pelly Lake 1992 and 1993) and a sample of nonspawning Arctic char from the 1994 upstream migration in Freshwater Creek.

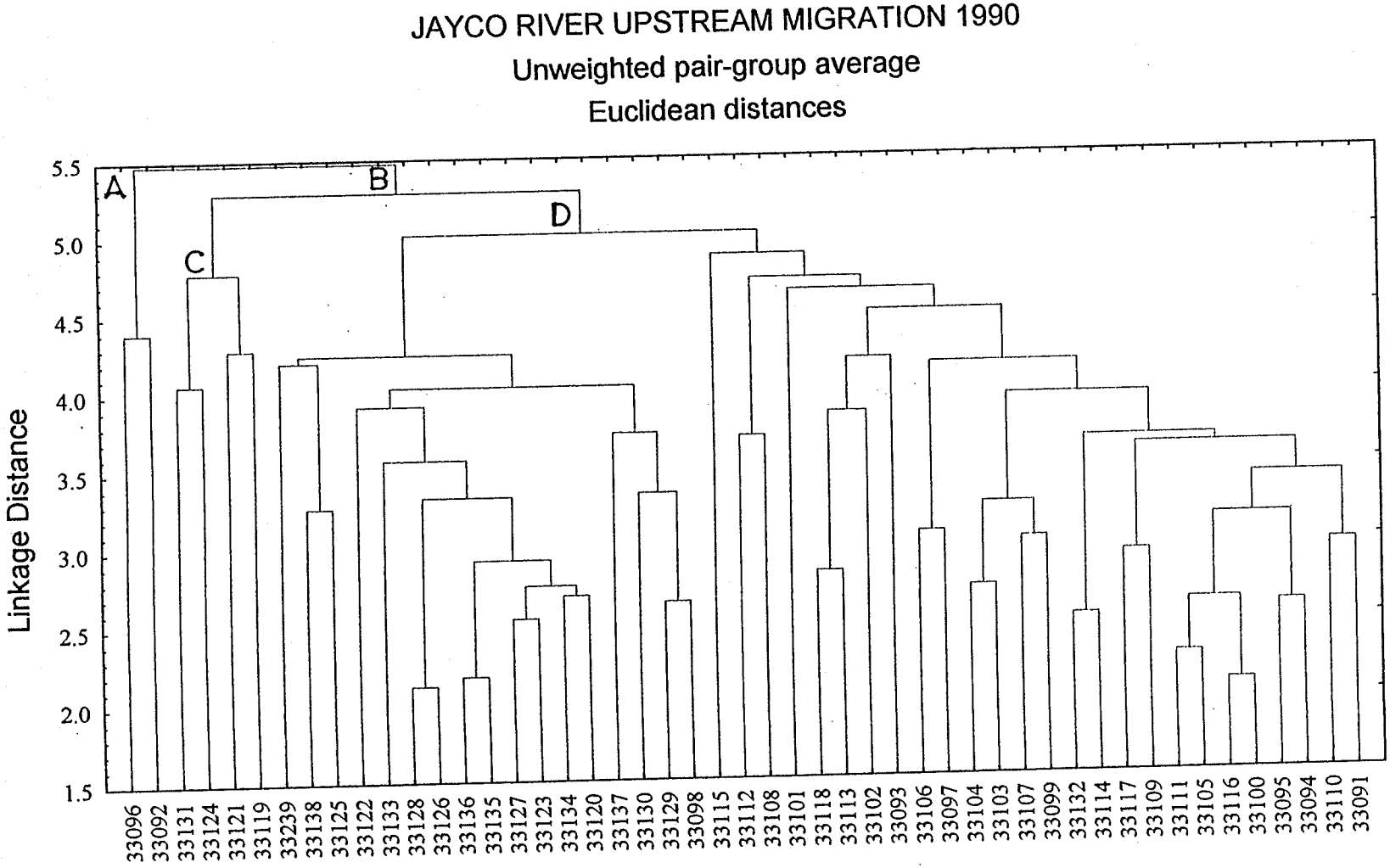

Figure 67. Cluster analysis of morphometric measurements of Arctic char from the 1990 upstream migration in Jayco River. Cluster D could represent a group. Sample identification number along abscissa.

sample from the Jayco River 1990 upstream migration was carried out. The Jayco River 1990 sample appears to be a separate group from the Char and Fish Trap lakes samples (Fig. 68). All Chi-square values with successive roots removed (0.1) were significant ($p < 0.001$). The variables that contributed most to the discrimination were head depth (HDD), trunk length (TTL), and body depth (BDD) in that order (Table 22). The Jayco River 1990 nonspawners were characterized by large mean head depth (Fig. 69a), long mean trunk length (Fig. 69b) and small mean body depth (Fig. 69c), compared with the spawners from Char and Fish Trap lakes. The relationship of trunk length to head depth for these three samples is shown in Fig. 70.

The cluster analysis of the sample of Arctic char taken by the commercial gillnet fishery at the mouth of the Ellice River during the 1990 upstream migration reveals the presence of one main group and a few outliers (Fig. 71). Cluster F separates from the outliers at a distance of about 5.5. Further separation of cluster F occurs at a distance of about 5 but may reflect intra-group variation at this level. This is the only sample of Arctic char that I was able to obtain from the mainland. I was not able to obtain a sample of spawners from this system. However, I wanted to compare a sample of Arctic char from the mainland with samples from Victoria Island. Therefore I carried out a discriminant function analysis between the Ellice River 1990 sample of nonspawners and the geographically closest samples of spawners from Victoria Island. The latter included the samples from Mount Pelly Lake 1992, Anderson Bay Lake 1993, and Anderson Bay Lake 1994 (Fig. 2). Results show that the Ellice River sample is distinct from these three samples of spawners (Fig. 72). The variables that contributed most to the discrimination were head depth (HDD), body depth (BDD) and pectoral fin length (PCL), in that order

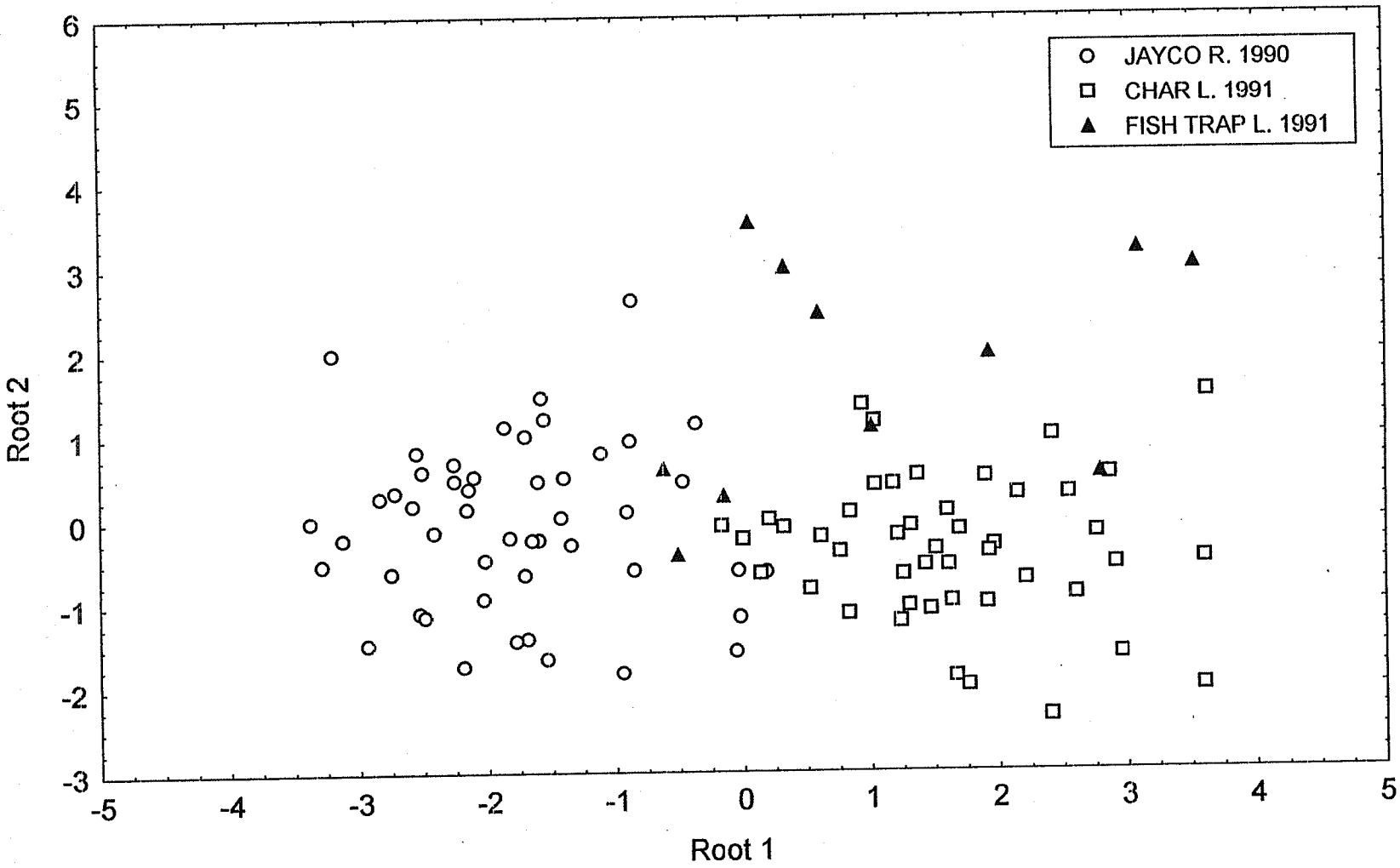

Figure 68. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in Char Lake and Fish Trap Lake in 1991 and a sample of nonspawning Arctic char from the 1990 upstream migration in Jayco River.

Table 22. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Char Lake and Fish Trap Lake, and a sample of nonspawning Arctic char from the 1990 upstream migration in Jayco River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 8, N of vars in model: 8; Grouping: GROUP (3 grps) Wilks' Lambda: .18958 approx. F (16,192)=15.561 p< .0000					
N=106	Wilks' Lambda	Partial Lambda	F-remove (2,96)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGBDD	.223004	.850106	8.46356	.000412	.637414	.362586
LOGHDD	.276434	.685795	21.99181	.000000	.591527	.408473
LOGPCL	.207788	.912355	4.61111	.012242	.425671	.574329
LOGOOL	.219774	.862598	7.64584	.000829	.793612	.206388
LOGTTL	.248598	.762584	14.94387	.000002	.441460	.558540
LOGPVL	.232310	.816050	10.81994	.000058	.358003	.641997
LOGCPD	.217747	.870630	7.13249	.001294	.519930	.480070
LOGPOL	.216622	.875151	6.84767	.001660	.356515	.643485

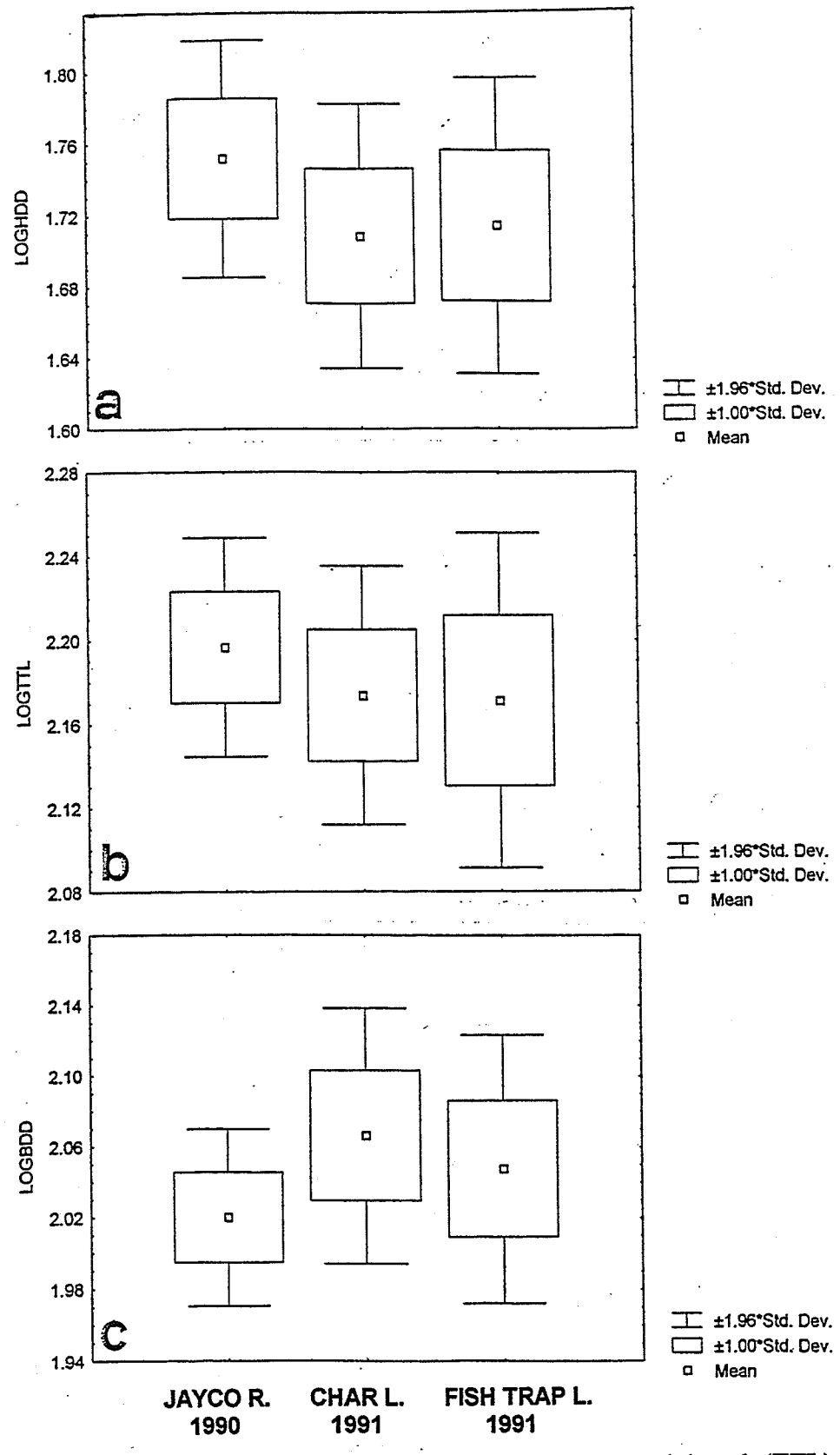

Figure 69. A comparison of mean log (a) head depth (HDD), (b) trunk length (TTL), and (c) body depth (BDD) among samples of Arctic char spawners from Char Lake and Fish Trap Lake in 1991 and a sample of nonspawning Arctic char from the 1990 upstream migration in Jayco River.

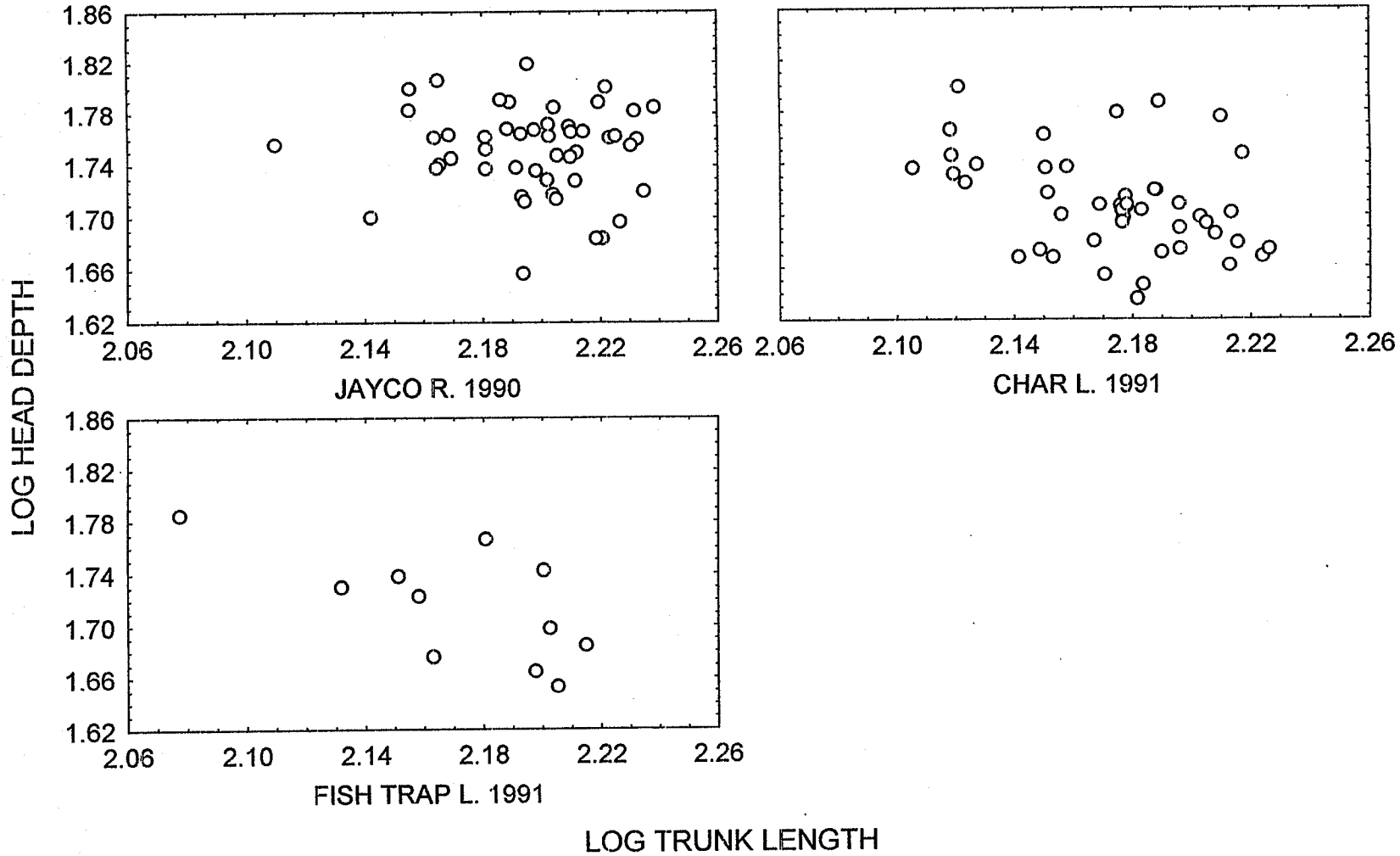

Figure 70. A plot of log trunk length (TTL) against log head depth (HDD) for Arctic char spawners from Char Lake and Fish Trap Lake in 1991 and a sample of nonspawning Arctic char from the 1990 upstream migration in Jayco River.

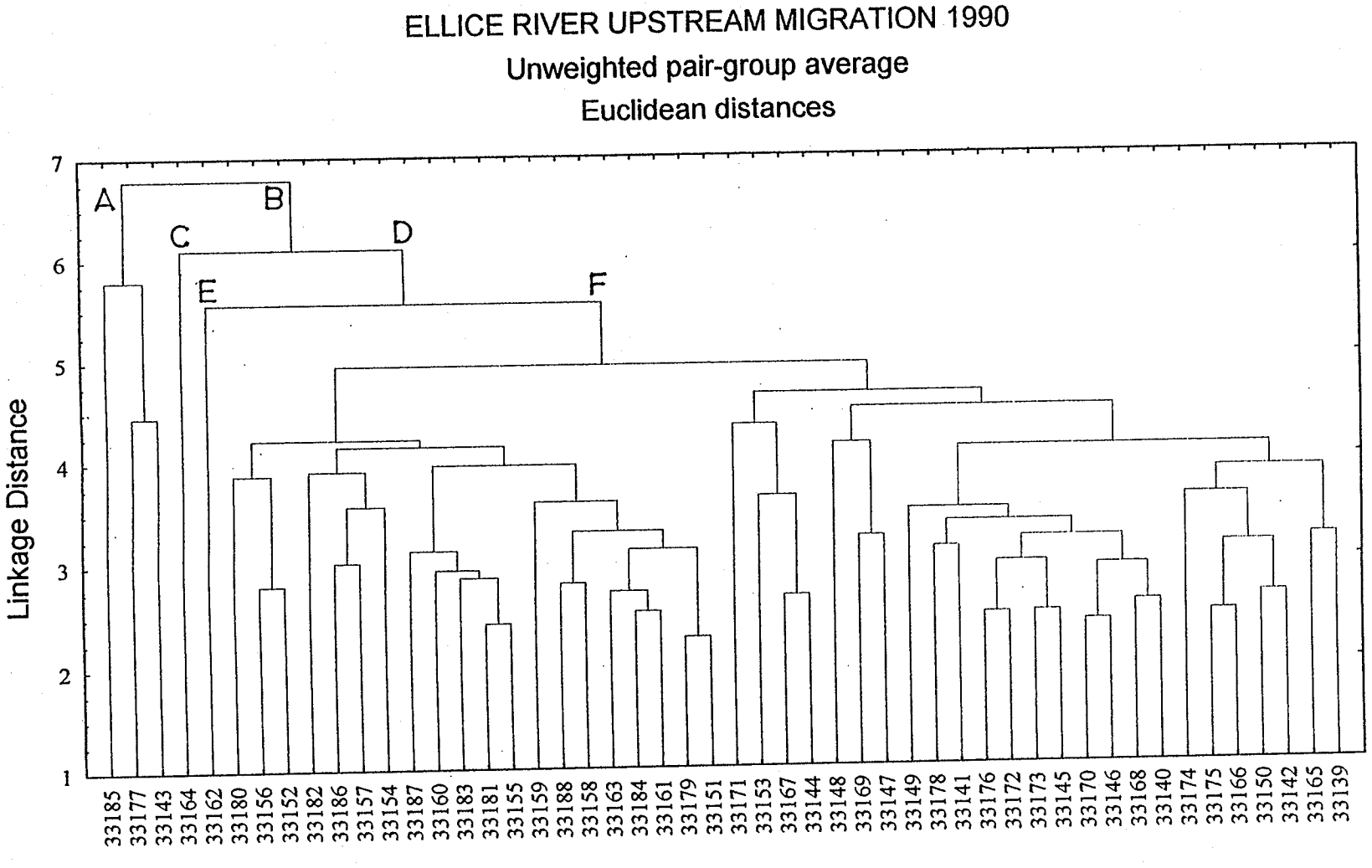

Figure 71. Cluster analysis of morphometric measurements of Arctic char taken by the 1990 commercial gillnet fishery at Ellice River. Cluster F could represent a group. Sample identification number along abscissa.

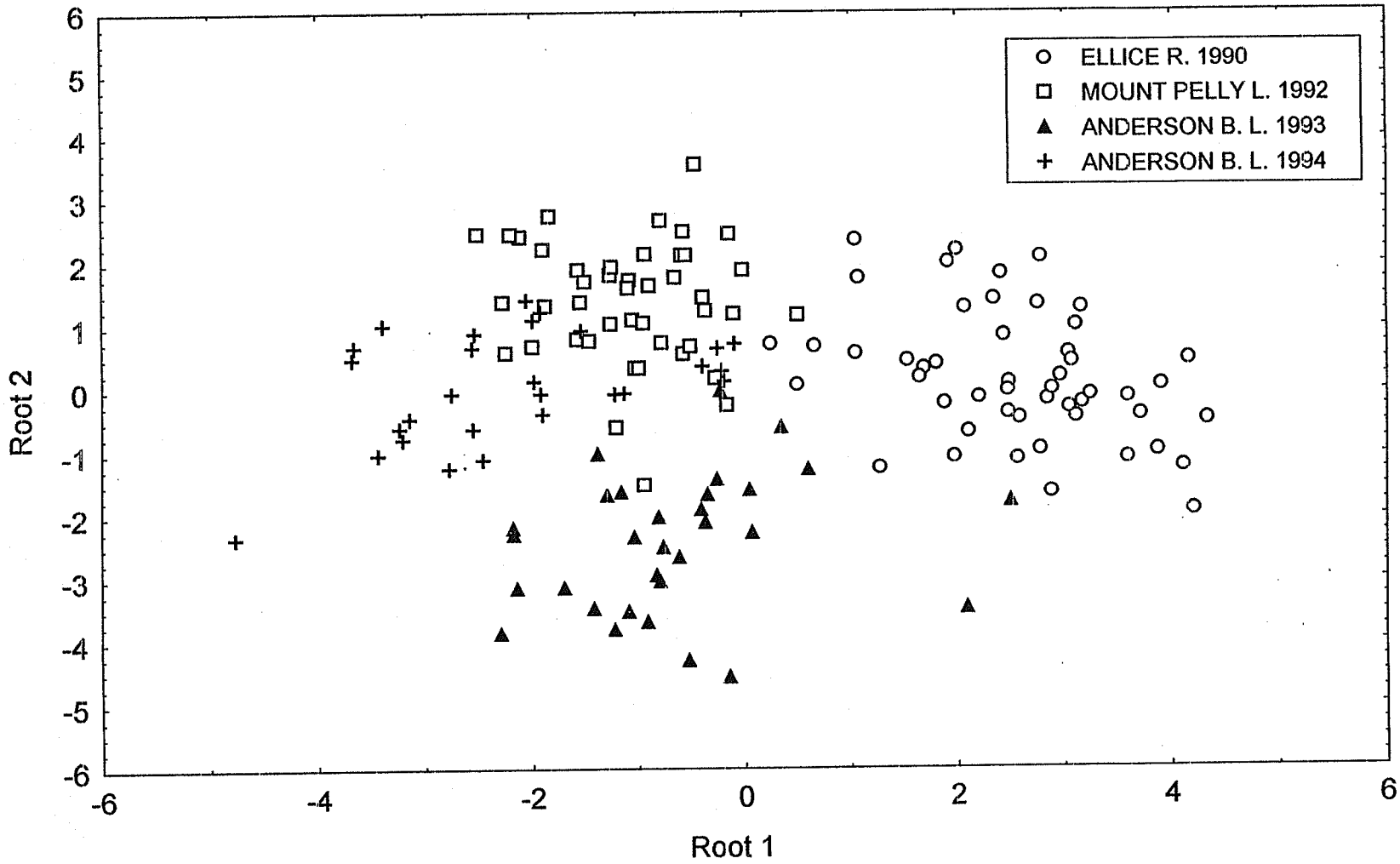

Figure 72. Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in Mount Pelly Lake 1992 and Anderson Bay Lake in 1993 and 1994, and a sample of nonspawning Arctic char taken by the 1990 commercial gillnet fishery at Ellice River.

(Table 23). The Ellice River char had a large mean head depth (Fig. 73a) and mean body depth (Fig. 73b) and short mean pectoral fin length (Fig. 73c) relative to the others. Only the Anderson Bay 1994 sample had a mean body depth similar to the Ellice River sample. The relationship of head depth to body depth for the four groups is shown in Fig. 74.

Comparison of Samples of Spawners and Nonspawners Using Meristics

Discriminant function analysis using meristic variables was carried on the same comparisons of Arctic char spawners as those using morphometric variables. The first comparison was among samples of spawning Arctic char from Ferguson, Lady Pelly and Wishbone lakes. Although there is evidence of group separation (Fig. 75), there is also considerable overlap. All Chi-square values with successive roots removed (0,1) were significant ($p < 0.001$). The meristic counts that contributed most to the discrimination were anal fin ray count (ARC), pelvic fin ray count (VRC) and pyloric caeca count (PYL) in that order (Table 24). Those were the only variables selected in the discriminant analysis. The sample from Lady Pelly Lake was characterized by a higher mean anal fin ray count (Fig. 76a) and higher mean pyloric caeca count (Fig. 76c) than the samples from Wishbone and Ferguson lakes. The sample from Wishbone Lake had the lowest mean pectoral fin ray count (Fig. 76b) of the three samples and the sample from Ferguson Lake had the lowest mean pyloric caeca count (Fig. 76c) of the three samples.

The discriminant function analysis of meristic variables for the remaining comparisons of spawners revealed less discriminating power than the above comparison. In three of the other comparisons, only two variables were selected, and in one, only one variable was selected. Anal fin ray count (ARC) was selected as the most effective

Table 23. Summary of the discriminant function analysis of morphometric measurements of Arctic char spawners from Mount Pelly Lake 1992, Anderson Bay Lake 1993 and Anderson Bay Lake 1994, and a sample of nonspawning Arctic char taken by the 1990 commercial fishery at Ellice River.

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 8, N of vars in model: 8; Grouping: GROUP (4 grps) Wilks' Lambda: .04380 approx. F (24,412)=33.346 p<0.0000					
N=153	Wilks' Lambda	Partial Lambda	F-remove (3,142)	p-level	Toler.	1-Toler. (R-Sqr.)
LOGHDD	.143192	.305895	107.4037	0.000000	.507702	.492298
LOGPCL	.066242	.661235	24.2499	.000000	.797301	.202699
LOGBDD	.067435	.649538	25.5390	.000000	.422499	.577501
LOGPOL	.056498	.775285	13.7195	.000000	.510440	.489560
LOGMXW	.052001	.842323	8.8605	.000020	.844774	.155226
LOGCPD	.047796	.916429	4.3164	.006030	.445749	.554251
LOGTTL	.060681	.721836	18.2402	.000000	.574497	.425503
LOGDOL	.055181	.793778	12.2971	.000000	.570761	.429239

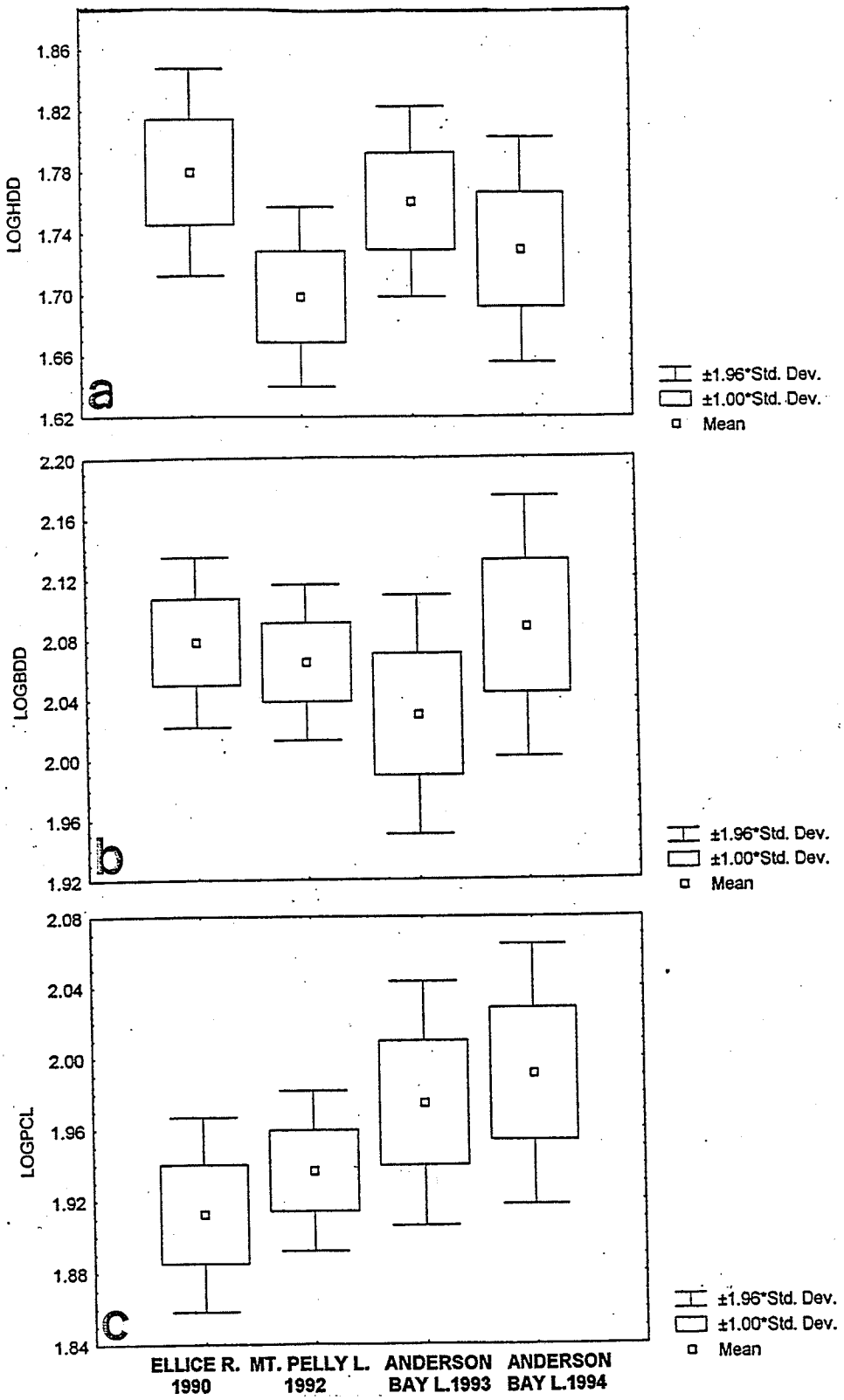

Figure 73. A comparison of mean log (a) head depth (HDD), (b) body depth (BDD), and (c) pectoral fin length (PCL) among samples of Arctic char from spawning aggregations taken in Mount Pelly Lake 1992 and Anderson Bay Lake in 1993 and 1994, and a sample of nonspawning Arctic char taken by the 1990 commercial gillnet fishery at Ellice River.

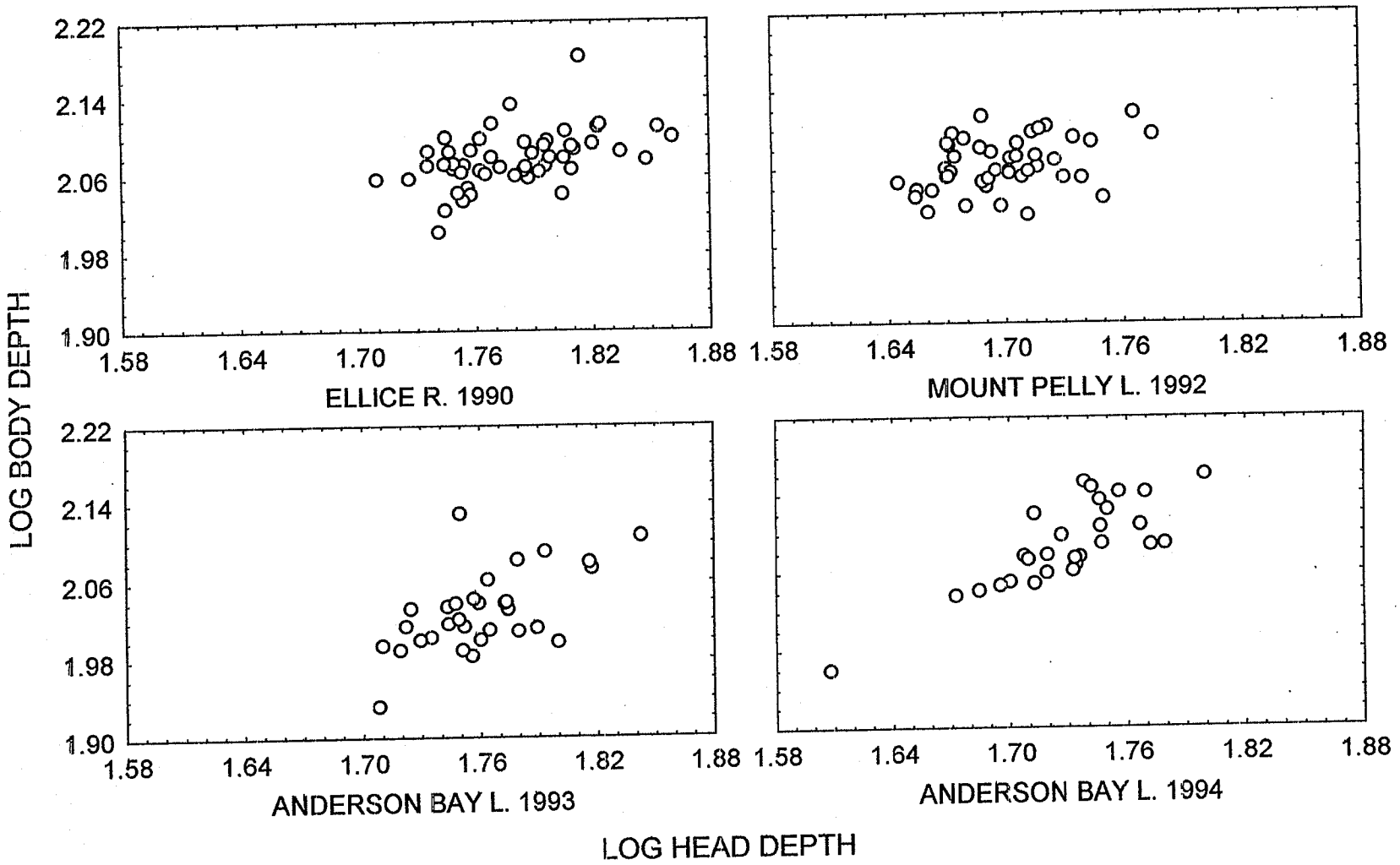

Figure 74. A plot of log head depth (HDD) against log body depth (BDD) for samples of Arctic char from spawning aggregations taken Mount Pelly Lake 1992 and Anderson Bay Lake in 1993 and 1994, and a sample of nonspawning Arctic char taken by the 1990 commercial gillnet fishery at Ellice River.

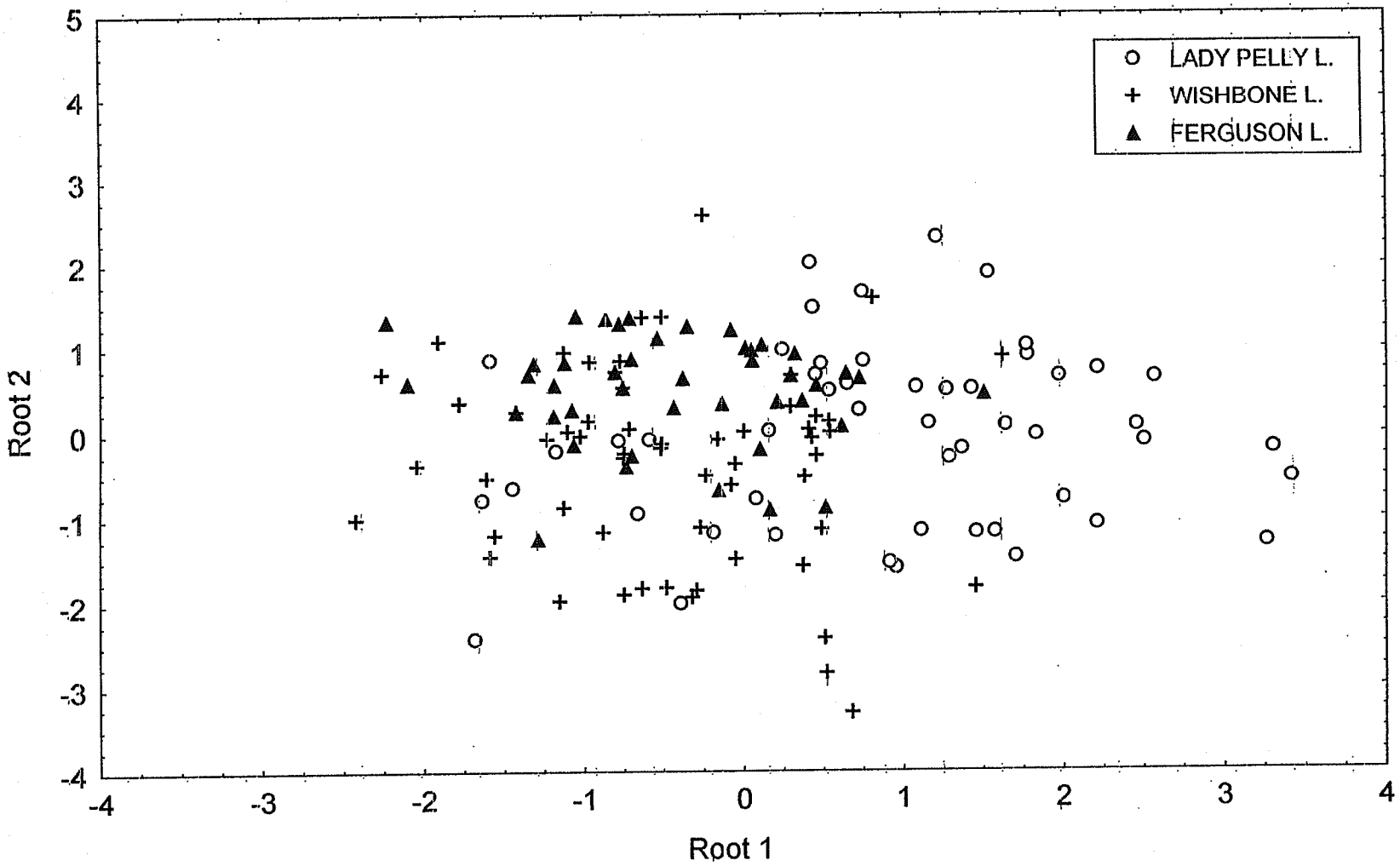

Figure 75. Discriminant function analysis of meristic counts from samples of Arctic char spawners from the Ekalluk River system (Ferguson, Lady Pelly and Wishbone lakes).

Table 24. Summary of the discriminant function analysis of meristic counts of Arctic char spawners from the Ekalluk River System (Lady Pelly, Wishbone and Ferguson lakes).

STAT. DISCRIM. ANALYSIS	Discriminant Function Analysis Summary Step 6, N of vars in model: 6; Grouping: GROUP (3 grps) Wilks' Lambda: .61678 approx. F (12,296)=6.7416 p< .0000					
N=156	Wilks' Lambda	Partial Lambda	F-remove (2,148)	p-level	Toler.	1-Toler. (R-Sqr.)
ARC	.727853	.847404	13.32555	.000005	.961347	.038653
VRC	.684543	.901017	8.12937	.000447	.977342	.022658
PYL	.657113	.938628	4.83846	.009216	.993733	.006267
UGR	.645875	.954960	3.49014	.033030	.926881	.073119
BRC	.627048	.983633	1.23134	.294874	.972640	.027360
DRC	.625668	.985802	1.06578	.347089	.968701	.031299

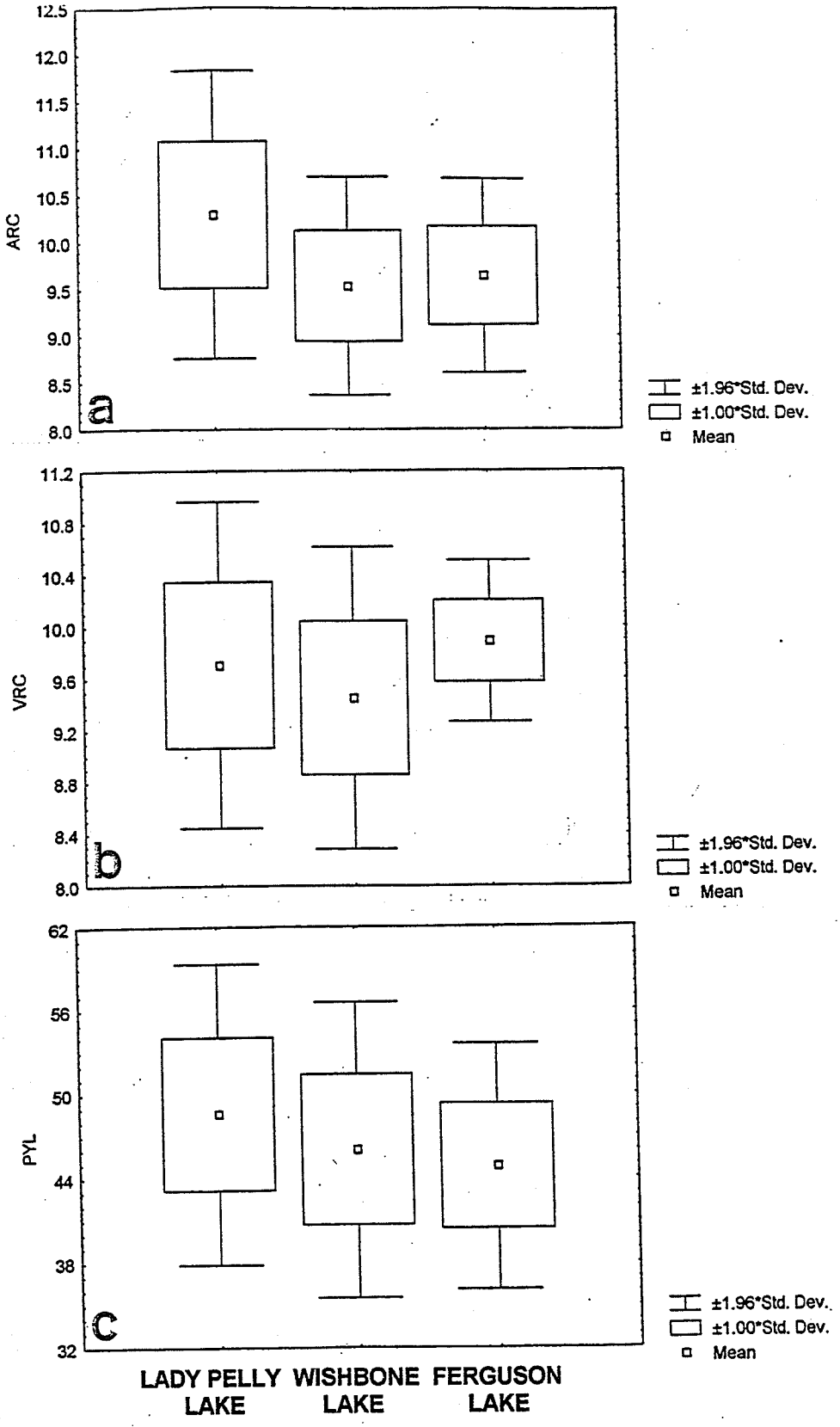

Figure 76. A comparison of (a) anal fin ray count (ARC), (b) pelvic fin ray count (VRC), and (c) pyloric caeca count (PYL) between samples of Arctic char spawners from the Ekalluk River system (Ferguson, Lady Pelly and Wishbone lakes).

discriminator in two of the comparisons as was pyloric caeca count (PYL) for two others. Upper gill raker count (UGR) was selected as the most important discriminator in one comparison of spawners. A comparison of means of these three meristic counts for the twelve samples of spawners examined in this study is shown in Fig. 77. The samples from Lady Pelly Lake, Anderson Bay Lake 1993, and Fish Trap Lake had the highest mean anal fin ray count (ARC) of all groups (Fig. 77a). The samples from Anderson Bay Lake 1993 and Anderson Bay Lake 1994 had the highest mean pyloric caeca count (PYL) of all the samples (Fig. 77b). The sample from Halovik Lake 1987 had the lowest mean upper gill raker count (UGR) of all the samples (Fig. 77c). Analysis of variance of these three variables across all 12 samples together revealed significant differences in mean values ($p < 0.001$) for each variable. All pairs of means were compared using the Least Significant Difference (LSD) test. Results of the comparison of mean anal fin ray count are shown in Table 25, those for mean pyloric caeca count in Table 26, and those for mean upper gill raker count in Table 27. The mean upper gill raker count for the sample from Halovik Lake 1987 was significantly different from that of all the other samples of spawners.

A pattern was evident when the samples from the six Ekalluk River upstream migrations of nonspawners were examined for meristic variation. The sample from the 1992 upstream migration showed the greatest variation in six of the eight meristic counts taken when compared with the other five samples (Figs. 78, 79). Also, the 1992 sample had the lowest mean anal fin ray count (Fig. 78a), the lowest mean upper gill raker count (Fig. 78b) and the lowest mean lower gill raker count (Fig. 78c) compared with the samples from the other five upstream migrations. As well, the 1992 sample had the

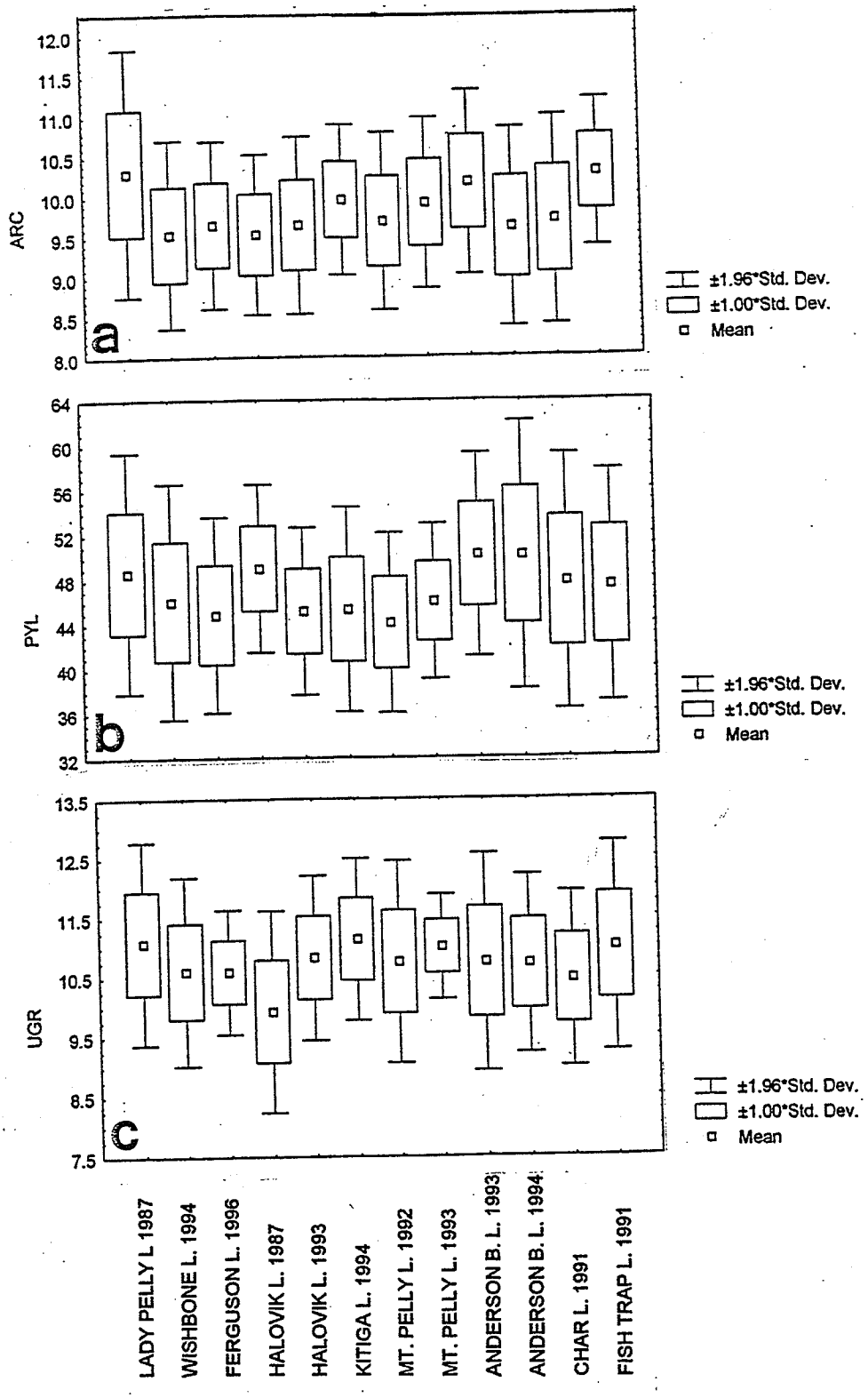

Figure 77. A comparison of (a) anal fin ray count (ARC), (b) pyloric caeca count (PYL), and (c) upper gill raker count (UGR) among the twelve samples of Arctic char spawners examined.

Table 25. Pair-wise comparisons of the mean values of the meristic variable anal fin ray count (ARC) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable ARC Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} 10.29412	{2} 9.525424	{3} 9.644444	{4} 9.500000	{5} 9.634615	{6} 9.954545
LADY PELLY L. [1]		.000000*	.000000*	.000054*	.000000*	.028742*
WISHBONE L. [2]	.000000*		.322038	.894759	.344474	.004856*
FERGUSON L. [3]	.000000*	.322038		.463974	.936598	.050066
HALOVIK L. 87 [4]	.000054*	.894759	.463974		.488691	.037402*
HALOVIK L. 93 [5]	.000000*	.344474	.936598	.488691		.038719*
KITIGA L. [6]	.028742*	.004856*	.050066	.037402*	.038719*	
MT. PELLY L. 92 [7]	.000001*	.196230	.771474	.357873	.704190	.085831
MT. PELLY L. 93 [8]	.056906	.054798	.195285	.106917	.173460	.839279
ANDERS. B. L. 93 [9]	.336821	.000003*	.000296*	.001450*	.000151*	.222136
ANDERS. B. L. 94 [10]	.000002*	.557455	.798460	.608941	.846871	.045054*
CHAR L. [11]	.000002*	.174043	.728332	.338355	.660530	.093026
FISH TRAP L. [12]	.915567	.000202*	.002215*	.002424*	.001641*	.156202

STAT. GENERAL MANOVA	LSD test; variable ARC Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} 9.681818	{8} 9.909091	{9} 10.16129	{10} 9.607142	{11} 9.688889	{12} 10.27273
LADY PELLY L. [1]	.000001*	.056906	.336821	.000002*	.000002*	.915567
WISHBONE L. [2]	.196230	.054798	.000003*	.557455	.174043	.000202*
FERGUSON L. [3]	.771474	.195285	.000296*	.798460	.728332	.002215*
HALOVIK L. 87 [4]	.357873	.106917	.001450*	.608941	.338355	.002424*
HALOVIK L. 93 [5]	.704190	.173460	.000151*	.846871	.660530	.001641*
KITIGA L. [6]	.085831	.839279	.222136	.045054*	.093026	.156202
MT. PELLY L. 92 [7]		.266981	.000821*	.610823	.956176	.004061*
MT. PELLY L. 93 [8]	.266981		.236791	.162574	.281055	.160481
ANDERS. B. L. 93 [9]	.000821*	.236791		.000509*	.000927*	.600897
ANDERS. B. L. 94 [10]	.610823	.162574	.000509*		.575828	.002185*
CHAR L. [11]	.956176	.281055	.000927*	.575828		.004432*
FISH TRAP L. [12]	.004061*	.160481	.600897	.002185*	.004432*	

Table 26. Pair-wise comparisons of the mean values of the meristic variable pyloric caeca count (PYL) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable PYL Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} 48.60784	{2} 46.05000	{3} 44.76744	{4} 49.00000	{5} 45.13726	{6} 45.30435
LADY PELLY L. [1]		.006996*	.000207*	.799012	.000451*	.008247*
WISHBONE L. [2]	.006996*		.195797	.052285	.333920	.539719
FERGUSON L. [3]	.000207*	.195797		.007240*	.718603	.675035
HALOVIK L. 87 [4]	.799012	.052285	.007240*		.012477*	.032154*
HALOVIK L. 93 [5]	.000451*	.333920	.718603	.012477*		.893238
KITIGA L. [6]	.008247*	.539719	.675035	.032154*	.893238	
MT. PELLY L. 92 [7]	.000011*	.043620*	.500190	.001702*	.288191	.326244
MT. PELLY L. 93 [8]	.114087	.975465	.461926	.140128	.600650	.701871
ANDERS. B. L. 93 [9]	.169296	.000201*	.000005*	.478448	.000011*	.000411*
ANDERS. B. L. 94 [10]	.198916	.000388*	.000012*	.505840	.000025*	.000631*
CHAR L. [11]	.400940	.078781	.004616*	.426298	.009541*	.052864
FISH TRAP L. [12]	.450384	.419280	.121672	.420537	.177166	.257485

STAT. GENERAL MANOVA	LSD test; variable PYL Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} 44.04651	{8} 46.00000	{9} 50.16129	{10} 50.10714	{11} 47.76087	{12} 47.36364
LADY PELLY L. [1]	.000011*	.114087	.169296	.198916	.400940	.450384
WISHBONE L. [2]	.043620*	.975465	.000201*	.000388*	.078781	.419280
FERGUSON L. [3]	.500190	.461926	.000005*	.000012*	.004616*	.121672
HALOVIK L. 87 [4]	.001702*	.140128	.478448	.505840	.426298	.420537
HALOVIK L. 93 [5]	.288191	.600650	.000011*	.000025*	.009541*	.177166
KITIGA L. [6]	.326244	.701871	.000411*	.000631*	.052864	.257485
MT. PELLY L. 92 [7]		.243864	.000000*	.000001*	.000456*	.048186*
MT. PELLY L. 93 [8]	.243864		.017146*	.020306*	.290201	.518926
ANDERS. B. L. 93 [9]	.000000*	.017146*		.966579	.037677*	.108361
ANDERS. B. L. 94 [10]	.000001*	.020306*	.966579		.048843*	.120411
CHAR L. [11]	.000456*	.290201	.037677*	.048843*		.811291
FISH TRAP L. [12]	.048186*	.518926	.108361	.120411	.811291	

Table 27. Pair-wise comparisons of the mean values of the meristic variable upper gill raker count (UGR) among the twelve samples of Arctic char spawners examined across the study area, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable UGR Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{1} 11.07843	{2} 10.60000	{3} 10.58140	{4} 9.923077	{5} 10.82353	{6} 11.13043
LADY PELLY L. [1]		.001367*	.002203*	.000003*	.099295	.790573
WISHBONE L. [2]	.001367*		.904930	.004741*	.132761	.005760*
FERGUSON L. [3]	.002203*	.904930		.007903*	.134118	.006655*
HALOVIK L. 87 [4]	.000003*	.004741*	.007903*		.000228*	.000010*
HALOVIK L. 93 [5]	.099295	.132761	.134118	.000228*		.117596
KITIGA L. [6]	.790573	.005760*	.006655*	.000010*	.117596	
MT. PELLY L. 92 [7]	.041137*	.332629	.313498	.000848*	.646713	.058453
MT. PELLY L. 93 [8]	.762190	.118300	.112592	.000813*	.496058	.648148
ANDERS. B. L. 93 [9]	.058623	.410648	.382347	.001583*	.645874	.070750
ANDERS. B. L. 94 [10]	.047591*	.521941	.482847	.002639*	.551421	.058410
CHAR L. [11]	.000102*	.347942	.450338	.029856*	.021030*	.000777*
FISH TRAP L. [12]	.762190	.118300	.112592	.000813*	.496058	.648148

STAT. GENERAL MANOVA	LSD test; variable UGR Probabilities for Post Hoc Tests MAIN EFFECT: GROUP					
GROUP	{7} 10.75000	{8} 11.00000	{9} 10.74194	{10} 10.71429	{11} 10.45652	{12} 11.00000
LADY PELLY L. [1]	.041137*	.762190	.058623	.047591*	.000102*	.762190
WISHBONE L. [2]	.332629	.118300	.410648	.521941	.347942	.118300
FERGUSON L. [3]	.313498	.112592	.382347	.482847	.450338	.112592
HALOVIK L. 87 [4]	.000848*	.000813*	.001583*	.002639*	.029856*	.000813*
HALOVIK L. 93 [5]	.646713	.496058	.645874	.551421	.021030*	.496058
KITIGA L. [6]	.058453	.648148	.070750	.058410	.000777*	.648148
MT. PELLY L. 92 [7]		.341735	.964813	.849705	.074805	.341735
MT. PELLY L. 93 [8]	.341735		.345842	.303369	.038314*	1.000000
ANDERS. B. L. 93 [9]	.964813	.345842		.891794	.115706	.345842
ANDERS. B. L. 94 [10]	.849705	.303369	.891794		.168275	.303369
CHAR L. [11]	.074805	.038314*	.115706	.168275		.038314*
FISH TRAP L. [12]	.341735	1.000000	.345842	.303369	.038314*	

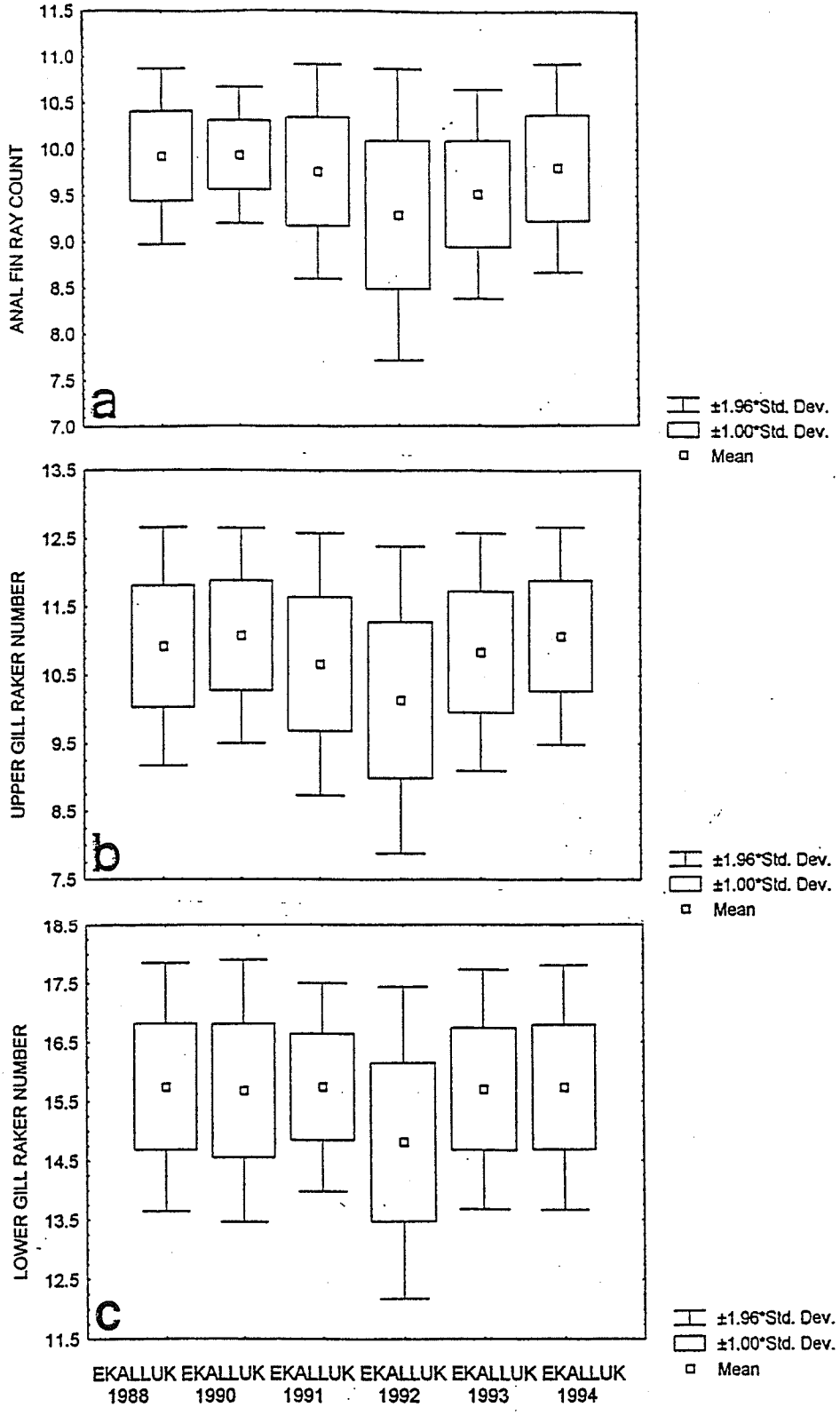

Figure 78. A comparison of (a) anal fin ray count (ARC), (b) upper gill raker count (UGR), and (c) lower gill raker count (LGR) among the six samples of nonspawning Arctic char taken in the upstream migration in the Ekalluk River (1988, 1990, 1991, 1992, 1993, 1994).

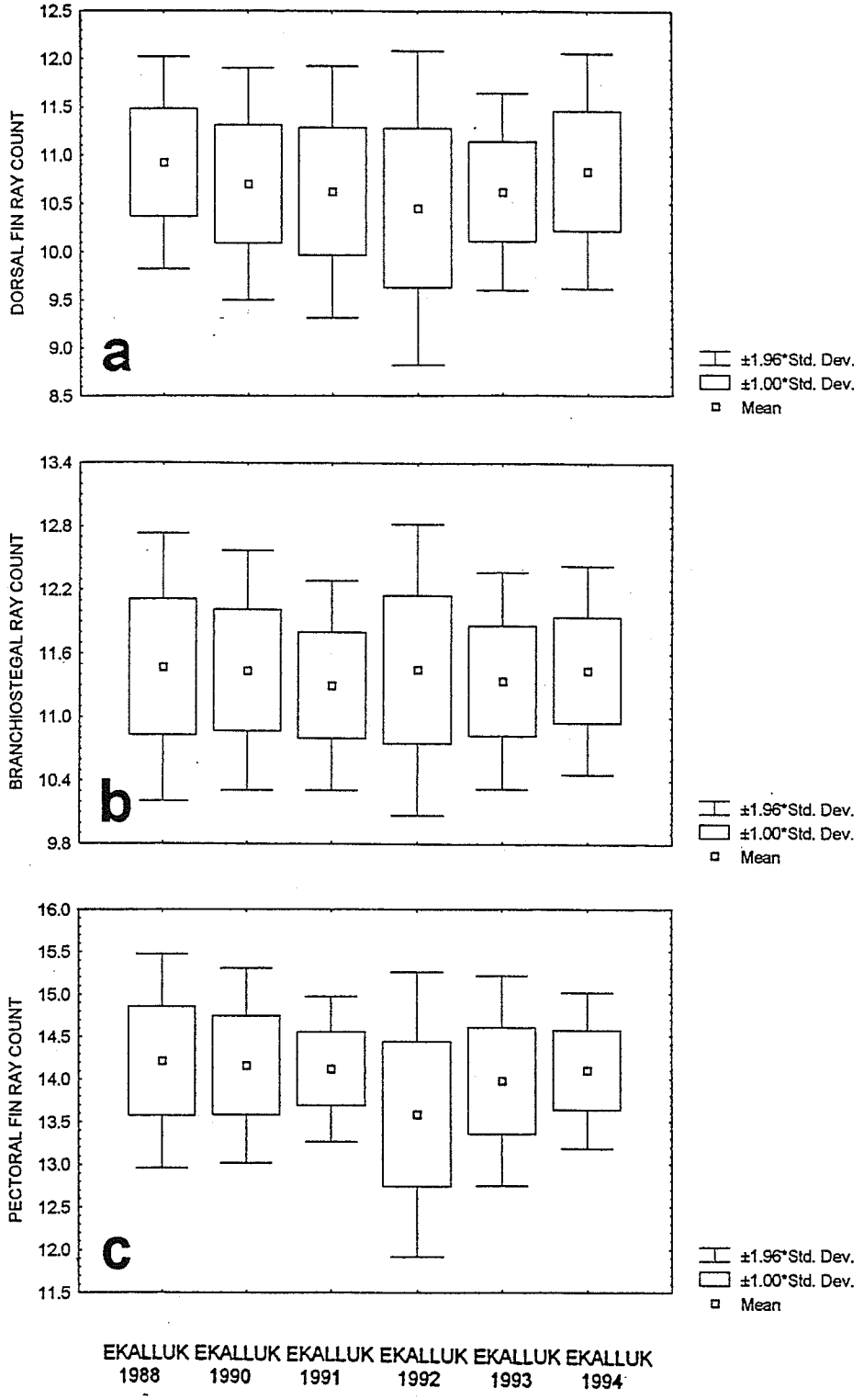

Figure 79. A comparison of (a) dorsal fin ray count (ARC), (b) branchiostegal ray count (BRC), and (c) pectoral fin ray count (PCR) among the six samples of nonspawning Arctic char taken in the upstream migration in the Ekalluk River (1988, 1990, 1991, 1992, 1993, 1994).

lowest mean dorsal fin ray count (Fig. 79a) of the six samples. The mean branchiostegal ray count of the 1992 sample was similar to that of the other five samples but again, the variation in this count was the largest of the six samples (Fig. 79b). The 1992 sample also had the lowest mean pectoral fin ray count of the six samples (Fig. 79c).

Genetic Analysis

Electrophoresis

Five samples of spawning Arctic char and nine samples of nonspawning Arctic char from the study area were examined by electrophoresis (Table 28). Electrophoretic patterns for the enzymes superoxide dismutase (SOD) and phosphoglucomutase (PGM) were invariant across all sample locations while those for esterase (EST), phosphoglucose isomerase (PGI) and isocitrate dehydrogenase (IDH) showed very little variation across all samples. Therefore, these enzymes were excluded from further analysis. Electrophoretic variability was detected among samples when malic enzyme (ME) phenotypes were examined. Malic enzyme is tetrameric with a model of two duplicated loci proposed to account for observed variation in brook char (*Salvelinus fontinalis*) (Stoneking et al. 1979). For this species, one locus (ME-2) is fixed and one locus (ME-1) is variable with three electrophoretically distinct alleles designated ME-1 (100), ME-1 (50) and ME-1 (0), based on the greatest to least mobility, respectively. Andersson et al. (1983) conducted an electrophoretic survey of 33 enzymes of Arctic char from 10 Swedish localities. Their results revealed 52 detectable loci, 37 of which were considered useable for population studies. One of these enzymes was malic enzyme. These authors found two anodal zones of activity for this enzyme in Arctic char. The less

Table 28. Samples of Arctic char spawners and nonspawners examined by electrophoresis.

Location	Spawners / Nonspawners	N
Lady Pelly Lake 1987 (Ekalluk R.)	Spawners	51
Ekalluk River Upstream 1988	Nonspawners	51
Ekalluk River Upstream 1990	Nonspawners	50
Ekalluk River Upstream 1991	Nonspawners	50
Ekalluk River Upstream 1992	Nonspawners	51
Paliryuak River 1992	Nonspawners	52
Halovik Lake 1987	Spawners	30
Lauchlan River 1987	Spawners	29
Mount Pelly Lake 1992	Spawners	45
FW Ck. Upstream 1988	Nonspawners	120
FW Ck. Upstream 1991	Nonspawners	70
Char Lake 1991	Spawners	46
Jayco River Upstream	Nonspawners	49
Ellice River Upstream	Nonspawners	50

anodal zone, from muscle extracts, was represented by three bands and was assumed to represent the expression of a duplicate pair of loci (ME-1 and ME-2) fixed for different alleles.This deviation from the expected five-banded pattern was observed in brook char and was assumed to be caused by reduced expression of protein products specified by the ME-1 locus relative to those of the ME-2 locus (Stoneking et al. 1979). Partington and Mills (1988) found a three-banded electrophoretic phenotype for malic enzyme from liver tissue in Arctic char from ten British lakes. Two loci were assumed to be involved but no variablilty was found at either one. Andersson et al. (1983) observed no variability for malic enzyme among Arctic char samples in their study.

Analysis of electrophoretic phenotypes of malic enzyme for Arctic char from this study suggests that the variable zone is a duplicated pair of loci, one being invariant, and the other variable for two alleles (J. Reist, pers. comm.). In this study, three distinct three-banded electrophoretic phenotypes predominated in all samples that I examined (Table 29). The phenotype with the symmetrical band pattern was assumed to be the heterozygote, based on a banding pattern expected for a tetrameric enzyme (May 1980). Two other phenotypes, not shown in Table 29, were observed occasionally in some of the samples. These may be due to possible variation at the presumptive invariant locus, a third allele of low frequency at the variant locus or variable activity resulting from uneven sample treatment such as differing freeze-thaw regimes (J. Reist, pers. comm.). Therefore, I ignored these phenotypes. The phenotypic patterns I observed are consistent with an inheritance pattern based on a single variable locus with two alleles. These phenotypes could be synonymous with ME-1 (100/100), ME-1 (100/50) and ME-1 (50/50) phenotypes reported by Stoneking et al. (1979) for brook char, given that the

Table 29. Results of electrophoresis of Malic Enzyme. Phenotypic frequencies and gene frequencies are shown as well as a test for Castle-Hardy-Weinberg (CHW) equilibrium. (* = 0.05, ** = 0.01 significance levels)

MALIC ENZYME PHENOTYPES								
	AA	AB	BB		GENE FREQ.			
				N	a	b	$\chi 2$	CHW
Lady Pelly L. (SP)	17	17	2	36	0.71	0.29	1.29	ns
Ekalluk R.88 (NS)	10	15	6	31	0.56	0.44	0.04	ns
Ekalluk R.90 (NS)	12	16	5	33	0.61	0.39	0.04	ns
Ekalluk R.91 (NS)	10	24	12	46	0.48	0.52	0.19	ns
Ekalluk R.92 (NS)	18	13	13	44	0.56	0.44	6.74	*
Paliryuak R92(NS)	11	11	12	34	0.49	0.51	3.96	*
Halovik L. 87 (SP)	9	11	4	24	0.60	0.40	0.11	ns
Lauchlan L.87(SP)	6	15	4	25	0.54	0.46	1.41	ns
Freshw. Ck 88(NS)	25	46	16	87	0.55	0.45	0.24	ns
Freshw. Ck 91(NS)	19	31	10	60	0.58	0.42	0.32	ns
Mt. Pelly L.92 (SP)	5	15	9	29	0.43	0.57	0.24	ns
Jayco R. 90 (NS)	9	21	7	37	0.53	0.47	0.94	ns
Char L 91 (SP)	13	16	7	36	0.58	0.42	0.27	ns
Ellice R. 90 (NS)	19	12	5	36	0.69	1.39	0.27	ns

electrophoretic mobility of ME-1 (50) is intermediate between the ME-1 (100) and ME-1 (0) brook char alleles. I therefore present these data based on this model.

All five samples of spawners examined by electrophoresis satisfied Castle-Hardy-Weinberg equilibrium as did seven of the nine samples of nonspawning Arctic char (Table 29). The samples of nonspawners from the Ekalluk River 1992 upstream migration and the Paliryuak River 1992 commercial fishery did not. Both of these samples showed a heterozygote deficiency. It is interesting to note that within the Ekalluk River 1992 sample, the subsample of morphologically similar Arctic char in cluster J (Fig. 42) satisfied Castle-Hardy-Weinberg equilibrium ($N = 27$, $\chi^2 = 1.96$, 1 df). Similarly, when the subsample of Arctic char in cluster N (Fig. 59) of the Paliryuak River 1992 sample was examined, it satisfied Castle-Hardy-Weinberg equilibrium ($N = 14$, $\chi^2 = 0.28$, 1 df) as well, with respect to phenotypic ratios of malic enzyme.

Comparisons of gene frequencies between samples of spawners revealed a significant difference ($p < 0.05$) between those from Lady Pelly Lake and those from Lauchlan Lake 1987 (Table 30). The gene frequencies for the Lady Pelly Lake sample were significantly different ($p < 0.001$) compared to the sample of spawners from Mount Pelly Lake in the Freshwater Creek drainage. Lady Pelly Lake spawners were marginally different ($p = 0.05$) when compared with the spawners from Char Lake. Spawners from Halovik Lake 1987 and Mount Pelly Lake showed a marginal difference ($p = 0.05$) in gene frequency.

Table 30. A comparison of gene frequencies of Malic Enzyme among samples. (* = 0.05, ** = 0.01, *** = 0.001 significance levels, ns = not significant, mar = marginally significant)

SPAWNERS:

	Lady Pelly L.	Halovik L. (87)	Lauchlan L.	Mt. Pelly L. (92)
Halovik L (87)	ns			
Lauchlan L.	*	ns		
Mt. Pelly L (92)	***	mar	ns	
Char L.	mar	ns	ns	ns

SPAWNERS AND NONSPAWNERS:

Lady Pelly L. Spawners	vs	Ekalluk River Nonspawners 1988	mar
Lady Pelly L. Spawners	vs	Ekalluk River Nonspawners 1991	**
Lady Pelly L. Spawners	vs	Jayco River Nonspawners 1990	*
Mt. Pelly L (92) Spawners	vs	Ellice River Nonspawners 1990	**

Within river systems, Arctic char spawners from Lady Pelly Lake were significantly different ($p < 0.01$) in malic enzyme gene frequencies compared with the sample of nonspawners from the Ekalluk River 1991 upstream migration. Lady Pelly Lake spawners were marginally different in malic enzyme allele frequencies ($p = 0.05$) when compared with the sample of nonspawners from the Ekalluk River 1988 upstream migration (Table 30).

Between river systems, the Lady Pelly Lake spawners were significantly different ($p < 0.05$) from the sample of nonspawners in the Jayco River 1990 upstream migration. The spawners from Mount Pelly Lake in the Freshwater Creek drainage system were significantly different ($p < 0.01$) from the sample of nonspawners taken from the Ellice River commercial fishery in 1990 (Table 30).

The model of a single variable locus with two alleles that I used to explain phenotypic ratios observed in this study is reasonable. All samples of spawners satisfied Castle-Hardy-Weinberg (CHW) equilibrium. The two samples of nonspawners that did not satisfy CHW equilibrium both showed a heterozygote deficiency, consistent with genetically mixed samples. Satisfaction of CHW equilibrium of a subsample of morphologically similar Arctic char (cluster analysis) from within each of these mixed samples further supports the model.

Mitochondrial DNA (mt DNA)

Thirty-nine specimens of Arctic char were examined for sequence variation in the mitochondrial DNA (mt DNA) control region (352 base sequence adjacent to the tRNA Proline gene). Specimens consisted of spawners from Halovik Lake 1993 (N=11) and

Anderson Bay Lake 1994 (N=5), as well samples of nonspawners from the upstream migrations at the Ellice River 1990 (N=5), the Ekalluk River 1993 (N=1) and the Ekalluk River 1994 (N=17). Three hundred and fifty-two bases were examined. One variable base position was found at sequence position 99 (Fig. 80). The reference specimen, from the Ekalluk River 1994 upstream migration (specimen No. 40271), had Thymine at the variable base position and was designated as Haplotype 1. Haplotype 2 had Guanine at the variable base position and Haplotype 3 had Adenine at the variable base position. Thirty-five of thirty-nine char examined were Haplotype 1, three were Haplotype 2 and one was Haplotype 3 (Table 31).

Table 31. Mitochondrial DNA haplotypes found in samples of Arctic char spawners and nonspawners during this study.

Location	Haplotype 1 (T)	Haplotype 2 (G)	Haplotype 3 (A)	N
Ellice R. 1990	5			5
Ekalluk R. 1993	1			1
Ekalluk R. 1994	14	2	1	17
Halovik L. 1993	10	1		11
And. Bay L. 1994	5			5

Given the lack of variability observed among these samples and the resources I had available to me, no further investigation of mitochondrial DNA sequencing was undertaken.

ATTAATAGGA TGATGCTGAA AGTTGGTGGG TAAAGACGGA GCCCGTGTTA

*

GTTGGAGTTT TGTTAATGTA GCAATTATCT AGGTTAAAAC AACCTAGTTG

Haplotype 2 AACCTAGTGG

Haplotype 3 AACCTAGTAG

GTTATTATCA CGTGTTTAGC TTATGTAAAT CTTGGGTTTA TGCTGATATA

TGAGGGCTTA AATTCACTTA TGTTGATAAT ACATATGATG TACTACTCAT

CATACAGGTA TTGTATATAT GGGTAAATAC ATAATATGCA ATATTATACA

TAGATGTATT ATGACACTAA TTTGTTGAGA TACAATATTC ATTATTGTAC

ATATTAGTGG GCGTCAGAGG GTAGTTTAAC TTAGAATCTT AGCTTTGGGT

GC

Figure 80. The 352 base sequence of the mitochondrial DNA control region adjacent to the tRNA Proline gene for Arctic char examined in this study. Haplotype 1 is displayed with an asterisk indicating the variable base position. The short segment (10 bases) indicates the difference with Haplotypes 2 and 3.

Stable Isotope Analysis

Stable isotope analysis was carried out on seventy specimens of Arctic char during this study (Table 32).

Table 32. The range of values of the stable isotopes of carbon (^{13}C), nitrogen (^{15}N), and sulfur (^{34}S) found in Arctic char examined during this study. The number of specimens examined is in brackets.

	Stable Isotope		
Location	^{13}C $^{0}/_{00}$	^{15}N $^{0}/_{00}$	^{34}S $^{0}/_{00}$
Jayco R. 1990	-26.0 to -18.8 (25)	7.5 to 14.7 (24)	-1.7 to 14.1 (15)
Char L. 1991	-22.2 to -19.1 (15)	12.7 to 14.9 (15)	10.6 to 15.3 (15)
Ellice R. 1990	-24.1 to -21.1 (10)	12.2 to 14.9 (10)	
Halovik R. 1992	-24.3 to -21.8 (10)	9.7 to 12.4 (10)	
Ekalluk R. 1992	-23.6 to -21.4 (10)	9.8 to 11.7 (10)	

The carbon and nitrogen isotopes of nonspawning Arctic char from the upstream migration in the Jayco River 1990 showed a wide range of values (Fig. 81a) compared with those from the Ellice River 1990 (Fig. 81 b), Char Lake 1991 spawners (Fig 81c) the Halovik River 1992 (Fig. 81d,) and the Ekalluk River 1992 (Fig. 81e). The char from Jayco River 1990 appear to be feeding at three trophic levels whereas those from the remaining samples appear to be feeding at one trophic level. Arctic char in the Ellice River and Char Lake samples appear to be feeding at a higher trophic level than those

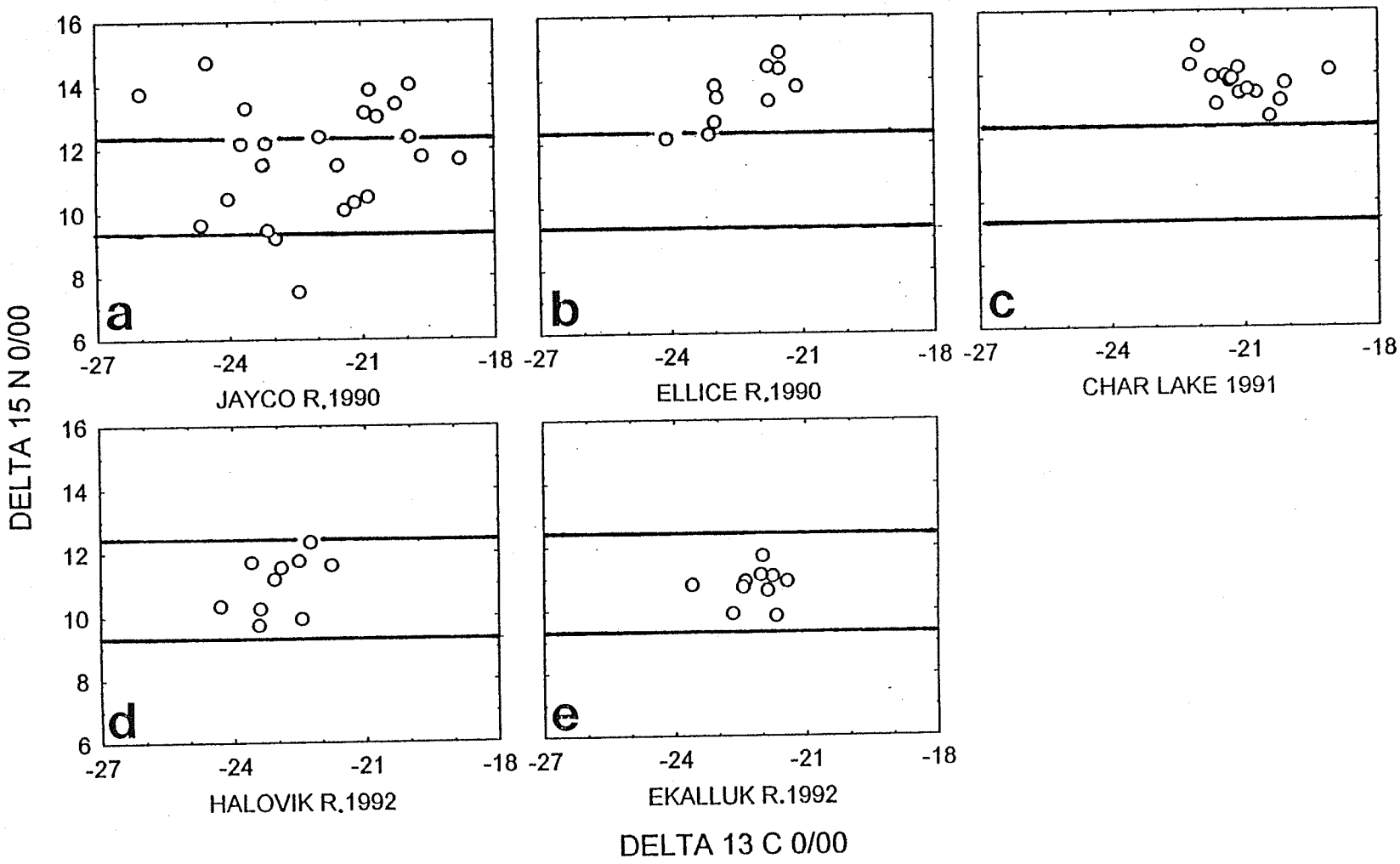

Figure 81. Carbon and nitrogen isotopes in Arctic char taken from the upstream migration in (a) Jayco River 1990, (b) Ellice River 1990, (c) Char Lake spawners 1991, (d) the upstream migration in the Halovik River 1992, and (e) the upstream migration in the Ekalluk River 1992. The solid lines denote trophic levels as per Hesslein et al. (1991).

from the Halovik River and Ekalluk River samples. The sulfur isotopes of the Jayco River sample also showed a wide range of values compared with those of the Char Lake spawners (Fig.82). Jayco River Arctic char appear to be feeding at several trophic levels and may be feeding on food sources from different areas. Char Lake fish appear to be feeding at one trophic level and apparently from a food source from a single location.

Micro-PIXE Analysis of Otolith Strontium Concentrations

Strontium concentrations in water samples taken from the spawning locations were compared with mean strontium concentrations in the early growth zones of otoliths of spawners captured there (Fig. 83). There is a strong linear correlation ($r^2 = 0.86$) between the two.

Micro-PIXE line scans were carried out on at least some specimens from each of the spawning aggregations examined (Table 33).

Four distinct patterns of line scans were observed (Fig. 84). The typical anadromous line scan (Fig. 84a) shows a relatively low strontium concentration in the early growth years that appears to remain constant until the char goes to sea for the first time. Seaward journeys are indicated by the marked spikes in strontium concentration. The strontium concentrations do not return to baseline levels between successive peaks. However, a return to baseline levels was observed in some specimens that apparently did not go to sea in successive years, based on otolith annuli.

The second type of anadromous pattern observed (Fig. 84b) shows a relatively high strontium concentration in the nucleus of the otolith followed by a decline in the early growth period. The strontium concentration then remained relatively constant until

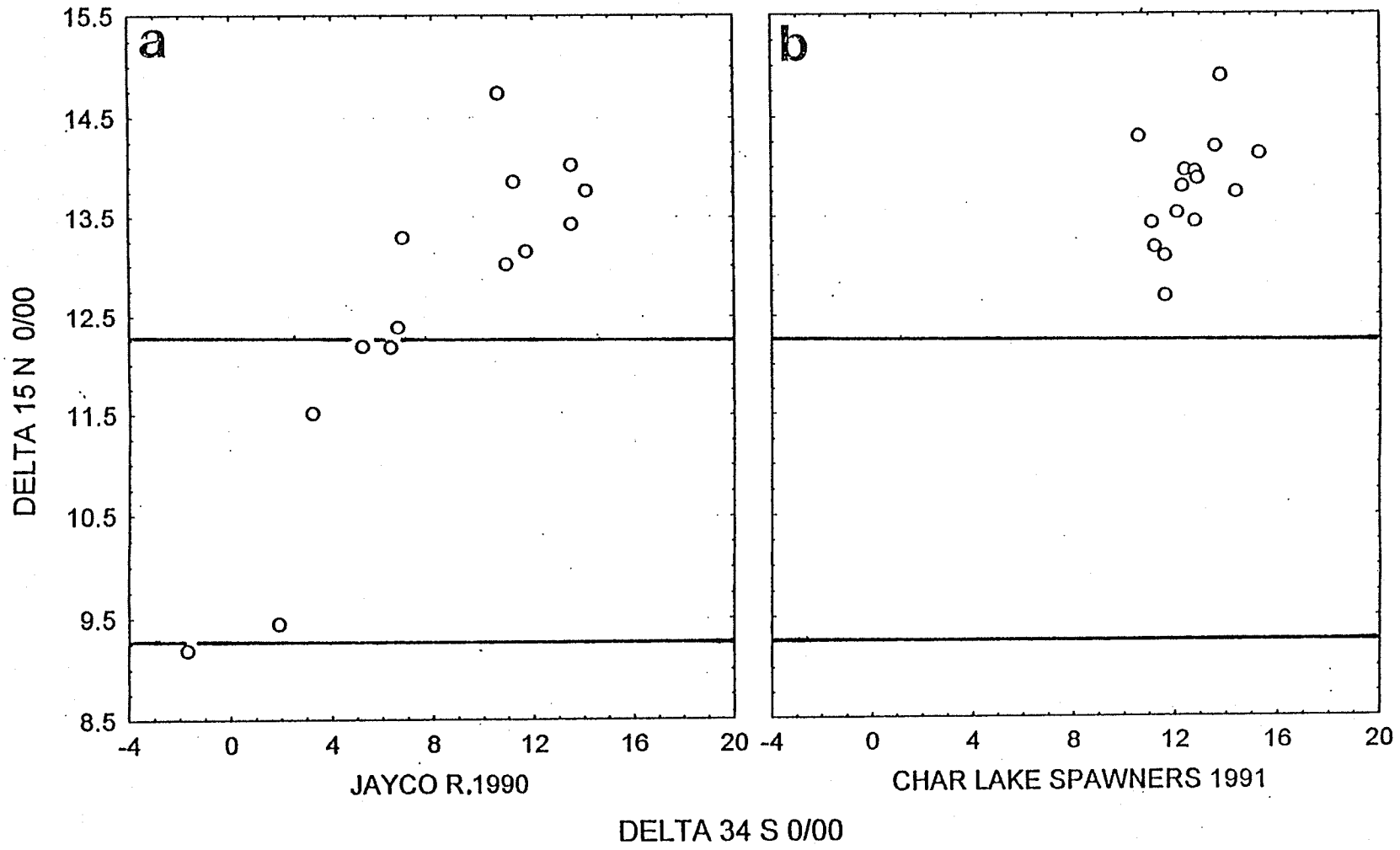

Figure 82. Sulfur and nitrogen isotopes in Arctic char taken from the upstream migration in (a) Jayco River 1990 and (b) Char Lake spawners 1991. The solid lines denote trophic levels as per Hesslein et al. (1991).

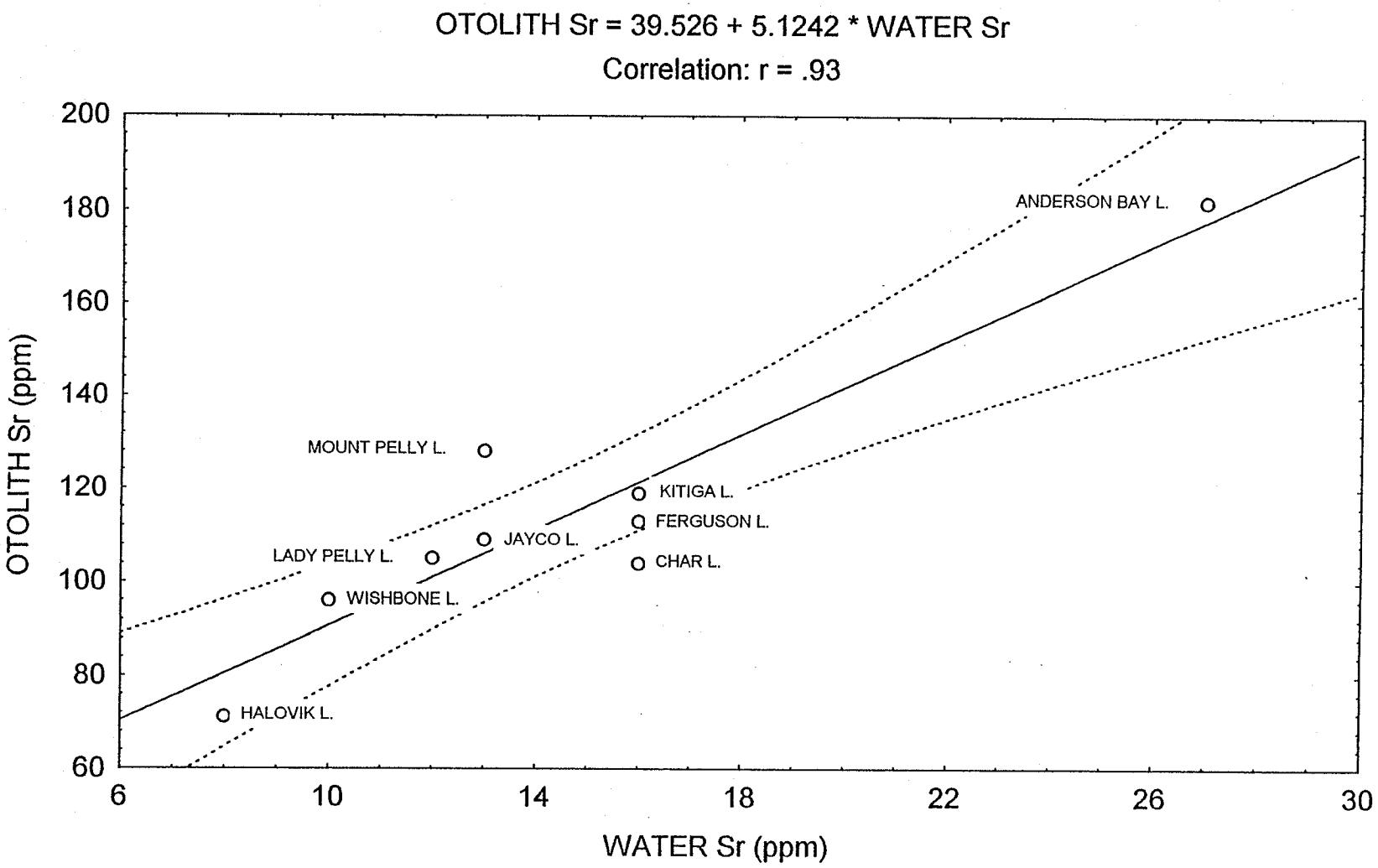

Figure 83. The relationship between strontium in water samples taken at the spawning grounds and strontium in the early growth regions of otoliths of Arctic char spawners captured there. The dashed lines represent the 95% confidence limits.

Table 33. A summary of Micro-PIXE line scan analysis of strontium in the otoliths of Arctic char spawners examined.

Location	N	Line Scans	Anad.*	Non.*	% Mat.	Dist. to Sea
Lady Pelly L.	51	49	14(2)	35(2)	6%	54 km
Wishbone L.	60	58	52(1)	6(0)	2%	98 km
Ferguson L.	45	43	41(29)	2(0)	67%	5 km
Halovik L. 87	13	5	4(1)	1(0)	20%	45 km
Halovik L. 93	52	48	45(3)	3(0)	6%	50 km
Kitiga L.	23	22	22(5)		23%	15 km
Mt. Pelly L.92	44	6	5(0)	1(0)	0%	14 km
Mt. Pelly L.93	11	11	11(10)		91%	14 km
And. Bay L.93	31	4	4(0)		0%	0.3 km
And. Bay L.94	28	26	17(0)	9(0)	0%	0.3 km
Char L.	46	3	3(1)		33%	12 km
Fish Trap L.	11	3	3(1)		33%	10 km

Number in brackets indicates the number of line scans showing a maternal effect.

* Anad. indicates the number of Arctic char in the sample that displayed an anadromous profile. Non. Indicates the number of Arctic char in the sample that displayed a nonanadromous profile.

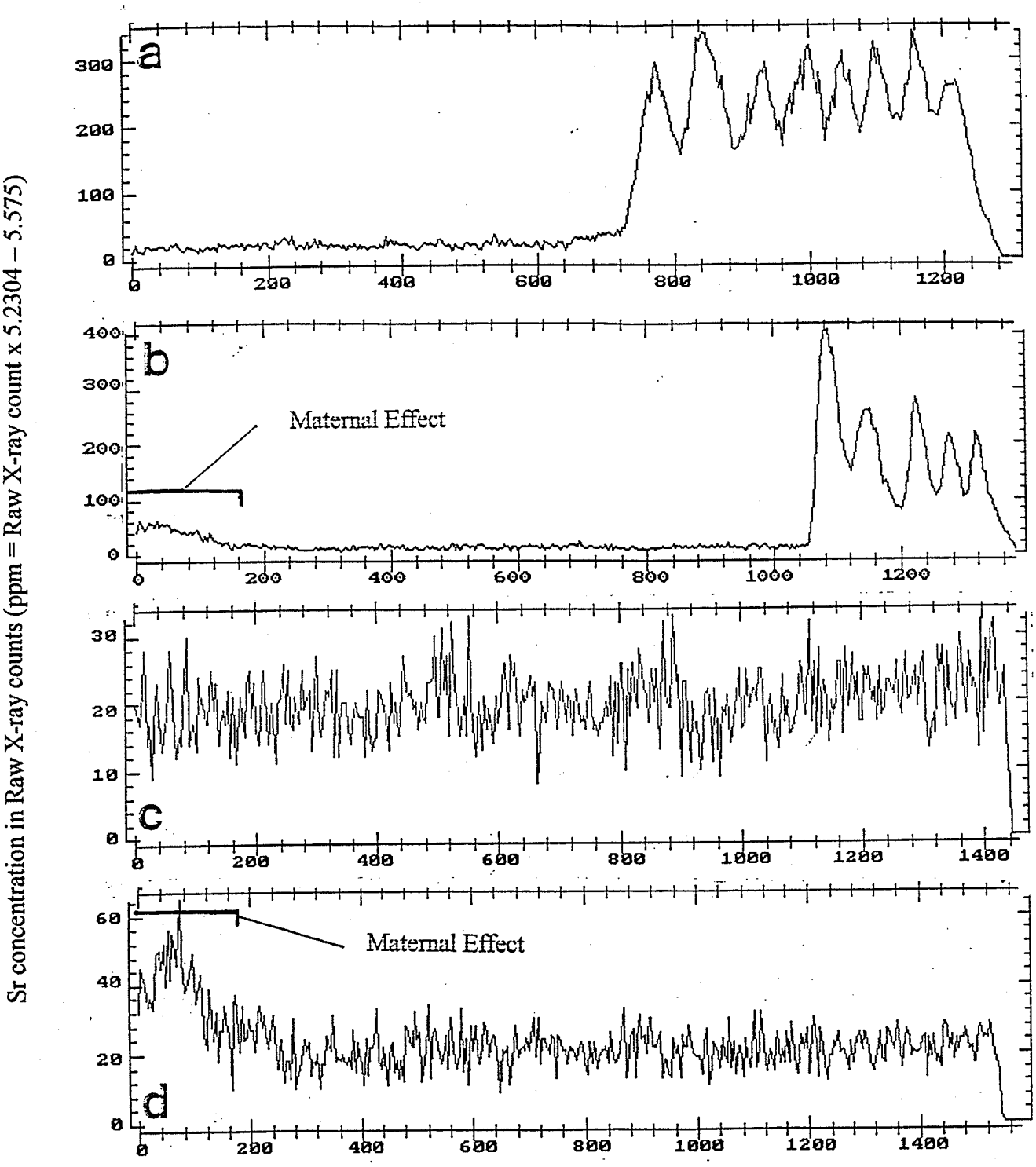

Figure 84. The four distinct patterns of strontium concentrations from the centre of the otolith to its outer edge as revealed by micro-PIXE line scans. The pattern in (a) is from an anadromous Arctic char, (b) is from an anadromous Arctic char showing the maternal effect in the early growth zone, (c) is from a nonanadromous Arctic char and (d) is from a nonanadromous Arctic char showing the maternal effect in the early growth zone.

the char first went to sea, as observed in the typical line scan of Fig. 84(a). The initial high strontium concentration in the nuclear area of the otolith is believed to be a caused by the female making a short excursion to the sea to feed during the summer prior to spawning (see Discussion). This so-called "maternal effect" was observed more frequently in samples from some locations than in others (Table 33).

The third pattern observed from the line scans was the typical nonanadromous pattern (Fig. 84c) whereby the strontium concentration in the otolith remains relatively constant from the nucleus to the edge. The fourth pattern (Fig. 84d) is that of a nonanadromous Arctic char that shows the "maternal effect" in the nuclear portion of the otolith.

Anadromous Arctic char were captured at every site (Table 33). Nonanadromous Arctic char were also found in some of the samples. Most of the spawners from Lady Pelly Lake were nonanadromous. All the specimens examined from Kitiga Lake, Mount Pelly Lake 1993, Anderson Bay Lake 1993, Char Lake and Fish Trap Lake were anadromous. Most of the specimens examined from Wishbone Lake, Ferguson Lake, Halovik Lake 1987, Mount Pelly Lake 1992, and Anderson Bay Lake 1994 were anadromous. The pattern of the line scan provides evidence of anadromy.

The incidence of char showing the "maternal effect" appears to be related to the distance of the spawning ground from the sea (Table 33, Fig. 85). A total of sixty-seven percent of the samples from Ferguson Lake showed this effect. This spawning ground is only 5 km from the sea. In contrast, only one of the specimens from Wishbone Lake, 98 km from the sea, showed this effect. Interestingly, none of the specimens from Anderson

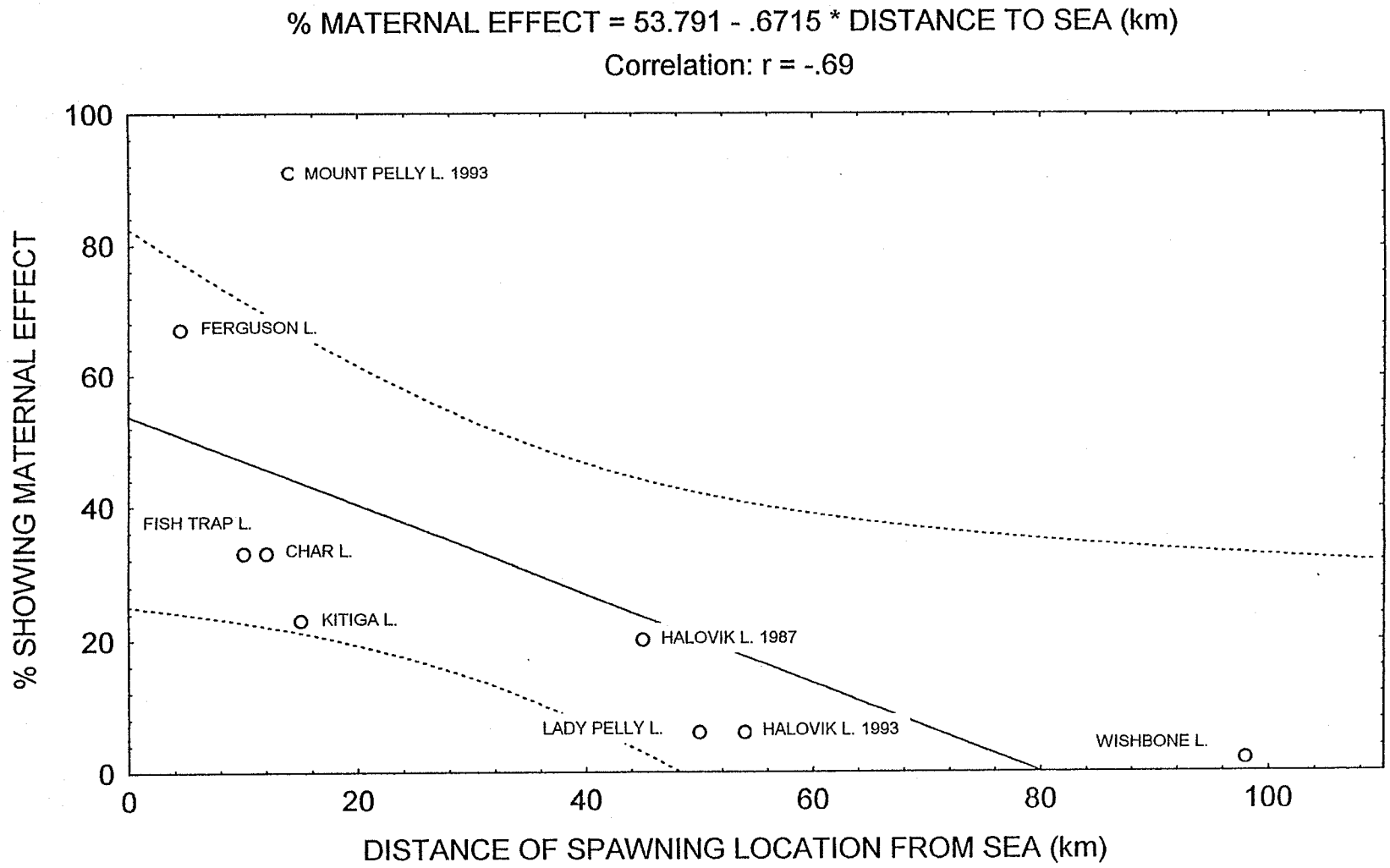

Figure 85. A comparison of the percent of spawners displaying the "maternal effect" of strontium concentrations in the otolith primordia with the distance of the spawning ground from the sea.

Bay Lake showed this effect even though the outlet of this lake to the sea is only 0.3 km long. It is, however, very shallow and may not allow passage of fish at times.

In order to remove the "maternal effect" so that the otolith strontium concentration that is characteristic of the rearing waters can be measured, an average of the strontium concentration over a distance of 100 μm, starting at a distance of 200 μm from the centre of the otolith, was taken. The "maternal effect" was generally not observed beyond this distance. The diameter of the otolith is about 500 μm post-hatch (J. Babaluk pers. comm.).

The mean strontium concentration in the early growth portion of otoliths of spawners examined varied among locations (Table 34). It ranged from a high of 182 ppm in Anderson Bay Lake 1994 spawners to a low of 66 ppm in Halovik Lake 1987 spawners. In marked contrast, the sample of nonspawners from the Ellice River on the mainland had a mean strontium concentration of 1040 ppm.

The mean strontium concentration in samples of spawners was compared by analysis of variance (ANOVA). Group differences were significant ($p < 0.001$). Pair-wise comparisons of group means (Table 35) revealed that all were significantly different with the exception of Halovik Lake 1987 and Halovik Lake 1993, Kitiga Lake and Ferguson Lake, and Mount Pelly Lake 1993 and Kitiga Lake.

The strontium concentration in the early growth regions of the otoliths of spawners was plotted against age (Fig. 86). In each case, strontium concentrations did not vary with age within each sample, whereas means differed among samples. The sample

Table 34. A summary of mean strontium concentration in the early growth region of otoliths of Arctic char spawners examined.

Location	N	Mean Sr (ppm)	Standard Dev.	Range (ppm)
Lady Pelly L.	48	105.5	10.62	78.7 – 138.7
Wishbone L.	58	96.4	14.49	69.0 – 139.0
Ferguson L.	43	112.8	24.20	112.8 – 218.0
Halovik L. 87	5	66.3	7.94	53.0 - 73.7
Halovik L. 93	47	71.0	13.67	11.0 – 73.7
Kitiga L.	22	119.0	14.06	73.9 – 218.0
Mt. Pelly L.93	11	128.4	16.59	101.1 – 154.4
And. Bay L.94	26	182.0	15.27	156.2 – 213.3
Ellice River 90*	49	1040.0	264.94	127.0 – 1822.7

* Ellice River is a sample of nonspawning Arctic char but is included for comparison.

Table 35. A comparison of mean strontium comcentrations (ppm) among all samples of Arctic char spawners, using the Least Significant Difference (LSD) test. (* = minimum 0.05 significance level)

STAT. GENERAL MANOVA	LSD test; variable MEAN_SR Probabilities for Post Hoc Tests MAIN EFFECT: GROUP							
GROUP	{1} 105.5132	{2} 96.35517	{3} 112.7814	{4} 70.98312	{5} 66.33334	{6} 118.9536	{7} 128.4309	{8} 182.0231
LADY PELLY L. [1]		.003392*	.030070*	.000000*	.000000*	.001145*	.000022*	0.000000*
WISHBONE L. [2]	.003392*		.000001*	.000000*	.000066*	.000000*	.000000*	0.000000*
FERGUSON L. [3]	.030070*	.000001*		.000000*	.000000*	.139065	.003829*	0.000000*
HALOVIK L. 93 [4]	.000000*	.000000*	.000000*		.533874	.000000*	.000000*	0.000000*
HALOVIK L. 87 [5]	.000000*	.000066*	.000000*	.533874		.000000*	.000000*	0.000000*
KITIGA L. [6]	.001145*	.000000*	.139065	.000000*	.000000*		.107033	0.000000*
MT. PELLY L. 93 [7]	.000022*	.000000*	.003829*	.000000*	.000000*	.107033		.000000*
ANDERS. B. L. 94 [8]	0.000000*	0.000000*	0.000000*	0.000000*	0.000000*	0.000000*	.000000*	

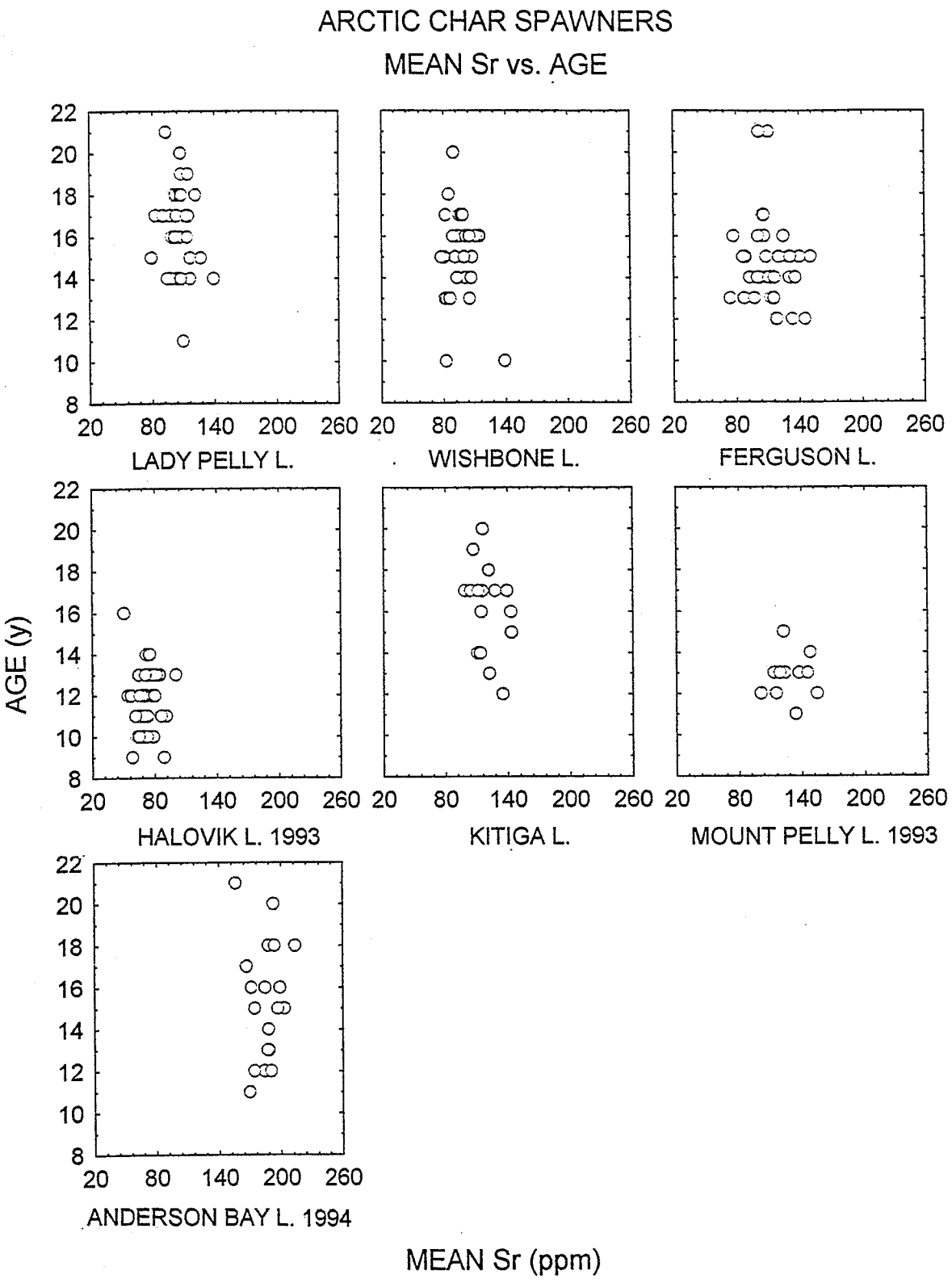

Figure 86. A plot of mean strontium concentration in the early growth region of the otolith against age for samples of Arctic char spawners.

from Ferguson Lake shows the greatest variation within each age group, but was still consistent among age groups. It is interesting to note that few spawners over the age of fourteen years were observed in the samples from Halovik Lake 1993 and Mount Pelly Lake 1993. The frequency distributions of strontium concentrations for the different spawning aggregations (Fig. 87) appear, for the most part, to have obvious modality and narrow range.

The range of values of otolith strontium concentrations by age group in samples of spawners is limited and clustered around the mean value compared with those in samples of nonspawners (Fig. 88). However, samples of nonspawners from each of the upstream migrations in the Ekalluk River show a greater range of strontium values within each age group compared with those of the spawners. There appear to be some "clumped" values amongst the samples from 1990, 1991, 1993 and 1994, whereas those from 1988 and 1992 appear to be spread out within each age group.

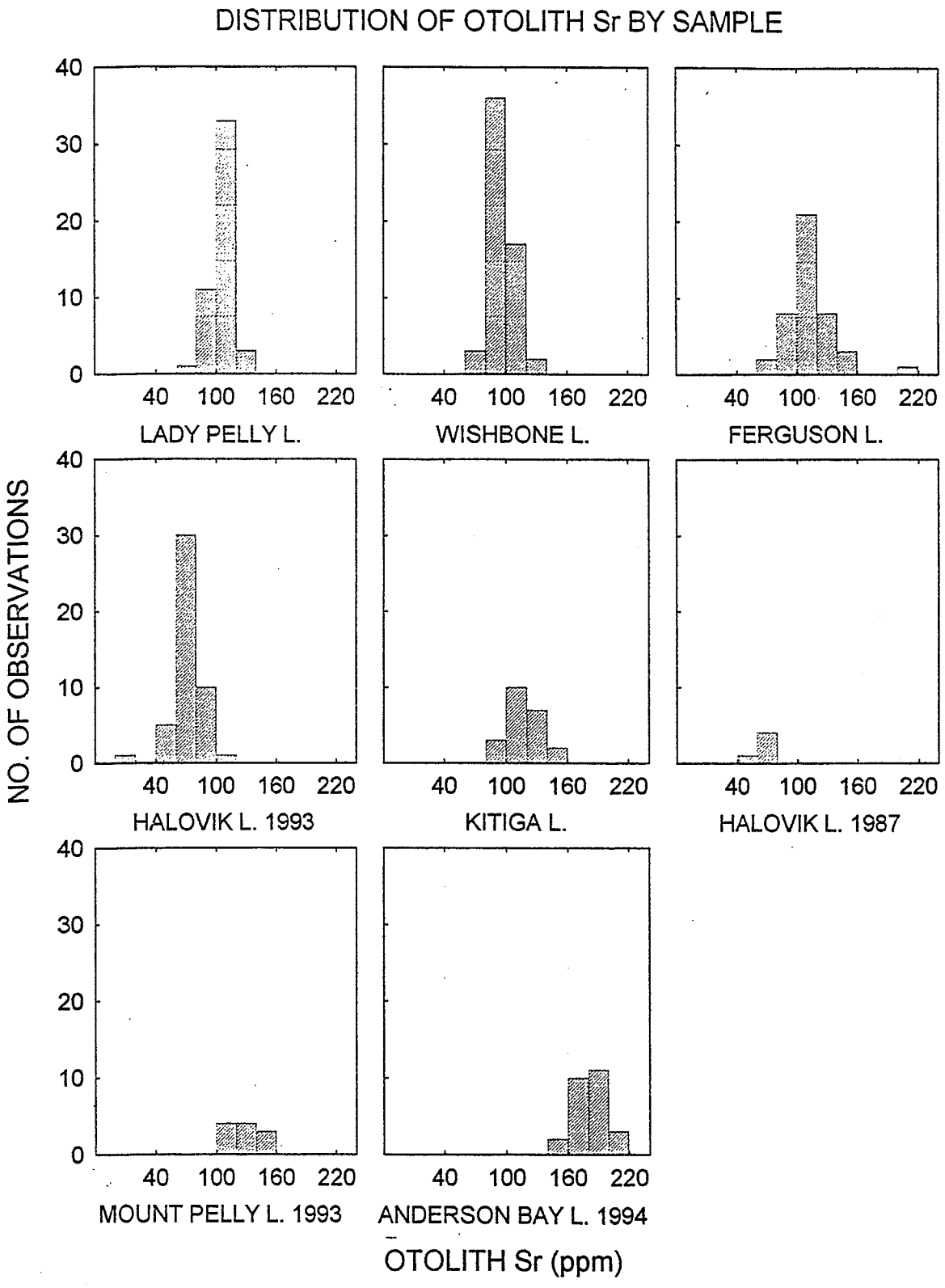

Figure 87. A comparison of frequency distributions of strontium concentration in the early growth region of the otolith among samples of Arctic char spawners.

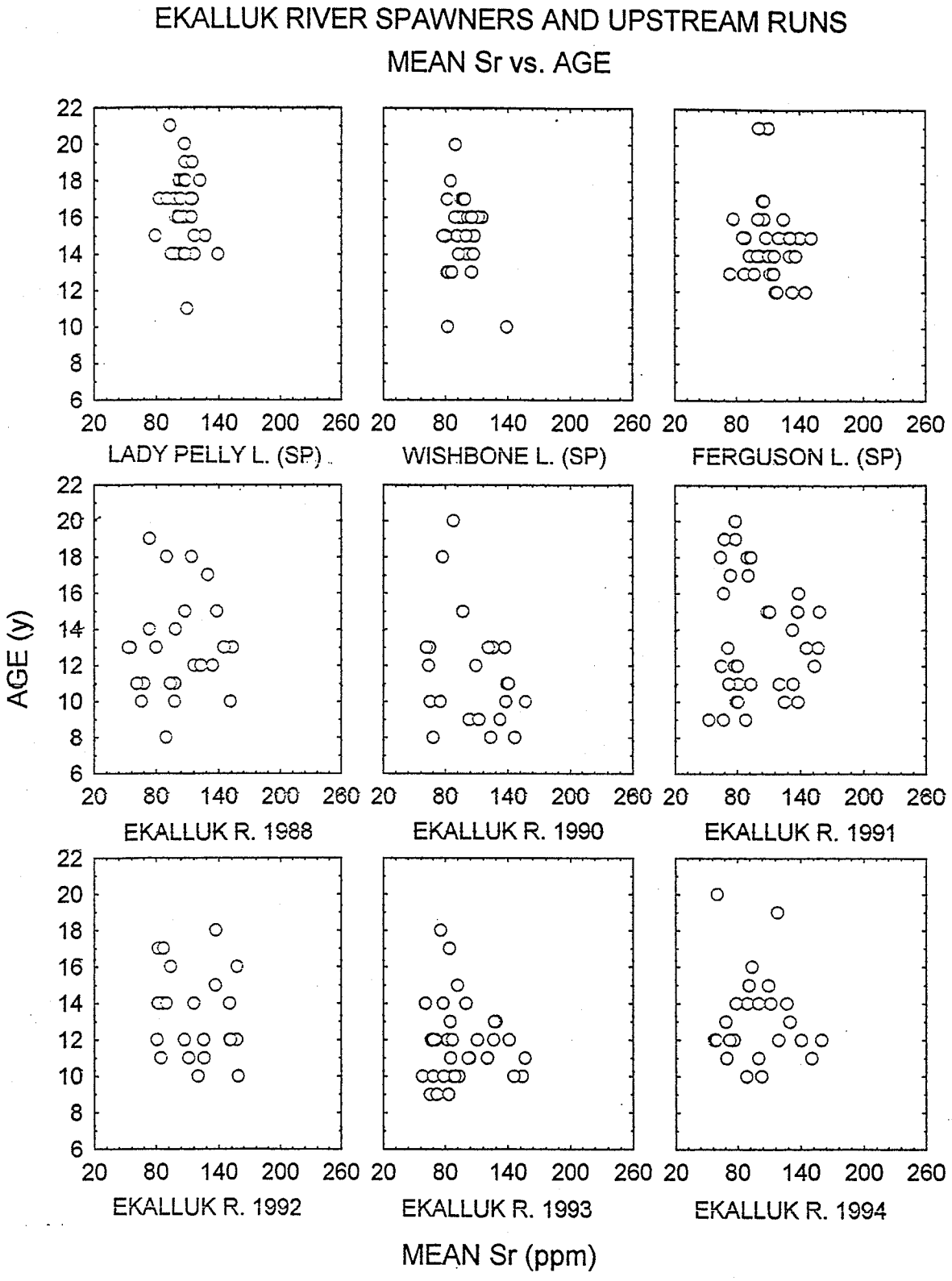

Figure 88. A comparison of mean strontium concentration in the early growth region of the otolith against age among samples of Arctic char spawners from the Ekalluk River system and samples of Arctic char from the six upstream migrations into the Ekalluk River (1988, 1990, 1991, 1992, 1993, 1994).

DISCUSSION

Evidence of Stock Structuring

Morphology

Life history studies of the freshwater form of Arctic char have revealed significant morphological differences among populations. Differences are found between and within lakes (Frost 1965; Johnson 1980; Hindar and Jonsson 1982; Jonsson and Hindar 1982; Nordeng 1983; Gardner et al. 1988; Partington and Mills 1988, Venne and Magnan 1989; Reist et al. 1995; Alekseyev et al. 1997; Alekseyev and Pichugin 1998; Alekseyev et al. 1999; Alekseyev et al. 2000). Few studies, however, have focussed on differentiating stocks of anadromous Arctic char based on morphology. Dempson and Misra (1984) identified seven stocks of anadromous Arctic char along the northern Labrador coast using a multivariate analysis of meristic data. Pectoral fin ray and upper gill raker counts were the most effective stock discriminators. Their samples were taken during the return migration from the sea into fresh water and not from spawning assemblages. Reist et al. (1997) found morphological differences among anadromous Arctic char over a broad geographic range in the central Canadian Arctic.

I present evidence that anadromous Arctic char spawners from geographically adjacent locations within the study area can be differentiated from one another on the basis of significant morphometric, and to a lesser extent, meristic differences. These differences are apparent between geographically adjacent river systems, and in a number of cases, within river systems. They can be distinguished from one another by at least one definable character difference and in most cases, by a number of such differences.

Therefore, they meet the criteria for discrete phenotypic stocks as defined by Booke (1981).

All morphometric and meristic characteristics have a genetic basis. However, because the expression of genes that code for some of these characteristics can be environmentally modified (Martin 1949; Svärdson 1952; Lindsey 1954; Loch 1974; Bodaly 1977; Balon 1980; Todd et al. 1981) some researchers consider these characteristics as unreliable for stock identification (Clayton 1981). In fact, they can be as valuable for stock identification as other, more genetically related features. A set of quantitative characters, such as morphological measurements may contain more information than an equal number of "directly genetic" characters (Thorpe 1976). Their utility for stock identification depends upon the stock behaving as a cohesive unit whose members exhibit common responses to environmental conditions within their respective geographic boundaries (Casselman et al. 1981). Clayton (1981), in a discussion of the relationship between organismal and molecular evolution as it relates to the stock concept, recommended that a combination of molecular and organismal data be used for stock identification purposes. However, he points out that there are situations where one or the other would suffice.

Stock discreteness can be obscured by spatial overlap during various seasons of the year (Casselman et al. 1981). That is why it is crucial to obtain samples for stock identification from spawning aggregations. Sampling spawning aggregations increases the likelihood of a homogeneous sample. Coupled with this is the necessity to include as many year classes in the sample as possible. If morphological characteristics particular to a sample are consistent within the sample over many successive generations, this is

evidence of environmental and/or genetic similarity from generation to generation. The morphological characters that I observed to be useful discriminators between stocks in this study showed this consistency between year classes within each sample. This is evidence that similar environmental/genetic influences have affected successive generations within each sample.

The meristic characters that I examined in this study did not provide the level of stock discrimination that the morphometric measurements did. Ihssen et al. (1981a) recommend that the two types of data be treated separately in multivariate analyses because the former are discrete variables and the latter are continuous variables. I examined the two types of data separately and found that where the meristic data showed group segregation, the results were identical to the group differences based on morphmetrics, especially for the three samples from the Ekalluk River system.

The phenotypic stocks identified in this study are allopatric, because the spawning grounds are separated geographically. At least three stocks of Arctic char inhabit the Ekalluk River system, including those that spawn in Ferguson Lake, Lady Pelly Lake, and Wishbone Lake. The minimum distance between the three spawning grounds is about 45-50 km and the maximum distance is about 100 km by water. There is possibly a fourth phenotypic stock utilizing the Ekalluk River, based on the morphological differences evident among the sample from the 1994 upstream migration and the three samples of spawners just discussed.

There are at least two discrete stocks that spawn in the Halovik River system, including those sampled in 1987 near the outlet of Halovik Lake and those sampled in 1993 upstream of the 1987 sample. The minimum distance between the two sampling

locations is about 2.5 km. The 1993 sample was a pooled sample consisting of Arctic char taken from two areas approximately 13 km apart. However, the 1993 sample appeared to be morphologically homogeneous (Appendix II).

Discrete phenotypic stocks of Arctic char inhabit Fish Trap Lake and Char Lake, both of which are part of the same river system that drains into Albert Edward Bay. The Char Lake sample was taken from two locations about 3 km apart and pooled. It appeared to be morphologically homogeneous (Appendix III). The Fish Trap Lake sample was a minimum of 2.5 km from the nearest Char Lake sample. The nonspawners from the Jayco River upstream migration appear to be morphologically distinct from the spawners from Fish Trap and Char lakes even though the mouths of both rivers are within 8 km of one another by water.

The samples of spawners from Mount Pelly Lake (Freshwater Creek system) taken in 1992 and 1993 were similar in all but three of the morphological characters. The differences indicate that they are discrete phenotypic stocks. The 1993 sampling location was within 500 m of the closest 1992 gillnet set. The considerable morphological heterogeneity observed within the samples of nonspawners from the 1988, 1991 and 1994 upstream migrations in Freshwater Creek when compared with the spawners from Mount Pelly Lake suggest that a number of morphologically distinct stocks inhabit this system as well. With the exception of a small cluster (cluster F) from the 1991 upstream sample that appeared to be morphologically similar to the Mount Pelly Lake 1993 spawners, none of the other samples showed any morphological similarity to the two samples of spawners examined from this system.

At least two discrete phenotypic stocks inhabit Anderson Bay Lake, including those sampled in 1993 and those sampled in 1994. Although the precise location of the 1993 sample is not known, it was not taken at the same location as the 1994 sample and Anderson Bay Lake is only 6.5 km in maximum dimension. Nonspawners from the Ellice River commercial fishery on the mainland were morphologically distinct from the closest samples of spawners (Mount Pelly and Anderson Bay lakes) on Victoria Island, over 100 km away.

Clearly, phenotypic stock structuring within the study area exists on a broad geographic scale. However, it also appears to exist on a very fine geographic scale (< 1 km) as evidenced by the two samples of spawners from Mount Pelly Lake.

The two samples of spawners in this study that are morphologically most similar to one another are those from Char Lake and Wishbone Lake. Interestingly, these two sample locations are the two that are most widely geographically separated at present. Although the two lakes are only 18 km apart in straight-line distance, each is in a separate drainage system. Wishbone Lake flows west via the Ekalluk River system into Wellington Bay while Char Lake flows east into an unnamed river that empties into Albert Edward Bay. However, this was likely not the case during the time that Arctic char colonized this area after the last glacial period. Wishbone Lake is at a present elevation of about 25 m above sea level (asl). Less than 1 km northeast of Wishbone Lake lies an unnamed lake in the Char Lake drainage basin that is also at a present elevation of about 25 m asl. These lake basins would have risen above sea level at about the same time, between 1250 and 2500 years ago, based on a rebound rate of 1-2 m per 100 years (Johnson 1962). Perhaps the morphologically similar Arctic char stocks which inhabit

Wishbone and Char lakes today are remnants of an ancestral stock that colonized this area when suitable freshwater habitat became available. If that is the case, the morphological similarity of these two stocks appears to have endured and could be the result of similar environmental/genetic influences acting on both stocks since separation.

The two samples of spawners that are most distinct morphologically from all of the others are those from Lady Pelly Lake and Halovik Lake 1987. The lake from which the Halovik 1987 sample was taken was apparently not inundated by seawater since glacial melt (Dunbar and Greenaway 1956; Wilson et al. 1958). Halovik Lake is at a present elevation of about 105 m asl, and could have been one of the first lakes in the study area to be colonized by Arctic char following deglaciation. Lady Pelly Lake is at a present elevation of about 30 m asl. Anderson Bay Lake, at an elevation of about 3 m asl, could have been one of the most recently colonized lakes within the study area.

Clearly, the process of isostatic rebound is the force that determined when the land in different parts of the study area rose above sea level. The development of suitable freshwater habitat to support Arctic char followed. Given the present elevations of the different lakes involved, some would have become available for habitation before others. However, attempting to draw conclusions about present-day morphological similarities or differences based on different times of colonization is speculative at best. What exists today is likely due to a combination of the reshuffling of char stocks that occurred at the end of each glacial period (Nyman 1989) and the effects of thousands of years of natural selection for adaptation to local conditions. Power (1981) has attributed the formation of over 500 stocks of anadromous Atlantic salmon (*Salmo salar*) in Newfoundland and the Quebec-Labrador peninsula to such local adaptation following colonization.

The Arctic char exhibits extensive morphological and ecological plasticity across its range (Johnson 1980; Behnke 1980). Nyman (1989) attributes this not so much to its wide geographical distribution but to the fact that it has lived and evolved near the margins of ice sheets. He maintains that this environment, where habitat change is pronounced, favours geographical isolation and the primarily lacustrine habitat occupied by Arctic char has augmented isolation between stocks.

Genetics

Genetic distinctness between two groups is evident if consistently significant differences in allele frequencies at one or more loci can be demonstrated between samples from the two groups (Ihssen at al. 1981a). Genetically distinct populations of freshwater forms of Arctic char have been reported throughout the geographic range of this species (Saunders and McKenzie 1971; Nyman 1972; Henricson and Nyman 1976; Child 1977; Johnson 1980; Kornfield 1981; Ryman and Ståhl 1981; Andersson et al. 1983; Hindar et al. 1986; Magnusson and Ferguson 1987; Partington and Mills 1988). These genetic differences were found among both allopatric and sympatric populations. However, little information is available on the genetic distinctness of anadromous Arctic char populations.

The significant differences in allele frequencies for malic enzyme that I found among samples of spawners from Lady Pelly Lake and Mount Pelly Lake 1992 is evidence that there is genetic distinctness among anadromous Arctic char stocks within the study area. This suggests that there is reproductive isolation between those stocks. Unfortunately, I could not compare all samples of spawners in this study for genetic

distinctness because of limited resources. However, the genetic data that I present complement the putative stock structuring based on morphology.

The significant differences in allele frequencies that I found when I compared the Lady Pelly Lake spawners with the sample of nonspawning Arctic char captured during the 1991 upstream migration into the Ekalluk River provides evidence that at least one other genetically distinct stock utilizes this freshwater system. Although this sample was most similar morphologically to the spawners from Wishbone Lake, I do not have evidence to prove that the Ekalluk River is its "home " stream. The most conservative interpretation is that at least two genetically distinct stocks of Arctic char (Lady Pelly Lake and this sample of unknown origin) inhabit this region of the study area.

The two samples of nonspawners that did not satisfy Castle-Hardy-Weinberg equilibrium provide additional, although indirect, evidence of genetically based stock structuring within the Wellington Bay area. Non-satisfaction of CHW equilibrium is evidence of non-random mating. A common cause is that the sample is comprised of an admixture of individuals from two or more populations that differ in allelic and genotypic frequencies (Ferguson et al. 1995). These mixtures are often characterized by a deficiency of heterozygotes (Wahlund 1928). This information is very useful if it is based on samples of non-spawning fish because it indicates that at least two genetically distinct stocks reside in the area of investigation (Utter and Ryman 1993). Indeed, the sample of nonspawners from the 1992 upstream migration in the Ekalluk River was characterized by a heterozygote deficiency. This sample also showed a high degree of morphological heterogeneity. A portion of the sample, whose members were morphologically similar (Cluster Analysis), satisfied CHW equilibrium when examined by itself. This is evidence

that Arctic char from at least two genetically distinct stocks migrated upstream in the Ekalluk River in 1992. Andersson et al. (1983) concluded that the non-satisfaction of CHW equilibrium for esterase (*est-2*) based on a significant heterozygote deficiency from a sample of Arctic char from a Swedish lake (Västra Trollsvattnet) was a genetic indication of more than one population of Arctic char inhabiting that lake. The 1992 sample I obtained from the Paliryuak River, although not taken from an upstream migration, appears to be comprised of an admixture of Arctic char from at least two genetically distinct stocks feeding in Wellington Bay as well. This sample also did not satisfy CHW equilibrium because of a heterozygote deficiency. Once again, a morphologically similar portion of this sample did satisfy CHW equilibrium when examined alone. The genetic differences observed between the Mount Pelly Lake spawners and the nonspawners from the Ellice River 1991 commercial fishery, paralleled by morphological differences, are evidence of stock structuring between stocks on Victoria Island and the mainland.

Interpretation of putative stock structure based on differences in allele frequencies must be done with care. The implicit assumption is that allozyme markers are selectively neutral and that genetic drift is responsible for stock differentiation (Ward and Grewe 1994). If they are not, then a single panmictic stock with different selection pressures in different areas could be incorrectly identified as a number of genetically distinct semi-isolated stocks with restricted gene flow. On the other hand, two stocks that are truly isolated, but subject to similar selection pressures, might appear genetically uniform, and therefore incorrectly considered as parts of a panmictic stock. One way to avoid the former error is to shift to non-coding DNA markers, discussed later, which are less likely

to be affected by selection (Ward and Grewe 1994). Another method is to ensure that the sample is comprised of spawners from a number of successive year classes. Homogeneity of genotypic/phenotypic characteristics among year classes within a sample is evidence of homing, the behaviour necessary to restrict gene flow. If homing can be proven, gene frequency differences, regardless of whether or not they are affected by selection, provide evidence of stock structuring.

When allozyme frequencies do not show evidence of differentiation, and thus there is insufficient evidence to reject the null hypothesis of a panmictic stock, it cannot be concluded that the samples represent portions of a panmictic stock although they may (Ferguson et al. 1995). Evidence from other lines of investigation, such as tagging and morphometric and meristic variation, should be used in conjunction with the genetic data to assess likely population structure (Ward and Grewe 1994). Such was the case in this study. Whereas I found no significant difference in allele frequencies of malic enzyme among spawners from Lady Pelly Lake, Halovik Lake 1987 and Char Lake, morphological differences among these three samples were evident.

Morphological differences often reveal stock structuring on a finer scale than allozyme electrophoresis. Such was the case in studies of lake whitefish (*Coregonus clupeaformis*) in Lake Winnipeg (Kristofferson and Clayton 1990). Two stocks could be separated based on significant differences in glycerol-3-phosphate dehydrogenase (G-3-PDH) allele frequencies. These differences were parallelled by morphometric and meristic differences. Further population discrimination was possible within each genetically similar group, based on morphological differences. Casselman et al. (1981) found better stock discrimination of lake whitefish in Ontario waters of Lake Huron using

tagging data, population parameters and morphometrics, than with allele frequencies examined by electrophoresis. The electrophoretic data identified two large groups, within which further stock discrimination was possible with the other methods utilized.

The study by Partington and Mills (1988) of nonanadromous Arctic char populations from ten British lakes focussed on growth, morphology and electrophoretic analysis. Significant differences were found among twelve groups of char from these lakes for each of 13 morphometric and two meristic variables. Distinctions could be made not only between allopatric populations, but also between some sympatric populations. Significant differences in allele frequencies for malate dehydrogenase (Mdh-4,5 (130)) and esterase (Est-1 (115)) were found which clearly separated spawners from two basins of the same lake (Windermere). Canonical analysis of morphometric measurements showed a clear distinction between these spawning groups as well. In another study, Kipling and Le Cren (1984) found a high degree of fidelity (99%) to spawning sites in Windermere over consecutive years, based on tagging studies. Homing behaviour of this nature contributes to reproductive isolation within the lake, resulting in genetic differences over time.

Genetic stock structuring on a small geographic scale has been demonstrated for Dolly Varden (*S. malma*) and brook char (*S. fontinalis*), two species closely related to Arctic char. Reist (1989) observed significant differences in allele frequencies for the enzymes superoxide dismutase (SOD) and glucose phosphate isomerase-3 (GPI-3) among anadromous samples of putative Dolly Varden from four adjacent river systems along the Yukon north coast and western Northwest Territories. Subsequent analysis has since confirmed that the species in question is Dolly Varden (Reist et al. 1997). Meristic

differences were also noted between samples from these locations. The samples compared were anadromous spawners and all allele frequencies met Castle-Hardy-Weinberg equilibrium. However, when he examined anadromous spawners from two different locations within one river system (Firth River), Reist (1989) found no significant differences in allele frequencies for these enzyme systems.

Jones et al. (1996) used allozyme analysis to detect high levels of population differentiation in brook char in Fundy National Park, New Brunswick, and eastern Canada. Most differentiation occurred among populations in different branches of the same river drainage. This genetic differentiation on a local scale is thought to be a product of small numbers of founders and subsequent population bottlenecks, and random genetic drift in combination with restricted gene flow between river branches. They concluded that little present-day gene flow exists among most of these populations.

Angers et al. (1995) used microsatellite analysis to examine intra- and inter-population genetic diversity among samples of brook char from five lakes in close proximity to one another (maximum distance apart = 22 km) in Quebec. Microsatellites are a class of nuclear loci that consist of variable number tandem repeats or VNTRs (Bruford et al. 1996), thought to be selectively neutral (Ward and Grewe 1994). Strong inter-population diversity was detected with highly significant differences in allele frequencies in all but two pairwise chi-square permutation tests between populations at all loci. As well, numerous population unique alleles were found in all five lakes.

I was not able to utilize microsatellite analysis in my study because the technique had not been fully developed for use with Arctic char at that time. However, Bernatchez et al. (1998) applied this technique to the analysis of gene diversity in anadromous Arctic

char from Labrador, Canada, using primers developed for other closely related species. They prefaced their study with a statement that predicting population structure of anadromous Arctic char may be complicated by their complex migratory behaviour and the lack of clear information about the extent of their homing behaviour. They analyzed six loci among 257 anadromous Arctic char taken from six locations along the Labrador coast and one sample from an inland lake in Newfoundland. The latter sample was used as a reference sample because it was not connected to the others by gene flow. Their samples were not taken on the spawning grounds. Their results indicated that all six loci were moderately to highly polymorphic. Significant genetic structure indices (F_{ST}) and differences in allele frequencies were observed among most samples, as well as heterozygote deficiency (Wahlund effect) in all but one sample. Based on this, these authors rejected the null hypothesis of absence of genetic differentiation among the Arctic char samples, implying the existence of genetically differentiated populations with restricted gene flow on a microgeographic scale (< 10 km). They concluded that the observed heterozygote deficency was an indication of population admixture, because their samples were taken during upstream migrations. They reported that their results reinforce the view that anadromous Arctic char may possess strong homing capability.

The high levels of polymorphism of microsatellite loci that Bernatchez et al. (1998) observed in their study was in marked contrast to low levels observed in studies of this species using allozyme and mtDNA analyses. Indeed, I found mtDNA sequence analysis of no value for stock identification within my study area and limited stock differentiation based on allozyme analysis. These authors suggest then that microsatellite

analysis potentially offers more sensitivity than allozyme and mtDNA analyses for the examination of fine-scale stock structuring of anadromous Arctic char.

Stable Isotopes

Isotope ratios in substances can change due to various chemical and physical reactions. This "isotope fractionation" occurs in predictable ways as elements cycle through the biosphere (Peterson and Fry 1987). This fractionation reflects reaction conditions and thus provides process information. Stable isotope distributions also provide information about the origin of samples, or source information. The source is an isotopic baseline that can subsequently be shifted by fractionation (Peterson and Fry 1987). Stable isotopes can therefore provide information on diet and trophic level (Gu et al. 1996; Hobson and Welch 1992, 1995). This information, in turn, can provide evidence of stock structuring (Welch and Parsons 1993).

In animals, isotopic compositions of carbon and sulfur are a direct reflection of diet but nitrogen values average 3 to 5 $^{0}/_{00}$ heavier than dietary nitrogen, mainly due to excretion of isotopically light nitrogen in urine (Peterson and Fry 1987). Therefore, nitrogen isotopic values increase 10 to 15 $^{0}/_{00}$ in many food webs due to an increase in ^{15}N content of 3 to 5 $^{0}/_{00}$ per trophic level (Minagawa and Wada 1984). No change with increasing trophic level is evident with sulfur (Mekhtiyeva et al. 1976; Peterson et al. 1986) which makes it a good indicator of the plant or bacterial food source of the consumers. Carbon is intermediate between N and S, increasing between 0.0 and 1.0 $^{0}/_{00}$ per trophic level. While overall isotopic composition of animals is controlled by diet,

both long-term and short-term diets are reflected in slow and fast turnover tissues (Peterson and Fry 1987).

Stable isotopes, such as ^{34}S and ^{13}C, which provide source information, may be used to identify different stocks of fish if the food sources differ in isotopic ratios, provided that the turnover time in the tissue examined is sufficiently slow so as to preserve such differences. The carbon isotopic composition of the whole body of an animal is directly related to its diet but the relationship of the carbon isotopic ratio of the tissue relative to that of the diet depends upon the type of tissue and the nature of the diet (DeNiro and Epstein 1978). The chemical and isotopic compositions of muscle, the tissue that I examined, reflect the diet that the fish has consumed over probably several months (Estep and Vigg 1985).

Four of the five samples that I examined for stable isotopes were from Arctic char that were returning from a summer of feeding in the sea at the time of capture. The similarity of $\delta^{13}C$ values (about - 21 $^{0}/_{00}$ to – 24 $^{0}/_{00}$) for three of the four samples (Ellice, Halovik and Ekalluk rivers) provided little food source information that might contribute to stock discrimination among these samples. The fourth, from the Jayco River, showed a wider range in $\delta^{13}C$ values (about –19 $^{0}/_{00}$ to – 26 $^{0}/_{00}$), indicating that these char were feeding on a wider range of food source than the other three.

I was not able to examine organisms at all trophic levels in the various food chains and thus could not determine the category of food item for each putative trophic level. However, I compared my data with that from Hobson and Welch (1992) who studied the trophic relationships within a high Arctic marine food web. These authors

found that marine amphipods had a $\delta^{15}N$ range of about 10 $^{0}/_{00}$ to12.5 $^{0}/_{00}$ while $\delta^{15}N$ values for marine fishes ranged from about 12.5 $^{0}/_{00}$ to 17 $^{0}/_{00}$. The $\delta^{15}N$ values for all four samples of sea run returnees that I examined provide some insight into stock differentiation based on the trophic level(s) at which they were feeding. The Arctic char from the Halovik River 1992 and Ekalluk River 1992 samples ($\delta^{15}N$ of 9 $^{0}/_{00}$ to 12.5 $^{0}/_{00}$) appeared to have been feeding on marine amphipods. Amphipods have been observed on a number of occasions in stomachs of Arctic char captured as they entered the Ekalluk River in autumn. The Arctic char in the sample from the Ellice River ($\delta^{15}N$ of 12.5 $^{0}/_{00}$ to 15 $^{0}/_{00}$) appeared to have been feeding on marine fishes. The sample from the Jayco River ($\delta^{15}N$ of 7.5 $^{0}/_{00}$ to 15 $^{0}/_{00}$) appeared to have been feeding at two trophic levels, possibly including both amphipods and fish. The four samples were from widely separated geographic areas. These data suggest that Arctic char stocks in the Cambridge Bay area may frequent separate summer feeding grounds that offer different prey items. Tagging data (Dempson and Kristofferson 1987) indicate that Arctic char from the Halovik and Ekalluk rivers feed mostly in Wellington Bay and Jayco River Arctic char feed mostly in Albert Edward Bay. Ellice River Arctic char most likely feed in nearshore areas along the mainland coast.

Welch and Parsons (1993) were able to identify a trophic hierarchy amongst five species of Pacific salmon along the west coast of Canada and Alaska, based on differences in $\delta^{15}N$ values. Chinook were at the top, followed by chum (*Oncorhynchus. keta*), coho, sockeye and pink (*O. gorbuscha*) salmon. They were also able to differentiate one stock of sockeye (Chilko) from four others (Adams, Early Stuart, Takla, Iliamna)

based on differences in $\delta^{15}N$ values. The Chilko stock had much lower $\delta^{15}N$ values than the other stocks. One explanation offered was that the Chilko sockeye stock feeds in regions of elevated nitrate levels. The alternate explanation is that the Chilko stock feeds at a lower trophic level.

The $\delta^{34}S$ values (10 $^{0}/_{00}$ to 16 $^{0}/_{00}$) for most of the Jayco River Arctic char that appeared to be feeding on marine fish were similar to those in the sample from Char Lake. However, the latter were spawners, captured in fresh water. Char Lake is one of the lakes that is very close to the sea, and the Sr profiles that were done on the otoliths of these char suggest that some may go to sea the summer prior to spawning. It is possible that the Arctic char spawners captured in Char Lake had gone to sea earlier in the summer and had been feeding on marine fish in Albert Edward Bay.

Homing

As stated earlier, the two behavioral characteristics fundamental to the formation and maintenance of discrete stocks of fishes are homing of spawners to natal spawning sites and imprinting during early life history stages to the natal site (Horrall 1981). Anadromous Arctic char in the Cambridge Bay area home to natal spawning grounds with a high degree of fidelity. This has manifested itself in the establishment of discrete spawning stocks that are readily distinguishable from geographically adjacent stocks on the basis of differences in morphometric measurements and, to a lesser extent, differences in meristic counts. There is a genetic component to this stock structuring as well. Reproductive isolation is evident, based on differences in allozyme frequencies between

some stocks. I present evidence of homing based on the direct relationship between strontium concentrations in the early growth zones of the otoliths of Arctic char spawners and the strontium concentrations in the surrounding waters of the spawning grounds where they were captured. The consistent similarity of the otolith strontium concentrations among all age groups within each sample of spawners provides evidence of philopatry over many generations. Therefore, I reject the null hypothesis that anadromous Arctic char in the Cambridge Bay area comprise a panmictic stock and accept the alternative hypothesis that anadromous Arctic char in this region are comprised of a number of discrete populations.

Trace elements found in mineralized tissues of fishes have proven to be useful for stock identification (Edmonds et al. 1989, 1991, 1992; Kalish 1990; Gunn et al. 1992; Campana and Gagne 1994). It is known that fish have the ability to concentrate chemical elements from the environment. Therefore, this approach is based on the premise that geographically distinct populations will reflect the chemical constituents of the water in which they reside (Simkiss 1974; Lapi and Mulligan 1981; Mulligan et al. 1987). The element strontium (Sr) has the same valence (2+) as calcium (Ca) and similar ionic radius (Ca, 0.99 Å, Sr, 1.13 Å), hence it substitutes readily for calcium in the mineralization process, particularly in otoliths (Simkiss 1974; Radtke 1989). The relative degree of the substitution of Sr for Ca depends largely on the relative concentrations of Ca and Sr in the ambient environment (Kalish 1990).

The uptake of strontium and its subsequent incorporation into hard tissues of fish has been confirmed by laboratory studies. Strontium can be incorporated into fish hard tissues through diet (Ophel and Judd 1968; Behrens Yamada et al. 1979; Beherns

Yamada and Mulligan 1982) and passively from the surrounding waters (Behrens Yamada and Mulligan 1987; Schroder et al. 1995) and is localized in the area of the tissue that is being formed during uptake.. Schroder et al. (1995) demonstrated that detectable levels of strontium were taken up by newly emerged chum salmon fry when immersed in a solution of strontium chloride for as little as 24 h. Elevated Sr levels were detected by bulk Inductively Coupled Plasma Mass Spectrometry (ICPMS) in the otoliths (sagittae), vertebrae and opercula compared with control fish.

The elemental composition of scales and vertebrae has been used with some success for stock identification (Lapi and Mulligan 1981; Gausen and Berg 1988; Mulligan et al. 1983). Scales are useful structures to examine for trace element composition because they are relatively easy to obtain without killing the fish. However, Mugiya and Watabe (1977) summarize a number of studies that indicate that scales are resorbed under certain physiological conditions such as starvation (Ichikawa 1953; Yamada 1956;), sexual maturation (Ouchi et al. 1972), and severe exhaustion due to spawning migration (Chrichton 1935) and diet (Wallin 1957). According to Simkiss (1974) there is no resorption of otoliths although Mugiya and Uchimura (1989) were able to show evidence of calcium resorption in the otolith of the goldfish induced by anaerobic stress. They concluded that otolith resorption occurred in very rare cases only. Thus, the otolith is the preferred structure to use for stock identification purposes due to its relative resistance to resorption compared with scales and bone.

The life history stage at which trace elements are incorporated into fish hard tissues has a direct bearing on the value of these elements for stock identification. A spawning ground may have a particular trace element "signature". This signature will be

most accurately reflected in the fish's hard tissue if it is incorporated from the spawning waters during the fish's early developmental stages (Campana et al. 1994). For this reason, Campana and Neilson (1985) recommend examination of the perinuclear region of the otolith. I examined both the nuclear and perinuclear regions of the otolith and, in most cases, found similar strontium concentrations between both regions. However, there were some cases where the strontium concentrations in the nuclear region were higher compared with those in the adjacent growth regions. The reason for this appears to be related to the behaviour of the female just prior to spawning.

Kalish (1990) has shown that the environment that the female occupies during vitellogenesis can affect the elemental composition of the nucleus of the otolith of its progeny, particularly with respect to strontium concentration. The process takes place during the formation of the oocyte in the female whereby the calcium moiety of vitellogenin, a phospholipoprotein-calcium complex yolk precursor (Mommsen and Walsh 1988), is substituted for strontium (Kalish 1990). Seawater contains about 8 ppm of Sr whereas fresh water contains about 0.1 ppm (Rosenthal et al. 1970) and, because the development of the ova in anadromous salmonids is virtually complete before these fish enter fresh water, their ova should contain higher levels of Sr than those of their nonanadromous counterparts. Kalish (1990) found that the ova of anadromous *Oncorhynchus mykiss* contained five times more Sr than their nonanadromous conspecifics.

The otolith nuclei are formed very early in the ontogeny of fishes and well before yolk utilization is complete (Brothers 1984; Kalish 1990). Therefore Kalish (1990) hypothesized that the higher levels of Sr in the yolk of anadromous females should

contribute to higher levels of Sr in the nuclei of the otoliths of their progeny compared with those of nonanadromous conspecifics. He used an electron microprobe to examine transects across otoliths from the nucleus to the otolith edge and observed higher Sr/Ca ratios in the nuclei of sagittal otoliths of anadromous *Salmo salar* and *S. trutta* compared with nonanadromous *Oncorhyncus mykiss* and anadromous *O. mykiss* reared from freshwater broodstock. He confirmed this hypothesis in a controlled rearing experiment using sea-farmed and freshwater *O. mykiss.* Rieman et al. (1994), using a wavelength dispersive microprobe, found significantly higher Sr/Ca ratios in the otolith nuclei of anadromous sockeye salmon (*O. nerka*) compared with those of nonanadromous conspecifics. In both of the above studies, otolith Sr/Ca ratios in the growth zones formed subsequent to yolk absorption were lower than those observed in the nucleus. The Sr concentrations in these ratios were directly related to Sr concentrations in the freshwater spawning environment in the latter study (Rieman et al. 1994).

The elevated levels of Sr in the nucleus of otoliths of some Arctic char that I observed in this study were similar to those observed by Kalish (1990) and Rieman et al. (1994) in the progeny of other anadromous salmonids. While most Arctic char in this study area do not go to sea the summer prior to spawning, I explain this elevated Sr concentration in the nucleus on the basis that the female parent went to sea for a short period of time during the summer prior to spawning. The greater frequency of occurrence of this Sr pattern in samples from spawning grounds close to the sea suggests that some Arctic char go to sea for a period of time during the summer prior to spawning, provided that the migration distance is relatively short. A feeding opportunity just prior to spawning may provide significant benefits to these char in terms of energy uptake and

may result in improved spawning success, and perhaps increased frequency of spawning events. Moore (1975a) observed both sexually mature male and female Arctic char in the sea near Baffin Island during the summer prior to spawning. Some Arctic char spawners have been observed in counting weirs as they returned from a summer trip to the sea (Kristofferson unpublished).

Spawning events are energy dependent and the number of spawners in a given year appears to be related to feeding success during the summer of the previous year (Johnson 1980). For most Arctic char that do not go to sea the summer prior to spawning, the energy lost due to overwintering alone can be significant. Dutil (1986) observed that nonspawners from the Nauyuk Lake system, nearby my study area, experienced a 30% loss in condition over the 10-month overwintering period. Postspawners contained as much as 46% less energy than nonspawners after spending two winters and a summer in fresh water. Postspawners were not able to recover this lost energy in one summer at sea, thus preventing them from spawning 2 yr in succession (Dutil 1986).

The Sr pattern in the otolith nucleus indicative of a summer feeding migration to the sea prior to spawning was seldom observed in Arctic char utilizing spawning grounds distant from the sea. This is likely related to energy as well. The cost of migrating to sea in terms of time and swimming energy expended may be more than the energy gained during a short feeding foray in the sea the summer prior to spawning.

The direct relationship between the Sr concentration in the otolith nucleus and that of the waters of the respective spawning ground suggests that the female parents of these char spent some time on the spawning grounds prior to spawning. The Sr concentration in the early growth zones of the otolith, formed after the yolk sac was

depleted and exogenous feeding had begun, also reflected that of the respective spawning ground. At this stage of development, otolith Ca, and most likely Sr, originate from ions taken up by the gills (Simkiss 1974) and are thus a reflection of the Sr concentration of the surrounding environment. These young char are not very mobile and likely confine their movements to the spawning grounds themselves. Many of the Sr profiles of these spawners show a remarkable consistency in otolith Sr concentration from the nucleus almost until they make their first migration to the sea. This suggests that they remain for a relatively long time (years) in waters with a Sr concentration similar to that of the spawning grounds. The Sr concentrations in the early otolith growth zones of Arctic char that displayed elevated Sr concentrations in the nucleus were lower than those in the nucleus and matched the Sr concentrations in the waters of the spawning grounds. Therefore, a more reliable measure of the relationship between otolith Sr concentration and Sr concentration of waters of the spawning grounds can be made by examining the early otolith growth zones formed just after yolk absorption. Indeed, this is what I measured for all spawners in this study.

The phenomenon of homing to natal spawning sites has great adaptive significance (Northcote 1978; Horrall 1981) and is widespread among both freshwater and marine species (Leggett 1977). It (1) maximizes reproductive success by synchronizing the return of mature individuals to proven spawning grounds that provide optimal conditions for egg and larval development; (2) regulates the number of adults using the spawning ground and thus prevents over- or under-utilization of a given area; and (3) facilitates reproductive isolation that contributes to the development of stock-specific adaptations to a particular habitat (Leggett 1977). Homing to natal spawning sites

for reproduction is well documented among salmonid fishes (Quinn 1993, and references therein). Homing of nonanadromous Arctic char to the natal site is also well documented (Alm 1951; LeCren and Kipling 1963; Frost 1963; McCleave et al. 1977). As Johnson (1980) points out, it seems unlikely that these nonmigratory char evolved the capacity to home since their isolation after the last glacial event. Most likely they inherited this behaviour from their anadromous ancestors. Homing has been documented in other closely related anadromous chars as well. Anadromous Dolly Varden are known to home with a high degree of fidelity to their natal stream to spawn (Armstrong 1974; Armstrong and Morrow 1980; Bernard et al. 1995).

Straying can be defined as the migration of mature individuals to spawn in locations other than their natal site (Quinn 1993). Straying is important because it allows for the exploration of new environments (Johnson 1980) and the colonization of new habitats (Milner 1987; Milner and Bailey 1989). Straying can be influenced by events that affect the water quality of the home stream (Quinn 1993). Stream blockages, including very low water levels, are obvious barriers that can affect the spawners return to natal spawning grounds. Pollution is another factor that can influence the degree of straying and there appears to be a positive correlation between the amount of straying and age, as has been observed in chinook salmon, *Oncorhynchus tshawytscha* (Quinn and Fresh 1984). Natural stream blockages in the study area do not appear to be common due to the low-lying nature of the surrounding topography. However, lowering water levels as a result of isostatic rebound over a long period of time, have the potential to increase the incidence of straying. No doubt this phenomenon has led to the colonization of new river systems since the retreat of the last glaciation. Pollution can be a problem, particularly in

some of the streams and rivers that are located near communities. However, given the evidence of stock structuring presented here, it appears that straying among anadromous Arctic char stocks in the study area in recent time has not been significant.

Two additional observations based on Sr concentrations in the early growth regions of otoliths of spawners are the incidence of nonanadromous Arctic char in the spawning sample, and the relative young age of spawners from two locations. First, nonanadromous Arctic char composed 71 percent of the Lady Pelly Lake spawners and 35 percent of the Anderson Bay Lake 1994 spawners. Access to the sea from both of these lakes is difficult, particularly in low water years. It is possible that both of these stocks are in the process of becoming landlocked. Second, few spawners over the age of 14 years were observed in the samples from Halovik Lake 1993 and Mount Pelly Lake 1993. This could be a reflection of stock-specific overexploitation, particularly for the Mount Pelly Lake stock, discussed later.

Evidence of Mixing During Overwintering

The Upstream Migration

The fall upstream migration into freshwater is primarily a migration to suitable overwintering areas. However, it is also a spawning migration for those char that will spawn that autumn or the autumn of the following year. Diadromy, the movement of fishes between fresh and marine waters, evolved because the gain in fitness (reproductive success × survivorship) from using a second habitat minus the migration cost of moving between habitats exceeded the fitness of staying in only one habitat (Gross 1987). According to Gross (1987), the most important biological factor explaining the presence

and direction of such migrations is the relative availability of food in marine and freshwater habitats. In temperate zones, the sea is more productive than freshwaters (Gross 1987), thus anadromy is common, particularly among the Salmonidae (McDowall 1987).

Amongst the North American Salmonidae, Rounsefell (1958) classified the Arctic char as optionally anadromous and at the low end of the scale in degree of anadromy compared with the others. This is based not so much on salinity tolerance (Nilssen et al. 1997) as on the short Arctic summer. In the middle and high-Arctic, including the study area, Arctic char are limited to a marine residence of only 4-8 weeks (Johnson 1980; Dempson and Kristofferson 1987; Gulseth and Nilssen 2000). In the presence of ice, Arctic char are able to resist freezing down to a temperature of –0.99 ° C, and in the absence of ice to a temperature of –1.2 ° C (Fletcher et al. 1988). However, winter seawater temperatures below –1.7 ° C, such as those reported off the coast of Labrador (Nutt and Coachman 1956), would likely be lethal to Arctic char. Therefore, they must return to fresh water to avoid freezing (Johnson 1980).

Heterogeneity in Genetics, Morphology and Otolith Strontium Concentrations in Samples from Upstream Migrations

I present evidence that the upstream overwintering migrations of anadromous Arctic char in the study area are comprised of an admixture of char from different stocks. This evidence is based on genetics, morphometric heterogeneity and variation in the Sr concentrations of otolith nuclei of the returning migrants. Consequently, I reject the null hypothesis that the upstream migration of anadromous Arctic char in river systems within the study area is comprised of individuals from a single homogeneous population. I

accept the alternate hypothesis that this upstream migration is comprised of individuals from an admixture of more than one discrete population.

The nonsatisfaction of the Castle-Hardy-Weinberg equilibrium when allozyme analysis was conducted on a sample of the upstream run in the Ekalluk River in 1992 is indicative of an admixture of stocks with different allele frequencies. Bernatchez et al. (1998) found nonsatisfaction of Castle-Hardy-Weinberg equilibrium of microsatellite gene frequencies within samples of upstream migrant anadromous Arctic char from a number of systems along the Labrador coast. They concluded that their samples represented an admixture of char from different populations that interchange among rivers for overwintering.

The 1992 Ekalluk River sample discussed above also showed considerable heterogeneity in meristic counts when compared with the other samples of the Ekalluk River upstream runs examined here. As well, evidence from the cluster analysis indicates that some samples of the upstream migrations I examined are comprised of Arctic char that differ in morphology. In many cases, the majority of the sample appears to form a morphologically similar cluster, although outliers are present in most of these samples. Most of these samples were taken in one or two days of fishing and could have consisted mostly of members of a single stock. This would suggest a temporal structure to the return migration of each stock. However, samples from the upstream run taken over a period of 16-30 days (Freshwater Creek 1988, 1991, 1994) appear to be composed of a number of morphologically different groups. For example, the Freshwater Creek 1991 upstream migration contains three morphologically distinguishable clusters. When these individual clusters were compared (discriminant function analysis) with the 1992 and

1993 samples of spawners from this system, only one cluster appeared to be morphologically similar to the 1993 sample of spawners.

The greater variation in Sr concentrations in the early growth region of the otoliths in the samples of returning migrants is obvious when compared with that seen in the samples of spawners. This indicates that the upstream migrant sample is comprised of an admixture of Arctic char from spawning grounds that differed in water Sr concentration.

Advantages of Mixing During Overwintering

The heterogeneity apparent in these upstream migrations is caused by a number of factors. The presence of at least three discrete stocks of anadromous Arctic char in the Ekalluk River system means that members of each of these stocks will participate in the annual upstream migration. Spawners will be obligated to return based on their homing behaviour. Their migration timing may overlap, resulting in a mixing of stocks during the run. This will take place in all rivers that are home to more than one spawning stock. Nonspawning Arctic char from each of these stocks will also be returning to fresh water and the timing of their migrations can overlap as well. Itinerants from other systems can also be a part of this upstream migration. During their limited time at sea, Arctic char movements are probably influenced by the spatial and temporal distribution of food items. This search for food might bring some char far from their home stream at the end of the summer. If they are not in condition to spawn the following year, the presence of a significant outflow of freshwater at a river mouth, in addition to the scent and presence of conspecifics upstream may signal a safe haven (Johnson 1980). Entry into this system to

overwinter would save the char the energy of migrating to the home stream and perhaps the risk of being trapped in the sea.

Arctic char tagged on the spawning ground in one river system have been recaptured overwintering in another river system in a later year (Kristofferson unpublished). Gyselman (1994) found overall fidelity of tagged Arctic char to the Nauyuk Lake system to be low (53 %). However, upon closer examination, he found that there was a high-fidelity group that were previously tagged that had a return rate of 70-90 % and a low fidelity group, newly tagged, that had a return rate of 35-55%. He considered the high-fidelity group to be representative of the "true" Nauyuk Lake stock that reproduced in the system, and the low-fidelity group to be transients from other systems that were using Nauyuk Lake to overwinter because of its easy accessibility. Beddow et al. (1998) used radio-telemetry to study the migratory and reproductive behaviour of anadromous Arctic char in two adjacent river systems in northern Labrador. They found that spawning occurred in both river systems, but the spawners from the smaller river system (Reid Brook) migrated back to sea and then ascended the larger river system (Ikadlivik River) to overwinter within a single year. Apparently suitable overwintering habitat was lacking in the smaller river. A similar migratory pattern of spawning in a home river and overwintering in another system has been well documented for Dolly Varden (Armstrong 1974; Armstrong and Morrow 1980; Bernard et al. 1995).

The apparent complex and variable migratory behaviour of anadromous Arctic char appears to be an evolutionary adaptation for maximizing habitat utilization and survival in a harsh environment (Johnson 1980). Homing optimizes reproductive success

and overwintering in a convenient but proven system can optimize energy uptake during summer feeding forays in the sea.

Population Richness of Anadromous Arctic char

The member/vagrant hypothesis formulated by Sinclair and Iles (1988) provides a framework for studying the role of ecological processes involved in establishing spatial patterns of abundance in aquatic species. Four aspects of populations considered are pattern, richness, absolute abundance, and temporal variability. One prediction of the hypothesis is that population richness of a given species will depend upon the number of environmental settings available to the species to effect closure of the life cycle. Thus, anadromous fish species that home to a natal stream for spawning and in which eggs and juveniles rear, should be composed of numerous populations determined by the number of rivers available (Bernatchez et al. 1998). Indeed, this has been proven for species of the genus *Salmo* and *Oncorhynchus* (Davidson et al. 1989; Sinclair and Iles 1988). According to Sinclair and Iles (1988), three observations are considered important. The first is that homing to specific river systems has been convincingly demonstrated. The second is that egg and larval phases are completed within specific river systems themselves. The third observation is that there is extensive mixing of the juvenile and adult phases of the life history. Bernatchez et al. (1998) were reluctant to consider anadromous Arctic char as population rich because of their complex migration patterns and the lack of convincing evidence of homing to natal spawning grounds. They did, however, conclude that genetically distinct populations existed on a microgeographic scale.

I have presented convincing evidence of homing of anadromous Arctic char to natal spawning sites, as well as evidence that eggs and larval stages are completed within a river system, based on the Sr concentrations within the early growth zones of otoliths. Therefore, I conclude that, based on the member/vagrant hypothesis, anadromous Arctic char is a population rich species, with the number of populations not only based on the number of river systems, but also on the number of suitable spawning sites within those river systems. This information must now be used to advantage for protecting and preserving this valuable resource.

The genetic diversity of Arctic char is contained within the aggregate of all the individual populations that exist. As stated earlier, human-induced threats to the genetic diversity of Arctic char within the study area and throughout its Canadian distribution include excessive harvest and habitat destruction. Although habitat destruction appears to be localized near communities and is presently not widespread, environmental degradation resulting from mining and oil and gas exploration is a constant threat. However, the most significant threat to this species at present is excessive harvest. What follows is a suggested management approach that should be considered for the management of this valuable resource within the study area.

Implications for Management

The Arctic char is an excellent food source. Inuit populations are increasing and so is the demand for more Arctic char to meet subsistence needs. Economic opportunities are few in the Arctic and Arctic char fisheries, both commercial and sport, offer the promise of economic gain if they can be developed. These factors are contributing to an increased demand to harvest more Arctic char. However, the Arctic char cannot sustain

heavy exploitation because of its relatively slow growth, low fecundity and infrequent spawning events (Scott and Crossman 1973; Johnson 1980). Therefore, it must be managed very carefully. I discuss two management approaches that have been applied to Arctic char fisheries in the study area, and suggest a third management approach for future consideration. The first management approach is the traditional one employed by the Inuit prior to contact with European Americans. The second is the conventional fishery management approach employed by government during the development of commercial fisheries starting in the early 1960's. The third is an adaptive management approach that can be implemented under the legislated comanagement that now exists in the study area.

Traditional Management

The Arctic is a harsh environment, with long cold winters, short cool summers and a general paucity of food resources. Human inhabitants had to utilize adaptive processes and survival strategies to ensure their existence over the long term (Balikci 1968). As an example, the Inuit of Pelly Bay, formerly called the "Netsilik Eskimos", followed an annual migration circuit. In winter they relied on seals out on the sea ice. In summer they moved inland, harvesting seals along shore, and occasionally hunting caribou. In early autumn they fished for Arctic char using the stone weir or "saputit". In late autumn the Netsilik fished for char through the thin river ice. In winter, they moved again onto the sea ice to pursue the seal (Balikci 1968). The Arctic char was a very important food source and most harvesting took place during the autumn upstream migrations. In areas where Arctic char were abundant, starvation was rare (Balikci 1980). The Inuit of my study area, formerly called "Copper Eskimos", had a seasonal economic

cycle identical to that of the Netsilik (Damas 1968). Survival required that critical decisions had to be made to relocate if food sources went into decline in any particular area. The Inuit had accumulated a great deal of ecological and environmental expertise on a local level that provided them with a basis for this decision-making (Riedlinger and Berkes 2001).

An excellent example of the traditional fishery management approach that aboriginal peoples have employed is described by Berkes (1999). He observed that the Chisasibi fishers, Cree Indians of James Bay, had developed an effective fishery management practice for lake whitefish (*Coregonus clupeaformis*) and cisco (*C. artedi*) with three essential components. The first was to concentrate fishing on aggregations of fish, the second was to pulse fish intensively for a time and then move on, and the third was to harvest a range of sizes of fish. This allowed them to maximize the return for their effort by fishing concentrations of fish at the start. Catching a range of sizes of fish instead of concentrating on the large (reproductive) ones would allow escapement of spawners to ensure perpetuation of the stock(s). Moving on to other fishing locations when catch per unit of effort declined had the beneficial effect of relieving fishing pressure on a stock and allowing it to recover so that it could be fished again in the future. All three components were driven by the fishers' finely tuned ability to detect a decline in catch per unit of effort in their fisheries. They used this as an indicator of when to move on.

The Inuit have practiced similar management methods to the Cree fishers discussed above. By fishing for Arctic char at the "saputit" during the autumn upstream migration, they maximized their return for effort because Arctic char were present in

great abundance in the upstream migration and were very vulnerable to capture in the shallow Arctic rivers. The char were also in prime condition after a summer of feeding in the sea and thus presented an ideal energy-rich food source. Arctic char of a variety of sizes were captured (Balikci 1980), thus allowing escapement of some of the potential spawners. By using a highly tuned ability to detect declines in resource abundance, they would relocate to other systems before the resource was lost to them. This management approach ensured their survival up to the time of regular contact with European-Americans. Starvation is a strong selection pressure against less effective management practices.

Traditional management, as summarized by Berkes et al. (1998), is adapted to the local area and resource users themselves are the "managers". Allocation decisions are not made individually and compliance is by social sanctions. This system tends to have a large moral and ethical context and there is no separation between nature and culture. Knowledge is primarily qualitative and data gathering is diachronic (long time-series of local information). However, examples exist where traditional managers incorporate quantitative thinking and collect synchronic (simultaneously observed) data.

The Inuit of the Cambridge Bay area lived the traditional way of life of following food sources throughout the seasons until about 1946/47. The construction of the L.O.R.A.N. station at Cambridge Bay at that time served to create a wage economy (see INTRODUCTION), which led to a concentration of Inuit in the settlement and a significant change from the traditional way of life. This event coincided with a decline in the market for fox furs so relatives of those employed drifted into Cambridge Bay for extended visits. This led to a further concentration of people in the community, and more

or less meant an end to their traditional lifestyle of living off the land (Abrahamson 1964).

Conventional Management

Conventional management, in contrast to traditional management, is based almost exclusively on scientific information and methods. Data are primarily quantitative and synchronic. Conventional management takes a reductionist approach to the resource and ecological complexities and uncertainties are often ignored. Resource managers are not resource users and allocation decisions are made at a distance from the community. This has led managers in the direction of tighter government controls over fisheries, which, over time, has often become unworkable (Berkes et al. 2001a). The conventional management approach was applied to the developing commercial fishery for Arctic char in the Cambridge Bay area. Government established fishing areas, a harvest limit or quota, fishing seasons and, ultimately, a minimum mesh size limit (139 mm) for gillnets used (Barlishen and Webber 1973; Kristofferson and Carder 1980; Kristofferson et al. 1984). There were no regulations limiting the subsistence harvest.

The Arctic char resource in nearby Freshwater Creek was once abundant, which was why Inuit gathered seasonally at this "fair fishing place"(see INTRODUCTION). However, the concentration of Inuit in the settlement of Cambridge Bay meant increased fishing pressure to meet the subsistence needs of a growing population. In 1961, when the fishing co-operative was formed to begin the commercial exploitation of Arctic char in the area, the first commercial fishery took place at Freshwater Creek. However, the Freshwater Creek Arctic char fishery was already showing signs of serious depletion

(Barlishen and Webber 1973) so the commercial fishery was relocated to the Ekalluk River in 1962 (Abrahamson 1964). At the outset, an annual quota of 18 000 kg was allocated to the Ekalluk River commercial fishery (Barlishen and Webber 1973). This river-specific quota remained in effect until 1967 when area fishers petitioned the federal government for an area quota for Wellington Bay. The intention was to allow commercial fishing to take place at the Lauchlan, Halovik and Paliryuak rivers that flow into Wellington Bay, as well at the Ekalluk River. An area quota of 46 000 kg was subsequently allocated to Wellington Bay.

The economic constraints of developing a commercial fishery in this area were severe. Float-equipped aircraft were used to transport the catch from the fishing sites to Cambridge Bay and the frozen product was flown to markets in the south. In order to make a profit, fishers had to maximize the harvest and minimize the overhead. This led to a concentration of fishing effort at the Ekalluk River from 1967 to 1969. The result was a serious decline in the average size of Arctic char in the catch at Ekalluk River by 1969. The average weight of Arctic char taken in the Ekalluk River commercial fishery in 1963 was 3.9 kg. This had dropped to 1.4 kg by 1969. Consequently, the commercial fishery at the Ekalluk River was closed in 1970.

Following the closure of the Ekalluk River commercial fishery, river-specific quotas were put in effect and remain so to the present. This was based on the assumption that each river supported a discrete stock of Arctic char (Kristofferson et al. 1984). Gillnets, with a minimum mesh size of 139 mm still predominate the fishery, but a weir has been used periodically at three sites (Jayco, Ekalluk and Halovik rivers). There is no minimum size limit for Arctic char taken in the weir, although experience has shown that

the larger char are selected. These river fisheries appear to have been sustained over the years. However, in light of the results of this study, the Arctic char resource, on a stock by stock basis, might well have been utilized in a less-than-effective manner.

This study has revealed that discrete stocks of Arctic char inhabit individual river systems in the Cambridge Bay area. This information supports the current river-specific harvest limits. However, this study has also revealed that multiple stocks of Arctic char spawn and overwinter within individual river systems. Therefore, upstream migrations are comprised of an admixture of Arctic char from the different resident stocks, as well as itinerant Arctic char from other river systems that migrate in only for overwintering purposes. The present conventional management approach is based on the assumption that the fishery is targeting a homogeneous stock at each fishing site. Random samples are taken each year from the commercial harvest that is carried out on these upstream migrations. Length and age data gathered over successive years are examined annually to determine the response of the stock to certain harvest levels. These random samples likely have no biological meaning because the harvest is comprised of Arctic char from more than one stock and the proportional contribution of each stock to the fishery is unknown. Such data would not be sensitive to a decline of smaller, more vulnerable stocks and larger stocks could be harvested at less than optimal levels. Thus, utilizing these data for monitoring and modeling purposes is likely to give spurious results. Clearly, there is a need to manage these Arctic char fisheries as mixed-stock fisheries.

A number of techniques have been used to estimate stock composition in the conventional management of mixed-stock fisheries. Examples of these techniques utilize stock differences based on morphology (Messinger and Bilton 1974; Cook 1982;

Fournier et al. 1984; Friedland and Reddin 1994), enzyme electrophoresis (Utter and Ryman 1993), mitochondrial DNA (Bermingham et al. 1991) and nuclear DNA (Galvin et al. 1995). These and other techniques should be investigated in terms of their usefulness for managing mixed-stock Arctic char fisheries in the study area. However, even when this is done, the current conventional management strategy alone will likely not deal adequately with this increased biological complexity and uncertainty.

Comanagement

Fisheries need to be managed on a small ecological scale taking into account local ecological factors such as habitat and local populations that are central to the health of the whole ecosystem. Fisheries management needs to be designed to fit this smaller scale by allowing resource users to take more responsibility for management and by utilizing their local knowledge of the resource (Berkes et al. 2001a). This can be accomplished through comanagement.

Comanagement has been defined as a sharing of power and responsibility between the state and resource users in the management of natural resources (Pinkerton 1989). Comanagement as a process is flexible and participatory and provides a forum for rule making, conflict management, power sharing, leadership, dialogue, decision making, negotiation, knowledge generation and sharing, learning and development among resource users, stakeholders and government (Berkes et al. 2001a). In contrast to the conventional management approach that relies almost exclusively on scientific information and methods, and the traditional management approach that fails to take into account ecological complexities, comanagement combines the benefits of these two systems while largely eliminating the shortcomings of both. Comanagement allows

passing of responsibilities to resource users who then become accountable for their decisions. It utilizes fishers' local knowledge so that they become active participants in the development of management plans. Today in Canada, almost all of the Arctic char resource is found within the Nunavut Territory and the Inuvialuit Settlement Region of the Northwest Territories. The settlement of land claims in these areas formalized resource comanagement (Berkes et al. 2001b). The details of sharing of jurisdiction for fisheries management can be found in specific sections of the *Nunavut Land Claims Agreement* (1993) and the *Inuvialuit Final Agreement* (1984).

Well before the *Nunavut Land Claims Agreement* came into effect in 1993, a form of comanagement developed between the Government of Canada, Department of Fisheries and Oceans (DFO), and the residents of Cambridge Bay. During the late 1970's and early 1980's, DFO staff used a weir to enumerate the upstream migration of Arctic char at various commercial fishing sites in the Cambridge Bay area. Local Inuit were hired to assist in these projects and became familiar with this counting technique. Presentations of the results of these projects to community members contributed to a better understanding of what could be accomplished with this technique. Community members were well aware of the dwindling Arctic char resource in the nearby Freshwater Creek. Through the local *Ekaluktutiak Hunters and Trappers Association* (now called *Hunters and Trappers Organization*), they approached DFO with a request to enumerate the upstream migration of Arctic char in Freshwater Creek as a first step towards rehabilitation of the stock. DFO complied with this request and the upstream migration was enumerated by weir in 1982. This included a tagging program to determine the level

of exploitation, harvest by fishery (recreational, subsistence), and the seasonal distribution of the Arctic char of Freshwater Creek.

The 1982 weir project counted 9 961 Arctic char in the upstream migration (McGowan and Low 1992) and 1983 returns on the 808 Arctic char tagged in 1982 revealed an exploitation rate in excess of 12 %. A study at nearby Nauyuk Lake (Johnson 1980) indicated that this was excessive for Arctic char stocks in the area. The estimated total harvest in 1983 was just under 2 000 Arctic char. A creel census taken in 1983 (Carder 1991), combined with tag returns from the various fisheries revealed that about 46 % of the harvest was taken by the recreational fishery, 50 % by the subsistence fishery, and 4 % by the commercial fishery. In the following years, 86 % of all tag recoveries (N = 163) were made in Freshwater Creek, the sea near Cambridge Bay, or nearby Greiner Lake. The small number of Arctic char counted in the 1982 assessment convinced the residents of Cambridge Bay to develop a recovery plan for the Freshwater Creek Arctic char stock. Although it took time to implement, it appears to have been somewhat successful. Following is a summary of the comanagement steps taken by the government and the community in this regard:

Government	Community
Weir count 1982 (9 961)	Moratorium on subsistence gillnets (1988)
Tagging program 1982 (N=808)	Door-to-door harvest survey (1992, 93,94)
Creel census 1983	
Weir count 1988 (36 933)	Community monitoring to comply with moratorium on gillnets

Reduce recreational limit (1 char daily)	Continue dialogue with DFO
1991	
Weir count 1991 (39 559)	Continue dialogue with DFO
Weir count 1994 (26 150)	Concern by community on lower count

The results of the tagging study revealed that both the recreational and subsistence fisheries were targeting the Freshwater Creek Arctic char stock. This provided information to the community and government that there was a need to reduce the harvest of both fisheries. The government responded by reducing the catch and possession limit for nonnative fishers and the community implemented a ban on subsistence gillnet fishing. The locations where tagged char were captured provided the information needed to delineate the area where fishing pressure had to be reduced. The periodic counts of the upstream migration and the increase in migrant char observed in these counts provided information to community residents that their recovery program appeared to be successful. The periodic monitoring of the harvest provided evidence of compliance with the fishing restrictions. The experience described above has shown that by working together, government and the community of Cambridge Bay were able to accomplish what has been interpreted as a recovery of the Freshwater Creek Arctic char stock. In terms of empowerment, government had the authority to reduce daily catch and possession limits for non-native fishers from 4 Arctic char daily and 7 in possession to 1 daily. Although government had no regulations to limit the subsistence fishery, the community put the moratorium on subsistence gillnetting into effect and ensured

compliance through community sanctions. As a footnote, although the number of Arctic char counted in the 1994 upstream migration was less than that counted in 1991, the average size of char in the run had increased by 1994 as had the proportion of char of reproductive size.

Clearly, comanagement is not a new concept to the residents of Cambridge Bay. The legislated comanagement put in effect in 1993 by the *Nunavut Land Claims Agreement,* has provided the Inuit with government legislation and policy necessary to establish legal rights and authority frameworks for the use of natural resources including fisheries. This is critical if comanagement is to be successful (Pomeroy and Berkes 1997, Berkes et al. 2001a).

The advantages of comanagement are many, as outlined by Berkes et al. (2001a). They include a more open and transparent process which is often more economical than centralized systems. Moreover, comanagement is adaptive, allowing participants to adjust their activities based on results obtained and lessons learned. Community members understand their own situations better than outsiders do and can devise and administer regulatory mechanisms that are often more appropriate than those imposed by external regulations. Most important, comanagement allows for the maximum use of indigenous knowledge and expertise as it applies to the resource in question. This knowledge can complement and strengthen scientific information gathering and interpretation as it applies to management. Community involvement gives fishers a sense of ownership that often translates into greater compliance with management measures over the long term.

Indigenous knowledge can and does play a vital role in effective fishery management where and when it is recognized. Berkes (1998) provides an operational definition of *Traditional Ecological Knowledge (TEK)* as it is often called. It is

> " *a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through the generations by cultural transmission, about the relationships of living beings (including humans) with one another and with their environment.* "

I would not have been able to conduct this study if it had not been for the traditional ecological knowledge that the fishers of Cambridge Bay so willingly supplied me with. At the outset, I was faced with a vast area of lakes and streams, and had only a map and a vague idea of where I might locate the many spawning grounds of the Arctic char that are a critical part of this study. After explaining the need to locate the spawning grounds to these fishers, I was shown on a map where to find them and in a number of cases, I was led directly to them. I have no doubt that a great deal of additional information of this type will be made available in future if fishers are given the chance to share it. The comanagement approach provides the opportunity to significantly improve upon the conventional fishery management approach that has been applied to this fishery.

Adaptive Management under Comanagement

Adaptive management is a relatively new management approach that has developed out of concern with practical problems of fishery and wildlife management (Holling 1978). As Berkes et al. (2001a) point out, adaptive management provides an opportunity to learn from successes and failures but it also relies on systematic feedback learning. It utilizes common-sense logic that emphasizes learning-by-doing and it

eliminates the barrier between research and management. It has the advantage of systematic experimentation and the incorporation of scientific research into the overall management scheme. Adaptive management can be viewed as a rediscovery of traditional systems of knowledge and management. Although there are differences between the two, adaptive management is, in a sense, the scientific analogue of traditional ecological knowledge because it integrates uncertainty into management strategies and it emphasizes practices that confer resilience (Berkes et al. 2000).

Adaptive and conventional management of resources differ primarily in the techniques of scientific methodology (McDonald 1988). Conventional resource managers attempt to reduce complex relationships occurring in harvesting systems to simplified associations. They also accumulate large quantities of data that form the basis of conservative policies until a better biological understanding is achieved. Adaptive managers, on the other hand, recognize that complex ecological relationships exist and that they do not fully understand them. They then attempt to identify key relationships that can provide them with a measure of how the resource responds to various management practices. While both management approaches recognize the need for renewable resource management in general, they differ in their perception of the role of biological uncertainty (McDonald 1988). The conventional approach assumes that biological uncertainty is small and can be resolved through careful modeling. The adaptive management approach recognizes the uncontrolled nature of ecological uncertainties and emphasizes the need to synthesize ideas, experience and experimentation to deal effectively with this uncertainty (Walters 1986).

Walters (1986) outlines three cyclical phases in the adaptive management process:

1. Structural analysis and synthesis to identify a range of alternative management options. These must be consistent with historical experience but must also provide new opportunities for improved harvest over the long-term. Attempts are made at predictive modeling of major processes to gain a better understanding of uncertainties against which experience can be tested and expanded. These models are used as predictors of possible outcomes rather than as instruments of policy analysis and decision.
2. Key management indicators are developed systematically through the use of alternative models and basic management options identified in the first phase. This is done to gain consensus among participants about the range of future management scenarios from which optimum policies can be developed to account for existing uncertainties. This takes into account the effects that current decisions might have on uncertainties that future decision-makers will face.
3. Design and implementation of effective monitoring programs that will detect the response of a system to management intervention and allow it to adapt quickly before unexpected changes result in undue economic or social hardship.

Comanagement is adaptive because it is based on a learning process where information is shared among stakeholders. This leads to continuous modification and improvements in management (Berkes et al. 2001a). It is now up to the participants, government and the resource users, to ensure that comanagement is implemented effectively. I suggest the following outline for the implement of an adaptive management

process for comanagement of the Arctic char resource in the Cambridge Bay area. Headings are from McDonald (1988).

Phase	*Implementation Action*
Dialogue	*Conduct a community presentation of the results of this study to outline the problem. This will include a discussion of the conventional management approach, identification of management goals and the need for an alternative approach.*
Field Study and Analysis	*Identify the need to collect and analyze additional information to provide a better understanding of the biological relationships within the ecological system that relate to key questions posed by management goals. Traditional ecological knowledge can be incorporated such as identification of additional spawning grounds within river systems. Develop methods to determine the relative contributions of different stocks to a mixed fishery.*
Design of Alternative Management Actions	*Explore alternative management options, such as pulse fishing, use of weirs etc., that can be tested*

	within the range of predictive outcomes.
Monitoring and Assessment of Management Actions	*Analyze management actions in relation to observed changes in the system and in relation to outcomes predicted by ecological theory. Identify key indicators in the system (index netting of spawning aggregations) to ensure the quality of the monitoring system.*
Evaluation	*Determine likely impacts of alternative management options (modeling) in view of the different approaches taken. Identify key questions posed by the management options which initiates subsequent rounds of the adaptive management process.*

CONCLUSIONS

As stated previously, the Arctic char resource is very important to the Inuit of the Cambridge Bay area as well as to resource users in other regions of the coastal Arctic. This study has provided information that has revealed a level of complexity in stock structuring of anadromous Arctic char that was previously suspected but not proven. Discrete stocks exist both within and between river systems, and upstream migrations are composed of an admixture of these stocks. In order to preserve the genetic diversity of this species in Canada, and hence the continued availability of this resource to users in perpetuity, future management approaches must consider this. The conventional management approach as it has been applied to this fishery has proven to be inadequate. An adaptive management approach, implemented under the legislated comanagement that is now in effect throughout most of the distribution of Arctic char in Canada, offers a more effective way to preserve the Arctic char resource while simultaneously providing optimum socio-economic benefits to the resource users. It will provide an opportunity to combine traditional ecological knowledge with the results of scientific research that will ultimately lead to a better understanding of the biological complexities of this species. It will provide for management options to deal with ecological uncertainties that will undoubtedly be encountered over time. It will also provide users with the incentive to utilize this resource in the best manner possible because of their participatory role in its management. Ultimately, it will contribute to more effective management of this valuable resource.

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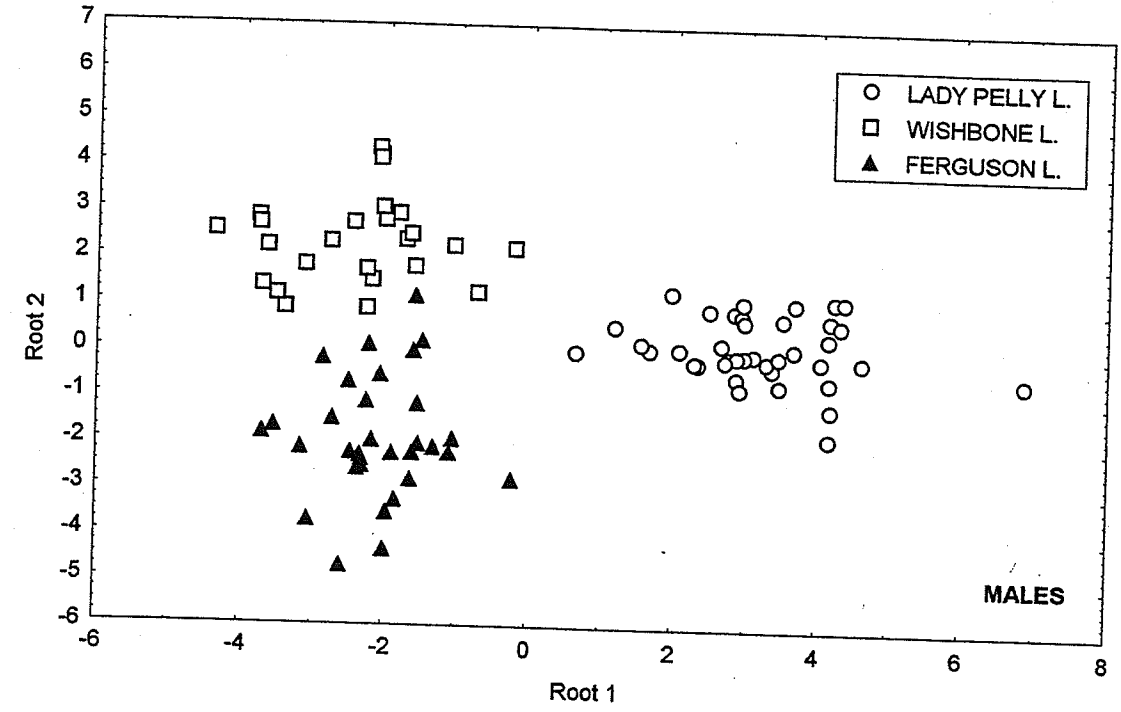
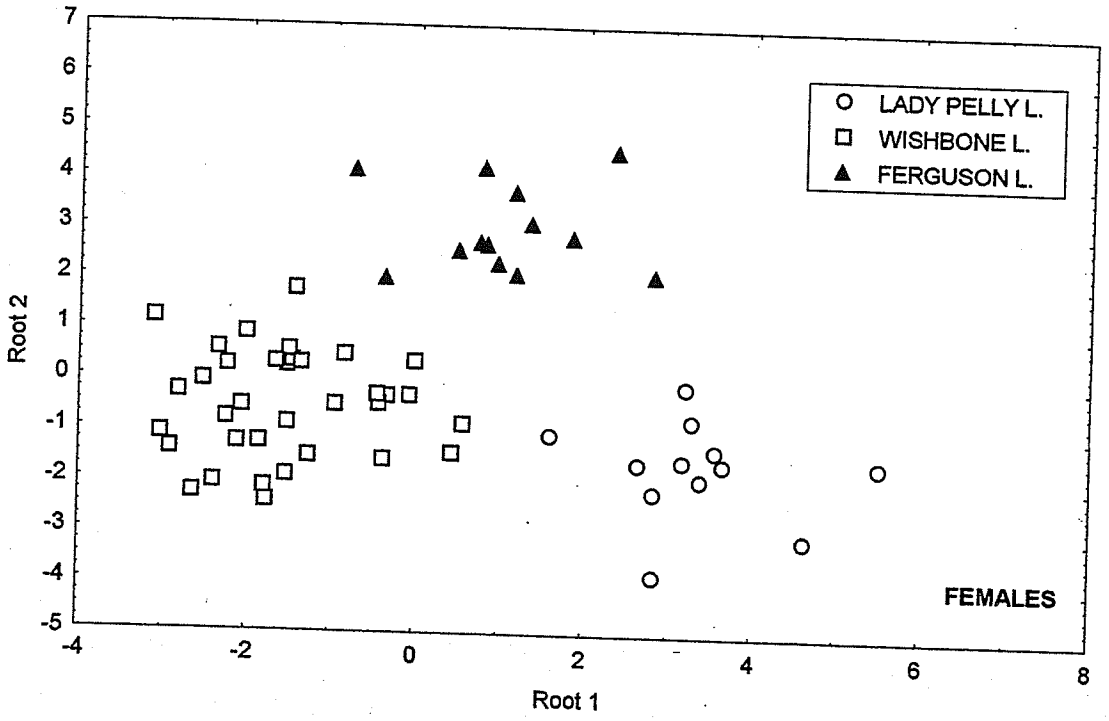
APPENDIX I

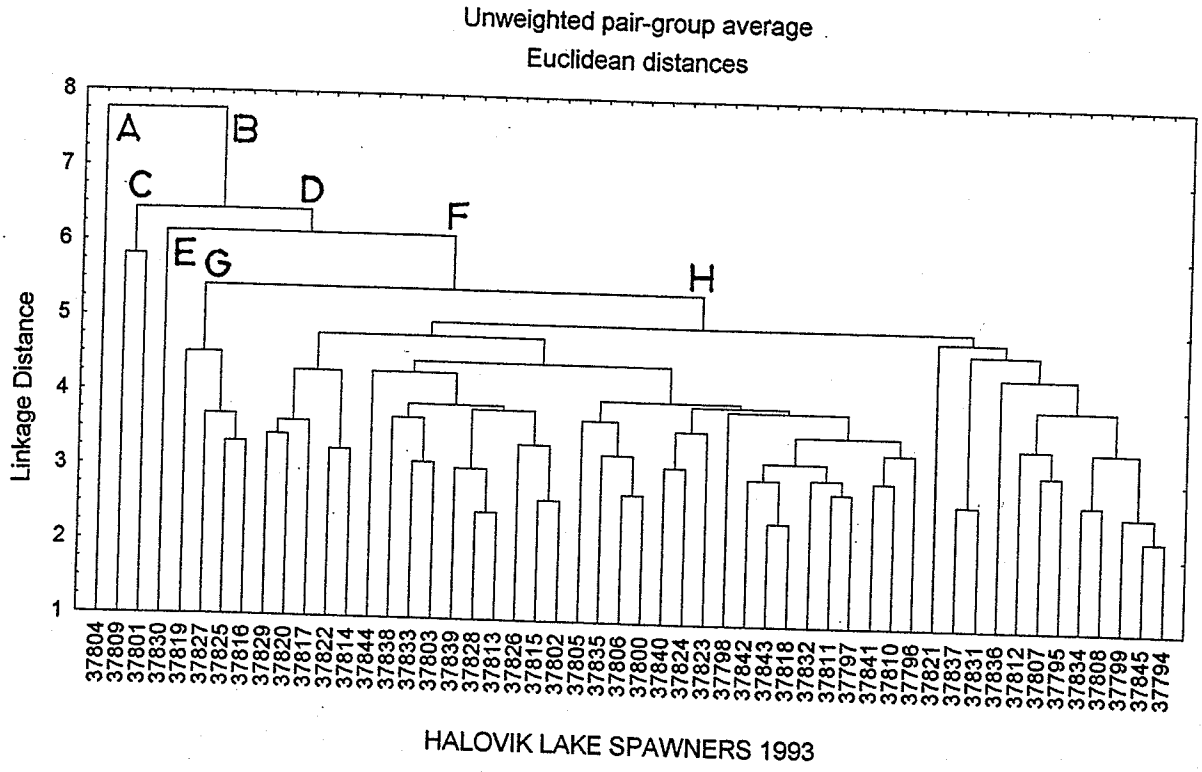
Discriminant function analysis of morphometric measurements of Arctic char from spawning aggregations taken in the Ekalluk River system from Lady Pelly Lake, Wishbone Lake and Ferguson Lake. Sexual dimorphism was evident in many morphometric measurements. Therefore, this analysis was carried out separately on **MALES** and **FEMALES.** The results are presented below and indicate that group separation is evident when the sexes are compared individually, as well as when they are compared together (Fig. 15).





APPENDIX II

Cluster analysis of morphometric measurements of Arctic char spawners taken from Halovik Lake and area in 1993. Specimens were obtained from a number of locations in and upstream of Halovik Lake (Fig. 5) and pooled to form the sample. Most of them appear to be morphologically similar and form a group as shown in cluster H. Group separation appears to take place at linkage distances between 5 and 6 in this study (Fig. 33).



APPENDIX III

Cluster analysis of morphometric measurements of Arctic char spawners taken from Char Lake in 1991. Specimens were obtained from two locations separated by about 3 km (Fig. 8) and pooled to form the sample. Most of them appear to be morphologically similar and to form a group as shown in cluster D. However, clusters E and F separate at a distance of about 5.3. While this could represent group separation, it could also be due to sexual dimorphism. Cluster F is comprised of 71 % females.